# Environmental Best Management Practices for Aquaculture

*Environmental Best Management Practices for Aquaculture* Edited by Craig S. Tucker and John A. Hargreaves

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**Edited by**

**Craig S. Tucker**
**John A. Hargreaves**

With 18 contributing authors

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# Preface

Silver minnows were devising
Water ballet so surprising. . . .

Ray Thomas (1971), *Nice to Be Here*,
Every Good Boy Deserves Favour

In 1992, a court-ordered consent decree committed the United States Environmental Protection Agency (USEPA) to a schedule for proposing and developing national effluent guidelines for new industries. As part of the consent decree, USEPA agreed to publish a list of candidate industries for rule making every two years. Five years later the Environmental Defense Fund (EDF) published *Murky Waters: Environmental Effects of Aquaculture in the United States*. In that widely read report, EDF recommended that the federal government implement the Clean Water Act for aquaculture by developing national effluent limitations. As a consequence of those two events, USEPA announced in January 2000 that it would undertake formal rule making for commercial and public aquaculture facilities. This decision resulted in a multiyear national dialogue to evaluate effluent management options for United States aquaculture facilities. Most of the authors contributing to this book were active participants in that process, serving to provide technical information and leadership.

Early in the rule-making process it became clear that best management practices (BMPs) would be a prominent feature of the new regulation. In support of this approach, a cooperative agreement was established in 2001 among USEPA, the United States Department of Agriculture Cooperative State Research, Education, and Extension Service (CSREES), and Mississippi State University to develop a guidance document that would provide USEPA with a summary of management practices for mitigating certain environmental impacts of finfish aquaculture. Eight experts were asked to contribute to the report, which was extensively reviewed in draft form by various state agencies, professional organizations, and technical authorities. The final report was submitted to USEPA in December 2003 as a white paper entitled *Best Management Practices for Flow-Through, Net-Pen, Recirculating, and Pond Aquaculture Systems*. The final aquaculture effluents rule was subsequently published in the *Federal Register* in June 2004. One year later USEPA granted us permission to use the white paper as the basis for a more comprehensive publication accessible to industry, aquaculture researchers, environmental scientists, regulators, and policy makers. Shortly thereafter, we secured an agreement to publish this book with Wiley-Blackwell, in conjunction with the United States Aquaculture Society, a chapter of the World Aquaculture Society.

This book could have been organized in many ways, but we chose to build it around six core chapters that describe better environmental management practices for aquaculture systems, rather than for individual species. There are shortcomings to any approach, but we believe that environmental performance—at least at the farm level—is tied more closely to management of the culture system than it is to the production of a particular animal. The initial focus of the white paper was on BMPs for minimizing the environmental impacts associated with effluents from aquaculture facilities. The core chapters (6 through 11) retain this focus. However, in preparing this book, we recognized an opportunity to broaden the scope by including BMPs for other important environmental impacts. Although the primary emphasis of the core chapters is on waste management, we include consideration of BMPs for disease management (in Chapter 12) and for site selection, escaped fish, predator control, and facility management, among others. The book also includes chapters on BMP development and implementation, economics of aquaculture BMPs, and BMPs for shrimp and shellfish aquaculture—all of which were absent from the USEPA white paper. We round out coverage of the topic by including appendixes that provide guidelines for monitoring programs, chemical use, and species introductions and transfers for aquaculture, among others.

Ultimately, this is a book about farm-level technical solutions. We decided very early to avoid participation in the debate about environmental issues associated with aquaculture development. Review of these issues in Chapter 1 and discussions scattered throughout the other chapters are limited to what is needed to provide context for the management practices that are the core of the book. Our decision to approach the subject in this manner was based on what we perceived to be an imbalance in the literature dealing with aquaculture and the environment. The voluminous and expanding literature on environmental impacts is not matched by a corresponding body of literature providing solutions to those problems. Those solutions are rooted in practice and in policy. This book emphasizes what we consider to be the current better farm-level practices. Although publication of this book "fixes" those practices, Jason Clay, in Chapter 2, warns that improvement must be a continuous process. As such, BMPs are best conceived as an approach—as exemplified by descriptions of current better practices—but should not represent an end unto itself, only a transitional phase to further improvement. Although many of the book's authors have experience in the policy arena, the path of policy-based solutions does not easily lend itself to generalization, and we have deliberately chosen to emphasize practices that can be implemented by large-scale or small-scale producers to improve environmental performance, with corresponding improvements in the overall sustainability of aquaculture. Despite their importance to sustainable aquaculture, we chose not to include better practices that address social impacts of aquaculture, which are often grouped with environmental impacts by critics of aquaculture. Similarly, food safety concerns are not explicitly addressed in this book, although these too have been emphasized by critics and the media as an important environmental issue. Finally, this book does not provide specific technical guidance for development of aquaculture at the sectoral or regional level—again, because these are matters of policy.

This book has been difficult to edit and we feel sure that our contributors would agree that the chapters were difficult to write. Although this book was the outgrowth of a narrowly defined project, it was developed and written against a backdrop of rapid and ongoing changes in global and national aquaculture. As our expectations for the book evolved over time, we asked our contributors to aim at a constantly elevating set of targets with respect to scope and depth of coverage. We appreciate the patience of our colleagues, all of whom probably feel that this was considerably more work than they originally agreed to.

We are grateful to all those involved in producing this book. Our contributors showed tenacity and patience, and we are proud of the collective body of work they ultimately produced. Gary Jensen deserves particular acknowledgment as the coordinator and facilitator of the original USEPA white paper, upon which this book is based. Further, Claude Boyd was instrumental in developing the concept of this book during a series of discussions in early 2005. We could easily justify including him as an editor, but we'll let his contribution to five chapters speak for his global influence on the topic of this book. We owe special debts of gratitude to Susan Kingsbury and Danny Oberle of Mississippi State University. Susan read and helped us improve each chapter manuscript and Danny was responsible for collecting, editing, and improving the quality of the photographs submitted by the contributors.

Craig Tucker and John Hargreaves

# United States Aquaculture Society Preface

The United States Aquaculture Society (USAS) is a chapter of the World Aquaculture Society (WAS), a worldwide professional organization dedicated to the exchange of information and the networking among the diverse aquaculture constituencies interested in the advancement of the aquaculture industry, through the provision of services and professional development opportunities (source: U.S. Aquaculture Society website: www.was.org/Usas/Default.htm). The mission of the USAS is to provide a national forum for the exchange of timely information among aquaculture researchers, students, and industry members in the United States. To accomplish this mission, the USAS will sponsor and convene workshops and meetings, foster educational opportunities, and publish aquaculture-related materials important to U.S. aquaculture development.

The USAS membership is diverse, representing researchers, students, commercial producers, academics, consultants, commercial support personnel, extension specialists, and other undesignated members. Member benefits are substantial and include issue awareness, a unified voice for addressing issues of importance to the United States aquaculture community, networking opportunities, business contacts, employment services, discounts on publications, and a semi-annual newsletter reported by regional editors and USAS members. Membership also provides opportunities for leadership and professional development through service as an elected officer or board member, chair of a working committee, or organizer of a special session or workshop, special project, program, or publication, as well as recognition through three categories of career achievement (early career, distinguished service, and lifetime achievement). Student members are eligible for student awards and special accommodations at national meetings of the USAS and have opportunities for leadership through committees, participation in Board activities, sponsorship of social mixers, networking at annual meetings, and organization of special projects.

At its annual business meeting in New Orleans in January 2005, the USAS, under the leadership of President LaDon Swann, voted to increase both the diversity and quality of publications for its members through a formal solicitation process for sponsored publications, including books, conference proceedings, fact sheets, pictorials, hatchery or production manuals, data compilations, and other materials that are important to United States aquaculture development and that will be of benefit to USAS members. As aquaculture becomes increasingly global in scope, it is important for USAS members to gain an international perspective on the reasons for successful aquaculture developments at home and abroad. *Environmental Best Management Practices for Aquaculture* will provide technical guidance to improve the environmental performance of aquaculture. The book addresses development, implementation, and economics of BMPs for specific aquaculture production systems in the United States but utilizes principles that can be applied globally. Written by internationally recognized experts in environmental management and aquaculture, this book will be a valuable reference for those involved in all aspects of the aquaculture industry.

Through collaboration with Wiley-Blackwell on book projects such as these, the USAS Board aims to serve its membership by providing timely information through publications of the highest quality at a reasonable cost. The USAS thanks the editors Craig Tucker and John Hargreaves for donating royalties, which will help provide benefits and services to members and to the aquaculture community, and Justin Jeffryes (Wiley-Blackwell) for his cooperation. The USAS Publications Committee members include Drs. Wade O. Watanabe (Chair), Jeff Hinshaw, and Jimmy Avery, with Ted Batterson and Jimmy Avery as immediate past and current Presidents, respectively.

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## Chapter 1

# Aquaculture and the Environment in the United States

*Craig S. Tucker, John A. Hargreaves, and Claude E. Boyd*

## The Global Demand for Fishery Products

> . . . the animals which live in the watery depths, above all in ocean waters . . . are protected against the destruction of their species at the hand of man. Their reproductive rate is so large and the means which they have to save themselves from his pursuits or traps are such that there is no evidence that he can destroy the entire species of any of these animals.
>
> Jean-Baptist de Lamarck (1908)

The oceans have historically been seen—and exploited—as an inexhaustible supply of food for human use. This perception, coupled with the concept of open access to that common resource pool, set the stage for ecological disaster. That disaster—in the form of a general collapse of commercial marine fisheries—either looms or has already become reality (see, for example, Pauly et al. 2002, 2003; Myers and Worm 2003; Caddy and Surette 2005; Worm et al. 2006). Persistent fisheries stock declines since the 1980s have been caused by a combination of factors, including increased industrial-scale fishing effort, advances in fishing technology, destructive fishing practices, and fishery management policies dictated by short-term economic interests. The result is that the number of fully exploited or overexploited stocks of marine fish is high and increasing, and the global potential for marine capture fisheries has been reached (FAO 2004c, 2006b).

Marine fisheries catch increased rapidly from 1950, reaching a peak of 80 to 85 million tonnes/year in the late 1980s. Since then, catch has been steady or even declining when corrected for presumed overreporting by China (Watson and Pauly 2001). Inland capture fisheries add about 8 to 9 million tonnes annually, bringing the total world catch from capture fisheries to about 90 million tonnes in 2003. About 30 million tonnes of the 2003 world fisheries catch was destined for nonfood uses—primarily reduction to fishmeal and fish oil for use in animal feeds. Therefore, approximately 60 million tonnes of fishery products destined for human consumption were extracted from world capture fisheries in 2003 (FAO 2004c).

Over the period 1990 to 2003, when foodfish output from capture fisheries was, at best, stagnant, global consumption of edible fishery products tripled to nearly 105 million tonnes annually. The difference between the nonexpanding supply from capture fisheries and the rapidly expanding demand was derived from aquaculture—farming aquatic plants and

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animals in oceans and inland waters. In 1980, world aquaculture production (excluding plants) was approximately 5 million tonnes, which was approximately 7% of total world foodfish supply. In 2004, nearly 46 million tonnes of fish and shellfish were produced in aquaculture (FAO 2006b), representing almost half of global foodfish production. The annual rate of increase in aquaculture production since 1980 has been approximately 10%, which is faster than that for any other animal food producing sector (FAO 2006b).

Population growth, rising per capita incomes, urbanization, and increased appreciation of the role of seafood in human health will continue to increase the global demand for seafood. Capture fisheries must provide a large part of the world's supply of fish and shellfish, but dramatic changes are needed to assure that marine resources are managed sustainably. Oceans must be protected from environmental degradation caused by pollution and global climate change, and marine fisheries must be managed intelligently to restore and maintain the oceans' biodiversity and ecological integrity. Current "best-case" scenarios for fisheries management indicate, however, that it will not be possible to increase marine fisheries landings past levels obtained in the 1980s (Pauly et al. 2003). Aquaculture must therefore continue to expand to meet any increase in demand for fishery products (FAO 2004a).

## The Changing Face of Aquaculture

Aquaculture evolved thousand of years ago as an activity with origins and goals similar to other animal husbandry activities. That is, methods were developed to provide animal protein when local human population growth or overexploitation of accessible wild populations made it difficult to obtain food by hunting—or fishing, in the context of aquaculture. Simple but elegant fish culture systems were developed in Asia that in many ways resembled natural aquatic systems in their fundamental ecosystem dynamics. For thousands of years aquaculture was practiced as a relatively low-input activity and was seen as a beneficial or, at worst, benign endeavor that provided high-quality animal protein for families or local communities. Much of current aquaculture remains rooted in these ancient practices. Countries in Asia and the western Pacific region presently account for approximately 90% of the world aquaculture production, and much of that activity is based on pond aquaculture of grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molotrix*), bighead carp (*Aristichthys nobilis*), and common carp (*Cyprinus carpio*)—the same species raised in traditional pond aquaculture in China thousands of years ago. In fact, freshwater pond culture of cyprinids for local consumption accounts for almost a third of global aquaculture production, including plants (FAO 2006b).

As aquaculture production rapidly increased in the last half of the 20th century, culture methods and technologies evolved in response to profit incentives and encouragement from aquaculture development agencies. In many instances, the goal of supplying food for local consumption changed to that of producing higher-value products for export. Associated with this trend was the use of culture practices with higher rates of resource use and greater environmental impacts than traditional aquaculture methods. The rapid expansion of aquaculture development occurred during a time of heightened environmental awareness and advocacy, and well-publicized problems in certain sectors led to closer scrutiny of aquaculture in general.

Based on real and perceived environmental impacts, some critics believe that aquaculture cannot—and should not—meet the increasing global demand for seafood. In one respect this argument is moot because capture fisheries clearly cannot grow to meet the demand. More importantly, critics of aquaculture often fail to see that aquaculture is a diverse endeavor and that a monolithic "aquaculture industry" does not exist. Culture practices and, correspondingly, environmental impacts vary widely. Further, although aquaculture is an ancient practice, little thought has been given—until recently—to the environmental impacts of aquaculture and to ways in which those impacts can be reduced. In that regard, commercial aquaculturists and aquaculture scientists are indebted to environmental groups and forward-looking members of the aquaculture industry for pointing out problems associated with certain aquaculture practices. The hope and expectation that aquaculture will meet the long-term shortfall in seafood production will be fulfilled by acknowledging and addressing the need for improved environmental performance.

Aquaculture production can, and must, increase over the foreseeable future and this expansion must be conducted in a responsible manner. Development must balance a number of difficult and, at times, conflicting issues and considerations, including consumer food preferences; short- and long-term economic benefits of aquaculture development; the role of aquaculture in rural development, trade balance, and food-supply biosecurity; and the capacity of the local, regional, and global ecosystems to support aquaculture production. Some issues will be difficult to address. For example, a common criticism of aquaculture involves the farming of high-value, carnivorous species that require considerable ecosystem support to produce. Addressing this concern will require nothing less than changing the social values of consumers in developed countries who are willing to pay relatively high prices for those products. On the other hand, many of the environmental problems ascribed to aquaculture can be addressed by changing or improving culture methods. The range of environmental impacts must be identified, and the aquaculture community must address problems by changing practices or developing new technologies to mitigate negative impacts. Significant improvements have been made in resource use efficiency and environmental performance of aquaculture, and further improvement is possible.

## Aquaculture in the United States

About 45.5 million tonnes of fish and shellfish were produced in aquaculture in 2004. Of that, 31 billion tonnes—nearly 70%—were produced in China. According to FAO (2006c), approximately 600,000 tonnes of fish and shellfish were produced in United States aquaculture in 2004. This is approximately 1.3% of global production, ranking the United States tenth in global fish and shellfish aquaculture (see Table 3.3 in Chapter 3 for a list of the top 20 aquaculture-producing nations). When China is excluded, United States aquaculture accounted for 4% of world production in 2004.

Despite the relatively small contribution to global production, aquaculture plays a significant role in United States trade and agriculture, and there is considerable incentive for further development. Per capita seafood consumption in the United States was 21 kg live weight equivalent in 2004 (NMFS 2005), which was slightly greater than the global average of about 16 kg live weight equivalent. This, coupled with a large population, makes the United States the third largest consumer of edible fisheries products in the world. Although the United States is one of the largest exporters of seafood products, it is second only to Japan as the largest importer of fishery commodities (FAO 2004b), resulting in a significant international trade deficit. In 2004, the United States imported $11.2 billion dollars of fish and shellfish products while exporting $3.8 billion, for a trade deficit of approximately $7.4 billion, which increased to more than $8.8 billion in 2006. In 2006 the trade deficit in fish and shellfish products was the 24th largest trade deficit item for all commodity groups and was the largest deficit item for any agricultural commodity. As with the global situation, United States seafood demand will continue to increase as a result of population growth and increased emphasis on eating seafood as part of a healthy diet. Assuming that desirable local, regional, and national economic and food security benefits accrue from producing fishery products rather than importing them, domestic aquaculture production should grow to meet the increasing demand for seafood by consumers.

### *Production*

The United States has a varied geography and climate, providing opportunities for a diverse aquaculture industry. Physical resources in the United States make it possible to raise fresh-, brackish-, or saltwater organisms from tropical, temperate, and arctic climates. At least 50 aquatic animal species are grown in commercial scale (USDA-NASS 2006), and probably at least that number again are raised for local use, recreation, developmental aquaculture, or research. Reported sales of aquaculture products in the United States exceeded $1 billion in 2005 (USDA-NASS 2006). Estimates of aquaculture production by weight vary among the various data-collecting organizations and range from about 450,000 to more than 600,000 tonnes for the 2003–2005 period (NMFS 2005; FAO 2006a, b, c; USDA-NASS 2006). Variation in reported aquaculture production depends on the basis for reporting shellfish harvest weights (live weight or meat weight only) and the extent to which species produced in “miscellaneous” aquaculture are included in the database.

Although many aquatic species are grown in the United States, production is skewed toward freshwater and a relatively small number of species (Table 1.1). Based on USDA-NASS (2006) figures, freshwater aquaculture contributes about 70% of total United States aquaculture production by weight and about 60% by value. One fish—channel catfish (*Ictalurus punctatus*)—accounts for almost 60% of total production by weight and nearly 45% by value.

Aquaculture production was reported from every state in 2005 (USDA-NASS 2006). Production is, however, unevenly distributed (Fig. 1.1). The four deep-south states of Alabama, Arkansas, Louisiana, and Mississippi account for almost 60% of United States aquaculture production value. Channel catfish is the primary species raised in Alabama and Mississippi, and catfish and baitfish are raised in Arkansas. Louisiana has a diverse aquaculture industry with significant production of crawfish, oysters, alligators, catfish, pet turtles, and baitfish. Idaho, Washington, California, and North Carolina lead the country in trout production. Florida has a diverse aquaculture industry and is unique because the most important crop is freshwater ornamental fish, with sales exceeding $40 million in 2005.

**Table 1.1.** Principal fish and shellfish produced in United States aquaculture, 2005.

| Species | Production (tonnes) | Production (1,000 pounds) | Value (1,000 dollars) |
|---|---|---|---|
| **Finfish** | | | |
| Catfish | 276,000 | 607,933 | 429,245 |
| Trout | 27,529 | 60,636 | 65,469 |
| Ornamental fish | | | 51,297 |
| Salmon | 9,409 | 20,726 | 37,439 |
| Tilapia | 7,810 | 17,203 | 29,620 |
| Baitfish | 5,181 | 11,411 | 38,018 |
| Bass, hybrid striped | 4,980 | 10,970 | 27,655 |
| **Crustaceans** | | | |
| Crayfish | 16,313 | 35,933 | 21,143 |
| Shrimp, marine | 3,648 | 8,037 | 18,684 |
| Prawns, freshwater | 218 | 482 | 2,680 |
| Crabs, softshell | 153 | 338 | 5,588 |
| **Molluscan shellfish** | | | |
| Oysters, eastern | 55,237 | 121,668 | 39,892 |
| Oysters, Pacific | 21,342 | 47,009 | 52,710 |
| Clams, hard | 38,669 | 85,175 | 56,130 |
| Clams, Manila | 3,937 | 8,673 | 16,653 |
| Mussels | 2,560 | 5,639 | 4,990 |
| Abalone | 253 | 557 | 9,179 |

*Source:* USDA-NASS (2006).

Washington state is the fifth largest aquaculture-producing state, with well-established molluscan shellfish and Atlantic salmon farming. Other states with significant marine aquaculture include Maine, which leads the country in Atlantic salmon production, and California, Connecticut, Florida, Louisiana, Massachusetts, Oregon, and Virginia—all of which have significant shellfish aquaculture industries.

Additional information on the major species grown in United States aquaculture is found in Chapters 6 through 12. Detailed production data and summaries of United States aquaculture are available in various FAO publications (FAO 2004b, c; 2006a, b, c), the United States Department of Agriculture's Census of Aquaculture (USDA-NASS 2006), the National Marine Fisheries Service's report on Fisheries of the United States (NMFS 2005), and the report on marine aquaculture prepared by the Marine Aquaculture Task Force (2007).

## *Facilities*

The goal of this book is to provide technical guidance to improve environmental performance of aquaculture in the United States. This presentation could be arranged by species or culture system because specific impacts vary with both factors. On balance, however, many environmental issues, such as pollution, water use, predator control, and escapes are more strongly related to culture system than to species, and that is the basis for the organization of this book.

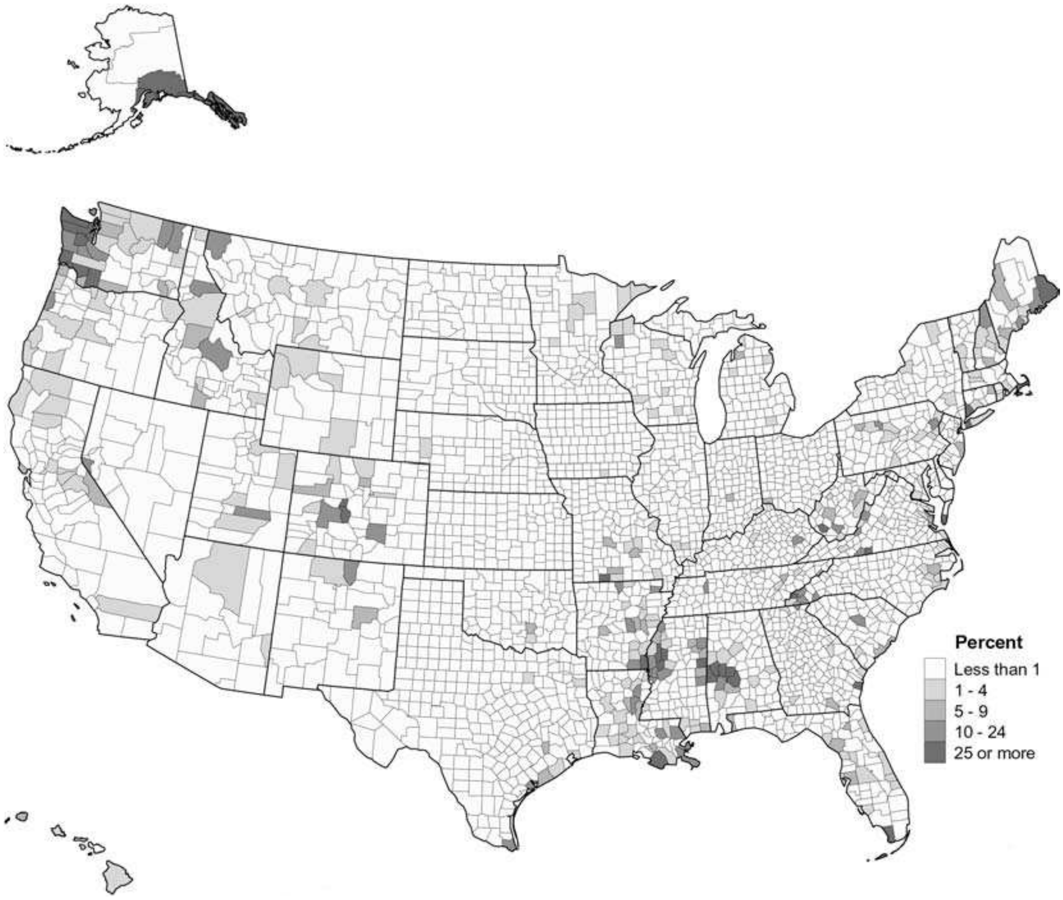

**Fig. 1.1.** County-by-county assessment of the value of aquaculture production as a percentage of total market value of all agricultural products in 2002. Note the major centers of aquaculture production in the United States: Alaska and the Pacific northwest (molluscan shellfish and salmon); Idaho and Colorado (trout); the Texas coast (catfish, hybrid striped bass, and marine shrimp); Arkansas, Mississippi, and Alabama (catfish and baitfish); Louisiana (molluscan shellfish, crawfish, catfish); central and south Florida (ornamental fish and molluscan shellfish); the Appalachian corridor (trout); pockets along the mid-Atlantic (molluscan shellfish); and Maine (salmon). *Source:* United States Department of Agriculture National Agricultural Statistics Service; available as Map 02-M032 at www.nass.usda.gov/research/atlas02

There were 4,309 aquaculture farms operating in the United States in 2005 (USDA-NASS 2006). Most farms were located in the southeastern United States, led by Louisiana with 873 farms, Mississippi with 403, Florida with 359, Alabama with 215, and Arkansas with 211. The two states outside the southeast with the highest number of aquaculture farms were Washington (194) and California (118). Although a wide variety of production facilities is used in United States aquaculture, ponds are by far the most commonly used culture system.

**Table 1.2.** United States aquaculture production by culture system.

| System | Production (% by weight) | Production (% by value) |
|---|---|---|
| Ponds | 65 | 65 |
| Net pens | 2 | 4 |
| Flow-through | 6 | 8 |
| Recirculating | 2 | 4 |
| Open-water mollusks | 25 | 19 |

*Source:* Calculated from data in USDA-NASS (2006).

### *Ponds*

Aquaculture ponds are confined bodies of standing water managed to produce a crop of finfish or shellfish. Ponds may be filled with fresh-, brackish-, or saltwater, and are usually constructed of soil, although some may be lined with plastic or other materials to reduce seepage. An important part of the definition of ponds is the long hydraulic residence time, which allows much of the waste produced during culture to be removed before water is discharged. In that regard, ponds are similar to water recirculating aquaculture systems, although water is treated in distinct unit processes in recirculating systems whereas waste treatment and aeration are inherent in the pond ecosystem.

Approximately 27 million tonnes of fish and crustaceans were produced in ponds throughout the world in 2003, representing about 70% of global aquaculture production, excluding plants (FAO 2006c). In the same year, more than 310,000 metric tonnes of fish, crawfish, and marine shrimp were produced in 140,000 ha of ponds in the United States, which was about 65% of United States aquaculture production (USDA-NASS 2006) (Table 1.2). Almost 90% of the finfish produced in the United States was grown in ponds and more than 99% of the ponds are inland, freshwater ponds used primarily to grow channel catfish, crawfish, bait and ornamental fish, and hybrid striped bass. A few hundred hectares of ponds located on the Texas coast are used to produce marine shrimp. Environmental impact management for freshwater pond aquaculture is summarized in Chapter 6; brackishwater ponds are discussed in Chapter 7.

### *Net pens*

Net pens and cages (collectively referred to here as net pens) are submerged, suspended, or floating confinement systems in which aquatic animals are grown. Net pens may be located along a shore or pier or anchored and floating offshore, either in freshwater or saltwater (Fig. 1.2). Net pens rely on tides, currents, and other natural water movements to supply oxygenated, high-quality water to farmed animals. Farms are often located in public waters leased from the government.

The use of net pens for aquaculture has grown rapidly since 1990, primarily as a result of the widespread interest in growing salmonids and other marine fish. Nevertheless, only about 15% of global aquaculture production by weight was derived from net pens and cages

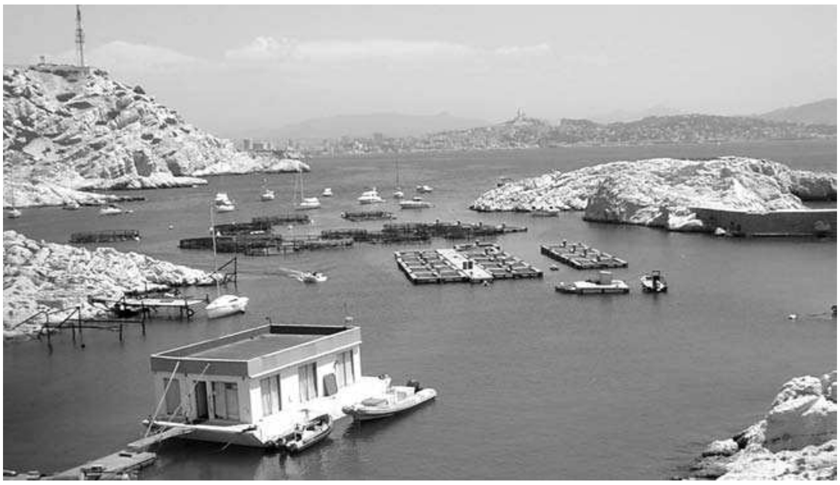

**Fig. 1.2.** Net pens for the culture of certified organic European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*) at Provence Aquaculture, adjacent to the Frioul Archipelago, approximately 6 km from Marseille, France. Photograph by John Hargreaves.

in 2003, although this represented almost 30% of production by value because net pens are primarily used to grow high-value species (FAO 2006b). In the United States, net pens are used almost exclusively to grow Atlantic salmon (*Salmo salar*), which in 2003 accounted for about 2% of domestic production by weight and 4% by value (Table 1.2). Environmental impact management of net-pen aquaculture is discussed in Chapter 8.

### *Flow-through systems*

Flow-through systems, as the name implies, are aquaculture systems with continuous water inflow and outflow. Suitable water quality for aquatic animal culture is maintained by the steady supply of oxygen in the incoming water and removal of waste products in the outflow. Culture units in flow-through systems include earthen or concrete raceways, or tanks constructed from a variety of materials. Culture units can be arranged so that water passes through each unit once without reuse or in a series where water flows by gravity from one culture unit to another. When operated in a series, water is reaerated and, possibly, treated to remove solids or other waste products before reuse in the next unit downstream. The most common water sources for commercial flow-through systems are artesian springs or water diverted from streams or rivers (Fig. 1.3). Rarely, water can be pumped from a water body, allowed to flow through the raceways or tanks, and then returned to the original body of water.

Flow-through systems are most commonly used to produce trout and other salmonids. Some warmwater species are also produced in flow-through systems, but to a much smaller extent than salmonids. Approximately 28,000 tonnes of fish, representing about 6% of total United States aquaculture production, were produced in flow-through systems in 2003 (Table 1.2). Environmental impact management for flow-through aquaculture is discussed in Chapter 9.

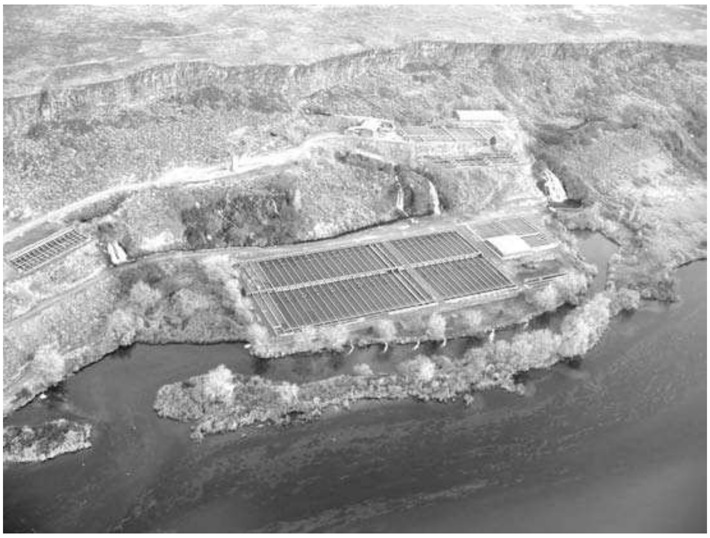

**Fig. 1.3.** The Snake River Canyon in southern Idaho is one of the most spectacular settings for aquaculture in the United States. This large flow-through aquaculture facility is used to grow rainbow trout. The facility is supplied with artesian springwater from the Eastern Snake Plain Aquifer. Several springs can be seen emerging from the canyon wall about two-thirds of the way down from the canyon rim. The water, with a year-round temperature of 15°C, is diverted through the raceways and is discharged into the Snake River in the foreground. Photograph courtesy of the University of Idaho Aquaculture Research Institute.

### *Recirculating aquaculture systems*

Recirculating aquaculture systems consist of a culture unit connected to a set of water-treatment units that allows some of the water leaving the culture unit to be reconditioned and reused in the same culture unit. Recirculating aquaculture systems minimally require water treatment processes to remove solids, remove or transform nitrogenous wastes, and add oxygen to the water. Other processes—such as temperature control, pH adjustment, gas removal, and disinfection—may also be required. Recirculating aquaculture systems minimize water use and effluent volume, and generally allow for greater control of the culture environment than is possible in other systems. However, the costs associated with construction and operation can increase the cost of producing fish. Commercial recirculating aquaculture systems are therefore used to produce relatively higher-value fish or in public facilities to produce fish for recreational stock enhancement or restoration of threatened and endangered species.

More than 75% of the annual United States tilapia production and about a third of the food-sized hybrid striped bass are grown in recirculating systems. Recirculating systems are also used in the hatchery and larval-rearing stages for several aquaculture species. Overall, about 2% of United States aquaculture production by weight derives from recirculating systems, representing about 4% of production by value (Table 1.2). Management of environmental impacts from aquaculture in recirculating systems is presented in Chapter 10.

### *Open-water molluscan shellfish culture*

Clams, oysters, mussels, and other molluscan shellfish are cultured in coastal embayments and estuaries along the Atlantic, Gulf, and Pacific coasts of the United States. Open-water mollusk culture is unique among other types of United States aquaculture because mollusks obtain their food by filter-feeding phytoplankton and particulate matter from the water, rather than being fed manufactured feeds. Although there may be some artificial feeding of larvae or juveniles in hatcheries, no feed costs are incurred during the grow-out phase and, on a net basis, mollusk culture removes nutrients and organic matter from surrounding waters.

Most oysters and clams are grown in on-bottom aquaculture, which involves seeding mollusks into prepared grow-out areas where they are allowed to mature to harvestable size. Off-bottom culture involves suspending mollusks in water column cages, racks, or bags, or attached to stakes or ropes. Off-bottom culture is not as common in the United States as it is in other parts of the world. Regardless of the method, cultured mollusks are grown in waters leased from the state; privatization through leasing provides the farmer with control over culture activities and protection of stock from poaching.

Open-water molluscan shellfish culture accounts for about 25% of United States aquaculture production by weight and 19% by value (Table 1.2). Environmental management in open-water molluscan shellfish culture is summarized in Chapter 11.

## Aquaculture and the Environment

### ***The Global Context: Human Dominance of Environmental Change***

Human activities now dominate land transformations, alterations in global biogeochemical cycling of water, carbon and nutrients, and extinctions and invasions of species (Vitousek et al. 1997). Humans appropriate most of the renewable supplies of freshwater (Postel et al. 1996), from 10 to 55% of terrestrial net primary production (Rojstaczer et al. 2001) and 24 to 35% of the net primary production from freshwater, continental shelves, and upwelling areas (Pauly and Christensen 1995). The most serious global environmental problems—climate change and loss of biodiversity—are in large measure caused by human activities. The increased demand for ecosystem services that supply food, freshwater, timber, and hydropower has been met by humans consuming a greater fraction of the available supply of these services and increasing the production of others through new technologies and expanded area, as in the case of food produced by aquaculture.

The Millenium Ecosystem Assessment (MEA 2005) focused attention on the relationship between human well-being and ecosystem services. Ecosystem services are the supporting, provisioning, regulating, and cultural benefits that humans obtain from ecosystems. Supporting services, such as photosynthesis, primary production, nutrient cycling, water cycling, and soil formation, are fundamental because they affect the ability of ecosystems to provide other kinds of services. Provisioning services are the products from ecosystems, such as food, freshwater, wood products, fiber, and genetic resources. Regulating services include climate, flood, water purification, waste treatment, and the effects of disease and pests. Cultural services include educational, recreational, aesthetic, and spiritual services.

Collectively, these services support human well-being, including the basic materials for living, personal health, security, and good social relations.

Changes to ecosystem services are affected by indirect and direct drivers. Classes of indirect drivers include demographic, economic, sociopolitical, science and technology, and cultural and religious beliefs. These in turn affect direct drivers of changes to ecosystem services. Examples of direct drivers include changes in land use, species introductions, applications of external inputs, resource consumption and harvest, use of particular technologies, climate change, and natural disasters. Two of these drivers—nutrient loading and global climate change—are expected to increase in importance in the future. The interactions among indirect drivers, direct drivers, ecosystem services, and human well-being occur across local, regional, and global spatial scales and across short- to long-term temporal scales.

For terrestrial ecosystems, the major direct driver of ecosystem change has been the conversion to cropland and the application of improved technologies that have increased the supply of food. For marine ecosystems, the major direct driver has been fishing, especially in coastal areas (about half of marine stocks are fully exploited). For freshwater ecosystems, the most important direct drivers have been flow modification of running waters, invasive species, and nutrient pollution. Coastal ecosystems are affected by eutrophication; habitat loss; invasive species; and pollution from adjacent land, upstream sources, or the marine environment. Nutrient loading in excess of carrying capacity has emerged as one of the most important direct drivers of change in terrestrial, freshwater, and coastal ecosystems. On the one hand, increased nutrient applications have resulted in increased food production, but the eutrophication that results from excess nutrients entering freshwater ecosystems has taxed the water purification ecosystem service. Increased nutrient loading has resulted in the greater frequency of harmful algae blooms, hypoxic zones, fish kills, human health problems, and damage to light-sensitive coastal ecosystems such as seagrass meadows and coral reefs. It is important to note that aquaculture can be a contributor to increased pressures on each of these ecosystems, but it can also be affected by a driver in a general way.

The MEA (2005) found that 60% of ecosystem services examined (15 of 24) are being degraded or used unsustainably, including freshwater supply, capture fisheries, waste treatment, and water purification. Capture fisheries and freshwater are now used at levels that exceed supply. Maximum global fish catch occurred in the late 1980s and is now declining. The mean trophic level of the fisheries catch is also declining (Pauly et al. 1998). Currently, more than 25% of fish stocks are overexploited or depleted. Much of the degradation of ecosystem services is a result of mankind's exploitation of ecosystems to meet the increased demand for food, freshwater, energy, and other natural resources. Although 60% of ecosystem services have been degraded, 4 of 24 have been enhanced, including food production from agriculture and aquaculture.

### *The Sectoral Context: The Environmental Impacts of Aquaculture*

Concern over the environmental impacts of aquaculture is a relatively recent phenomenon. Aquaculture has a long history, particularly in Asia, and during most of this time, the environmental effects of aquaculture production were perceived to be acceptable. It was not until global aquaculture production increased rapidly in the 1980s and 1990s that local aquaculture industries grew sufficiently large to attract the attention of environmentalists, regulators, and consumers. In particular, the rapid growth of penaeid shrimp farming in tropical coastal ponds and salmon farming in marine net pens has stimulated concern about the environmental sustainability of these forms of aquaculture, and by extension, all of aquaculture (Pillay 2004).

The environmental effects of aquaculture are value-based, which is to say that the positive and negative effects of aquaculture are determined by societal values as shaped by factual knowledge and individual perceptions. Aquaculture has known benefits to society, such as the increased availability of high-quality animal protein, poverty alleviation, increased employment, foreign exchange earnings for developing countries, and profit for entrepreneurs and investors. Aquaculture also has societal costs, as exemplified in conflicts over access to resources and land traditionally considered to be common property or open access. Certain forms of aquaculture are also seen to be environmentally benign, or even beneficial, while others are not. For example, the aquaculture of shellfish and seaweeds can mitigate the eutrophication of coastal waters. However, most forms of aquaculture are perceived to have some adverse environmental effects.

Potential environmental effects depend on the trophic level of the cultured species, culture system type, production intensity, and extent or concentration of landscape development in aquaculture. In general, culture of species at higher trophic levels, culture systems that are more open to the environment, intensive culture systems, and high concentrations of aquaculture facilities are seen to have adverse impacts on the environment. The deleterious environmental effects of aquaculture on the aquatic environment should be seen in the context of other assaults. The intensification of agriculture (especially animal agriculture), deforestation, industrialization, and urbanization contribute to the degradation of aquatic environments. Thus, many environmental impacts have multiple causes, of which aquaculture is one possible contributor.

Environmental impacts of aquaculture can be divided into near-field and far-field effects. Near-field effects are the localized effects of aquaculture production, which are, in most cases, reversible. Examples of near-field effects are benthic disturbances beneath net-pen facilities and habitat conversion when ponds are constructed. Near-field effects have been the best-studied, primarily because they are more amenable to evaluation. Far-field effects of aquaculture are less well understood, primarily because they are often one of many sources of impact and estimating the relative contribution of aquaculture to environmental change is difficult. Examples of far-field effects are introduction of nonnative species, pathogen exchange between captive and wild populations, and effects of predator control at aquaculture facilities on wildlife populations and biodiversity. The uncertainties associated with far-field environmental effects of aquaculture are large.

Improving aquaculture's environmental performance requires solutions implemented at spatial scales ranging from individual culture units to the entire biosphere. Solutions also range from farm-level implementation of improved practices to fundamental changes in social and economic values. This conceptual distinction—where solutions to environmental problems may be characterized as either technological or value-oriented—corresponds to broader discussions of the relative roles of technocentric and ecocentric approaches to achieving sustainability of human activities (O'Riordan 1981). These themes have also been compared in the context of economic growth, where they help define contrasting views of the economics of resource depletion and the value of technology and "man-made capital" in offsetting resource degradation (Hediger 1999). Recently the concepts of ecocentrism and technocentrism have been used to help define and contrast the concepts of "sustainability" and "sustainable development" (Mebratu 1998; Robinson 2004).

Ecocentric approaches to sustainability are loosely defined by ecosystem preservation, changes in social values and lifestyles, and minimizing resource use. Issues with ecocentric-dominated solutions tend to have large spatial scales and are future-oriented. Global climate change is a familiar example of an issue requiring ecocentric-dominated solutions. Addressing climate change requires fundamental changes in social and economic values, and a highly developed concern for the well-being of future generations. Technocentricism is characterized by ecosystem conservation, technology development, and improving efficiency of resource use. Technocentric solutions to environmental problems also tend to focus on issues of smaller spatial scale and of more immediate concern. Although these distinctions have been widely discussed, refined, and debated—especially in the literature of ecological and social economics—it should be clear that they are artificial typologies and that the full range of environmental impacts from most human activities—including agriculture and aquaculture—can be addressed only in the context of both philosophies. For example, global climate change, while clearly a future-oriented problem requiring fundamental changes in social and economic values to address, will nevertheless rely on technology to provide, as one of many examples, alternative energy sources with lower greenhouse gas emissions.

As such, ecocentrism and technocentrism are merely viewpoints rather than alternative solutions, both of which must be integrated into a broad approach if the impacts of human activities are to be reduced so that we preserve capacity to provide for the well-being of future generations. Distinctions between ecocentric and technocentric solutions to environmental problems (and, in a broader context, as means to achieve sustainability) do, however, serve as useful counterpoints to arrange the remainder of this chapter. The following section describes impacts related to broad-scale resource use. Following that, we describe impacts that are more closely related to facility operations. Both are amenable to the improvement of the environmental performance of aquaculture through better management practices.

Addressing the basic problems related to resource use ultimately depends on shifts in social and economic values, particularly for people in the developed nations of the world. Using salmon net-pen aquaculture as an example, energy efficiency can be improved at the farm level by adopting improved technologies, such as more efficient equipment and husbandry practices that improve feed utilization, growth rate, and survival of fish. These are technocentric solutions and are important in conserving resources as well as improving the economic performance of the facility. However, the reduction in energy use (per unit protein production) achievable by adopting improved technologies is at least an order of magnitude less than the reduction achievable by farming animals from lower trophic levels, such as tilapias or carp.

Choosing to farm carnivorous aquatic species, such as salmon, is based on consumer demand and willingness to pay the relatively high marketplace price that is, in part, related to the high energy costs of production. As long as consumers are willing to pay for aquaculture products with relatively high resource-input requirements, someone, somewhere, will produce them. Radical changes in overall energy use in aquaculture will occur only when social values change (that is, consumers demand "low trophic-level fish" based on their concern for the environment) or when changing economic conditions drive up the cost of production to the point where species with high energy-input requirements become too expensive to purchase. An analogous situation exists in the argument for large-scale adoption of vegan lifestyles based on resource use and environmental impacts associated with food production. Although protein choice significantly influences agriculture's environmental performance (Goodland 1995; Goodland and Pimentel 2000; Reijnders and Soret 2003), lifestyle changes on a scale great enough to have significant impact on global energy use in agriculture are difficult to envision until induced by market pressures.

## Resource Use in Aquaculture

The major physical resources required in aquaculture are energy, land, water, and feed. All are finite and the impacts of aquaculture on resource availability depend on the overall rate and efficiency of use. Aquaculture may also impact resource availability by altering, rather than using, a resource. For example, flow-through aquaculture systems consume almost no water but they alter its quality by adding wastes produced during culture. Effects of resource alteration must be managed so aquaculture does not diminish the value of the resource for some other use.

Resources are also subject to conflicting demands on their use and, ultimately, these conflicts are difficult to address because they involve trade-offs. The fundamental question is whether the use of a particular resource in aquaculture has more social or economic value than its use in some other activity. The conflicting or alternative use might be in another food-producing sector of agriculture or it might be an environmental function, such as the biodiversity afforded by a wetland that is being considered as a site for an aquaculture facility. Some conflicts can be addressed through technology or improved management, but many are resolved only through economic incentives and market mechanisms, changes in how society values a resource, or development of environmental policies or regulations by governments or other institutions.

### *Energy*

Aquaculture, as is true of agriculture in general, is a process whereby solar and fossil fuel energy are transferred from the environment into the culture system and converted into food energy. Although this concept oversimplifies the process because it ignores nonenergy aspects of food quality, it is conceptually useful because most inputs to food production can be expressed in energy units, thereby making it possible to compare resource use among various aquaculture and agriculture production systems. For example, water use can be converted to energy units by quantifying the energy used to pump water, as well as the energy required to build and install pumps, pipes, and other infrastructure related to the water supply. Quantifying energy use across various aquaculture production activities (production of juveniles, facility construction, feeds and feeding, labor, processing, and so on) also provides a means of identifying production inefficiencies where alternative practices may lead to energy and costs savings.

The two primary energy sources for aquaculture are solar radiation and fossil fuels. No aquaculture system relies entirely on solar radiation, although sunlight is ultimately the major source of energy for all agriculture because plant material produced in photosynthesis is the base for nearly all food chains. But even in extensive cultures of seaweed and other aquatic plants where solar energy fully supports crop growth, fossil fuels are expended in functions such as harvesting and processing. Likewise, certain types of shellfish aquaculture can be highly energy efficient because filter-feeders grow by consuming phytoplankton swept past the beds or farms by tidal currents, but fossil fuel expenditures are made in the hatchery, harvesting, and processing phases of production and human labor is required during production, harvesting, and processing.

Traditional pond aquaculture, as originally practiced in China, relied heavily on solar energy incident on the culture system to provide food, via photosynthesis, to support fish production. Primary production was enhanced by fertilizing the system with plant nutrients derived from terrestrial plants, animal manures, or processing by-products of agricultural crops. Two or more fish species, usually carp, were cultured together (*polyculture*) to make efficient use of the variety of natural foods produced within the pond. As originally conceived, fish were locally consumed as fresh product, which reduced energy costs for transportation and eliminated energy costs for storage.

In the last half of the 20th century, global aquaculture transitioned from low-input systems relying heavily on solar radiation incident on the culture facility to systems requiring greater imports of energy from other sources. The goal of aquaculture shifted from low-intensity subsistence production of diverse species to intensive aquaculture focused on maximizing economic benefits through increased yields. As the goals of aquaculture changed, aquaculture systems increasingly relied on fossil fuels and appropriation of fixed solar energy from other ecosystems.

### *Energy inputs*

Energy used in fisheries and aquaculture can be categorized as 1) ecosystem support; 2) direct energy inputs, and 3) indirect or embodied energy (Troell et al. 2004; Tyedmers 2004). *Ecosystem support* accounts for solar energy fixed in other ecosystems and then "imported" to the aquaculture system. An example of ecosystem support is the solar energy used in photosynthesis to produce soybeans and other plant feedstuffs that are used in manufactured feeds. Similarly, photosynthesis by marine phytoplankton is the base of the food web culminating in pelagic marine fish harvested for fishmeal and fish oil. Ecosystem support also includes energy used by natural processes to assimilate wastes produced during culture. For example, waste nitrogen and phosphorus produced during aquaculture may be discharged to a wetland where they are assimilated by plants. A certain amount of solar radiation and ecosystem area is needed to support the plant growth required to assimilate those nutrients. In general, aquaculture systems relying on manufactured feeds to support production (which includes much of finfish aquaculture in the United States) and those systems that discharge directly to public waters (net pens and flow-through systems) require a large ecosystem area outside the culture system to concentrate solar radiation into the chemical energy of feedstuffs and to process and assimilate wastes produced during culture.

*Direct energy inputs* are predominantly fossil fuels and labor used to provide most other resources needed in production. Examples include easily measured farm-level inputs such as energy used for pumping water and mechanical aeration. Other direct energy inputs are not so obvious. For example, a significant input to many types of aquaculture is fuel and labor used by farms and mills to produce and then process plant feedstuffs into aquafeeds (Box 1.1). Another important set of energy inputs is the fuel, electrical energy, and labor used by fishing fleets and fish reduction plants to provide fishmeal. Direct energy inputs are highest for culture systems that rely on high-quality aquafeeds and in recirculating aquaculture systems where waste processing requires fossil fuel input.

*Indirect energy inputs*, also called *embodied energy inputs,* account for the energy needed to construct and maintain tanks, nets, ponds, buildings, pumps, aerators, boats, and

### BOX 1.1
### Diet Composition and Salmonid Feed Energy Costs

Papatryphon et al. (2004) estimated energy costs and other impacts associated with production of salmonid feeds. This study is enlightening because it compared the energetics and impacts of producing a diet with high levels of fishmeal and fish oil with alternative diets manufactured with either a low level of fish-derived feedstuffs or none. As such, the study has relevance for species, such as catfish, that use feeds formulated with low levels of fishmeal. The study is also of interest because it is commonly believed that fish-derived feedstuffs have higher energy costs than those derived from plants (Troell et al. 2004).

The diets were isonitrogenous (40% crude protein) with 26% fat and a digestible energy content of 19.5 kJ/g of feed. The three diets compared were a high-fishmeal salmonid diet containing about 40% fishmeal and 20% fish oil, a low-fishmeal diet with 5% fishmeal and 25% fish oil, and a diet with all fish products replaced with plant ingredients (wheat, corn, rapeseed, and soybean) and plant-derived lipid (linseed oil). The low- and no-fishmeal diets were fortified with minerals dicalcium phosphate and synthetic lysine and methionine to offset deficiencies of phosphorus and sulfur-containing amino acids.

Total energy expenditures to procure and process feed ingredients and to manufacture and deliver the feed to the farm were similar for all three feeds. This is somewhat counter-intuitive because large amounts of energy are required to harvest, transport, and render marine pelagic fish into fishmeal and fish oil. This analysis, however, indicated that equally large amounts of energy are also needed to fertilize, grow, harvest, transport, and process the high-quality plant materials that substituted for fishmeal.

Papatryphon et al. (2004) also showed that relatively small improvements in feed conversion ratio (weight of feed fed/fish weight gain) had a greater effect on feed energy costs per unit fish production than did changing feed formulation from high fishmeal inclusion to all-plant protein. This demonstrates the value of farm-level practices for improving environmental performance. Note, however, that energy use is only one of several impacts associated with feed formulation. Feed-choice decisions should be based on consideration of all potential impacts, including fish performance and waste production.

other fixed assets needed to produce the aquaculture crop. Depending on the extent to which energy inputs are accounted, indirect energy costs may even include the energy and labor needed to obtain the raw materials—such as steel, wood, and plastic—used to fabricate the asset. Indirect energy inputs are highest for intensive aquaculture facilities that have significant physical infrastructure, but indirect energy inputs typically represent only a small fraction of overall energy costs of intensive aquaculture production because of the overwhelming energy inputs associated with production of manufactured feeds.

### *Life-cycle energy assessment*

Life-cycle assessment (LCA) is a scientific discipline that attempts to account for all environmental impacts of providing specific goods and services to society (Pennington et al. 2004; Rebitzer et al. 2004). Life-cycle assessment derives its name from the concept that all products have a "life" starting and ending at predefined points that set boundaries for the assessment. Product life in agriculture may, for example, begin with acquisition of raw materials (fertilizers, feedstuffs, etc.) and include production, processing, transportation, and so on. Assessments can be made on the basis of any impact of interest. For example, total contribution to greenhouse gases can be estimated for all activities involved in production and retirement of a particular product. Other commonly used impacts in LCA include eutrophication, ozone creation, ecotoxicology, carcinogen production, land use, and water use. One of the most useful, and common, bases for LCA is energy input over product life. Energy as a basis for LCA is appealing because it is the simplest and most intuitive "common currency" for comparing impacts of all activities involved in production, use, and retirement among various products, processes, or activities.

Studies using LCA methodology consistently show that the energy used to produce manufactured feeds dominates the energetics of many modern aquaculture production systems. For example, more than 75% of the total energy cost of producing Atlantic salmon in net pens is used in procuring or growing feed ingredients and manufacturing the feed (Folke 1988; Troell et al. 2004; Tyedmers 2004; Ellingsen and Aanondsen 2006). The remaining energy inputs, in order of importance, were fuel and electricity used to operate the facility, embodied energy costs (manufacture, maintenance, etc.) associated with physical infrastructure, and energy used to produce smolts. Feed production dominates energy budgets of all aquaculture systems relying on manufactured feeds, regardless of species, and overall energy use per unit protein production decreases in aquaculture systems less reliant on manufactured feeds (Troell et al. 2004).

### *Energy use in aquaculture*

The energy efficiencies of various aquaculture systems span perhaps the widest range of any agricultural sector (Fig. 1.4) (Troell et al. 2004; Tyedmers 2004). Traditional carp polyculture in ponds fertilized with agricultural by-products lies at one end of the spectrum as one of the most energy-efficient food production systems ever devised. When energy efficiency is expressed on the basis of industrial energy input per unit of edible protein energy produced, traditional carp polyculture rivals even vegetable crops for energy efficiency, with energy input/output ratios approaching 1. Most agricultural activities have energy input/output ratios much greater than 1, meaning that energy inputs during

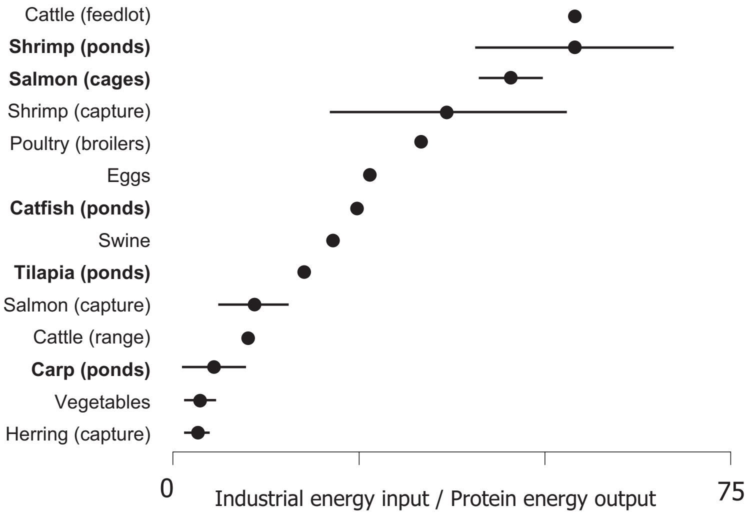

**Fig. 1.4.** Industrial energy input per unit of edible protein energy produced for several terrestrial crops and seafood produced in aquaculture (bold) or capture fisheries (Troell et al. 2004; Tyedmers 2004). Horizontal lines represent the range of values for those foods where more than one estimate is available.

production far exceed food protein energy output. Relative to traditional pond culture of carp, aquaculture systems that rely heavily on manufactured feeds and other ecosystem support functions lie at the other end of the spectrum, with energy input/energy output values exceeding 50. Nonetheless, most modern aquaculture systems are generally comparable to terrestrial animal production systems with respect to energy efficiency. For example, input/output energy ratios for pond-grown tilapia and channel catfish are similar to those for several common animal production activities, such as eggs, poultry (broiler), and swine production (Troell et al. 2004; Tyedmers 2004). Likewise, input/output energy ratios for marine shrimp aquaculture, which are among the highest of the major aquaculture systems, are in the same general range as that for shrimp trawling.

Comparing energy use in aquaculture and other forms of agriculture is difficult—and sometimes misleading—because few energy analyses of aquaculture have been conducted. Further, studies may not include adequate information on the boundaries of the analysis, which will bias comparisons among systems. Depending on the intent of the analysis, an almost endless number of input functions can be included in an LCA for an agricultural activity. Most studies of energy use include only the most easily quantified inputs, such as direct electrical and fuel inputs for the most obvious production functions (such as feed manufacture, water pumping, aeration, and so on).

Life-cycle assessment of energy use can include postharvest functions such as processing, freezing, refrigeration, storage, transportation, marketing, waste treatment, and even household activities such as refrigeration, freezing, and cooking. Energy use in these activities apparently has not been assessed for aquaculture but may be an important part of the overall energy costs of delivering aquaculture products to a consumer's plate. For example, energy used in on-farm production of the United States food supply accounts for only about 20% of the energy used to deliver food to the consumer's plate (Heller and

Keoleian 2000). Postharvest processing and transportation each consume about 15% and household preparation accounts for more than 30% of the total energy consumed. Ultimately it will be economically and socially imperative to improve the energy efficiency of all aspects of the food-supply chain. However, it is possible that greater overall gains in energy savings can be made by improving the efficiencies of processing, transport, retailing, and even household storage and preparation than can be made by improving energy efficiency in the production sector. This may have particular relevance to aquaculture, where important products are produced only in certain regions (marine shrimp in the tropics; salmon in the north-temperate) and are stored and shipped long distances for consumption.

## *Land*

Aquaculture uses land in two ways. First, aquaculture facilities occupy a defined area or space on land or in water. But facility area accounts for only a portion of the total land or water area needed to produce an aquaculture crop. Additional ecosystem area is needed to provide support or service functions. The two most important of those functions are food production and waste treatment.

### *Facility area*

The area occupied by aquaculture facilities in the United States varies widely. There are approximately 125,000 ha of commercial aquaculture ponds in the United States, with 50,000 ha devoted to channel catfish culture. Contiguous blocks of catfish ponds in Mississippi may cover several hundred hectares on individual farms. By comparison, the total United States production of Atlantic salmon is derived from only a few hundred hectares of net cages on the Atlantic and Pacific coasts.

The land or water area needed to produce a unit of aquaculture crop is inversely proportional to production intensity. Production intensity is a vague term that attempts to describe the nature of resource use in aquaculture production. A simple, and common, measure of intensity is crop yield per unit of resource use, such as land. The land or water area needed per unit production of aquaculture crop varies over more than two orders of magnitude. At one extreme are highly intensive water recirculating aquaculture systems (Chapter 10), which are capable of annually producing 1 to 2 million kg of fish per hectare of culture unit (Timmons et al. 2002). Rainbow trout production in raceways (Chapter 9) is about 10 times less intensive and therefore requires about 10 times the surface area per unit of fish production. Fish and shrimp production in ponds (Chapters 6 and 7) requires several hundred times the land area compared with intensive recirculating systems.

Differences in the relative sizes of aquaculture facilities (or, more simply, the intensity of the system) are not simply a function of one system being inherently more efficient than another. Rather, the area required to produce a unit crop yield depends on the extent to which food production and waste treatment are subsidized by ecosystems or processes external to the culture system. For example, much of the ecosystem support for traditional pond aquaculture is inherent in the system. Traditional aquaculture ponds used in Chinese carp polyculture function not only to confine fish, but also to provide an internal area for food production and waste treatment. Land requirements for pond aquaculture are therefore relatively large. In net-pen culture, on the other hand, the culture unit functions only to confine the crop. Food is produced and wastes are treated in separate, external ecosystems. As such, the relative area needed for a net-pen facility is much smaller than for ponds.

### *Ecosystem support: Food*

Many, if not most, aquaculture systems in the world rely on plant photosynthesis either within the culture unit (ponds) or in nearby waters (open-water molluscan shellfish culture) to produce most of the food that supports aquaculture production. In ponds relying on *autochthonous* (within-pond) food production, aquaculture yield is limited by the rate of primary production, which in turn is ultimately limited by the amount of solar radiation impinging directly on the culture unit. Such systems are usually fertilized with plant nutrients to make fullest use of incident solar radiation and often contain two or more herbivorous and omnivorous species to make efficient use of the wide variety of natural foods produced in fertilized ponds. Production in molluscan shellfish aquaculture depends on solar radiation over a wide area to produce natural foods that are swept past and captured by the filter-feeding organisms.

Production of herbivorous or omnivorous fish can be quite impressive (3,000 to 10,000 kg/ha per year, or more) in fertilized ponds. The food web in these systems is relatively simple, and solar energy captured by plants is transferred efficiently to fish at these lower trophic levels. To increase aquaculture productivity past that achievable in systems dependent only on autochthonous primary production, food produced outside the culture system must be imported. In some systems, that food may be low-quality organic matter that might otherwise be considered a waste product, such as agricultural by-products or livestock manures. In many aquaculture systems worldwide—and in nearly all commercial systems in the United States—the *allochthonous* (from outside the system) organic matter added to increase per-area production consists of high-quality manufactured feeds made from plant (soybean and corn, for example) and animal (usually fish) meals. Production of feedstuffs requires land external to the culture unit.

Soybean meal, wheat middlings, cornmeal, and cottonseed meal are common plant products used in aquafeeds. Boyd et al. (in press) calculated land areas needed to procure terrestrial feed ingredients to produce 1 tonne of various aquaculture species by using typical aquaculture production data, feed composition, and information from the United States Department of Agriculture (USDA 1994) for average plant seed and meal yields. Channel catfish is an example of a species grown on feeds with high levels of plant materials (>85% of the diet) and low levels of fishmeal and fish oil (<5% of the diet). Producing 1 tonne of channel catfish requires about 0.4 ha of cropland to produce plant feedstuffs. Atlantic salmon are fed diets with relatively low amounts of plant ingredients (20 to 40%) and high amounts of fishmeal and fish oil (60 to 80% of the diet). Atlantic salmon production requires a land area of about 0.1 ha/tonne for plant feed ingredients.

Marine ecosystems are required to produce small pelagic fish for reduction to meal and oil for inclusion in manufactured feeds. The appropriated marine ecosystem area can be calculated from the primary productivity of the fishing area and the trophic level of the pelagic fish captured for reduction. Values range from less than 10 to more than 100 ha of marine ecosystem area per tonne of fishmeal produced (Folke 1988; Larsson et al. 1994;

Tyedmers 2000). Assuming a value of 50 ha of marine area per tonne of fishmeal, and typical feeds and production conditions used by Boyd et al. (in press), approximately 2.2 ha of ocean area is needed to provide fishmeal to grow 1 tonne of channel catfish and about 18 ha of ocean is needed to grow 1 tonne of salmon. These values are indicative rather than definitive because marine areas needed for fishmeal production vary greatly depending on the type of fishmeal used, the productivity of the fishery, and feed conversion when fed to fish. For example, the value of 18 ha/tonne calculated here for net-pen cultured Atlantic salmon is higher than the value of 14.2 ha/tonne reported by Tyedmers (2000) and much lower than the value of 100 ha/tonne reported by Folke (1988). The qualitative implications of this exercise are 1) providing terrestrial ingredients for fish feeds appropriates relatively small areas of land whereas providing fish-derived feedstuffs requires relatively larger ecosystem support areas and 2) total appropriated ecosystem area for food production in intensive aquaculture is reduced when animals, such as channel catfish, from lower trophic levels are cultured.

Ecosystem support is often expressed on the basis of hectare of support area per hectare of culture area. When expressed in this manner, the dependence on ecosystem support varies over four orders of magnitude, depending upon culture system and feed composition. Intensive net-pen culture of carnivorous fish, such as salmon, requires an ecosystem support area for food production that is more than 10,000 times the area of the culture system (Folke 1988; Folke et al. 1998). Growing the omnivorous species, channel catfish, in ponds appropriates an area for procurement of feedstuffs that is approximately 10 times the area of the pond (recalculated from Boyd et al., in press, using additional data on ecosystem areas needed for fishmeal). At the extreme, carp, tilapia, and other fish from lower trophic levels can be grown in ponds fertilized with agricultural wastes or by-products, and do not require external ecosystem area for food production (Berg et al. 1996). Those systems have a value of 1.0 for the ratio of ecosystem support to culture area.

Open-water molluscan shellfish culture is unique in that animal growth depends on natural foods produced in marine or brackishwater ecosystems that are much larger than the culture area. Those foods are swept over the culture area by tidal currents and removed by the filter-feeding animals. In one context, mollusk culture "appropriates" food produced in an area much larger than the culture area, but this food is not cultivated and requires no additional input of resources past solar radiation and nutrients already present in the water. Natural food organisms consumed by mollusks and the nutrients that supported their growth are usually considered underutilized, and their removal from the ecosystem is seen as beneficial. Accordingly, no additional ecosystem support area should be assigned to the final grow-out phase of open-water mollusk culture.

### *Ecosystem support: Waste treatment*

With the exception of molluscan shellfish culture, all aquaculture systems use resources procured from one ecosystem, concentrated, and then added to the aquaculture system, inevitably producing waste. In addition to land area for facilities and to produce food, ecosystem area is therefore required to assimilate those wastes. In recirculating aquaculture systems and ponds operated with long hydraulic residence times, significant quantities of waste produced during culture are treated within the facility and there is relatively little external area needed for waste treatment. On the other hand, much of the waste produced in raceway and net-pen culture is discharged directly to the outside environment. The ability of the external ecosystem to assimilate those wastes may limit aquaculture production either by polluting the surrounding water to the point where animal welfare inside the facility is endangered (*self-pollution*) or by imposing regulatory constraints on the amount of waste that can be discharged. In addition to effects on aquaculture production, waste discharge into public waters may create societal externalities such as degraded water quality that limit options for use, water treatment costs, and other downstream impacts.

The ecosystem area needed for waste assimilation, expressed as hectares of waste treatment area per hectare of production facility, varies over at least two orders of magnitude, depending on the type of production system. At one extreme are aquaculture ponds with low to moderate stocking and feeding rates that can, in theory, be operated for many years without intentional water exchange to remove wastes. Natural biological, chemical, and physical processes active inside the pond remove or transform wastes at rates adequate to prevent year-to-year accumulation of potential pollutants. In theory, no outside ecosystem support area is needed to treat wastes produced during culture and, therefore, the ratio of land area for waste treatment divided by facility area is one. In other words, the pond functions as its own waste treatment facility. In practice, of course, ponds must be occasionally drained and some overflow is inevitable during periods of heavy precipitation. Nevertheless, for ponds operated with long hydraulic residence times, more than 90% of the waste organic matter, nitrogen, and phosphorus produced during culture is assimilated inside the pond before water is discharged (Tucker et al. 1996).

Internalizing waste treatment imposes a relatively high direct land cost to pond aquaculture, and this cost is evident in the large size of pond facilities (Fig 1.5). Extensive land use is the result of the pond functioning as both an animal confinement area as well as a waste treatment facility. For example, more than 95% of the total area of a catfish pond functionally acts as a photosynthetic waste-treatment lagoon and less than 5% of the total area serves as a "fish-holding" area (Brune et al. 2003). In effect, more than 95% of the

**Fig. 1.5.** Pond aquaculture requires considerable land area because support functions such as waste treatment and, in some systems, food production are inherent in the ecosystem rather than being appropriated from ecosystems outside the culture system. This catfish research facility in Mississippi covers almost 100 ha. Several catfish farms in the region have more than 1,000 ha of land converted to ponds.

land and construction costs for ponds can be assigned to waste treatment functions, and the relatively large land area occupied by a pond aquaculture facility is a price the farmer pays for treating wastes on site rather than discharging the waste to public waters. Engle and Valdarrama (2002) explored other costs (such as aeration, labor, etc.) associated with internalizing waste treatment in channel catfish ponds and calculated that almost 30% of the total cost of producing channel catfish can be ascribed to internal waste treatment processes. Land area requirements and other costs resulting from internalizing waste treatment in ponds limit profitable culture only to areas where large tracts of flat land are available at a reasonable price.

Aquaculture production in ponds is therefore limited by the finite capacity of the pond ecosystem to treat wastes produced during culture (Hargreaves and Tucker 2003). Further intensification of production is possible only if wastes are treated external to the culture unit, usually by discharging wastes to public waters. Accordingly, ecosystem area outside the culture facility is used to assimilate wastes, and in most instances the cost of that treatment is borne by society, not the aquaculturist.

Relatively few studies have been conducted to determine the external ecosystem areas needed to treat aquaculture wastes produced by aquaculture in raceways or net pens. Furthermore, requirements will vary depending on the hydrology and biology of the ecosystem into which wastes are discharged. Based on the few studies conducted, it appears that ecosystem support areas between 100 and 300 times the facility area are needed to treat wastes produced from cage and net-pen fish culture (Berg et al. 1996; Kautsky et al. 1997; Folke et al. 1998; Brummett 1999). These values for ecosystem waste assimilation area are somewhat larger, but still within the same approximate order of magnitude as the ratio of waste treatment area to fish-holding area in the catfish ponds described above. This is not a coincidence, because the same biological and physicochemical processes are responsible for waste treatment whether the water is inside a pond or in the lake, stream, or estuary in which cages are suspended. Areal requirements for waste treatment should therefore be of similar magnitude. The difference, of course, is that the ecosystem area needed for waste treatment in ponds is, for the most part, inherent in the production system, whereas waste treatment for cage and net-pen culture is external to the system.

Mollusks generate wastes in the form of feces and pseudofeces that are deposited in sediments around shellfish culture areas (see Chapter 11). Those wastes may impact the local environment and ecosystem area is required to assimilate those wastes. However, on a larger scale, mollusks are net consumers of particulates and nutrients, so in a sense, the local ecosystem area needed to assimilate wastes produced in the shellfish-growing area is less than the overall ecosystem area that would have been required to assimilate the waste in the absence of the filter-feeding shellfish. The concept of ecosystem support required to treat wastes is difficult to apply to open-water molluscan shellfish aquaculture.

### *Land-use issues in aquaculture*

Regions suitable for land-based aquaculture are limited by the right combination of climate, soil type, geomorphology, water availability, and access to other resources such as labor, markets, feeds, and larvae or juveniles for stocking. Nevertheless, land use per se is seldom a limiting factor in aquaculture development. This is particularly true in the

United States, where relatively few locations are significantly developed into aquaculture. The Yazoo-Mississippi River alluvial valley in northwest Mississippi is the most intensely developed aquaculture region in the United States, with aquaculture ponds occupying more than 45,000 ha of land. Yet ponds account for only about 2% of land use in the region. Even in sub-watersheds within the Yazoo basin with more intense development, ponds account for only 10 to 20% of the watershed (Fig. 1.6). Aquaculture development in the United States is more likely constrained by water availability, regulatory constraints on land development, or the value of land for alternative uses than by the availability of suitable land for facility construction.

At times, availability of the right combination of resources leads to localized overdevelopment of aquaculture. In this respect the problem is not necessarily the physical concentration of facilities, but rather ecological imbalances associated with the inability of the local ecosystem to provide support services, such as adequate water supply or waste treatment. A good example is the study of the ecosystem support area needed for semi-intensive shrimp farming in the Bay of Barbacoas area of Colombia, South America (Larsson et al. 1994; Kautsky et al. 1997). The estimated local ecosystem support area needed to assimilate waste nutrients from shrimp farms closely matched the mangrove area available to provide that service. Local capacity for waste treatment was used to its fullest extent and additional development could lead to self-pollution of the water supply, spread of disease, and other environmental impacts that have been associated with the collapse of shrimp farming in other overdeveloped areas (Primavera 1993).

Most problems associated with land use in aquaculture are related to the value of alternative uses of the land. These conflicts arise when aquaculture must compete with other land uses. Land-use conflicts tend to be especially acute in coastal regions, which are limited in area, have proportionately large areas of sensitive and environmentally valuable ecosystems, and are intensively used for a range of often conflicting purposes by dense human populations. Coastal regions also tend to be more commercially developed and the land more costly, especially in the United States.

Clearing mangrove forests to build ponds for shrimp and fish culture has been one of the most contentious land use conflicts in aquaculture (Primavera 1993; Naylor et al. 1998; Boyd 2002). Mangrove ecosystems have high inherent aesthetic and environmental value. They protect coastlines from erosion and flooding and provide habitat and food for a tremendous variety of aquatic, terrestrial, and avian species. Mangroves also act as natural purification systems for waters interacting at the interface of freshwater and marine environments. They are also convenient—although far from ideal—locations for brackishwater aquaculture ponds, especially for growing shrimp. In the 1980s and early 1990s, when global shrimp aquaculture was expanding rapidly, thousands of square kilometers of ponds were built in mangrove areas. Much of this land had been cleared previously for other uses, but the destruction was often attributed to shrimp farming. Although environmental advocacy groups overstated the involvement of shrimp farming in the historic loss of mangrove, worldwide awareness of the problem resulted in stricter governmental oversight of the use of mangrove forests and stimulated significant changes in shrimp production practices to protect these valuable ecosystems (Boyd 2002; FAO 2006b).

Aquaculture can affect sensitive ecosystems other than mangroves. Marine benthic communities may be impacted by net-pen aquaculture, and construction and operation of freshwater ponds can destroy sensitive wetlands. Certain types of open-water molluscan

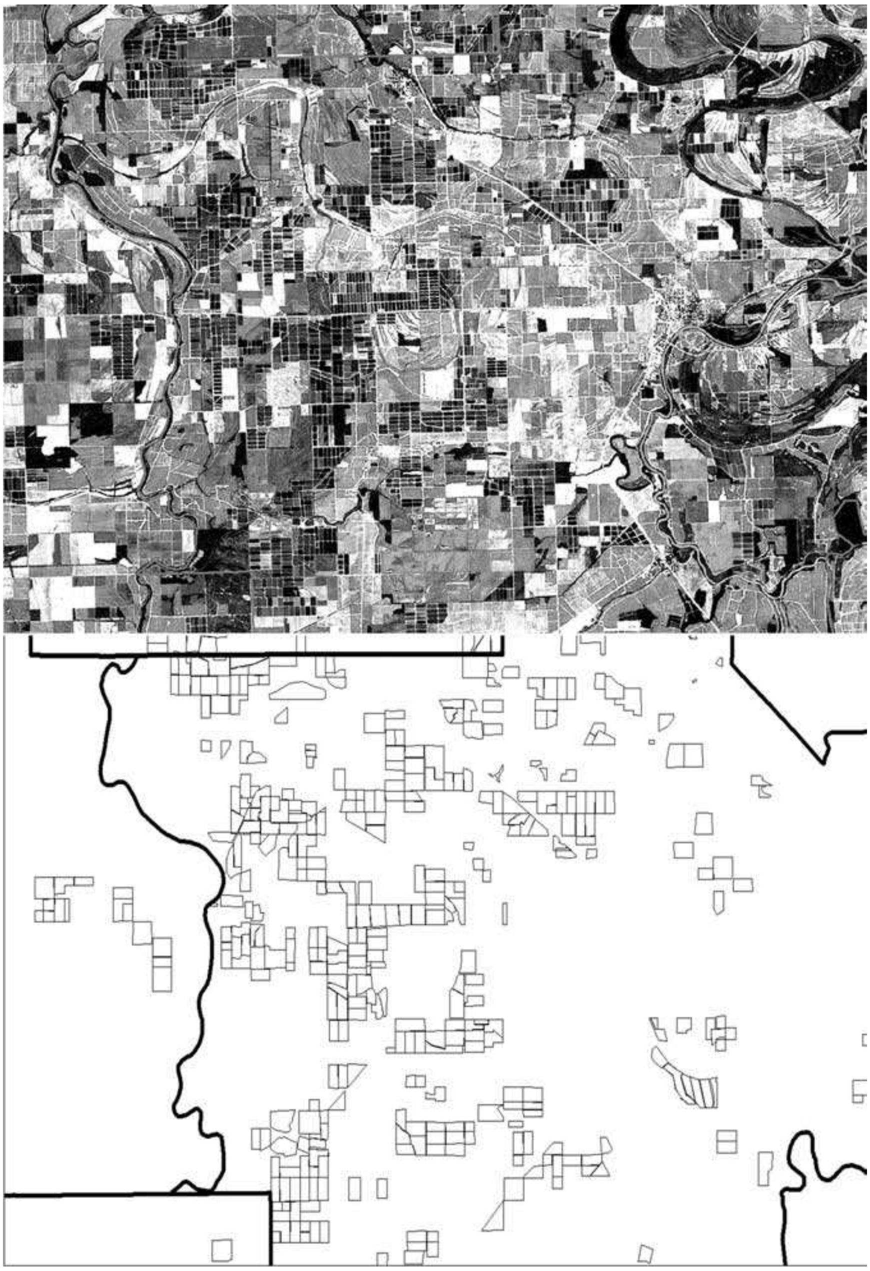

**Fig. 1.6.** Superimposable images of a 17 by 25 km block of land in central Humphreys County in the Yazoo-Mississippi River floodplain of northwest Mississippi. This is one of three areas within the floodplain with intensively developed catfish pond aquaculture. The top photograph is a satellite image showing the general landscape. The area is bounded by the Yazoo River with its oxbow lakes to the east and the Sunflower River on the west. Catfish ponds are seen as dark, regular shapes (usually rectangular) in groups of several to dozens of ponds in contiguous blocks. Most of the land is planted in cotton, soybeans, or rice. The bottom image is a mapping of pond blocks supplied with water from a common well and clearly shows the proportion of the land developed into ponds. Although this is one of the most intensively developed aquaculture regions in the United States, ponds represent less than 15% of the total land area. Photograph and map courtesy of the Yazoo-Mississippi Delta Joint Water Management District.

shellfish culture—usually viewed as an environmentally benign endeavor—can damage seagrass beds due to siltation and the mechanical effects of certain culture practices.

Marine aquaculture also faces unique conflicts unrelated to the physical area occupied by the facility or the impacts of culture activities. Conflicts may arise from competition with other users of the area or region, including activities such as tourism, shipping and navigation, capture fisheries, and urban development. Conflicts may even arise from esthetic considerations, including the effect of aquaculture development on the scenic quality of an area (the *viewscape*) and disturbances related to increased activity and noise associated with culture practices.

Nearly all problems arising from land-use conflicts in aquaculture can be avoided by prudent site selection. Better management practices for facility site selection are described in each of the production system chapters of this book (Chapters 6 through 11).

## Water

### Agriculture and water resources

Cultivated systems, including freshwater aquaculture, now cover 24% of the terrestrial surface of the planet. Most of the increase in food production in the last 50 years has been derived from agricultural intensification, not an increase in cropland area. Intensification has increased pressure on water resources (both for supply and waste treatment) and fisheries and cropland resources for feed, and it requires increased energy resources, nearly all derived from fossil fuels.

Freshwater is a scarce resource on the planet, with less than 1% of total freshwater resources available for human use. Renewable freshwater resources available for human use are derived from precipitation that falls on land. This precipitation runs off (including infiltration to groundwater) or is lost by evapotranspiration from land and water surfaces and through plants. Humans use about 10% of renewable freshwater supplies (Postel et al. 1996), although some countries use more than 100% of renewable supplies. About 40 to 50% of freshwater runoff is appropriated for human use. The available supplies of global freshwater are used by agriculture (75%), by industry (20%), and for domestic purposes (5%) (UNEP 2002).

Aquatic resources are impacted by numerous human activities. Running waters are exploited to supply irrigation and drinking water, generate electricity, and receive wastes. Running waters are also affected by land use in adjacent watersheds. Threats to running waters include alteration of habitat; changes in water chemistry; and changes in biodiversity caused by land transformations, channelization, and industrial or urban development. Standing waters provide water for agricultural, industrial, and domestic uses. Threats to standing water ecosystems include eutrophication, chemical contamination, and the introduction of invasive species.

### Water use in aquaculture

Water is an obvious and essential resource for aquaculture. No single factor influences the success of aquaculture more than availability of an adequate supply of good quality water. Availability of freshwater increasingly constrains all forms of human development, so aquaculture must compete with other uses, including irrigated agriculture, industry, and urbanization. Competition for finite water supplies is particularly acute in arid regions or where freshwater is supplied primarily from groundwater resources. Sparing water for other uses by adopting conservative water use in aquaculture is therefore a social obligation. Water use is also inextricably tied to issues of waste discharge because water input and discharge are variables on two sides of the hydrological equation: increasing water input volume will increase water volume discharged.

Water use in aquaculture may be classified as either total use or consumptive use (Boyd 2005). Total water use is the sum of all inflows (precipitation, runoff, seepage inflow, and management additions) to production facilities. Depending on the type of culture system, a portion of the water entering the facility passes downstream in overflow or intentional discharge and is available for other purposes (e.g., ecosystem support, irrigation). For example, essentially all water flowing into flow-through systems is discharged, whereas some ponds have no discharge at all. Consumptive use can be defined as water used in aquaculture that is not available for other purposes. Consumptive water use includes water lost by evaporation and seepage from an aquaculture facility, withdrawal of fresh groundwater, and water removed in biomass of aquatic animals at harvest (Boyd 2005). Water in harvest biomass averages about 0.75 L/kg, a minor quantity compared to other uses.

The requirement for water by aquaculture varies depending upon the type of culture system. Flow-through systems (such as raceways) require large volumes of water per unit fish produced. For example, water volume use in raceway culture of rainbow trout in the United States is approximately 98 $m^3$/kg (Table 1.3). The most common water supplies for flow-through systems are artesian springs or surface waters diverted from streams or

**Table 1.3.** Water use per unit aquaculture production ($m^3$/kg) for different culture systems and crops.

| | | Water Use ($m^3$/kg) | |
|---|---|---|---|
| System | Description | Total | Consumptive |
| Recirculating | Tilapia[a] | 0.1 | 0.1 |
| Pond | Channel catfish, embankment, well water | | |
| | Drained annually[b] | 6.1 | 3.7 |
| | Undrained[b,c] | 3.8 | 1.3–2.2 |
| | Channel catfish, watershed, runoff | | |
| | Drained annually[b] | 10.8 | 2.2 |
| | Undrained[b] | 10.8 | 2.2 |
| | Penaeid shrimp | | |
| | Intensive, 20% water exchange[c,d] | 40–80 | <5 |
| | Intensive, 100% water reuse[d] | <5 | <5 |
| Flow-through | United States average, rainbow trout[e] | 98 | <0.1 |
| | Unaerated raceways, rainbow trout[c] | 83–117 | <0.1 |
| | Aerated raceways, rainbow trout[c] | 17–42 | <0.1 |

[a] Timmons et al. (2002).
[b] Boyd (2005).
[c] Yoo and Boyd (1994).
[d] Hamper (2000).
[e] Hargeaves et al. (2002).

rivers. Pumping water from wells or other sources is too expensive for large-scale commercial aquaculture and is seldom used except in small public hatcheries or in commercial hatcheries that are used for only part of the year (as in channel catfish farming, for example; Tucker 2005). Water flowing into culture units provides dissolved oxygen and water flowing out carries away metabolic wastes, such as carbon dioxide, ammonia, and fecal solids. Flow-through systems are usually configured so a given parcel of water is used more than once as it flows through a series of culture units. However, without treatment of the water to add oxygen or remove products of fish metabolism, there is a limit to the number of raceway segments that can reuse the same parcel of water.

Although flow-through systems require large volumes of water, they do not consume water unless it is pumped from aquifers. Except for negligible amounts of water lost to evaporation and fish harvest, inflow equals outflow. Boyd (2005) estimated that consumptive water use in a typical trout flow-through facility is about 0.03 $m^3$/kg of production, or less than 0.05% of total water use. The common interpretation of water conservation is, therefore, meaningless in flow-through aquaculture because essentially no water is lost. However, efficiency of water use can be improved by using technologies that increase fish production per unit water flow. Although modern waste-management technologies used in flow-through aquaculture can remove a large proportion of the wastes added to water during culture, it is inevitable that some waste is discharged in flow-through system effluents. In that regard, flow-through systems "use" water because downstream ecosystems are impacted and "appropriated" for waste treatment.

Water use in net-pen culture is similar to that in raceways. Adequate water quality within net pens depends on the exchange of water from outside the unit by tidal currents or river flow. In essence, net pens are simply flow-through systems constructed in water instead of on land. Like flow-through systems, large quantities of water must flow through the culture units to provide adequate dissolved oxygen and remove wastes, but net-pen facilities do not consume water. Most of the waste produced during culture is discharged directly into public, multiple-use water bodies and, as with raceways, net pens appropriate ecosystem area for waste treatment. The impact of appropriating surrounding areas for waste treatment can be minimized through proper site selection (see Chapter 8).

In contrast to flow-through and net-pen systems, many recirculating aquaculture systems are operated with very low water exchange rates. Water within culture units is reused many times by cycling water through mechanical and biological treatment processes to add dissolved oxygen and remove solids, ammonia, and dissolved carbon dioxide. In the extreme, water is used only to replace evaporative losses (which are small) and to replace water lost when concentrated waste solids are discharged from the system. Total and consumptive water use in recirculating can be less than 0.1 $m^3$/kg of production (Timmons et al. 2002).

Water use in ponds is functionally similar to that in recirculating systems in that water quality is maintained by mechanical and biological processes. However, in recirculating systems, treatment takes place in discrete units, such as screens, filters, or settling basins, whereas in ponds the processes are inherent parts of the ecosystem. Water use in ponds varies over a much wider range that for any other aquaculture system, depending primarily on the frequency of intentional water exchange (flushing) and pond drawdowns for harvest. At one extreme, water exchange in some ponds is so frequent that the systems operate hydrologically more like flow-through systems than ponds. In the 1980s and 1990s, marine shrimp ponds were routinely operated with daily water exchange rates of 10 to 20% of pond volume, and total water use (40 to 80 $m^3$/kg of shrimp produced) (Yoo and Boyd 1994) approached that of flow-through systems. Water used for water exchange is pumped from bays or estuaries and discharged back into the same water body, so only water lost to evaporation and seepage is used consumptively. More important than water use alone, however, water exchange generates large volumes of waste, increases the risk of pathogen transfer to and from the outside environment, and increases production costs associated with pumping. Eliminating or reducing water exchange by using water-reuse technologies can reduce total water use in shrimp ponds to less than 2 $m^3$/kg (see Box 7.3 in Chapter 7).

Total water use in channel catfish farming (as an example of pond aquaculture in general) varies greatly depending on water source and phase of culture (see Chapter 6). Ponds may be filled with either watershed runoff or from wells, and consumptive use is much greater for ponds using groundwater. Consumptive use also varies among the different phases of catfish culture because fingerling ponds are drained and refilled each year whereas brood ponds and foodfish ponds are operated for several years without draining. As such, more water is used for the fingerling phase because water drained each year must be replaced. Average consumptive water use in the foodfish-production phase is relatively low (less than 2 $m^3$/kg) (Hargreaves et al. 2002) because ponds are operated for long periods without draining. However, actual water use to produce foodfish must include water used in fingerling and brood phases of culture. When annual water use in the three culture phases are added and then divided by total annual foodfish production, average consumptive water use for pond-grown catfish in the southeastern United States is approximately 3 $m^3$/kg.

Consumptive water use is much higher in ponds than for other culture systems, and significant opportunity exits for water conservation. Considerable attention is therefore given to hydrology and water conservation in Chapters 6 and 7. Additional information on pond hydrology and water budgets is available in Yoo and Boyd (1994), Boyd and Tucker (1998), Hargreaves et al. (2002), and Boyd (2005).

The relatively high economic value of water used in aquaculture (also called the *consumptive water value index*) (Boyd 2005) can be shown by comparing consumptive water use and gross economic value for aquaculture and irrigated terrestrial crops grown in the same region. Using data from the southeastern United States, channel catfish aquaculture requires more water than irrigated cotton, corn, and soybeans, but an amount comparable to rice (Table 1.4). However, the value of various crops per unit volume of water used is much greater for catfish than other crops. If this is interpreted as an index of water use economic efficiency, catfish aquaculture is a more efficient user of water than irrigated row crops.

## *Feed*

The goal of aquaculture is to manage a body of water so that it will produce more fish, crustaceans, mollusks, or other animals than it would without management. Except for molluscan shellfish culture, this is accomplished by concentrating resources to provide

**Table 1.4.** Consumptive water use and consumptive water value index for selected crops in the United States.

| Crop | Water Use (cm) | Consumptive Water Value Index ($/m$^3$) |
|---|---|---|
| Channel catfish | 50–220 | 2.12–0.39 |
| Cotton, irrigated | 46–83 | 0.26–0.12 |
| Corn, irrigated | 37–88 | 0.21–0.08 |
| Soybeans, irrigated | 24–80 | 0.20–0.07 |
| Rice | 73–123 | 0.18–0.09 |

*Sources:* Hargreaves et al. (2002) and Boyd (2005).

**Fig. 1.7.** A handful of extruded catfish feed pellets. Photograph courtesy of Danny Oberle.

food for the animal. There are two ways to provide food for aquatic animals: 1) fertilize an outdoor system to enhance natural food production and 2) grow foods outside the culture unit. The energetics and land-use issues associated with these two approaches were discussed above.

In the context of the ecosystem-level support for food production, the common aquaculture systems used in the United States range from open-water mollusk culture, with no intentional resource input to enhance food supply, to net-pen and flow-through system culture of salmonids, where animal growth is totally dependent on resource expenditures outside the culture unit. Between those extremes is a continuum of food-supply strategies. In addition to molluscan shellfish culture, several other species are grown with relatively low resource input (aside from labor). For example, crawfish ponds operated at low intensity depend on development of a detrital food web based on natural plant forage. Some baitfish and ornamental fish ponds are also operated at relatively low intensity and are fertilized to promote an abundant supply of natural foods. However, more than 95% of all commercial finfish aquaculture and 70% of total aquaculture production in the United States depends on manufactured feeds. Worldwide, manufactured feeds support approximately 40% of all animal aquaculture production (FAO 2006b).

Manufactured feeds (Fig 1.7) are formulated to provide all essential nutrients and energy needed to promote rapid growth of healthy animals. Diet composition varies widely (Table 1.5) depending on the nutritional requirements of the species cultured, cost of feedstuffs, and the relationship of feed formulation to body composition, disease resistance, and waste production. Feeds are typically formulated from a mixture of animal and plant feedstuffs (Lovell 1998). The major animal feedstuff in most aquafeeds is fishmeal derived from pelagic marine feed fish such as anchovy, menhaden, and herring. Other animal feedstuffs include poultry and beef processing by-products. The primary plant feedstuffs are meals or by-products derived from soybeans, wheat, corn, canola and rapeseed, rice, sorghum, cotton seed, or peanuts. Diets may also contain various animal and plant fats or oils to increase feed energy content, provide essential fatty acids, and reduce dust or fines produced during feed handling. Fish oil is presently an indispensable ingredient in diets for salmonids and other carnivorous finfish and is a coproduct of fishmeal production. Feeds may also contain supplemental vitamins and minerals, binding agents, or pigments. Summaries of feed formulation for most aquaculture species are provided in Lovell (1998) and Webster and Lim (2002).

**Table 1.5.** Major ingredients in typical or generalized manufactured feeds for four aquaculture species.

| | Composition of Diet (%) | | | |
|---|---|---|---|---|
| | Atlantic Salmon[a] | Rainbow Trout[b] | Shrimp[c] | Channel Catfish[d] |
| **Ingredient** | | | | |
| Fishmeal | 25–50 | 40 | 20 | 2–4 |
| Fish oil/other oil or fat | 20–30 | 12–21 | 4 | 1.5[e] |
| Poultry by-products | | 4–8 | | |
| Blood meal | | 0–5 | | |
| Squid meal | | | 5 | |
| Shrimp head meal | | | 13 | |
| Soybean meal | 0–15 | 5–10 | 25 | 24–50 |
| Corn meal/by-products | 5–20 | | | 30–40 |
| Wheat grain/by-products | 10–18 | 12–25 | 30 | 15–20 |
| Other grains/seed meals | | | | 0–10 |
| **Composition** | | | | |
| Crude protein | 35–55 | 40–45 | 35 | 28–32 |
| Crude fat | 30–40 | 15–25 | 5–10 | 4–6 |

[a] Storebakken (2002).
[b] Hardy (2002); Gatlin and Hardy (2002).
[c] Boyd et al. (in press).
[d] Robinson and Li (2002).
[e] Sprayed on finished feed to reduce dust.

### *Environmental issues associated with manufactured feed*

Two environmental issues have become associated with using manufactured feeds in aquaculture. First, wastes derived from uneaten feed and excreted nutrients are a potential source of pollution if culture water is discharged from the facility. Relationships among waste production, feed composition, and feeding practices are therefore critical to managing potential impacts of aquacultural effluents (Gatlin and Hardy 2002). Better management practices for feeds and feeding are included in each of the "systems" chapters of this book (Chapters 6 through 10).

In addition to the relationship between feed and waste production, additional concerns have been raised about the environmental impacts of procuring ingredients for aquaculture feeds. In the broadest sense, the concern is that procuring and manufacturing aquaculture feeds have impacts far beyond the culture facility. Two of these issues have already been discussed. First, feedstuff procurement, manufacture, and other associated activities consume the largest proportion of energy used in producing fish or crustaceans that rely on manufactured feeds (Fig 1.8). Second, land and sea area is appropriated from outside the facility to supply feedstuffs that are then processed and combined in a manufactured feed that is used to grow confined aquatic animals. Depending on the species cultured and the nature of the production system, the external ecosystem support area for food production may range from near zero to many thousands of times larger than that of the facility itself. Questions associated with large facility "footprints" of intensive aquaculture of carnivorous species include whether a given ecosystem can indefinitely provide resources to support aquaculture production and whether the appropriated resources have greater social or economic value with some other use. These questions are most often debated in the context of fishmeal. A larger ecosystem support area is required to produce fishmeal than terrestrial feedstuffs, and fishmeal may become limiting to expansion of certain forms of aquaculture because there is little prospect for increased global supply from marine capture fisheries.

### *The fishmeal issue*

Fishmeal is produced by cooking, pressing, drying, and milling whole fish, fish scraps, or fish-processing wastes. Fish oil is a valuable coproduct of fishmeal production. Fish and

**Fig. 1.8.** A large catfish feed mill in Mississippi. The cost, energy input, and land use associated with feedstuff procurement and feed manufacture dominate many forms of aquaculture. Photograph courtesy of Danny Oberle.

crustaceans do not have a dietary requirement for fishmeal or fish oil. Rather, aquatic animals require specific nutrients contained in the meal or oil, and in the past they were an economically favored feedstuff to provide those nutrients. Fishmeal is an excellent protein feedstuff, especially for aquaculture, because it has a well-balanced amino acid profile that closely matches the dietary requirements of carnivorous marine finfish, is highly palatable, is highly digestible, and until recently, was a relatively inexpensive protein source. Fish oil has historically been an economical source of long-chain, highly unsaturated fatty acids that are essential in the diet of carnivorous fish and crustaceans. Fish oil, as part of aquaculture feeds, is also useful in manipulating the tissue fatty-acid profile to provide higher levels of the omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Adequate dietary intake of omega-3 fatty acids by humans has been shown to reduce the risk of cardiovascular diseases and is a highly publicized benefit of increasing the consumption of seafood rich in these fatty acids.

About 85% of the global fishmeal supply is derived from capture of pelagic fish, primarily from nutrient-rich, oceanic upwelling areas of continental margins. The remainder is derived from fish scraps and processing waste (Tacon et al. 2006). Roughly 30 million tonnes of fish, representing about 23% of global fisheries landings, were reduced to about 6.5 million tonnes of fishmeal and 1 million tonnes of fish oil in 2004 (FAO 2006b). The capture of fish for reduction to fishmeal has been stable since the mid-1980s, except when Peruvian and Chilean anchovy fisheries decline precipitously from disruptions to upwelling water currents known as the El Niño Southern Oscillation. Most reduction fisheries stocks are considered fully exploited, with some stocks overexploited and some moderately exploited. There is no reason to expect increases in the global fishmeal supply.

Although global fishmeal supplies have been static since the 1980s, increased demand has caused fishmeal prices to rise. Among various users of fishmeal, the aquaculture sector has been more willing to pay the increased price and the proportion of fishmeal used by different agriculture sectors has changed dramatically. In the early 1990s, aquaculture used 10 to 15% of the world's fishmeal supply; the remainder was used primarily in swine and poultry production. In 2005, aquaculture used 53% of global fishmeal supplies and 87% of fish oil, despite aquaculture representing only 3% of total industrial animal feed production (Tacon et al. 2006).

Aquaculture is projected to consume an even larger proportion of the global fishmeal supply as farming of shrimp and carnivorous fish expands. Marine shrimp and marine finfish represent about 25% of global aquaculture production, but consume 75% of the fishmeal and fish oil used in aquaculture feeds (Tacon 2004). Also important is the large-scale change in Asian aquaculture, particularly in China, where traditional extensive pond culture of carp is rapidly giving way to carp aquaculture based on manufactured feeds containing fishmeal (Tacon et al. 2006). The potential demand for fishmeal by this aquaculture sector is immense.

Using fish in feeds for other fish has raised a concern that is often cited as possibly the most significant environmental impact of aquaculture: that is, the culture of fish and crustaceans on high-fishmeal feeds does not contribute to an overall increase in global fish production. In other words, each kilogram of farmed fish consumes more than 1 kg of feed fish in the form of fishmeal (Naylor et al. 1998, 2000, 2001; Naylor and Burke 2005).

The amount of feed fish needed to grow a kilogram of fish or crustacean in aquaculture (called the *feed-fish equivalence,* or *FFE*) is calculated from the feed conversion ratio achieved during culture (FCR = weight feed fed/weight fish produced), the percentage fishmeal in the feed, and the ratio of the quantity of feed fish required to produce a unit of fishmeal. The weight of feed fish required to produce a unit weight of fishmeal varies among species, but usually ranges from 4 to 5 (Tacon et al. 2006). Assuming that 4.5 kg of feed fish is reduced to 1 kg of fishmeal, the feed-fish equivalence is calculated as follows:

$$\text{FFE} = [(\%\ \text{fishmeal in feed} \times 4.5) \times \text{FCR}] \div 100 \qquad (1.1)$$

For example, assume 1 kg of Atlantic salmon is grown with a feed containing 35% fishmeal at a feed conversion of 1.2. The feed-fish equivalence is 1.9 kg of feed fish from pelagic fisheries. Channel catfish cultured with a feed containing 2% fishmeal and a feed conversion of 2.2 would require 0.2 kg of feed fish for every 1 kg of catfish produced. Based on these two examples, it could be argued that Atlantic salmon aquaculture reduces overall global seafood production and that channel catfish production is a net contributor. Species groups that are net consumers of fish include river eels, salmon, marine finfish, trout, and marine shrimp. Species groups that are net producers of fish include carp, catfish, tilapia, milkfish, and freshwater crustaceans (Tacon et al. 2006). Globally, 20 to 25 million tonnes of feed fish were used in aquaculture to produce 30 million tonnes of fish and crustaceans in 2003 (Tacon et al. 2006).

The concern with “fish eating other fish” is that, for some species, it appears to be ecologically inefficient (Box 1.2). Superficially this is true, but it neglects other considerations (Tidwell and Allan 2002). Feed fish and high-valued fish and shrimp produced in aquaculture do not substitute equally either socially or economically, so accounting based on “fish-in versus fish-out” is too simple to assess the deeper significance of fishmeal use in aquaculture. Most fish caught for reduction to fishmeal are not desirable as human food in many countries. Using fishmeal in aquaculture feeds adds value by converting low-value protein not used for human food into a high-value product. The additional steps in the process of using feed fish for animal food rather than human food also creates additional economic opportunities, such as jobs in the feed manufacturing and aquaculture sectors. The apparent ecological inefficiency of the process is also misleading because inefficiencies are inevitable in nature when organisms at one trophic level consume biomass from a lower trophic level. In fact, some have argued (Asgard et al. 1997; Forster 1999) that it is considerably more efficient to capture, process, and feed pelagic fish to salmon than to allow the fish to be eaten naturally by wild fish where ecological inefficiencies are on the order of tenfold for each change in trophic level. Perhaps the most important consideration is that aquaculture has not caused greater overall use of fishmeal. Global fishmeal production and use has been relatively stable since the 1980s and has been redistributed only among various users, with aquaculture using a larger proportion over time.

Although some forms of aquaculture are, as described above, net consumers of fish, it is worth remembering that fishmeal use in poultry and swine production also does not add to global seafood supplies. The argument might be made that fishmeal use in feeds for certain terrestrial animals is a better use than in aquaculture because dietary inclusion rates are low and the net result is an increase in global supplies of edible animal protein. The same argument could, however, be made for using fishmeal in feeds for fish—such as channel catfish, tilapia, and carp—that also have low fishmeal inclusion levels in feeds.

## BOX 1.2
## "Fishing Down and Farming Up the Food Web"

Using fishmeal to grow carnivorous aquatic animals is one side of a larger seafood production issue captured in the phrase coined by Daniel Pauly: "Fishing down and farming up the food web" (Pauly et al. 2001b). In brief, capture fisheries have more or less serially exploited species from higher to lower trophic levels. As large, long-lived top carnivores were fished and depleted, fishermen increasingly turned to smaller, shorter-lived species from lower trophic levels (Pauly et al. 1998). Meanwhile, aquaculture, which traditionally relied on culture of herbivorous or omnivorous species in fertilized ponds, has seen rapid expansion in aquaculture of salmon, shrimp, and other species reliant on feeds with high levels of fishmeal. In other words, the mean trophic level of species produced in aquaculture has increased over time—just the opposite of the trend for capture fisheries (Pauly et al. 2001a, b).

Trends in mean aquaculture trophic level vary greatly among countries and regions. The mean trophic level for species grown in Canada, Chile, Norway, and the United Kingdom increased rapidly—more than one whole trophic level unit—from 1980 to 1997 (Pauly et al. 2001a, b). This corresponds, of course, to expansion of salmon aquaculture in those countries. Over the same period, the mean trophic level for species grown in China remained essentially unchanged and those grown in the United States decreased slightly. In fact, of the eight countries analyzed, the United States had the lowest aquaculture mean trophic level. This was attributed to the dominance of United States aquaculture by channel catfish, a species grown on feeds with low levels of fishmeal inclusion. Since 1997 (the last year in the analysis by Pauly et al. 2001b), increased usage of fishmeal in feeds for carp and other species in China (Tacon et al. 2006) has probably caused increases in the trophic level index for that country. Meanwhile, catfish aquaculture continued to expand and fishmeal levels in catfish feeds have decreased even further since 1997. Also, other sectors of low trophic level aquaculture—such as freshwater crawfish and molluscan shellfish—have contributed significantly to United States aquaculture, and the mean trophic level for cultured species has undoubtedly continued to decrease.

Many of the potential environmental impacts of aquaculture are localized in the vicinity of aquaculture facilities. In contrast, the use of fishmeal and fish oil in aquaculture is an issue that is global in scope, affecting all sectors that are supported by manufactured feeds. The main environmental and social concerns associated with fishmeal and fish oil use in aquaculture include

- Fishmeal and fish oil resources are limited. As discussed above, the yield from reduction fisheries for small pelagic species has been static since the 1980s and further increases in supply are highly unlikely. This has obvious implications for the sustainability of different forms of aquaculture, particularly those dependent on fishmeal as a protein source in manufactured feeds. Allocation of this finite resource among

various forms of animal protein production is likely to become much more competitive in the future.
- Reduction fisheries are currently managed to maximize long-term yield, without consideration of wider ecosystem effects. Important among these impacts are the trophic interactions that occur in ecosystems in which small pelagic species support a fishery for carnivorous species or function as food resources for marine species with inherent value with respect to biodiversity, but without commercial value.
- Some of the species that are currently harvested and reduced to fishmeal are suitable for direct use as human food. Reducing these fisheries resources to fishmeal, incorporating into aquaculture feeds, and feeding to marine shrimp and finfish raises ethical issues about allocation of global supplies of animal protein and effects on human well-being.

Fishmeal and fish oil use in aquaculture may be a self-limiting issue due to market factors. Fishmeal prices, which have doubled since 2005, will continue to rise as increasing demands are made on the finite fishmeal supply. Contributing to the price increase will be steadily increasing fishing fleet fuel costs. Under the scenario of higher fishmeal prices, there will be increased incentives to grow aquatic animals with lower dependence on fish products in manufactured feeds and to develop dietary substitutes for fishmeal and fish oil in aquaculture feeds, which remains an active area of research. There is considerable scope for the reduction of fishmeal and fish oil content of aquaculture feeds for marine finfish. There has been some progress in replacing fishmeal with oil-seed meals, although much less progress in replacing fish oil. Forms of aquaculture that continue to depend on high levels of fishmeal inclusion in feeds may become uneconomical.

There is a significant environmental trade-off regarding fishmeal in aquaculture feeds. Regardless of the ethics or economic implications of using fishmeal and fish oil in aquaculture feeds, incorporating them into feeds at appropriate inclusion levels can be one of the most effective strategies for reducing waste production in aquaculture. The use of highly digestible, high-energy feeds is especially important when fish are grown in open aquaculture systems such as raceways and net pens (see Box 9.1 in Chapter 9). Improvements in feed formulation can improve the efficiency of feed utilization and thereby reduce the discharge of waste nutrients. However, reducing the demand for fishmeal and fish oil from aquaculture would not necessarily reduce pressure on reduction fisheries because these products are globally traded commodities.

## Potential Environmental Impacts of Aquaculture

The environmental effects of aquaculture are often described in terms of the sources (type and quantity) or causes of a potential effect, and this convention will be followed here. Impacts are potential because effects depend on characteristics of the environment in which aquaculture production systems are embedded. For example, releasing waste into a closed basin will have a qualitatively greater (more adverse) impact that releasing the same quantity and type of waste into an open basin.

Contrasting to broad issues related to resource use, many of the problems commonly attributed to aquaculture—such as the adverse effects of habitat conversion, waste discharge, consumptive water use, and release of chemicals and antibiotics—are related to facility operations and can be addressed on shorter time scales through technology-based approaches (*better management practices,* or *BMPs*). Solutions to problems of this nature are the focus of this book.

### *Habitat Conversion*

Ponds are the most common aquaculture production system in the United States and the world. In most cases, pond construction requires conversion of terrestrial or wetland habitat to aquatic habitat. Aquaculture ponds must be located near sources of water, so they are commonly constructed in coastal or riverine floodplains. Thus, pond construction may convert floodplain land or wetlands to ponds (Fig. 1.9).

Pond construction in or near coastal wetlands, particularly the conversion of tropical mangroves to shrimp ponds, is controversial. Coastal wetlands are multiple-use, mostly open-access resources that are increasingly threatened by a wide range of development pressures, including aquaculture. Coastal wetlands provide a number of ecosystem

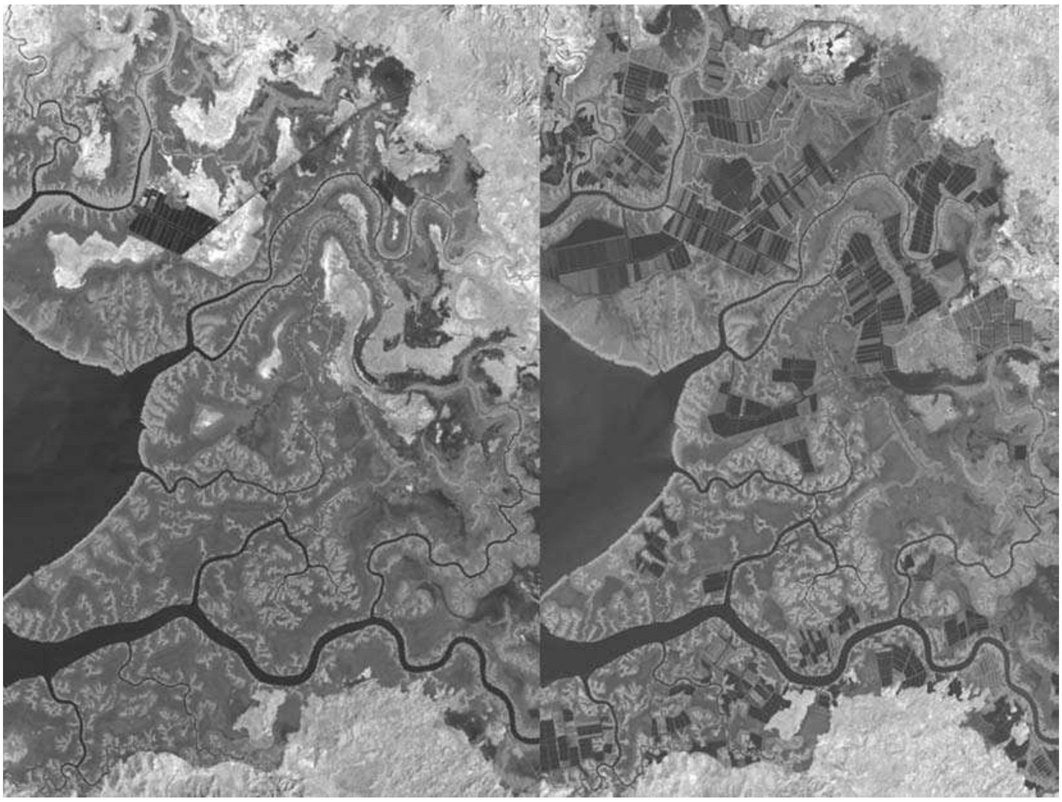

**Fig. 1.9.** An example of land transformation by aquaculture: conversion of coastal wetlands to brackishwater shrimp ponds. The two images illustrate the extent of land transformation near the Gulf of Fonseca, on the border between Honduras and Nicaragua. The image on the left was captured on 6 January 1987 and the image on the right on 19 November 1999. Note that a variety of coastal land types were transformed, but especially salt flats, indicated by bright white areas in the image on the left. Landsat images from Jesse Allen, Earth Observatory, NASA.

services, including waste treatment, storm protection, food production (especially as a nursery for many aquatic species), recreation, and a source of raw materials. The environmental impact of pond construction in coastal wetlands can be described in terms of the degree to which these services are lost by conversion to ponds. The total economic value (including the value of nonmarketed ecosystem services) of sustainably managed mangrove wetlands often exceeds the value associated with conversion to shrimp ponds (Rönnbäck 1999; MEA 2005). Coastal development, including aquaculture, in tropical areas can adversely affect adjacent, light-sensitive ecosystems, such as coral reefs and seagrass meadows.

Approximately 35% of mangroves have been lost in the last 2 decades (MEA 2005). Estimates of the relative contribution of aquaculture to the loss of coastal mangroves are uncertain, although less than 10% of the global loss of mangrove area has been attributed to conversion into shrimp ponds (Macintosh and Phillips 1992; Boyd and Clay 1998; World Bank et al. 2002). Nonetheless, conversion to aquaculture ponds can be the major component of mangrove loss in some coastal areas, particularly in southeast Asia (Primavera 2006). Mangrove wetlands are increasingly seen as having intrinsic value, being poor sites for pond construction, and undesirable sources of social conflict when aquaculture projects are developed. Pond aquaculture in coastal wetlands is much less common than in the past. In many places in Asia, mangrove clearing has been banned and rehabilitation and restoration programs are active.

### *Waste Loading*

Nearly all aquaculture production systems produce waste nutrients and organic matter. Depending on the production method, organic fertilizers (manures and agricultural by-products), inorganic fertilizers, and nutrient-dense feeds are applied to production units in most aquaculture facilities to promote growth of finfish, crustaceans, and other species. Approximately 70 to 80% of nutrients in feed are released as waste into the culture unit in aquaculture production systems where cultured animals are fed.

The degree to which the culture unit is open to the environment will determine the proportion of waste excreted by cultured animals that is released to the environment. For example, ponds and recirculating systems are operated with a long hydraulic residence time, so a very small proportion of nutrients are released to the environment. In contrast, culture systems with a more direct hydrological connection with the outside environment, such as flow-through systems and net pens, will release a large proportion of waste nutrients and organic matter.

The ecological effects of discharged nutrients will vary depending on production intensity, facility density, the hydraulic retention time and trophic state of receiving waters, and dilution rate. In relatively closed production systems such as ponds, feeding invariably results in the eutrophication of pond water. In more open systems, the effects of nutrient discharge are far less predictable. If the flushing time of the water body is less than the generation time of phytoplankton, an increase in limiting nutrient concentration can result in eutrophication. It is important to emphasize the point that phytoplankton respond to changes in nutrient concentration, particularly of those nutrients that tend to limit production (phosphorus in freshwater and nitrogen in seawater), not to increases in nutrient mass loading per se.

Potential adverse environmental effects attributed to organic waste loading from aquaculture include increases in phytoplankton density in response to elevated nutrient concentration, increased variation in dissolved oxygen concentration in response to increased phytoplankton density, increased frequency of dissolved oxygen depletion, reduced dissolved oxygen concentration caused by the discharge of effluent with high biochemical oxygen demand, and changes to benthic communities caused by localized sedimentation of suspended solids. Nutrients discharged from aquaculture facilities have not been linked to the development of harmful algal blooms.

In many coastal areas, discharges from aquaculture production facilities represent one of many nutrient sources contributing to eutrophication. Truly addressing problems related to eutrophication therefore requires that the relative contribution of aquaculture be evaluated in terms of all sources and considered in the context of a watershed or whole-basin approach (Boyd and Green 2002). In certain locations, particularly closed basins, aquaculture operations can be the primary contributor to localized eutrophication. The effects of effluent discharge tend to be localized near the discharge point. The susceptibility of receiving waters to eutrophication depends on trophic status prior to enrichment. For a given level of nutrient loading, oligotrophic waters are more susceptible to trophic state changes than mesotrophic waters.

Most discussions of waste loading from aquaculture consider only the components of the waste stream, which includes nutrients, organic matter, potential pathogens, chemicals or therapeutants, and escaped fish. However, they do not consider how the environment responds to waste loading. Often missing is the notion of environmental carrying capacity, which requires an understanding of the waste assimilation capacity of the environment and consensus on an acceptable level of environmental change.

Aquatic environments have an inherent capacity to assimilate nutrients through well-known biological and physicochemical processes. In some areas, aquaculture facilities are sufficiently concentrated and production intensity is sufficiently great that the majority of the assimilative capacity of receiving waters is used by aquaculture. Appropriation of the waste treatment ecosystem service by aquaculture has been criticized on the basis that the cost of waste treatment is externalized by aquaculture operations and born by society. In general, nutrient enrichment is perceived to have negative consequences, although in some environments, eutrophication may be beneficial and perceived as desirable. Changes in trophic state have no inherent value; the acceptability of the change is a matter of societal values and policy.

### *Benthic Impacts*

Organic wastes produced in open aquaculture production systems can accumulate on the sediment in the vicinity of culture units. Soil eroded from pond embankments and organic matter in pond water can settle in receiving water bodies adjacent to discharge points. Organic matter discharged from flow-through systems can accumulate near the discharge point, leading to localized suppression of dissolved oxygen concentration and changes in benthic communities. Depending on current speed and water depth, organic matter mainly derived from feces and uneaten feed can accumulate on the sea floor beneath net pens. Sedimentation rates within net-pen facilities are reported to range from about 15 to 100 g of total volatile solids (TVS)/m$^2$ per day, with most estimates between 25 and

50 g TVS/$m^2$ per day (Brooks and Mahnken 2003a). The accumulation of organic matter can extend from 145 to 205 m downcurrent from the perimeter of net-pen facilities (Brooks and Mahnken 2003a), although significant effects are usually restricted to less than 60 m from the perimeter (Nash et al. 2005). Of all the potential environmental impacts of salmonid net-pen aquaculture, changes to the sediment beneath net pens are considered to represent the greatest risk to the environment (Brooks and Mahnken 2003a; Nash et al. 2005), although these changes are temporary and largely reversible.

If the rate of organic matter sedimentation exceeds the rate of decomposition, organic matter will accumulate. Organic matter accumulation will depend on loading rate, temperature, oxygen supply, current velocity, and other physical and chemical factors. The deposition of organic matter creates a dissolved oxygen demand for decomposition that may exceed supply. In this case, the redox potential will shift to lower (more negative) values, indicating anaerobic conditions. Mats of the sulfide-oxidizing filamentous bacteria *Beggiatoa* may cover the sediment surface. Reduced substances such as ammonia, dissolved phosphorus, methane, carbon dioxide, and especially in marine waters, hydrogen sulfide will diffuse into the overlying water. Some of these substances are potentially toxic to benthic invertebrates and cultured fish, but rarely accumulate to levels that will affect fish culture performance.

Anaerobic conditions in the sediment will also cause a shift in the assemblage of benthic invertebrates toward a less diverse community dominated by pollution-tolerant species. The effects described here tend to be localized around effluent discharge points and within 25 m of the perimeter of net-pen farms (Karakassis et al. 2000; Pearson and Black 2001). These effects are also more pronounced for poorly flushed sites (current velocity <10 cm/second) with fine-grained sediments. In well-flushed sites (>50 cm/second), the abundance and diversity of benthic infauna frequently increases (Brooks and Mahnken 2003a). Chemical remediation of marine sediments beneath net pens occurs within months to 1 year, but biological remediation may require 2 to 3 years in some sites, largely depending on water temperature, current velocity, and concentration of sediment organic matter. In general, the effects of sedimentation are localized and reversible.

Sedimentation can also occur as a result of alteration in hydrodynamics caused by the deployment of aquaculture structures such as rafts, longlines, and cages. These can reduce current velocity in the lee of culture facilities, creating a depositional environment. In addition, feces and psuedofeces produced by shellfish can accumulate in the vicinity of shellfish rafts. Hydrodynamics can be altered by material that accumulates near effluent outfalls, which can reduce stream depth and obstruct water flows, increasing the potential for flooding.

Some metals will accumulate in sediment, but there is no evidence that these accumulations have had negative impacts on benthic invertebrates or rates of biogeochemical transformations (Brooks and Mahnken 2003b). Zinc is added to fish feeds as an essential nutrient, and elevated concentrations have been measured in sediment beneath net pens. Copper is used in antifouling paints and net treatments and can accumulate in sediment beneath net pens. In marine environments, the accumulation and bioavailability of copper and zinc depend on sulphide concentration, with reduced bioavailability with elevated sulphide concentration. Concentrations decline during site fallowing.

### Chemical Pollution

As with other forms of agriculture, chemicals are used in aquaculture for a broad diversity of purposes. Perhaps most importantly, pesticides, disinfectants, and antibiotics are used for disease treatment and pest management. Chemicals are also used for soil and water treatment, enhancing natural productivity, feed manufacture, control of reproduction, growth enhancement, transportation, and processing. Major classes of chemicals include therapeutants (including antibacterial agents), disinfectants, anesthetics, hormones, feed additives, antifouling paints, herbicides, and pesticides (GESAMP 1997; Boyd and Massaut 1999; Gräslund et al. 2003). Soil and water are treated with chemicals such as inorganic and organic fertilizers, liming agents, flocculating agents, and bacterial amendments. Chemical and drug use are highly regulated in the United States (as summarized in Chapter 12), and even usage of legally registered substances is relatively uncommon for reasons of economics. This is not necessarily true elsewhere, however. On average, a shrimp farmer in Thailand uses 13 chemicals, with four pesticides and disinfectants, and three soil and water treatment products (Gräslund et al. 2003). Thai shrimp farmers use an average of one antibiotic per farm, most commonly fluoroquinolones.

Chemicals used in aquaculture can be divided into three groups based on the different ways they affect the environment (Gräslund and Bengtsson 2001). One group of chemicals encompasses those with acute or chronic toxicity to nontarget organisms, including cultured animals. Another group are the antibiotics that are released to the environment. These can lead to the development of resistant strains of pathogenic bacteria and alter microbial community composition, affecting biogeochemical processes. The third group are nutrients that can lead to eutrophication if discharged, a particular concern for light-sensitive seagrass and coral reef ecosystems often found adjacent to coastal shrimp ponds.

Chemicals can also be grouped into three categories based on the environmental or human health risk associated with their use (GESAMP 1997). The first group includes chemicals with a high risk associated with their use, such as chloramphenicol, malachite green, and organophosphates. Chemicals in a second group can be used safely if applied according to label directions, but may present an environmental or human health hazard if used incorrectly. A third group of chemicals can be used safely at most locations, but may present an elevated risk at certain sites because of particular characteristics of that site.

Chemicals have various fates when released from aquaculture production systems to the environment, so environmental persistence is variable. The persistence of chemicals in the environment depends on physicochemical factors that affect solubility and reactivity (especially temperature, pH, dissolved oxygen concentration, and light intensity) and biological factors, especially the type and density of microorganisms. Some chemicals can accumulate in sediments. Other chemicals dissipate or degrade by physicochemical reactions such as photooxidation or adsorption to sediment minerals or organic matter. Others are transformed or degraded biologically by reactions mediated by microorganisms. The environmental toxicity of reaction products can be greater or less than that of reaction substrates. In general, but with some important exceptions, most chemicals used in aquaculture do not persist in the environment (Gräslund and Bengtsson 2001).

The environmental and human health issues associated with chemical use in aquaculture were summarized by GESAMP (1997). These include persistence in aquatic environments, residues in noncultured organisms, toxicity to nontarget organisms, stimulation of bacterial resistance, effects on sediment biogeochemistry, nutrient enrichment, health of workers exposed to chemicals, and residues in seafood that affect product safety. Many of these effects can disturb natural aquatic communities, altering community structure and reducing biodiversity.

There is a strong disincentive to use many chemicals in aquaculture because use increases production costs and some chemicals may be toxic to cultured aquatic animals. Chemical use also presents a food safety problem by increasing the risk of consumption of aquatic animals containing chemical residues. Improper use of antimicrobials can stimulate the development of drug-resistant forms of microbial pathogens in cultured animals, water, or sediment. Chemicals can also bioaccumulate in nontarget organisms and become biomagnified as they move through aquatic food webs to higher trophic levels.

In the particular case of salmonid net-pen aquaculture, there has been concern about the use and fate of pesticides and drugs applied to control infestations of various species of parasitic copepods known collectively as sea lice and the antibiotics used to control bacterial diseases. In some countries, sea lice are controlled with bath treatments of nonspecific and broad-spectrum organophosphorus and pyrethroid pesticides and with the antibiotic ivermectin incorporated into feed. The chemicals used in bath treatments disperse rapidly and are usually not detected beyond 25 m from a net pen, although these chemicals have the potential to affect nontarget organisms, particularly crustaceans. Research on the fate of antibiotics used to control bacterial diseases indicates that antibiotic residues will accumulate and persist in sediment beneath cage sites and have been measured in nontarget organisms (Samuelson et al. 1992; Smith et al. 1994; Weston 1996; GESAMP 1997). There is concern about the increased risk of the development of drug-resistant strains of bacteria that are pathogenic to fish (Samuelson et al. 1992), particularly when antibiotics are used prophylactically. Similar concerns have been expressed about the development of drug-resistant strains of bacteria in shrimp farming (Gräslund and Bengtsson 2001; Holmström et al. 2003).

### *Salinization*

Salinization refers to increases in the salinity of soil, surface water, and groundwater. Excessive salinization of water and soil can limit the use of surface waters for irrigation, reduce crop yields, displace salt-intolerant crops, and limit the use of water for domestic purposes. Salinization is primarily a concern with coastal pond aquaculture, where water is pumped to maintain appropriate salinity in ponds for penaeid shrimp culture. However, salinization has become a concern with the increase in inland aquaculture of marine shrimp. These facilities are supplied with brine transported from coastal waters or saline groundwater from wells, and salinization can occur when this water is discharged to inland streams. Salinization can also occur when accumulated sediment is removed from coastal aquaculture ponds and disposed in freshwater areas. Salt contained in the sediment leaches out following rainfall and can cause salinization (Boyd et al. 1994).

The discharge of water from coastal or inland brackishwater ponds into freshwater bodies can impair surface water quality to limit their use, especially for agriculture (Dierberg and Kiattisimkul 1996; Braaten and Flaherty 2001; Boyd et al. 2006). In sites with improperly compacted soils, water can seep from these ponds into underlying freshwater aquifers. Alternatively, excessive pumping of groundwater can result in saltwater intrusion of aquifers, thereby limiting use. Excessive pumping of groundwater to control salinity in coastal aquaculture ponds has led to salinization of groundwater aquifers and land subsidence and consequent damage to infrastructure in Taiwan (Lin 1989; Huang 1990). Pumping groundwater was widely used to manage salinity in brackishwater ponds in the past, but the practice is now banned or restricted in many places.

### *Pathogen Transmission*

In aquaculture production systems, animals are usually held at much greater densities than in the natural environment, a condition that facilitates the transmission of pathogens among cultured animals. Elevated production intensity can lead to environmental conditions in the production unit that stress cultured animals, potentially increasing the susceptibility to infection by pathogens that may lead to disease. Thus, the conditions that promote disease are more prevalent in aquaculture production systems than in the natural environment. Intensive culture conditions can also cause amplification of pathogens that are ubiquitous in the environment.

Pathogens are a constituent of water that is discharged from or flows through aquaculture facilities. Water exchange in open production systems facilitates the transmission of pathogens to the environment, specifically between cultured and wild fish. There are numerous examples of diseases caused by the discharge of pathogens from aquaculture production facilities. Wild fish also serve as a reservoir of pathogens for the infection of cultured fish. The transfer of pathogens to wild fish can potentially affect the susceptibility of wild fish to disease and, in extreme cases, could affect wild fish abundance and local biodiversity.

The discharge of pathogens does not necessarily lead to disease. Infection with a pathogen is a much more common occurrence than disease. Infectious diseases result from the interaction of the health and immunological status of the host, the dose and virulence of the pathogen, and environmental conditions that affect host-pathogen interaction. The health of wild fish populations is influenced by natural factors, such as genetics, nutrition, environmental conditions, and the biology of pathogen and host organisms. Fish health is also affected by anthropogenic factors that put pressure on wild fish populations, including climate change, floods, drought, impoundments, dams, chemical contaminants, and fishing pressure.

The risk of disease caused by a particular pathogen is affected by the characteristics, distribution, survival, and fate of pathogens in the environment; factors affecting the route of pathogen transmission; the characteristics of pathogen exposure; the effect of environmental stressors; and the susceptibility of wild hosts to infection that can lead to disease (Blazer and LaPatra 2002). In general, the relative importance of each factor is difficult to understand and assess in wild populations, leading to a high degree of uncertainty associated with the risk of transfer of pathogens between cultured and wild fish populations (Coutant 1998; Raynard et al. 2007).

Wild fish can be affected by the introduction of new pathogens attendant with the introduction of native or nonnative species to an area for culture. These pathogens can infect wild individuals of the same or different species. Pathogens can also be introduced to wild fish through transportation of native or nonnative species that are not intended for aquaculture.

### *Interactions of Escaped Fish with Wild Populations and Natural Ecosystems*

Aquaculture production facilities are embedded in natural ecosystems with varying degrees of intimacy, depending on characteristics of the culture system. The hydrological connection to natural ecosystems can be remote and intermittent (e.g., recirculating aquaculture systems) or intimate and continuous (e.g., shellfish and net-pen systems). The risks of containment failure also vary with culture system type. As such, the probability of occurrence of escape is variable. Escapes can be defined as the unintentional and unplanned release of cultured animals or their gametes or offspring to the environment. Escapes do not include intentional releases of cultured animals for stock enhancement or ranching.

Mechanisms that lead to the escape of cultured organisms can be grouped into four classes (Myrick 2002). In each case, the mechanism leads to a breach in the barrier between a culture unit and the environment, allowing escapes to occur. The causes of containment failures that can lead to escape include 1) catastrophic natural events, 2) human error associated with facility operation, 3) vandalism or poaching, and 4) attacks by nuisance or predatory wildlife. Culturists have no control over natural disasters, but facilities can be constructed to withstand or minimize the risk of escapes by other mechanisms.

Escape of cultured animals is not desirable from an economic standpoint because escapes represent a loss of potential revenue. Therefore, there is a strong incentive to construct and manage production units to minimize losses from escapes, disease, poaching, and other causes. Above and beyond the undesirable economic impact on producers, escaped culture organisms can alter the physical environment and the structure of ecological communities, cause genetic changes in stocks of wild conspecifics, introduce parasites and diseases, and cause various socioeconomic impacts (Beveridge and Phillips 1993).

Escaped individuals may interbreed with natural populations, although interbreeding requires the satisfaction of several criteria. First, cultured organisms must be sexually mature or, if not mature, they must survive to maturity. The timing of the escape event must also coincide with the natural breeding season of the wild population; in other words, sexually mature individuals in the wild population must be receptive to escaped fish.

Intraspecific hybridization between escaped and wild conspecifics can reduce the genetic variance, and presumably fitness, of wild populations through outbreeding depression (Kapuscinski and Brister 2001). This may increase the vulnerability of natural populations to environmental change from the loss of genetic differences between cultured and wild (natural) populations. The effect of inbreeding will depend on the degree of local adaptation. Geographically structured populations are more susceptible to the effects of interbreeding than undifferentiated stocks.

The principles of interaction between wild and escaped fish have been reviewed by Youngson et al. (2001). The overall concern is related to a reduction in fitness and a reduction in the effective population size of wild populations. First, the genetic profile (i.e., allele frequencies) of wild populations can change from the transfer of genes from cultured stocks into wild populations. Second, the genetic profile of cultured stocks may contain alleles that are rare or unusual in wild populations but were selected on the basis of performance traits, and that are transferred to wild stocks. Third, the abundance of wild populations may decrease if escaped fish displace wild fish, but then demonstrate low reproductive fitness. Although all of these mechanisms of interaction are plausible, demonstrating a measurable effect on the fitness of wild populations is difficult.

The consensus view is that the risk of adverse genetic effects on natural populations of conspecifics is not as severe as potential ecological effects of escapes. The intensity of the ecological impacts of escapes is a function of the number of organisms that escape, the timing of an escape event, the biology and life history of the escaping species, interactions of escaped organisms with wild populations, and ecological characteristics of the host ecosystem. Even nonreproductive animals can have ecological impacts if they escape in sufficient numbers.

Potential adverse impacts of escapes on natural populations may include any or all of the following (Myrick 2002):

1) Competition with natural populations for habitat, food resources, nesting or spawning sites, or mates;
2) Predation on endemic fish populations if escaped fish are piscivores;
3) Predation on endemic fish populations if escaped fish attract predators;
4) Transmission of pathogens or parasites with deleterious effects on wild populations;
5) Amplification of the effect of endemic pathogens;
6) Alteration of habitat, such as changes in turbidity and substrate; and
7) Colonization of habitat, with negative effects on wild populations, and in the worst case, displacement of native species.

Overall, the potential outcomes of escapes may include a reduction in fitness in wild conspecific populations and a reduction in fitness in other wild populations.

Many of the adverse impacts described above are exacerbated when invasive species escape from aquaculture facilities. Although only one of many pathways for the introduction of potentially invasive species, aquaculture has played an important role in the introduction of nonnative species, especially in freshwater. The majority of introductions of nonnative species since the 1970s can be attributed to aquaculture (Welcomme 1988) and arguably the introduction and establishment of invasive species from aquaculture has had the greatest adverse effect on the environment of all potential impacts. In any case, the effects of escapes by cultured species on biodiversity are difficult to partition from the effects of habitat degradation or loss and other causes of biodiversity reduction.

### *Collection of Wild Aquatic Animals for Spawning or Stocking*

There is a long history in aquaculture of capturing wild larvae and juveniles for stocking into culture units for growth to market size. The culture of milkfish, mullet, penaeid shrimp, and many other species was long dependent on wild stocking material. Capturing wild juveniles is usually an interim step in the development of a species for culture. Once the techniques for spawning and early larval rearing are developed to close the life cycle, juveniles can be reliably produced in hatcheries, allowing the development of a sustainable aquaculture industry for that species. Most species in freshwater aquaculture are now spawned in captivity. The dependence on wild-caught stocking materials is becoming much less common, although reliance is still strong in brackishwater and marine aquaculture. The capture-based aquaculture for eels, groupers, tunas, and yellowtails remains dependent on capture of wild juveniles (Ottolenghi et al. 2004).

There are several problems related to the use of wild juveniles for stocking. Collection of juveniles may place additional pressures on wild stocks of the target species, reducing recruitment to natural fisheries if density-dependent mechanisms regulate abundance. Furthermore, depending on the homogeneity of aggregations of juveniles, individuals of nontarget species of commercial or ecological importance may be collected incidentally as by-catch, placing pressure on wild stocks of those species. For example, in the Philippines, milkfish fry constitute only 15% of collections and the 85% of by-catch is discarded (Primavera 2006). The effect of capture of wild fish as juveniles on target or nontarget wild populations will depend on the size- and age-structure of the population, population size, age at maturity, natural and fishing mortality rates, and quality and availability of suitable habitat. Selective collection of wild juveniles can also have a negative effect on fish community structure, depending on the trophic role of the species and the complexity of the community structure. Depending on the gear employed, juvenile collection can result in physical disturbance of the substrate, impacts on benthic communities, and in the worst case, destruction of habitat. Finally, wild seed are undesirable from a biosecurity standpoint because the health status of wild-caught juveniles is questionable. Shrimp producers now perceive that postlarvae produced in a hatchery are less susceptible to important diseases than wild postlarvae.

In the culture of some species, sexually mature broodstock are collected from the wild and induced to spawn in hatcheries. Broodstock collection can also place pressure on wild fish resources. For example, in Thailand, Vietnam, and some other Asian countries, the availability of wild-caught black tiger shrimp (*Penaeus monodon*) for broodstock has declined drastically in recent years. Adult *P. monodon* broodstock are now rare in trawl catches. Capture of mature adults for use in shrimp hatcheries likely has been one of the reasons for the decline. This decline in *P. monodon* broodstock has been a major reason why shrimp producers in Thailand and other Asian nations have imported non-native, farm-reared broodstock of the Pacific white shrimp (*Litopenaeus vannamei*). This species has replaced much of the *P. monodon* culture in Thailand.

### *Predator Control and Other Effects on Wildlife*

The concentration of potential food resources in aquaculture facilities provides attractive foraging opportunities for birds and other predators of cultured animals, which are viewed as a nuisance by aquaculture producers. The construction of aquaculture ponds has created new aquatic habitat while suitable habitat for wildlife with an aquatic orientation, especially migratory waterfowl, has decreased elsewhere. Ponds are attractive to waterfowl and migratory birds as sources of food and shelter. Aquaculture structures such as net pens and shellfish rafts create a complex, three-dimensional environment in the water column that attracts and aggregates wild fish, their predators, birds, turtles, and marine mammals.

Aquaculture producers use a range of nonlethal and lethal techniques to control predation of cultured animals. Most methods are intended to harass wildlife and induce them to move elsewhere. Although lethal controls are used occasionally, it is unlikely that lethal control will have negative effects on wildlife populations, especially of those for which aquaculture has allowed an expansion of population abundance. Most wildlife is protected by international conventions and national regulations. It is possible that location in migratory pathways and near breeding grounds could cause disruption to wildlife populations, but it is unlikely that these sites would be selected or permitted for aquaculture.

There is some risk that wildlife may become entangled or trapped in nets, ropes, and floating or submerged structures for fish and shellfish. This could lead to drowning or starvation, but properly designed, constructed, and managed facilities do not present a major risk of entrapment or entanglement. In sum, there are few negative interactions with wildlife and the probability of negative consequences is very low.

## From Environmental Impacts to Better Management Practices

This chapter provided a brief summary of the state of global aquaculture and the structure of aquaculture within the United States. Most of the chapter described various aspects of the relationship between aquaculture and the environments in which it is embedded. The focus has been on resource use and the specific environmental impacts associated with aquaculture production. The remainder of this book will endeavor to provide farm-level solutions to potential adverse environmental impacts of aquaculture. Throughout this chapter, we tried to emphasize that the impacts of aquaculture have broad spatial and temporal scales and, correspondingly, that solutions have wide-ranging context—from simple changes in farm management to complex solutions grounded in societal values. The better management practices provided in this book are intended to address near-field effects at a local level to improve the environmental performance of aquaculture.

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## Chapter 2

# The Role of Better Management Practices in Environmental Management

*Jason W. Clay*

## Introduction

Best management practices (BMPs) are increasingly regarded as meaningful goals in the overall reduction of on-farm and processing impacts and, by extension, cumulative impacts of agriculture. The adoption and encouragement of BMPs are often seen as an end itself in attempts to achieve continuous improvement in environmental performance. The assumption is that if the "best" practices are in place, producers are doing all that they can to avoid the worst impacts of production. This approach, whether BMP or GAP (good aquaculture practice), tends to divide the world into two camps—best or worst, good or bad. In reality, the implementation of a specific BMP will result in a range of environmental performance among producers, with most falling somewhere in the middle (Fig. 2.1). Although there can only be one "best" practice, many are likely to be "better" than a range of others. For that reason, throughout this chapter and most of this book, BMP refers to *better management practices*.

If continuous improvement is the goal, BMPs, by definition, are transitory and merely a means to an end, not the end itself. Furthermore, today's best practice will be tomorrow's norm and will eventually become the worst practice, to be avoided at some point in the future. If incremental improvement is the goal, surely today's BMPs will give way to even better ones tomorrow. For these reasons the term *best management practice* is gradually giving way to better management practices. Fortunately the abbreviation BMP applies to both. Although subtle, the difference signals a fundamental shift in thinking.

One shift is the recognition that no single BMP reduces a key impact equally, whether considering all producers in a specific country or all producers of a particular species globally. There is no one-size-fits-all solution. The most effective BMPs depend on, among other things, the species cultured, type and magnitude of impact, scale of production, resources (capital, labor, land) available to the producer, and the overall management system already in place.

Another fundamental issue is that BMPs are often used as proxies for performance. It is assumed by many that the mere adoption of a BMP will always yield an acceptable

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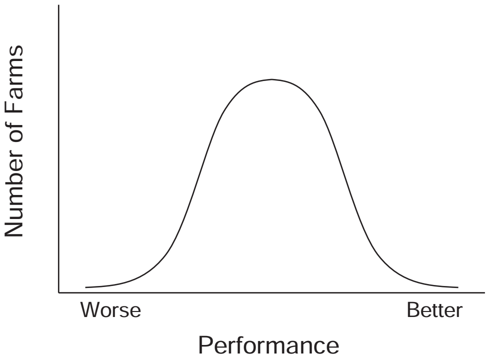

**Fig. 2.1.** A curve describing variation in environmental performance for a given farming activity or practice. Performance or impacts vary from bad to good, with most farms falling in the middle.

improvement in performance and that specific BMPs will have consistent and predictable individual or collective impacts. But this has never been demonstrated for a range of different producers with different intensities or scales of production. Given the constantly evolving nature of individual practices and combinations of them in complex management systems, there is constant change in the practices employed—and there should be.

Governments and certification programs often use BMPs as proxies because it is easier to verify whether a practice is in use than whether an impact has been meaningfully reduced. Meaningful proxies, however, should be created from data and not be a substitute for it. In theory, BMPs are the easy way out—adopt this or that practice and everything will be all right. BMPs are easier—it is easier to tell people what to do than to go out on a site and determine whether they did it. In addition, many producers want to know what to do and don't want to have to think about it. This makes their life easier because they can comply much easier. In practice, however, BMPs are an inexact shortcut. How to think about achieving a performance result is more complicated.

Finally, the focus on BMPs tends to be prescriptive: if effects are this, then do this. Prescriptive solutions tend to result in compliance, but also may not. The achievement of meaningful results depends on whether the BMP can significantly reduce a particular impact and whether the BMP selected was the correct one and implemented properly by the producer.

Trends indicate a future with more targeted and measurable results and less attention to how results are achieved. Once an explicit part of regulations and standards, whether required or voluntary, BMPs are now relegated to guidance documents and workbooks. Thus, the current focus on BMPs globally is shifting from prescription to helping producers improve performance against a baseline and giving producers the flexibility to develop their own ways to improve performance.

This chapter explores the opportunities and limitations of BMPs as a tool for environmental management, improving overall environmental performance, and reducing waste in a world where reduced impacts are demanded by governments, investors, buyers, and nongovernmental organizations (NGOs). BMPs are also a tool for producers to increase their competitiveness in markets that are becoming increasingly competitive.

## History of the Use of BMPs

The desire to produce more, reduce effort, and reduce inputs and costs has probably been around since the dawn of agriculture. This is the impetus to find better ways to undertake tasks such as producing food, fuel, building materials, and fiber. Even domestication can be seen as a form of BMP, and it has been an ongoing process for each of thousands of different crops for thousands of years in many separate locations. In association with domestication, individual producers have been trying to produce more with less for nearly as long. Most of the history of BMPs represents an effort to reduce costs and increase production efficiency, whether in forestry, agriculture, aquaculture, or other industries.

The vast majority of BMPs have been invented by producers—not researchers, regulators, government extension agents, buyers, investors, or NGOs. In as much as there are better and worse ways to undertake virtually every known production activity, it goes without saying that BMPs exist for virtually every production activity.

BMPs are most easily promoted when they increase income immediately or at least in the short term. As market competition increases, BMPs can be promoted because they reduce costs and input use or increase overall efficiency. Finally, if producers are fined for waste or pollution, BMPs can also be used to reduce fines, liability, or risk. Traditionally, BMPs have been most easily disseminated when there has been a direct impact on income. BMPs that reduce impacts but do not have a positive impact on income are much less acceptable to producers. Yet, this can be the case when BMPs are proposed or required by governments or the private sector.

In the past few decades BMPs have been seen as a means to improve overall environmental management and performance. Nonetheless, there is considerable overlap between the two aims—reducing inputs and increasing efficiency of resource use per unit of production generally improves overall environmental performance. Among other things, inefficient resource use can result in pollution.

### *Forestry*

BMPs have long been adopted in forestry as a way to increase production and production efficiency, reduce costs, and increase net profits. BMPs have been used to improve a wide range of impacts related to harvesting efficiency, reforestation and planting, forest growth rates, use of inputs, and processing.

Improved practices allow timber harvesting and conversion to be more efficient. Clay and Amaral (2001) reviewed the potential of BMPs to improve the efficiency of conventional logging practices in the Amazon River basin while reducing overall environmental impacts. Nearly 20% of the logs cut in the Amazon are lost because cutters do not coordinate with skidder operators. Skidder operators, in turn, compact the soil and damage twice as many trees (including commercially valuable ones) when they do not map their evacuation routes. In turn, trails are cleared where there are no logs, and trails to access logs are often not the ones needed to pull them out. Planned logging roads are 33% narrower than unplanned ones. As a result they are cheaper to build and operate while having fewer environmental impacts.

Improved planning yields significant environmental gains in many cases. Log depots are not strategically placed in many cases, and unplanned operations use 2.5 times as much land for depots as planned operations. About 7% of tropical timber in Brazil is damaged by insects and rain before it is sawn at the mill. In addition to lost timber and needless environmental damage, operators also waste time and fuel. For every 1 $m^3$ of timber harvested in unplanned operations, 2 $m^3$ was damaged, 73 km of forest roads were built, and 221 $m^2$ of canopy were opened (twice that of planned operations). Planned timber harvests extract an average of 25% fewer trees than unplanned operations. The second cut in managed forests yields more than twice as much commercial timber as in unmanaged forests (Clay and Amaral 2001; Clay 2004a).

BMPs can also be supported by governments to improve performance at a national level. In the 1960s, there was increasing concern about the ability of the United States to meet its own sawn wood requirements. A small team was organized to visit each of the thousands of sawmills operating throughout the United States. Within a decade the efficiency of sawn timber per cubic meter of roundwood was increased 40 to 60% (Clay 2004a).

Not only can technically focused BMPs lead to increased income and efficiency and reduced environmental impact, but social BMPs can also improve income and reduce impacts. Worker incentive programs increase overall productivity, reduce costs, increase net profits, and improve workers' income and job satisfaction. To date much less attention has been focused on this issue. However, such incentives will become an even more important factor as ever-increasing amounts of wood and pulp are produced in plantation forests and out-grower schemes.

### *Agriculture*

In agriculture, as economic competition increases globally, the most efficient producers will be the ones who survive. They will be defined by their ability to invent, identify, or adapt practices that reduce input use as well as waste and pollution. Such producers will be more profitable, or at the very least will remain competitive in the face of globally declining real prices. Those who remain competitive will not merely focus on how to produce a single commodity better. They will focus on their overall production systems and periodically evaluate what crops to produce to best utilize physical, financial, and market advantages. The specific crops, like the practices to produce them, will change. This would tend to favor those BMPs that offer the best financial returns rather than those that perhaps reduce key impacts most significantly.

Experiences in agriculture suggest that there are BMPs for larger and smaller producers as well as for those with more money to invest and those with less. As with other production systems, BMPs for agriculture vary by site, crop, scale and intensity of production as well as the human and financial resources available to the producer. As such no single BMP or suite of BMPs will work equally effectively for all producers. In fact, any recommended BMPs are likely to favor some producers over others.

Because of their importance to the overall reduction of impacts and the sustainability of agriculture, the adoption of some BMPs cannot be left to the market alone. Most producers in the world will probably not make the transition to those better practices without support. Targeted government subsidies can, in the short term, provide incentives for the adoption of those BMPs that address impacts that are not affected by improvements in resource use efficiency. Government regulatory and permitting systems can also encourage the identification and adoption of BMPs.

## Role of BMPs in Aquaculture

The role of BMPs in aquaculture has been similar to that in other industries. They have been promoted by governments, development agencies, input suppliers, industry groups, academics, and NGOs as a way to reduce costs and waste, increase income, reduce pollution, produce higher quality products, gain or maintain access to new markets, and obtain regulatory relief. The assumption is that BMPs produce positive, verifiable, and predictable results on the ground. The value of BMPs in measurably reducing key impacts is rarely monitored and therefore is much less clear than whether they have been adopted. Most BMP-based programs measure compliance (e.g., was a practice adopted) rather than performance.

The adoption of BMPs has been most rapid where there is a perceived benefit by the producer (particularly but not always with respect to income), where BMPs are a condition of permitting and licensing, or where adoption has allowed producers to avoid regulations. When BMPs are required by law, however, they may or may not always make financial sense for a range of different-performing producers. There will be some need to identify the specific types of producers, performance levels, or cumulative impacts that may not be addressed by required BMPs as compared to the most effective BMPs.

BMPs are also adopted more quickly if they are seen to enhance a producer's "license to operate" (that is, if they are accepted by neighbors and others locally). In fact, social acceptance may actually slow the adoption of BMPs if they go against what is believed locally. For example, it was assumed for some time that building shrimp ponds in former mangroves was a best practice because that was where shrimp were found in the wild and that constructing ponds above the high-tide mark incurred unnecessary expenses. Similarly, retailers in the United Kingdom believed that salmon should be fed high concentrations of fishmeal and oil because that is what they would eat in the wild. These beliefs impeded adoption of better practices because they were based on faulty reasoning.

### *Reducing Key Impacts*

It is difficult to reduce the key impacts of aquaculture before there is agreement on what the impacts are locally, much less globally. Given that considerable effort and expense may be required to reduce impacts, it will be very important to identify and rank impacts by their overall significance. Although it is not easy to compare apples and oranges, if the number of impacts cannot be limited, it is likely that very little will be accomplished. Yet, if six to eight key impacts can be reduced through concerted effort and focus, it will be possible in the future to address the next tier of significant impacts.

BMPs are a tool—a means to an end—that can be used by producers to reduce key impacts. In the process of reducing key impacts, many BMPs also increase producer efficiency, reduce waste, and improve income. In many cases, BMPs are the ultimate win-win tool. This is precisely why producers are often keen to adopt them (when they know and understand the practices and any risks associated with them), buyers and banks want to encourage them, regulators want to require them, and NGOs encourage them in most of their industry engagement strategies.

## *Increasing Efficiency*

BMPs can help producers achieve increased efficiency. This translates directly into reduced use and costs of inputs. Less water exchange means less pumping, less energy use, and lower costs of production. Improved feed conversion means less feed used, better water quality, less pollution, higher profits, improved relations with neighbors and other resource users, fewer court cases and legal battles, and a more secure license to operate. Reduced disease means more stocked animals are harvested, higher feed conversion, less downtime, less quarantine, fewer conflicts with neighbors, and higher profits. Fewer escapes means less money wasted on animals that are never sold, higher feed conversion, fewer conflicts with others, and higher profits.

In short, any BMP that improves performance will tend to reduce some if not all other associated risks. There are, however, some key areas where the total benefits from all BMPs are compounded, i.e., greater than the sum of the parts. Perhaps more importantly, producers can select different BMPs that will allow each to achieve a comparable performance level (Fig. 2.2). Figure 2.2 shows the performance curves for three practices where some of the producers using each practice perform above the acceptable level, but not all producers using any single practice perform above the acceptable performance level. Thus, in the hands of different producers, each BMP gives a different performance and there is overlapping performance among BMPs. For some BMPs, most producers achieve acceptable performance; for other BMPs, only exceptional producers achieve acceptable performance. Producers may select different practices to manage water and water quality, feeds and feeding, diseases, and escapes. In doing so, producers will achieve different environmental performance levels with respect to effluent pollution, invasive species, disease transmission, and genetic pollution.

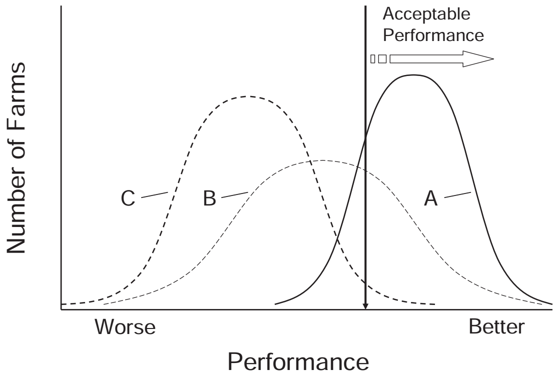

**Fig. 2.2.** Performance curves for three individual practices implemented to improve environmental performance. Farmers can adopt a range of practices to achieve acceptable environmental performance, but when "acceptable" performance is clearly defined, some practices (such as that for practice A) are more effective than others (practices B and C) in achieving an acceptable level of environmental performance. Most of the farmers adopting practice A will achieve an acceptable performance level, whereas most farmers adopting practices B and especially C will not achieve acceptable performance.

### *Reducing Waste*

Waste is currently defined as that which is not used efficiently. Most improvements in overall efficiency will also reduce waste. Aquaculture facilities can either produce physical wastes or operate inefficiently (e.g., less biomass of product per unit of energy input). One of the greatest incentives for reduced waste and pollution is cost rather than regulation. From a producer's perspective, cost is probably the most important issue. In business, perspectives on waste have been largely influenced by input costs. The more expensive an input, the more wasteful it is not to use it efficiently.

From a societal perspective, it may be important to define performance levels that are acceptable and those that are not. Voluntary standards do this through market mechanisms. They are only voluntary, however, to the degree that producers want to be able to sell into different markets. Governments regulate and set additional requirements through permits and licenses.

In defining these performance levels, awareness of scarcity is a key factor in assigning value to an input. There is a general and increasingly reinforced perception that natural resources are finite, but the focus to date has been primarily on the environment and those natural resources that are perceived to have value. Wasting labor and employee's skills are not something most producers think about. Biodiversity, natural habitat, and ecosystem services are not perceived as having market value, even if they have intrinsic value. This perception is changing, and as it changes it will considerably influence the definition of waste and inefficiency.

Waste or inefficiency is a target that moves as a result of changes in science, public perceptions, market pressures, or a combination of all three. Concerns about water, carbon, energy, and greenhouse gases will very likely drive standards development in the future. The World Wildlife Fund, for example, is addressing such issues in aquaculture dialogues and standards development efforts. Tesco, the largest retailer in the United Kingdom, now requires all suppliers to calculate "food miles" to understand the carbon emissions associated with transporting food products to market.

## What Has Been Learned?

Any use of natural resources has impacts. The questions, surely, are to identify the most important impacts and to define acceptable levels of impact. By defining some impacts as more important than others, the magnitude or scale of the less important impacts are implied to be more acceptable or at least do not require initial or immediate attention. Besides, it is also clear that no one—producers, governments, buyers, or NGOs—can possibly work effectively on all impacts. To be effective, we must be more strategic.

By the same token, improved profitability and farm-level economic performance alone are insufficient as incentives to reduce every key impact of aquaculture. Given a choice, producers will selectively adopt those BMPs that improve net profits or reduce a significant impact without reducing overall income levels. Although reduction of key impacts overlaps somewhat with saving producers money or actually making them more, it is clear that some key impacts will not be reduced through market forces alone. The only way to know

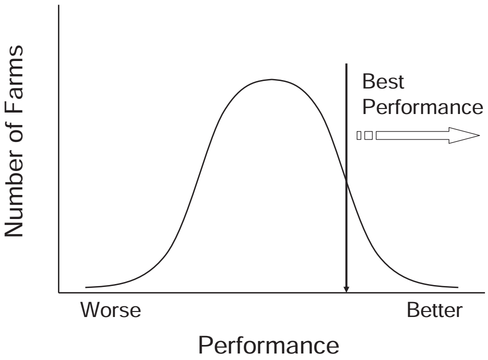

**Fig. 2.3.** Best producers are those whose measured performance is better than a clearly defined threshold. Unfortunately, it is not possible to identify "best-in-class" producers based merely on BMPs.

for sure is to identify the key impacts, undertake business-case (sensitivity) analyses for the BMPs and determine the financial implications of various practices.

### *Incorporation of BMPs into Certification and Ecolabel Programs*

Most certification and ecolabel programs claim that those producers who receive certification are actually best-in-class producers. They imply that certified producers are better than average producers (Fig. 2.3) and that they should receive price premiums. But given that performance against a baseline for key impacts is only rarely, if ever, measured in any ecolabel or certification program, this is more talk than action. Without metrics, comparisons of ecolabel and certification programs become subjective rather than science-based. Another issue is that some programs urge continuous improvement. Yet, without performance benchmarks (e.g., local, national, or global), it is impossible to determine whether someone is truly best in class.

### *Old Focus: Proscriptive and Practice-Based*

Most certification and ecolabel programs have focused on identifying what producers should and should not do, irrespective of whether the focus has been on better management practices, best management practices, or good aquaculture practices. Adoption of a single practice has been assumed to be the best way to improve overall performance across the board, but it is not. It is convenient, easier, and probably cheaper than the alternatives, but no single practice will predictably and uniformly reduce a key impact across all producers.

Figure 2.2 shows the problem, which is in fact two problems. First, given the wide range of producer realities, no single set of practices will reduce key impacts to acceptable levels. Second, producers who adopt a particular practice will have widely different on-the-ground results. One size does not fit all. This is true when addressing a single impact, more than one impact, or cumulative impacts. In short, whether BMPs work or not will be hit or miss. The point here is that BMPs do not guarantee performance. If a performance result is what is wanted, it should be asked for and the producer should be allowed to find the best way to achieve it.

If the goal is to reward better producers, the certification program needs to be able to single out such producers based on performance, not practices. In many cases, BMPs are not entirely or even mostly transferable. What works for one will often not work for another. Furthermore, good performance in one area may cause poorer performance in another. For example, high fishmeal, high-fat diets produce better feed conversion (less waste) in salmonids, but the trade-off is the increased use of fishmeal. In shrimp production, water exchange improves water quality but uses tremendous amounts of nonrenewable energy.

The issue is about balanced thinking. More specifically it is about *how* to think, not *what* to think. Proscriptive programs yield compliance that may or may not yield the desired results. If the required practices are well targeted, such programs may result in continuous improvement but not necessarily in acceptable performance levels. Continuous improvement for very poor practices might in 10 years result in a producer achieving the industry norm. Unfortunately, by that point the norm will have improved. For example, Chilean salmon farmers used significantly more chemical therapeutants per tonne of production than their counterparts in Norway a decade ago. Over the past decade, Chilean farmers have improved their performance, but have lost even more ground to the Norwegians who have done an even better job of reducing the use of therapeutants. There is no acceptable performance level that is written in stone. What is acceptable is based on what is possible—and that is constantly improving. By their very nature, what is certain, however, is that proscriptive-based BMP programs will encourage compliance, not innovation.

### *New Focus: Performance-Based Standards or Results*

Increasingly there is awareness that ecolabels and certification programs imply improved performance standards that cannot be or are not verified on the ground. This is the case because few, if any, ecolabel or certification programs actually measure impacts, either before or after producers join the program. Ideally, such programs would incorporate global or regional performance benchmarks and then be able to show credibly how their program ensures that producers exceed those standards.

Thus, BMP- or GAP-based programs assume better performance but cannot guarantee it. Continuous improvement, although important in some respects, requires benchmarking if it is to be credible. There is nothing to prevent a poor performer from continually improving for years and years and still be a far poorer performer than others who are better in class.

Performance-based standards quickly raise and give direction to other important issues for discussion. What is the appropriate scale for performance: A pond or net pen? A facility or business unit? A company? An ecoregion? Consideration of scale also allows clear definition of a significant impact. For example, is it energy use per tonne of production in a pond or net pen, food miles to market, the energy that is embedded in feed that is used to grow or catch feed ingredients, transport ingredients and feed, etc.? Clearly it depends on the regulator, the buyer, the certification program, or more likely than not, awareness at the time. For example, most people do not realize that most of the embedded energy in aquaculture-produced salmon is in the fishmeal and oil in the feed, not in the production system or the transport of fish to market. So, once again, the question is what are the key impacts and what is the best scale to look at them? While reasonable people may disagree on these issues and while some may be too cumbersome or expensive to measure, a focus on practices does not lend itself to this kind of approach.

Within the context of performance-based standards, BMPs are means to various ends. However, it is important to recognize that they are not ends themselves. Thus, BMPs do not belong in standards; they belong in workbooks and guidance documents. Such documents are more widely useful when there are several BMPs that can be shown to achieve desired performance levels, depending on the specific resources and conditions of a producer. Figure 2.2 demonstrates how performance curves for different practices would allow individual producers to meet overall performance requirements of any given program. Of course, to the extent that guidance documents can also provide concrete information on the investments required, the return on the investments to adopt BMPs, and the overall payback period, the more likely and quickly others will adopt them. Finally, it is important that such documents identify the BMPs that are known to favorably complement and reinforce other practices. Those BMPs that address one environmental impact, but inadvertently create another undesirable impact must also be identified.

## Role of BMPs for Different Groups

As BMPs have been developed, adapted, and adopted by producers, many different groups have seen their value as proxies. Producers see them as a way to make money. Buyers see them as an indication of higher-quality product that is associated with fewer risks. Investors see them as a way to differentiate between better and worse credit risks. Regulators use them to define the line between good and bad performance. The role of BMPs for each group involved with production is discussed below.

### *Producers*

Producers invent most BMPs, often in response to a specific problem (e.g., disease, increased costs of inputs, regulations, market requirements, etc.). In the past, BMPs were seen as tools for individual producers to adopt or not. Increasingly, however, producer groups are beginning to realize that the reputation of all can be affected by a few. This can affect local reputations, market access, or government regulation. As a consequence, BMPs are now an important part of producer codes of conduct. Groups of salmon, shrimp, catfish, shellfish, and trout producers—to name but a few—have all identified, agreed to, and incorporated BMPs into codes of conduct and certification programs.

Many producers are reluctant to share financial information because they fear it will be used against them or by their competitors to gain market advantage. Most producers are interested in increasing production and/or net profits and any funding they have would be directed at those issues. Most governments, by contrast, tend to guide what resources they have toward identifying BMPs that contribute significantly to the reduction of targeted impacts.

## *Research Scientists*

Although the vast majority of BMPs (the total may be 90% or more) were originally invented or discovered by producers, it is not the role of producers to document or explain how BMPs work, how they can be adapted and disseminated for different growers, or the cost of the BMP and the financial payback for different types of producers. This work falls squarely in the domain of research and extension scientists. At this time, however, there is too little funding to undertake this work. Many of those who know and can describe the technical aspects of BMPs do not have the skills to understand and describe the financial implications.

## *Seafood Buyers*

Seafood buyers are increasingly using BMPs to discourage worse production practices or encourage better ones. Buyers are motivated by a desire to ensure basic seafood health and safety and other product quality issues, while simultaneously avoiding reputational risk issues that could be associated with products produced in ways that can be linked directly to harmful impacts, particularly ones that are of increasing public awareness and concern.

Programs like EurepGAP require that producers comply with the legal requirements of the country where the product will be sold. The emphasis here is clearly on health and safety and food quality. Although producers are usually required to meet European Union standards to sell into those markets, those standards are often significantly higher than those that many producers are required to meet in their developing country homes. In some contexts, the practices used to meet local or international standards are GAPs. This confuses the issue somewhat as it implies that anything that is legal is good and anything that is not is bad. Although the latter may be true, the former probably is not.

The Global Aquaculture Alliance/Aquaculture Certification Council program has a similar approach. However, in this case, although producer certification standards exist, some 90% of certifications to date have been for processing plants, demonstrating the clear preference for food quality and health and safety concerns first. Although this is clearly the preference of GAA supporters like Darden Restaurants, this approach does not address the key on-farm social and environmental impacts of shrimp aquaculture.

Other buyers want the products they sell to be produced to higher standards. They achieve this by purchasing products from producers on the most efficient or best end of the performance curve for key issues. Buyers who seek product from producers who are best-in-class now purchase from those who are certified by third parties and ecolabel programs, or work with NGOs or independent consultants to create their own standards. Either way, the goal is to go well beyond compliance with either local or importing-country laws by purchasing from producers who have adopted or often created the best-known practices to reduce each of several different impacts. Whether they can actually do this without measurement is another question.

Buyers are rarely interested in paying a premium for product, whether or not the premium encourages better producers or discourages worse ones. They may enter into longer term contracts to buy products, but they will rarely lock in price ahead of time or for a longer period of time (e.g., 6 to 12 months). Buyers may pay a higher price for a product with specific attributes if demand for such products increases faster than supply. This means that producer-level BMPs need to either pay for themselves directly or, if undertaken together, have a net positive impact on income.

Because buyers will generally not pay more for products, any certification or verification system that ensures that BMPs have been adopted must be focused, limited in scope, and inexpensive to undertake. Also, to the extent that buyers care about specific issues, they will want to verify producer claims of reduced impacts against a baseline. All of these reasons suggest that BMP-based certification or verification programs should be limited in scope. Fortunately, much of the research suggests that only six to eight activities cause most of the impacts that the public cares most about and that might affect buyer reputations.

### *Investors*

Given a choice, private-sector investors tend to evaluate projects based solely on financial risks and returns. In the past, most of the focus has been on the financial viability of the entity borrowing money. Over the past 30 to 40 years, governments and multilateral lending agencies (e.g., the World Bank, the Asian Development Bank, and the International Finance Corporation) have incorporated social and environmental impact assessments into project evaluation, increasingly making it a condition of lending for aquaculture projects. Over time, some private sector lenders have seen that reduced environmental and social impacts actually implies better overall management, which has positive financial implications.

### *Regulators*

Regulators are increasingly interested in finding ways to use BMPs to improve performance and reduce waste and pollution. For many, BMPs are a proxy for achieving regulatory compliance and/or a condition of permitting or licensing. However, regulators face the same problems as other nonproducers who try to use BMPs as a proxy for performance: each BMP will yield a range of results. In fact, most regulators, at least in the short term, want to eliminate the worst impacts (Fig. 2.4). The thinking is that those who produce those impacts must be using worse practices. Although this may be true to some extent, it certainly is not true across the board. Any number of practices can yield unacceptable impacts, but it is quite likely that many of those same practices in the hands of other producers could have acceptable results.

This caveat aside, there may be times when a BMP-based approach works for regulators. This would most likely occur where production systems are similar throughout a regulated aquaculture industry. In this case, it is more likely that BMP-based regulatory approaches will yield expected and desired results. This is perhaps true for more mature industries or in regions where producers have adopted the same technological systems for the production of the same species.

The variation in appropriate and effective BMPs by species is an added complication for a BMP-based regulatory system. What works for one species will not work for another. There are even differences among the BMPs for different bivalve mollusks (e.g., clams,

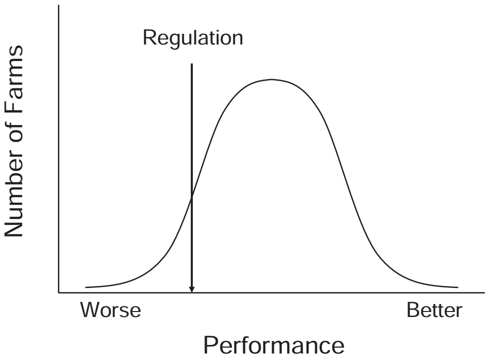

**Fig. 2.4.** Regulation tends to focus on producers associated with poor environmental performance. Poor-performing producers may be using the same practices as all other producers, but may not be as effective at implementing them.

oysters, mussels, and scallops) in terms of how they are produced and harvested. In effect, this means that regulators need to have robust BMP-based regulatory systems for each of the main species or species clusters if they are going to have the desired impacts and reflect species-specific differences.

Finally, as mentioned earlier, BMPs change—in some cases relatively rapidly. Regulators need to revisit any BMP-based producer requirements regularly (e.g., every 3 to 5 years). This is further complicated by the considerable lag time that often exists between when BMPs are first invented and when the consensus is built to the point that they become acceptable as a basis for regulations, permitting, or licensing.

Another consideration is whether a BMP-based regulatory system actually encourages or discourages the identification of new BMPs that can reduce the key impacts even more. BMPs are usually invented in order to solve a problem. In many cases the problem is perceived as regulatory compliance. Government regulators ask producers to do something (e.g., reduce risk, waste, or pollution) that may be beyond what many are doing currently. Regulators telling producers what they can do to allow them to be in compliance (i.e., adopt a BMP) will not really encourage innovation. Many BMPs are invented in other countries or for other species. A BMP-based regulatory system may not sufficiently encourage producers to go beyond compliance in their efforts.

In the long term, shifting the performance curve of most producers against previous benchmarked performance will allow government to develop stricter regulatory, permitting, or licensing systems. In less than 10 years, performance levels that are deemed unacceptable can be as high as what was previously considered to be above-average performance in any given system (Fig. 2.5). This shift is possible because of innovation, the creation of a new set of BMPs, or because a voluntary program set a high-performance goal that challenged industry to perform at a higher level. Although it is not clear that regulators can ever set the performance bar so high, it is clear that society can and should take advantage of new norms that are shown to be profitable in voluntary programs.

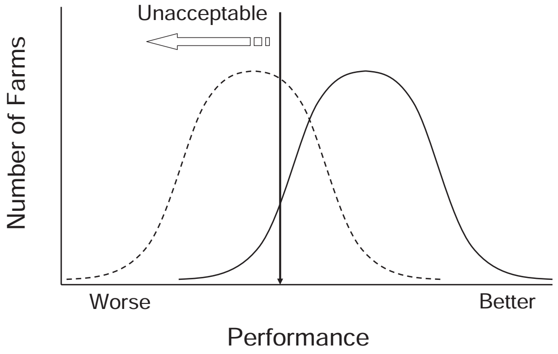

**Fig. 2.5.** Over time, the adoption of BMPs that are targeted for different producers will cause the environmental performance of all producers to shift from relatively worse performance (dashed curve) to relatively better performance (solid curve). Although BMPs are essential for achieving improved environmental performance, all producers may not achieve an acceptable performance level with the same BMP.

## Limitations of BMPs

In addition to the obvious limitations of an approach that focuses on processes and practices rather than measurable performance levels, BMPs as currently defined have other limitations. They do not allow producers—individually or collectively—to understand, much less reduce to acceptable performance levels, their cumulative social or environmental impacts. BMPs for a single producer operating in relative isolation will be based on what is financially and technically feasible. However, acceptable performance levels for many producers operating in the same area may be much more stringent because of the cumulative impact (e.g., water use, effluent quality, etc.) associated with a concentration of production. Most BMP-based systems are not focused on and generally do not address social issues at the producer level, so they will have no ability to predict community or regional issues. As mentioned before, specific BMPs or packages of BMPs will inevitably favor some producers over others. By focusing on existing BMP adoption rather than results, there may be little incentive to develop or invent new practices or to look to other industries for insights as one would have to do with increased performance requirements. Although it is beyond the scope of this chapter to do more than speculate, there may be a lag time for ecological impacts that may be either simply too long to measure or too late to change once identified. This suggests that BMPs are means to various ends. However, they will not spur innovation or improve performance over time. In fact, the best way to address cumulative impacts remains an open question.

### *Cumulative Environmental Impacts at a Landscape or Ecoregional Level*

Virtually all BMPs focus on what producers can do individually to address identified impacts. However, from an environmental perspective, the impacts of a single producer using BMPs will not produce results that are significant at the landscape or ecoregional level unless that producer is quite large or the impacts particularly egregious. At some point beyond the individual producer, however, small changes made by many producers can make a difference.

The carrying capacity of a landscape or ecoregion can be exceeded even though individual producers have adopted and implemented BMPs. The point here is that even with BMPs, there is a limit to how much activity can take place before the cumulative effect exceeds the capacity of the surrounding area (defined at an appropriate scale) to assimilate that impact. Different BMPs may allow more production, others less. However, aggregate impacts are not limited to the number of producers or widespread adoption of a specific BMP. Carrying capacity takes all practices into account. Strategically, it would be best to focus on those practices that cause the most significant impacts individually or whose impacts are compounded when combined with other practices.

Finally all the BMPs in the world will not correct the problems that can be caused by siting aquaculture production facilities in the wrong place (Clay 2004b). This may be due to impacts on critical habitat, biodiversity, or environmental services. Some locations may become obsolete because technology has changed or our understanding of the most significant impacts has changed. For example, through the early 1990s, shrimp farmers were told by technical consultants that it was best to construct ponds in former mangrove areas. They were also told to use 20% water exchange to maintain water quality. Now we know that neither of these is necessary.

Increasing awareness of impacts can also suggest not only new issues, but also performance standards and the BMPs that might help to achieve them. A good example of this is an increasing awareness of how carbon, energy, food miles, and climate change are affected by different production systems and practices. Tesco has asked all its suppliers to give the company a number for the amount of carbon embedded in the food miles for each product Tesco buys from them. Energy-intensive systems may be advisable for some producers, but they are now being looked at through a different, energy-efficient lens. In the future, water, biodiversity, liability and risks for escapes, etc., are likely to be similar issues. Impacts are not static, because science and the awareness that it drives is not static.

### *Larger Social and Political Issues*

Although BMPs can be developed to address any issue, they have typically been used to help workers reduce environmental impacts to more acceptable levels. Producers, for their part, see BMPs as a way to improve performance and increase efficiency and net income. Thus far, BMPs have not been widely seen as helpfully addressing social issues. Some producers have shown that incentive programs increase their net income by two to four times, and adult literacy programs can reduce worker turnover rates within 2 years from 80 to 20% per year and improve efficiency at the same time. Although there is a lot of work that could be done on BMPs that improve social performance, to date very little is known about their costs, their effects, and their impacts on profitability.

On the social side, the focus of ecolabel, certification, and government regulatory programs is limited mostly to obeying the law. Even certification programs that promote fair trade are focused mostly on the prices paid to producers (and obeying the law), not the conditions of the labor hired in aquaculture production or processing facilities or the impact of operations on neighboring communities. Simply put, there has been little intellectual or political interest to address more broadly defined social issues within BMP programs. Enlightened producers have found ways to improve their social performance and many have been rewarded by increased profits as well as in a number of less tangible but locally important ways.

With the exception of those issues about which there is consensus and the issues that are already codified in labor and other laws, there is little agreement about what other issues can or should be addressed by BMPs. In the nine aquaculture and agriculture commodity dialogues that World Wildlife Fund is helping to convene, there is broad and generally easy consensus about environmental impacts and therefore the types of BMPs that might reduce them. On the other hand, there is little or no consensus about the key social impacts for any single species and the different ways it may be produced, and even less across a wide range of species and each with a range of production systems. In part this is cultural. Different countries have different social and cultural values and different ideas about what government, producers, and society as a whole should do. Where there is agreement, the BMPs tend to be codified in law. However, there is often little consensus nationally beyond what is in the law, and little if any global agreement on these issues.

### *Many Are Best for Specific Types of Producers*

BMPs tend to be linked to specific types of production systems or to specific product quality and handling issues. The party who requests or requires BMPs will have much to do with specifying BMPs they want to see. For example, buyers will want practices that enhance product quality and address known health and safety issues. Some producers will have a comparative advantage over others in complying. In addition to species cultured, the key variables appear to be scale, intensity, producer country norms, availability of capital, and cost of labor. The issue is not just that BMPs are not one-size-fits-all, but rather that there are BMPs that will make every producer perform better.

Many certification and ecolabel programs, particularly those that intend to be global, are based primarily on the reality of a certain type or class of producer. Such programs can inadvertently exclude others. A BMP for extensive, semiextensive, intensive, or superintensive production systems will vary considerably. Similarly, the impacts that are acceptable for black tiger prawns (*Penaeus monodon*) are different than those for Pacific white shrimp (*Litopenaeus vannamei*). Because the biological and cultural requirements differ for the two species, performance standards will differ for feed conversion, stocking densities, survival rates, depth of the water, and harvest times. This is also true of basa (*Pangasius bocourti*) and channel catfish (*Ictalurus punctatus*) and trout or tilapia raised in different ways in different places.

From the perspective of a global program, it is easiest to have a single program with standards that are clear to the producer and easy to verify. It is also clear that many buyers, brands, and retailers would—all things being equal—prefer to support those BMPs that reflect the types of systems that they think best address food quality and health and safety issues.

## *No Home for BMPs*

Many producers do not have access to information about BMPs that would allow them to identify, much less adopt, those BMPs that might best serve their needs. In today's world of instant information it often takes up to 10 years between when a BMP is invented and when it is made more widely available to others. This diffusion time period is faster than other industries, which typically adopt a new technology at a large scale 50 to 70 years after invention (Grubler 1998). For BMPs, the inventor will test the practice for a few production cycles and then gradually roll it out. It will become known and talked about locally, and then a researcher from a university or a government agency will appear. They will spend time documenting what is going on, undertaking independent trials, and having their results reviewed and verified by others, and eventually after a lag of a year or two they will write up the results and get them peer reviewed and then published.

By this point the producer who originated the BMP has invented something more or better that supersedes the last one. What is being rolled out globally is already obsolete. We need to shorten the amount of time that this process takes. To do that we will need to be more strategic. If we assume that we can look at the practice in isolation rather than document how it fits into the entire production system this will speed things up considerably. Also, because BMPs cannot be transferred indiscriminately from one farm to another, we can assume that what is important is how the inventor thought about the practice and how it fit into the operation rather than documenting the specific details of the practice. Here again the issue is how to think, not what to think. This kind of information, and the general financial and other implications, can be captured and conveyed far more quickly than has been done to date.

Even so, there is a need for a home or several homes for BMPs. It would be a tremendous boon to the aquaculture industry if BMPs, the results they achieve on the ground, and their impact on production and income could be documented and made more readily available to others. This can be accomplished through a dedicated website. Although many aquaculture producers would have access to such technology, many, if not most, around the world would not. Radio programs might be effective in some areas, farmer field schools like those run by the United Nations Food and Agriculture Organization (FAO) or farmer exchanges could fill part of the niche, and certification programs could as well. Government extension programs would be ideal but they have less funding than in the past. Increasingly the private sector is doing this through contract producers, processors, input suppliers, or loans.

Whatever the delivery mechanisms, it would be the full-time job of several people to develop such information and deliver it to and through the appropriate channels. It would probably need to be in one language initially, but relevant parts (e.g., impacts, species, and practices) could be translated as appropriate.

Given the transitory nature of BMPs, such information would have to be updated regularly. However, the goal is help producers better understand how other producers from around the world have been able to solve problems that affect them. Clearly today's BMP is tomorrow's norm and the one that needs to be replaced the day after.

## Conclusions

Better management practices are better than worse practices. No surprise there. They are also better than either good or bad aquaculture practices. They are not, however, a credible proxy for performance. If we are to strategically reduce the most significant impacts from aquaculture production, we must first agree on what they are. Science-based consensus is very important on this issue, particularly when there is so much information of dubious value in the public domain and even in peer-reviewed articles.

Once we have agreed on the key impacts of different aquaculture production systems, the task is to measure those impacts at this point in time. If we cannot define the range of performance for a given impact, it will be hard to draw a line regarding what is acceptable and what needs improvement. Because aquaculture is a global industry and products traded around the world compete with each other, the goal should be to understand average global performance benchmarks and why and how they vary around the world.

There is an old adage: If you don't know where you're going any road will get you there. This is only half true. It is essential to know where we are *and* where we are trying to go. Reasonable people will disagree about priorities and strategies under the best of conditions. Knowing where we are globally and what the range of performance is will be essential to developing a viable strategy for moving forward. There is considerable evidence to suggest that with regard to the same potential issue, some producers can have 10 to 100 times more impact than others. When our thinking about goals or current realities is based on assumptions, impressions, or concerns rather than science and reliable data, the disagreements will be even more intense. Credibility comes with metrics.

As important, innovation comes from metrics. Innovation comes from clearly agreeing on and defining a problem and letting each producer find the best way to achieve acceptable performance levels. Setting challenging performance standards, not identifying a set of BMPs, will be key to the future of sustainable aquaculture, because as soon as a BMP is written in stone, it is obsolete.

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## Chapter 3

# Better Management Practices in International Aquaculture

*Claude E. Boyd*

## Introduction

The United States imports about 85% of its fisheries products, and fish, shrimp, and molluscan shellfish originating from aquaculture are a major component of this trade. Several environmental nongovernmental organizations (NGOs) became highly critical of aquaculture and particularly about marine shrimp and salmon farming in the 1990s. Attempts by more radical environmental NGOs to effect consumer boycotts of these species in the United States and other western nations failed. However, several moderate NGOs persisted in efforts to promote environmental and social responsibility in aquaculture. Criticism of aquaculture practices by World Wildlife Fund, Environmental Defense, Conservation International, and other environmental NGOs has caused aquaculture organizations to promote environmental responsibility, governments to increase environmental regulations for aquaculture, and some retailers and other food service buyers to seek environmentally and socially responsible aquaculture products. Most negative environmental and social impacts of aquaculture occur at the farm level, and particular emphasis has been given to encouraging producers to adopt best management practices (BMPs) designed to lessen these impacts. The NGOs also have succeeded in obtaining the participation of the United Nations Food and Agricultural Organization (FAO), World Bank, and other international development agencies in efforts to promote responsible aquaculture. Moreover, educational programs by NGOs to encourage more responsible seafood choices by consumers apparently are beginning to influence the market.

Aquaculture in the United States has been subject to various federal and state environmental regulations for years. However, the United States Environmental Protection Agency (USEPA) only recently developed a federal rule for aquaculture effluents. This rule-making activity was initiated because of intervention by environmental NGOs. And, environmental NGOs appear to have become interested in United States aquaculture mainly because of their experiences with salmon and shrimp farming in other nations. USEPA decided that domestic aquaculture is not a major source of pollution. The effluent rule basically recommends adoption of BMPs by operations large enough to be considered concentrated aquatic animal production facilities. Changes in aquaculture sourcing policies by major buyers seeking products from responsible aquaculture likely will have greater

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effects on United States aquaculture than the USEPA effluent rule and other environmental regulations.

The purpose of this chapter is to provide an overview of international aquaculture, discuss programs for improving environmental and social responsibility of international aquaculture, and consider possible effects of these programs on United States aquaculture.

## World Aquaculture Production

World aquaculture has grown from a few million tonnes annually in the 1950s to nearly 60 million tonnes in 2004. Statistics from FAO (2006) are used below to provide an overview of current world aquaculture production.

### *Production by Environments and Species Categories*

Aquaculture is considered by FAO to be done in three environments: freshwater, brackishwater, and marine. In 2004, total aquacultural production for the three environments were 25.8 tonnes in freshwater, 3.4 tonnes in brackishwater, and 30.2 million tonnes in marine environments. The data are summarized by major species groups (Table 3.1). Freshwater aquaculture is largely fish culture, crustacean culture dominates brackishwater aquaculture, and aquatic plants (primarily seaweeds) and mollusks (mainly bivalves) are the main marine aquaculture crops. If only aquatic animals are considered, aquaculture production in freshwater is considerably greater than that of brackishwater and marine environments combined.

Further analysis of the FAO data (Table 3.2) reveals that carp species dominate freshwater production, but there also is significant production of unspecified fish species and tilapia. Production of Pacific white shrimp (*Litopenaeus vannamei*) and black tiger shrimp (*Penaeus monodon*) dominates brackishwater aquaculture. Bivalve mollusks are the main categories of marine animal culture, but Atlantic salmon (*Salmo salar*) is also significant. Of course, marine plant production is slightly greater than bivalve mollusk production in marine aquaculture.

**Table 3.1.** World aquacultural production (tonnes) in 2004 according to environment and major species groups.

| Species Group | Freshwater | Brackishwater | Marine |
|---|---|---|---|
| Aquatic plants | 44,890 | 22,886 | 13,859,291 |
| Crustaceans | 973,249 | 2,155,538 | 550,996 |
| Freshwater fish | 23,431,603 | 434,938 | — |
| Diadromous fish | 727,075 | 531,159 | 1,593,281 |
| Marine fish | 155,329 | 188,258 | 1,103,396 |
| Mollusks | 208,097 | 59,670 | 12,975,064 |
| Miscellaneous | 256,280 | — | 137,474 |
| Total | 25,796,523 | 3,392,449 | 30,219,472 |

*Source:* FAO (2006).

**Table 3.2.** Production (millions of tonnes) during 2004 for some major species categories in freshwater, brackishwater, and marine environments.

| Freshwater | | Brackishwater | | Marine | |
|---|---|---|---|---|---|
| Species | Production | Species | Production | Species | Production |
| Carp | 18.30 | Pacific white shrimp | 1.39 | Oysters | 4.60 |
| Unspecified finfish | 3.39 | Black tiger prawn | 0.72 | Clams, cockles, and arkshells | 4.12 |
| Tilapia | 1.82 | | | Mussels | 1.86 |
| Crustaceans | 0.95 | Milkfish | 0.57 | Atlantic salmon | 1.24 |
| Channel catfish | 0.35 | Grey mullet | 0.13 | Scallops and pectens | 1.17 |

*Source:* FAO (2006).

**Table 3.3.** The 20 leading aquaculture-producing nations in 2004.

| | Production (tonnes) | | |
|---|---|---|---|
| Nation | Fish and Shellfish | Plants | Total Aquaculture |
| China | 30,614,968 | 10,714,610 | 41,329,578 |
| India | 2,472,335 | | 2,472,335 |
| Philippines | 512,220 | 1,204,808 | 1,717,028 |
| Indonesia | 1,045,051 | 410,570 | 1,455,621 |
| Japan | 776,421 | 484,389 | 1,260,810 |
| Vietnam | 1,198,617 | 30,000 | 1,228,617 |
| Thailand | 1,172,866 | | 1,172,866 |
| South Korea | 405,748 | 547,108 | 952,856 |
| Bangladesh | 914,752 | | 914,752 |
| Chile | 674,979 | 19,714 | 694,693 |
| Norway | 637,993 | | 637,993 |
| United States | 606,549 | | 606,549 |
| North Korea | 63,700 | 444,295 | 507,995 |
| Egypt | 471,535 | | 471,535 |
| Myanmar | 400,360 | | 400,360 |
| Spain | 363,181 | | 363,181 |
| Taiwan | 318,273 | 9,164 | 327,437 |
| Brazil | 269,699 | | 269,699 |
| France | 243,870 | 37 | 243,907 |
| United Kingdom | 207,203 | | 207,203 |

*Source:* FAO (2006).

## Geography of Aquaculture

The world is divided into six aquaculture regions by FAO. The following are the regions and the 2004 production of each: Oceania, 139,273 tonnes; Africa, 570,113 tonnes; North America, 955,178 tonnes; South America, 1,137,825 tonnes; Europe, 2,238,683 tonnes; Asia, 54,367,372 tonnes. Asia provides 91.5% of world aquaculture production.

Although many nations have aquaculture, relatively few nations provide most of the world's production of cultured aquatic organisms. Nine of the top ten and twelve of the top 20 aquaculture nations are in Asia (Table 3.3). According to FAO (2006) statistics, China is responsible for more than 50% of world aquaculture production, with more than 41 million tonnes annual production. The FAO can officially report only fisheries data provided by governmental sources in each nation. Most experts agree that the Chinese government has traditionally inflated their aquaculture data—possibly by a factor of 2 or 3 (Boyd et al. 2005). Nevertheless, even if the Chinese data are inflated fivefold, China still has more than twice the aquaculture production of India, the second largest aquaculture producer.

### *Aquaculture Products in International Trade*

The top ten species and species groups produced by aquaculture (Table 3.4) include salmonids, tilapia, shrimp, oysters, clams, scallops, and mussels, popular with consumers in developed nations where a high percentage of seafood is imported. For example, about 2.1 million tonnes of seafood are consumed annually in the United States, of which about 80% is imported. Average per capita consumption of seafood in the United States is 7.4 kg, and 10 species or species groups account for over 90% of the total consumption (Table 3.5). Aquaculture is an important source of shrimp, salmon, catfish, crab, tilapia, clams, and scallops for United States consumers. Only one species listed in Table 3.5, channel catfish (*Ictalurus punctatus*), is almost totally from domestic aquaculture. Two species not listed in Table 3.5, red swamp crayfish (*Procambarus clarkii*), known in the United States as crawfish, and rainbow trout (*Oncorhynchus mykiss*), also are popular with United States consumers, and these two species are produced mainly in domestic aquaculture.

**Table 3.4.** Major species of fish, crustaceans, and mollusks produced in aquaculture, 2004.

| Species Group | Production (tonnes) | Species Group | Production (tonnes) |
|---|---|---|---|
| Carp, barbels, cyprinids | 18,303,847 | Oysters | 4,603,717 |
| Salmon, trout, smelt | 1,978,109 | Clams, cockles, arkshells | 4,116,839 |
| Tilapia | 1,822,745 | Scallops | 1,166,756 |
| Other finfish | 6,044,787 | Mussels | 1,860,249 |
| Shrimp | 2,476,023 | Other mollusks | 1,065,191 |

*Source:* FAO (2006).

**Table 3.5.** Top ten seafoods consumed in the United States, 2005.

| Species or Group | Consumption (kg/capita) | Species or Group | Consumption (kg/capita) |
|---|---|---|---|
| Shrimp | 1.86 | Crab | 0.29 |
| Canned tuna | 1.41 | Cod | 0.26 |
| Salmon | 1.10 | Clams | 0.20 |
| Pollock | 0.66 | Flatfish | 0.17 |
| Catfish | 0.47 | Top ten total | 6.81 |
| Tilapia | 0.39 | All seafood | 7.36 |

*Source:* National Fisheries Institute (www.aboutseafood.com/media/top_10.cfm).

## Contrasts Between United States and International Aquaculture

Environmental issues in aquaculture are described in Chapter 1. There are, however, major differences between aquaculture in the United States and other developed countries and aquaculture in developing nations. In developed nations, most seafood is imported from developing countries, and aquaculture is limited mainly to a few species of moderate or high value for domestic markets. For example, channel catfish, rainbow trout, and crawfish produced in aquaculture in the United States are almost exclusively marketed domestically. Several countries in the European Union produce trout, salmon, and bivalve shellfish by aquaculture. Although some of this production is exported, much is for the European market. Carp production in Europe is for domestic markets.

In developing nations with large aquaculture sectors, there is greater variety of culture species than in developed nations. Although most of the production is consumed domestically, some developing countries export large quantities of aquacultured shrimp, tilapia, salmon, and several other species.

Farms in developed countries usually must be fairly large to be profitable, and there are relatively few producers. For example, in 2006 there were 1,035 catfish farms in the United States and the average farm size was 67 ha (USDA-NASS 2007). Labor is expensive, so mechanization and automation is used as much as possible. Even family farms must invest in the latest technology to be profitable.

There are tens of thousands of small aquaculture farms in many developing nations. In pond culture, farms typically have water surface areas of 0.25 to 5 ha. Other production systems also are much smaller than those in developed nations. There are some extremely large shrimp, tilapia, and salmon farms in developing nations, but the combined production by small farms in many nations, especially in Asia, greatly exceeds that of large farms.

Small-scale farmers tend to be poor and live in rural areas. They are poorly educated, lack knowledge about aquacultural technology, and are unaware of environmental issues. Production practices often are substandard, and few producers use BMPs to lessen negative environmental impacts. Large farms usually hire highly qualified managers and use better production practices than small farms. Because labor is inexpensive in developing countries, large farms are not as mechanized as those in developed countries. Nearly all large farms in developing countries focus on the export market.

There often are dense concentrations of small aquaculture farms in developing nations (Fig. 3.1). The environmental implications of such dense clusters of farms are obvious, and the likelihood of negative impacts often is exacerbated by lack of effective governmental regulation of effluents, wetlands, predator control, water use, and other factors. The combined effect of many small farms on the environment can be as great or greater than that of a large farm.

Aquaculture facilities in developed nations also tend to be concentrated in specific areas. In the United States nearly all catfish farms are located in a few counties of Alabama, Arkansas, Louisiana, and Mississippi. In Alabama about 50% of catfish farms in the state are on the catchment of a single creek, but the farms occupy only 7.5% of the surface area of the catchment (Silapajarn and Boyd 2005). The largest portion of the United States trout industry is located along a stretch of the Snake River in Idaho. Nevertheless, the facilities usually are separated by distances of 1 to several km. Environmental regulations

**Fig. 3.1.** Dense concentration of coastal aquaculture ponds.

also are imposed on aquaculture in wealthy nations, and there are few alleged or documented negative environmental impacts of aquaculture.

Developed nations generally have more equitable social conditions than found in developing countries. In many poor countries, agricultural workers may not be paid a legal minimum wage, working and living conditions on farms may be inadequate, and there may be no benefits or job security. Large aquaculture companies may be given priority over other stakeholders for use of land, water, and other resources, resulting in conflicts with local communities. Companies may hire laborers from other places in preference to local workers. Child labor also may be used at some farms. Small-scale producers usually do not hire workers, but underaged family members are expected to work on farms. This is acceptable provided children are not denied the opportunity for an education. Obviously, social injustices are more likely to result from aquaculture in developing nations than in the United States or other developed nations.

Environmental NGOs continue to criticize aquaculture on environmental and social grounds, but discussions with officials in several of these organizations suggest a change in attitude. They have come to realize that aquaculture is a necessary component of the world's food production system, and that when done properly, aquaculture can be more environmentally responsible than fishing (Boyd et al. 2005). Fishing is analogous to hunting and gathering, while aquaculture is a form of agriculture. Humans no longer depend on hunting and gathering as a primary source of food and fiber from terrestrial sources. Likewise, we should increasingly turn to responsible aquaculture as an alternative to fishing for sources of aquatic food.

## Codes of Conduct and BMP Programs

There are a number of initiatives to improve the environmental and social performance of international aquaculture. These range from programs encouraging voluntary adoption of

BMPs to certification programs in which BMPs are implemented as a means of complying with verifiable environmental and social standards. There has been widespread use of BMPs to improve resource use and lessen the amount of nonpoint source pollution in traditional agriculture (Hairston et al. 1995; Clay 2004). Thus, the initial response of promoting codes of conduct and BMPs in response to the criticism of environmentalists over negative impacts of aquaculture was not surprising (Boyd 2003). The efforts mostly were initiatives of aquaculture associations, government fisheries and aquaculture agencies, and international organizations that support aquaculture development. It is noteworthy that the promotion of better practices began well before there was concern in the international market about environmental and social issues related to aquaculture.

### *FAO Involvement*

The FAO has a long history of promoting better aquaculture practices to increase production, improve efficiency of resource use, and avoid negative environmental and social impacts. The FAO Fisheries Department (1997) published a *Code of Conduct for Responsible Fisheries* that has served as guiding principles for many of the recent responsible aquaculture programs. Shrimp aquaculture has been a particular focus of FAO. Expert consultancies were held in Bangkok, Thailand (1997); Rome, Italy (1998); and Sydney, Australia (2000) to discuss the environmental impacts of shrimp farming and to develop best management practices for preventing these impacts.

### *The Consortium on Shrimp Farming and the Environment*

The World Wildlife Fund (WWF), Network of Aquaculture Centres in Asia-Pacific (NACA), and World Bank joined with the FAO and the United Nations Environment Programme (UNEP) to form a consortium to investigate shrimp farming practices worldwide. The consortium conducted case studies of shrimp farming in several countries. For example, in Ecuador, studies were conducted on capture of wild postlarvae, farm effluent composition, and effects of shrimp farming on mangroves. Thematic studies that cut across countries were prepared for topics such as chemical use, inland shrimp farming, shrimp diseases, etc. Many of the case studies have been posted at the NACA website (www.enaca.org). The findings of the case studies were used to develop better management practices for shrimp farming (FAO et al. 2006).

### *Government Programs*

Aquaculture products are important sources of foreign exchange in many countries. Thus, governments of nations with significant aquaculture have the dual task of protecting the environment and promoting the export of aquaculture products. Some countries have programs to assist producers in developing and adopting codes of conduct and BMPs for responsible aquaculture. The government of Madagascar developed a code of conduct for shrimp farming with recommended practices, including some legal aspects to be considered later (Edaly 2003). The Thailand Department of Fisheries devoted much effort to promoting a code of conduct (CoC) program for marine shrimp farming (Tookwinas et al. 2000). Recently, the Thailand Department of Fisheries also initiated a good aquaculture practices (GAP) program for Thai shrimp farming that is less strict than the CoC program.

Producers can choose between the CoC and GAP programs (Waraporn Prompoj, Thailand Department of Fisheries, personal communication). The Malaysia Department of Fisheries also made a CoC for shrimp farming that is an example of general guidelines for voluntary adoption by producers.

### *Industry Efforts*

Aquaculture industry associations in several nations have developed environmental policies, codes of conduct, or codes of practices for their members. One of the first and best-known programs is the code of practices of the Irish Salmon Growers Association (1991). Some other examples are programs of the British Trout Association, Ornamental Fish Industry (United Kingdom), Washington Fish Growers Association, Aquaculture Foundation of India, Pacific Coast Shellfish Growers Association, and the Association of Scottish Shellfish Growers. The Australian Prawn Farmers Association developed one of the first codes of practice for shrimp culture (Donovan 1998). The Global Aquaculture Alliance (Boyd 1999) and several other organizations have since developed codes of practice for responsible aquaculture and especially for responsible shrimp farming.

### *Voluntary Adoption of BMPs*

Because of the huge amount of attention given to the negative environmental impacts of aquaculture and promotion of better practices, there no doubt has been voluntary adoption of BMPs by individual farms. It is unlikely that voluntary adoption has been widespread or systematic, because BMP implementation depends on the individual farmer's perception of the effect of adoption on farm profitability. It is usually easier to assess the costs of BMP implementation than it is to measure benefits, so farmers often have a distorted picture of the farm-level economics associated with BMP adoption. If they perceive that BMP adoption is too costly, they will not change their behavior. BMPs that are directly associated with better production efficiency (such as practices that improve feed conversion) will be more readily adopted than practices that are management-intensive or require investment in additional infrastructure. No studies have been conducted to determine the degree of independent, voluntary adoption of aquaculture BMPs.

## Retailer Purchasing Policies

Several large retailers have developed purchasing policies and production standards for use in sourcing responsible aquaculture products. Examples are Marks & Spencer and Tesco in the United Kingdom, Carrefour in France, and Wegmans Food Markets, Inc., and Bon Appétit Management Company in the United States. Retailer programs tend to focus on the production process, product specifications, and product quality. However, they generally include environmental and social requirements. Standards may vary considerably among different companies. Standards may be agreed upon between buyer and producer and not disclosed to the public. Some retailers, e.g., Wegmans and Bon Appétit Management Company, apparently will disclose their policy and standards. Retailers have their own specialists to audit producers or they rely on auditing companies.

Retailer programs can be important in providing safe, high-quality products and in reducing negative environmental and social impacts. The standards, however, are developed specifically for the retailers' marketing objectives and customer base. The standards may not be revealed to the public, and development of standards is not always a transparent process. Some retailers are hiring professionals with experience related to aquaculture and environmental issues. Others are contracting with environmental NGOs to obtain assistance in developing purchasing policies and standards. Of course, this approach possibly also is a means of obtaining an endorsement from the NGO.

The primary purpose of retailer programs is for a company to differentiate itself by developing its own standards. This suggests that the retailer understands and controls the suppliers. The standards also suggest that the retailer is seeking a product specifically for its customers. These programs are marketing strategies intended to satisfy a company's customer base and to demonstrate that the company is concerned about the environment and social issues.

## Certification

The purpose of aquaculture certification is to provide products certified to have been produced by environmentally and socially responsible methods. There are several generally accepted requirements for developing certification programs. The standards should be developed through a broad, deliberate, and transparent process that involves all stakeholders. These standards should be available to the public. Producers participating in certification must comply with the standards, and compliance must be verified through regular and unannounced inspections by a qualified third party. Noncompliance with certification requirements must be corrected within a specified period, or certified status is revoked. Product traceability is a key feature of certification because it must be possible to trace a certified product back to the farm of origin.

### *Government Programs*

The French Label Rouge program is an example of government-controlled certification. This program certifies many food products for the French market and it has standards for aquaculture certification. It is run by an association of industry and certifying organizations with oversight by the French government. Like retailer programs, it focuses on product quality but it has environmental and social standards.

In Thailand, the Department of Fisheries has developed two BMP programs for shrimp culture that have been promoted (so far unsuccessfully) as a means of assuring buyers that shrimp have been produced responsibly. One is called the *Thailand Marine Shrimp Farming Code of Conduct (CoC)* and the other is known as the *Good Aquaculture Practices (GAP)* for marine shrimp farming. Both programs require implementation and verification of specific BMPs but do not have clearly defined standards. Based on the practices required for compliance, the CoC program appears more rigorous than the GAP. The Department of Fisheries has trained inspectors for these programs and many farms have been certified. Representatives of the shrimp culture industry were involved in discussions related to formation of both programs, but apparently few other stakeholders had input. The method for inspecting farms for compliance with certification requirements does not appear to be a true third-party system.

The CoC and GAP programs have created an interesting situation. The DOF was encouraged by the World Bank and other outside groups to develop the CoC and GAP as a proactive approach. The Thai Department of Fisheries wants its certification program to be accepted by foreign shrimp buyers, and it desires sole responsibility for certification of farms in Thailand. So far, foreign shrimp buyers are not willing to accept the Department of Fisheries program as a credible means of sourcing environmentally responsible shrimp. Some in the Department of Fisheries feel slighted because of the lack of confidence in the CoC and GAP, and they have responded by not cooperating with those interested in installing other certification programs. The FAO has announced an initiative to develop international guidelines for aquaculture certification. The first expert consultancy was held in Bangkok, Thailand, from 27–30 March 2007, and at least three more consultancies are planned for other venues. This effort possibly will provide suggestions for inclusion of national interest in development of standards and administration of certification programs.

The shrimp farming code of conduct developed in Madagascar can be considered a type of government certification. Many of the practices presented in this document are legally binding (Razafitseheno 2003; Edaly 2003). This code prohibits shrimp farms in mangrove areas, specifies minimum distances between shrimp farms, prohibits imports of broodstock and postlarvae, places limits on production intensity, and requires effluent monitoring. Adoption of the practices by all producers has allowed shrimp to be sold under a "Product of Madagascar" label and receive a premium price.

### *An Industry Certification Program*

The Global Aquaculture Alliance (GAA) developed certification standards for shrimp aquaculture and licensed these standards to the Aquaculture Certification Council (ACC). The GAA has shrimp certification standards for hatcheries, farms, and processing plants. The ACC has held several training programs to train inspectors, and many farms have been certified. This program was given a great boost recently when Wal-Mart signed an agreement with ACC to sell only ACC-certified shrimp as soon as the program can be widely implemented (Chamberlain 2005, 2006). The GAA currently is developing standards for certification of several fish species at the request of Wal-Mart and several other buyers.

The relationship between GAA and ACC has been the subject of considerable controversy. The GAA was established in 1997 with the stated mission "to further environmentally responsible aquaculture." The GAA developed BMPs for voluntary adoption by shrimp farmers (Boyd 1999). This effort led to the idea of certification. Certification standards were developed for which producers would have to install BMPs to achieve compliance. This program was called *Best Aquaculture Practices (BAP)* certification. The program has been widely criticized by NGOs for not involving a wide range of stakeholders in developing the standards. This criticism is not entirely valid, for several environmentalists were invited to review the standards, but only a few did. The ACC was developed by GAA as the certifying body for the BAP program. Environmental NGOs complained that GAA and ACC were in reality the same organization because there was much overlap on the board of directors of the two organizations. The two organizations have gradually become independent bodies, and today, only one individual is a member of the board of directors of both organizations. The ACC and GAA have distanced themselves and operate independently, and the criticism, in my opinion, is no longer valid.

The ACC developed the procedures for verification of compliance with BAP standards and trained inspectors for the program. The environmental NGOs correctly argue that the ACC is not a true third-party certification program because the inspectors are not from an independent organization. At Wal-Mart's request, Conservation International (CI) evaluated the GAA standards and the ACC procedures. GAA and ACC incorporated changes suggested by CI, but the ACC certification program still is viewed with suspicion by most environmental NGOs.

Originally, certification was promoted as a way of obtaining a higher price for aquaculture products. However, Wal-Mart apparently does not plan to pay a higher price for ACC-certified shrimp. The producer will have to bear the extra cost of certification to assure sales to Wal-Mart. Environmentalists would like to see producers benefit from a higher price for their products. Nevertheless, they are probably willing to accept the Wal-Mart model because it will result in a much wider need for certification than would result from high-end markets for certified aquaculture products. Wal-Mart's competitors already are initiating efforts to market certified aquaculture products. It is not yet clear as to whether they will pay producers more for a certified product.

### *An Environmental NGO Certification Effort*

The WWF conducted a study of the issues that should be considered in developing certification standards for shrimp, salmon, catfish, tilapia, trout, oysters, mussels, clams, scallops, abalone, and seaweed (Boyd et al. 2005). Reports have been prepared on the use of fishmeal in aquaculture and on the markets for certified aquaculture products. Stakeholder dialogues have been conducted for salmon, channel catfish, tilapia, and shellfish certification issues, and additional dialogues are scheduled. The WWF received additional funding for this effort in early 2007, which has allowed them to hire several specialists to manage the dialogues for different species or species groups. The timeline for the project calls for stakeholders to reach agreement on issues and develop the initial certification standards for the different aquaculture species by the end of 2009.

The WWF program emphasizes adoption of better practices to improve the performance of aquaculture (Clay 2004). Clay also suggests use of the term *better management practices* instead of *best management practices* because practices are evolving (see Chapter 2). Adoption of better practices will allow farms seeking certification to comply with a system of numerically verifiable standards.

Although the WWF is devoting much effort to aquaculture certification, it will not be the certifying body. A suitable organization to oversee the certification program will be found and the WWF effort entrusted to it. This is the same way that the WWF and its donors operated in developing the Marine Stewardship Council (MSC) and the Forest Stewardship Council (FSC). The MSC develops standards for sustainable fisheries, but an independent certifying body is responsible for determining whether a fishery complies with the standard. This is true third-party certification. The FSC operates in much the same way as the MSC.

There have been discussions among the GAA, ACC, WWF, and MSC about possibilities for combining efforts. A certification program developed and operated through collaboration among the WWF, GAA, and ACC would probably be more widely acceptable than either an NGO or industry program alone. However, the author is of the opinion that aquaculture certification and fisheries certification should not be combined. Aquaculture is potentially more responsible than fishing, and the aquaculture industry should promote their products separately.

### ISO Certification

Certification by the International Standards Organization (ISO) has been achieved by several aquafeed plants and processing plants for aquaculture species. A few shrimp and fish farms also have obtained ISO certification. There are several types of ISO certification; the applicable ISO programs for the aquaculture industry are 9001 (quality), 14001 (environment), and 22000 (food safety). ISO currently does not recommend aquaculture production standards, but the program provides a procedure through which producers can develop and implement practices for compliance with standards from another source. In ISO certification, an organization says what it will do and then proves it does what it says it will do (von Zharen 1996). Retailers and other buyers of aquaculture products likely view ISO certification favorably because it suggests that farms and processing plants are well managed. ISO certification is not proof of environmental and social responsibility, because the entity undergoing certification often makes its own standards without stakeholder involvement. Nevertheless, ISO certification is established and respected, and most environmental NGOs probably have a positive opinion of it.

### EurepGAP Certification

The EurepGAP program is promoted as responding to consumer concerns on food safety; animal welfare; environmental protection; and worker health, safety, and welfare. This program, administrated from offices in Germany, was developed initially for traditional agricultural products. EurepGAP recently extended its standards to include aquaculture.

EurepGAP has an *Integrated Aquaculture Assurance* document with which all certified facilities must comply. This document does not have clearly stated standards. Instead it has several general principles related to worker safety, facilities management, chemical use, animal welfare, environmental protection, product quality, and product testing. It requires the preparation of many action plans and has a huge record-keeping component. A total of 213 control points are identified in the basic aquaculture assurance document, and each must be audited for compliance with stated criteria. Some control points have multiple criteria. For each individual aquaculture species or species group, there is an add-on module for specific control points. The add-on module for shrimp has an additional 32 control points. There are major, minor, and recommended control points. A facility must comply with all major criteria and 90% of minor criteria, but compliance with recommended criteria is not mandatory. Although the EurepGAP program is extremely detailed, it is much weaker on environmental and social requirements than most other programs discussed above. The requirements for written plans and record keeping are complicated. Only a large farm capable of dedicating one or more employees to the tasks could comply with the criteria. The author has not heard environmentalists comment on the EurepGAP program, but it seems unlikely that they would find this program satisfactory for lack of social standards. Moreover, it is unlikely that producers would choose such a complex program over a simpler one unless forced to do so by buyers.

EurepGAP was a presenter at the 27–30 March 2007 FAO consultancy on international certification standards for aquaculture in Bangkok, Thailand. It appears that EurepGAP will develop specific aquaculture certification programs for different countries. For example, a presenter from China talked about a EurepGAP-China aquaculture certification program "based on the realities of Chinese aquaculture." This suggests that EurepGAP is planning to make changes in its program that will facilitate certification of small-scale producers in developing countries.

### *Organic Certification*

Organic certification of terrestrial food products has a long tradition. The primary purpose of standards is to verify that products are organically produced, but a few environmental and social standards usually are included. Organic certification recently has been extended to aquaculture products by several organizations. The most popular ones are Naturland (Germany) and Soil Association (United Kingdom). The International Federation of Organic Agriculture Movements (IFOAM) developed aquaculture standards for inclusion in the IFOAM Basic Standards in 2005. The French Ministry of Agriculture and Fisheries is working on organic standards for aquaculture products, but presently organic aquaculture standards for France are based on agricultural standards. For example, OSO in Madagascar and the French auditing company Bureau Veritas developed organic shrimp standards that were validated by the French Ministry of Agriculture and Fisheries.

The United States Department of Agriculture (USDA) is developing standards for organic aquaculture under the National Organic Standard Board (NOSB). The Aquatic Animal Task Force has developed draft organic standards that have been approved by the NOSB and will now undergo interagency review. Once standards are approved, the USDA National Organic Program will publish an organic aquaculture certification rule in the Federal Register. After implementation of the rule, all organic aquaculture products sold in the United States must comply with USDA organic standards.

## Constraints in Responsible Aquaculture Programs

The responsible aquaculture movement is based on the premise that consumers in developing nations desire fish, shrimp, and other aquatic food products from environmentally and socially responsible sources. Therefore, retailers, restaurateurs, and other larger buyers are seeking such products. Environmental NGOs are interested in promoting environmental and social stewardship. Thus, they see aquaculture labeling programs as an effective way of promoting their policy agenda. International development agencies such as the World Bank, Asia Development Bank, and FAO are committed to environmental stewardship and programs by buyers to source responsible products that are compatible with that goal.

Processors and exporters of aquaculture products would obviously participate in responsible aquaculture as a business opportunity. However, despite the popularity of responsible aquaculture, there remains perplexing issues that are seldom considered.

### *Extending BMP and Labeling Programs to Small-Scale Producers*

Most aquaculture is conducted in developing countries, and a large amount of the production is from small farms. Although much of the production of small farms is consumed by farm families or sold in the local market, some of it enters the export market. The large demand for imports of aquaculture products in wealthy nations cannot be satisfied by the production of large farms alone. However, the current effort on aquaculture labeling is directed almost exclusively at large farms. The cost of implementation of practices, analyses, and record keeping necessary for compliance with certification or other labeling programs and the expense of third-party inspection is more than most small-scale producers can bear.

In 2006, the GAA convened an expert consultation in Bangkok, Thailand, on issues related to certification of small shrimp farms in Asia. The participants agreed that small farms need to be arranged in clusters to reduce the costs of compliance and verification. Moreover, it will require much work to develop procedures for establishing and administrating these clusters. The situation will differ from country to country and a single model for cluster farms would be unworkable. The participants also concurred that standards for ACC certification would require modification for application to small farms. Small-scale producers would often not have title to their land, few would be able to demonstrate social stewardship, and effluent monitoring and other analyses would be excessively expensive. Small-scale farmers may integrate aquaculture with poultry, swine, or cattle production. Water supplies for small-scale farms may be highly polluted, and farm families may reside beside ponds and discharge domestic waste into them. These scenarios raise food safety issues that must be addressed by labeling programs. The GAA has charged a committee with developing certification standards for cluster farms. The objective is to require the same degree of environmental and social stewardship for small farms as expected for large ones, but this may prove an impossible task.

Some feel that environmental concerns are being favored over social issues in BMP and labeling programs. In a policy analysis of the ongoing effort to apply BMPs to shrimp farming, Béné (2005) suggests that the BMP effort is a scientific approach that, by basically ignoring social issues, has allowed a number of key stakeholders to refocus the debate on scientific solutions, thereby preventing other groups concerned with more intractable social and political issues from engaging in the policy process. Béné apparently feels that widespread use of labeling programs will further marginalize small-scale producers. Although Béné does not offer any solutions, he hints that policy making in shrimp farming is too political to be reduced to the application of BMPs and other technical interventions. Béné's eloquent argument could be applied equally well to other forms of aquaculture, but it is not clear how to avoid some of his concerns and yet progress toward an environmentally responsible aquaculture. New (2003) also expresses concern that the responsible aquaculture movement will further marginalize small-scale producers. He stresses that responsible aquaculture should be profitable but also have a conscience.

## *Demonstration of Benefits*

Programs promoting voluntary adoption of BMPs and labeling programs requiring verification of BMPs or compliance with standards are in their infancy. Studies of the adoption of these programs have not been made, but it is certain that current participation represents only a minuscule proportion of aquaculture production. Most consumers in the United States presently cannot find environmentally labeled aquaculture products without shopping around, because few supermarkets and restaurants carry them. Moreover, there is scant documentation that adoption of BMPs and compliance with labeling programs has environmental and social benefits.

Verification of environmental and social benefits would require carefully designed studies. In some places, comparisons could be made between farms participating in BMP and labeling programs and those not participating. These comparisons could include variables such as efficiency of water use, fishmeal and protein use in feeds, feed conversion rate, effluent volume and quality, wetland destruction, and social issues such as compensation and working conditions for workers and relationship with local communities. In other places, it may be possible to make such comparisons before and after implementation of BMP or labeling programs at a facility. However, aquaculture often is only one of several activities that can influence environmental and social conditions. In such situations, negative impacts caused by other resource users could mask positive effects that might result from better aquaculture practices.

Constraints in assessing the benefits of implementation of BMPs and compliance with labeling program standards could be overcome by use of indicators (Boyd 2005a, b; Boyd 2006; Boyd and Polioudakis 2006). Effectiveness of voluntary adoption of BMPs could be revealed by improvements in values of indicators. Indicators could reveal ranges in the use of water, land, protein, fishmeal, energy, and other resources and in the amount of wastes produced per tonne of production for different species and culture methods. Evaluation of these ranges could be used to establish minimum acceptable values of each indicator for compliance with labeling programs. Of course, social issues and some environmental concerns such as facility siting, predator control, exotic species, antibiotic and chemical use, and general sanitation possibly cannot be addressed by indicators.

## *Discrepancies in Programs*

Differences among sites, culture systems, production methods, and species also raise issues about aquaculture labeling. With regard to sites, mangroves and other wetlands are prohibited in responsible aquaculture programs as sites for new farms or expansions. However, many existing farms were constructed in wetlands. Such farms obviously should be encouraged to adopt better practices. However, should they be allowed to participate in labeling programs?

The potential for water pollution varies among culture systems and increases in the following order: ponds < flow-through systems < cages and net pens. Practices are available for reducing the pollution load in effluents from ponds and flow-through systems, but nothing can be done to reduce nutrient and organic matter release from cages other than to lessen feed input. At some sites, dilution and dispersal of waste may be adequate to avoid water pollution by cage and net-pen culture. Thus, should cage and net-pen facilities be denied access to labeling programs or should those that are sited well be allowed to participate?

Water exchange has been used to flush ponds and improve water quality. This practice shortens hydraulic retention time and lessens effectiveness of natural processes in assimilating wastes. Should water exchange be strictly prohibited, restricted, allowed for emergencies, or allowed on a case-by-case basis in labeling programs?

The culture of some species is more likely to have serious negative environmental impacts than the production of other species. Boyd et al. (2005) suggested that contention with issues related to certification of some common species or species groups would increase as follows: seaweeds < bivalve shellfish < abalone < channel catfish < tilapia < trout < shrimp < salmon.

As there are differences with respect to certification issues among sites, systems, methods, and species, it is not reasonable to consider all certified aquaculture products equal with regard to environmental responsibility. For example, certified tilapia from ponds might have a better environmental record than certified tilapia from cages. The environmental impact per unit of production might be greater for salmon cultured in cages at a certified facility than for channel catfish grown in ponds at a noncertified farm.

The problems of organizing small-scale farms for certification and harmonizing certification requirements for large- and small-scale facilities has already been mentioned. However, when compared with discrepancies related to sites, systems, methods, and species, differential treatment of small-scale producers in labeling programs would appear to be a minor issue.

The fact remains that most aquaculture in the developing world will not be included in the responsible aquaculture movement because programs are directed at facilities producing for the export market. National governments should take the responsibility for regulating aquaculture facilities to minimize negative environmental impacts. Moreover, social issues should also be addressed by national governments. Unfortunately, in many nations with a large aquaculture sector, national governments have neither the resources nor the will to deal effectively with environmental and social issues. Thus, the benefits of programs for responsible aquaculture likely will be eclipsed by the negative impacts of domestic aquaculture.

### *Influence on United States Producers*

Most foreign producers have lower production costs than producers in the United States because they have access to cheaper labor and are subject to fewer regulations. Aquaculture imports may compete directly with the products of United States aquaculture. For example, basa *(Pangasius bocourti*) and tra (*Pangasius hypophthalmus*) from Vietnam compete with channel catfish. Catfish farmers succeeded in preventing basa and tra from being sold in the United States as catfish and an antidumping tariff also was imposed. However, China has begun to ship channel catfish to the United States and governmental intervention into this trade is unlikely.

Widespread adoption of labeling programs by retailers, restaurateurs, and other buyers would require both domestic and foreign producers to comply with requirements of these programs. As a general principle, participants in labeling programs must exceed minimum legal requirements for environmental and social stewardship. Aquaculture in the United

States is regulated more strictly than in developing countries. It should be much easier and cheaper for a United States producer to comply with labeling program requirements than it would for a producer in a country with few regulations. Thus, labeling should make United States aquaculture more competitive.

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## Chapter 4

# Best Management Practice Programs and Initiatives in the United States

*Gary L. Jensen and Paul W. Zajicek*

## Introduction

Best management practices (BMPs) are specific—and often detailed—protocols, practices, or procedures to manage specific operations in a socially and environmentally responsible manner, and they are typically based on risk analysis and the best available scientific information (Nash 2001). Usually they are a component of a larger regulatory or voluntary effort to assist farmers in achieving environmental stewardship goals of government or a producer organization. These environment-oriented BMPs may or may not contribute to the economic success of the facility.

In this chapter we summarize regulatory and other initiatives related to aquaculture BMPs in the United States. We address 1) background and progression of events for developing federal effluent limitation guidelines (regulations) with significant supporting actions and lessons learned, 2) general description of a nationally coordinated stakeholder process that helped formulate these regulations, 3) experiences of state governments and industry initiatives with BMPs, and 4) participatory processes in regulatory development. To gather current information from the different states on the status and implementation of programs employing BMPs, we prepared and distributed an electronic questionnaire to state agencies, universities, and industry organizations during November and December 2005. Follow-up interviews and published literature filled information gaps.

## Background

The quality and safety of water sources for aquaculture operations and potential external sources of contamination are major concerns reinforcing the need to manage and protect natural aquatic resources. Management is required to maintain desired water quality within production systems and to control discharges of substances defined as pollutants in government regulations. The Federal Water Pollution Control Act of 1948 (33 USC §1251 *et seq.*), also known as the *Clean Water Act (CWA),* is the primary federal legislation

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concerning water quality. The CWA was amended significantly in 1972 (Public Law 92-500), 1977 (Public Law 95-217), and 1987 (Public Law 100-4). The first amendment required a technology-based approach to discharge limits. The last amendment emphasized water quality-based effluent limits as a basis for National Pollutant Discharge Elimination System (NPDES) permits outlined in the 1977 amendment for point source discharges into navigable waters.

The CWA prohibits the discharge of pollutants from a point source without a discharge permit. These permits are issued by the United States Environmental Protection Agency (USEPA) or a state program authorized by USEPA to administer the State Pollutant Discharge Elimination System program. Currently 45 of 50 states can issue NPDES permits after optional USEPA review. National Pollutant Discharge Elimination System general permitting regulations in 1983 defined concentrated aquatic animal production (CAAP) facilities subject to the NPDES permit program for controlling discharges from point sources into waters of the United States (40 CFR Sections 122 [§122.24, §122.25, and Subpart D Appendix C] and 123 [§123.25]). The NPDES permit program also applies to discharges from aquaculture projects or surface waters into aquaculture facilities to stimulate production as food inputs (Section 318 of the Clean Water Act and 40 CFR §122.25). National Pollutant Discharge Elimination System permits can be issued for an individual facility (individual permit) or numerous common facilities with similar operating and environmental conditions (general permit). Permits are valid for 5 years and new requirements or modifications can be made at the time the permit is renewed for another 5-year cycle.

Water quality regulations during the 1970s and 1980s focused on controlling point source pollution through NPDES permits. Categories of CAAP facilities are defined as hatcheries, fish farms, or other facilities that grow or hold aquatic animals with the following criteria (40 CFR §122.24, 40 CFR Subpart D Appendix C, and 40 CFR §123.25):

1) Coldwater fish or other aquatic animals in structures that discharge at least 30 days/year but exempts facilities that produce less than 9,090 kg/year (20,000 pounds/year) and feed less than about 2,272 kg (5,000 pounds) during the calendar months of maximum feeding
2) Warmwater aquatic animals in facilities that discharge at least 30 days/year but exempts facilities that produce less than about 45,454 kg/year (100,000 pounds/year) and facilities with closed ponds that discharge only during periods of excess runoff
3) Facilities that are determined on a case-by-case basis by the permitting authority to be significant contributors of pollution to waters of the United States.

When writing a discharge permit, the authorized state or federal authorities apply either USEPA technology-based standards for an industry-specific process, end-of-pipe discharge standards, or effluent criteria; or more stringent water quality standards if the discharge is likely to affect water quality based on the designated uses of receiving waters. States are required to identify waters that do not meet water quality standards and designate them as water quality limited. States are then required to establish a priority rating for such waters, and in accordance with that ranking, establish total maximum daily load (TMDL) limits for specific pollutants (McCoy 2000). States may establish stricter standards than federal requirements to maintain designated water uses and prevent water quality degradation. Water quality-based standards and requirements take precedence over technology-based effluent limitations. The NPDES permits for aquaculture facilities are issued based on the permit writer's best professional judgment in the absence of an applicable USEPA effluent limitation guideline for CAAP facilities.

## Historical Milestones

The need to develop a national effluent limitation guideline for aquaculture facilities evolved over more than 20 years. The National Research Council (NRC 1978, 1979) noted the need for national effluent regulations for aquaculture. The passage of numerous environmental protection and marine fishery conservation laws by Congress in the late 1970s also created new regulatory challenges (Jensen, in press). Early attention by USEPA on aquaculture effluents in 1977 and 1987 resulted in limited technical guidance to NPDES permit writers but no national regulation (Jensen 2000). The USEPA (1980) evaluated the use of aquaculture systems as a technique for municipal and industrial wastewater treatment. The first National Aquaculture Development Plan noted the importance of federal environmental regulations and the need for applied research to reduce pollution impacts from aquaculture facilities (JSA 1983a, b). Renewed emphasis on water quality and the environment resulted in technical guidance provided to public agencies and decision makers (Oceanic Institute 1991).

Diverse stakeholders identified the need to characterize effluents, document and minimize environmental impacts, and improve regulations through proactive dialogue among producers, regulators and public interest groups. Without a national guideline specific to aquaculture discharges, permit requirements varied among states based on the permit writer's best professional judgment. Permits were often developed based on experiences with disparate types of industrial and municipal discharges. This regulatory system and limited scientific information challenged local permitting authorities and aquaculture operations—especially flow-though raceway facilities and emerging net-pen operations in state waters of the Pacific Northwest. In response, concerned stakeholders synthesized technical progress and available data, and developed prioritized recommendations (Blake et al.1992; Jensen 1992).

To address aquaculture effluents, a federal interagency coordinating body, the Joint Subcommittee on Aquaculture (Public Law 96-362), created a Working Group on Water Quality/Effluents in 1991. The Working Group facilitated national coordination of cooperative research, education and public policy activities with producers and producer associations, state natural resource agencies, relevant federal agencies, academia, and other stakeholders. The Working Group helped assess existing information and identified information gaps to guide research projects in anticipation of a national discharge regulation or proactive voluntary options to strengthen environmental stewardship. The Working Group was discontinued in 1993. Coordinating leadership was then provided by five United States Department of Agriculture (USDA) Regional Aquaculture Centers. The Centers support aquaculture research, development, demonstration, and extension education. They directed federally funded research to characterize effluents, develop BMPs, and improve environmental management through better culture technologies and wastewater treatment methods (CTSA 1991, 1992; WRAC 1998; Tucker 1998; NCRAC 1997, 2001, 2006; Yeo et al. 2004). The Centers also coordinated research through an interregional aquaculture waste management initiative. Further work improved the understanding of key environmental regulatory issues, analyzed current information, and recommended options for regulatory policy with reference to design and implementation of cost-effective BMPs (Rubino and Wilson 1993).

During this period, the National Research Council (NRC 1992) conducted an assessment of technology and opportunities for marine aquaculture in the United States. This assessment included recommendations to develop environmentally sensitive, sustainable systems; streamline permitting process for marine aquaculture; and address the lack of a formal regulatory framework to govern leasing and development of commercial aquaculture in federal waters. The importance of continued research and technology development to protect national aquatic resources was emphasized in a national aquaculture research and development strategic plan (JSA 1994).

From late in the 1970s until the late 1990s, the USEPA demonstrated little interest in directing limited resources to develop a national effluent limitation guideline for aquaculture because of its relatively small size and minor environmental impact compared with other point source industries. The full responsibility for issuing NPDES permits fell to the authorized states and regional EPA offices assigned to states lacking approved program authority.

Three events converged for USEPA to promulgate a national effluent limitation guideline for CAAP facilities. First, a federal court consent decree settlement obligated USEPA to develop new or revised standards for various industry categories within a specific time frame (*Natural Resources Defense Council, Inc. et al. v. Whitman*, D.D.C. 89-2980; 31 January 1992). Since 1974 USEPA had completed guidelines for more than 50 major manufacturing and chemical industry categories and was now considering smaller industries. Second, a national environmental advocacy organization recommended that USEPA implement the CWA for aquaculture facilities by developing effluent limitations (Goldburg and Triplett 1997; Goldburg et al. 2001). The third event was a public notice by USEPA, under the court consent decree settlement, that solicited comments and information for its next effluent guidelines biennial plan. For the first time, this plan included fish hatcheries and farms as one of several candidate industry categories under consideration for rule-making projects (Federal Register 1998a).

Based on public comments and limited information, USEPA decided more information was needed (Federal Register 1998b). Shortly thereafter USEPA announced a preliminary study of the aquaculture industry to evaluate current wastewater controls and the opportunity for improved environmental protection (USEPA 1999a). Before completing the preliminary study, USEPA and litigants amended the court settlement agreement to develop regulatory options for certain types of aquaculture facilities (*Natural Resources Defense Council, Inc. et al.* v. *Leavitt*, Civ. No. 89-2980; January 31, 1992, as modified). The USEPA launched an activity to develop pollution controls in the form of a national effluent limitation guideline for commercial and public aquaculture operations (USEPA 2000; Kreeger 2000).

The settlement resulted in a multiyear national dialogue and formal rule-making process to evaluate options for nationally applicable technology-based performance standards for the diversity of aquaculture facilities. The USEPA final rule, promulgated about 30 years after first recommended in the late 1970s, established a national regulatory framework and baseline compliance criteria specifically for effluent discharges from CAAP facilities similar to other industry categories to meet CWA requirements.

## Federal Environmental Regulatory Approach and Experience

The USEPA made a decision to begin rule making before completing the preliminary study. The decision to undertake formal rule making for CAAP facilities ensured that funds were available to support data collection and to complete standard and customary engineering, economic, environmental, and other studies. The USEPA staff had no direct experience with aquaculture. Accordingly, as is customary practice for final rule development, USEPA contracted several private companies to support data-gathering and complete intensive analytical modeling.

Although USEPA could have used a traditional approach to rule development, the agency supported the assistance of the federal interagency Aquaculture Effluents Task Force (AETF). The AETF mobilized diverse expertise nationwide to assist, USEPA in developing the effluent regulation for aquaculture operations. The two groups shared a common goal to use science and innovation as central components of assessing environmental protection regulatory options. The challenge was to identify reasonable options applicable under federal rule-making procedures that recognized the continuous evolution of innovation, scientific knowledge, and discovery.

### *Interagency Coordinating Task Force Model*

With the decision by USEPA to conduct a preliminary study covering all aquaculture facilities, the federal interagency Joint Subcommittee on Aquaculture (JSA), created the Aquaculture Effluents Study Task Force (AESTF) in 1999 to assist USEPA develop industry sector profiles (Jensen 2000, 2001). The USEPA senior management fully supported this innovative interagency collaboration as a means of gaining expertise about the aquaculture industry and status of pollution prevention practices. A technical consultative process was established among USEPA project managers and their contractors, AESTF leadership, and recruited individuals with specific technical knowledge. The AESTF responded to requests for information and technical reviews of draft USEPA documents. The first collaborative actions were preparation of frequently asked questions and answers to educate the interested public and creation of an open-access website to post USEPA information and new developments.

When USEPA decided on formal CAAP facility rule making in 2000, the AESTF was renamed the *Aquaculture Effluents Task Force (AETF)*. The potentially broad scope of this national regulation created a rare opportunity that rallied and unified diverse national, regional, and species-oriented producer associations and trade organizations. The AETF provided a coordinated national forum for dialogue among stakeholders and mobilized national expertise. It provided USEPA with scientific knowledge, fundamental environmental effects data, state regulations, technical assistance, and information about facility practices in compliance with existing state effluent regulations. The participation of key federal agencies with regulatory authority for approving drugs (United States Food and

Drug Administration) and aquatic animal health permits (Animal and Plant Health Inspection Service, National Marine Fisheries Service, and United States Fish and Wildlife Service) facilitated resolution of cross-jurisdictional issues and independent interagency legal consultations.

The AETF had as many as 11 technical subgroups composed of members with recognized scientific knowledge or extensive professional experience. Technical subgroups addressed distinct production systems and priority regulatory concerns, i.e., drugs and chemicals, economics, feeds, exotic species, and aquatic and human pathogens. The AETF voluntarily prepared scientific reviews or special studies on drugs and chemicals, human pathogens, and economic impact analyses (Engle et al. 2005). The USEPA and USDA also collaborated through an interagency agreement to cofund a comprehensive aquaculture BMP technical guidance document that is the foundation of this book.

The AETF sought collaboration to gather benchmark information and data on the current status of state regulatory permit and monitoring requirements for aquaculture facilities. This same collaboration verified reporting by some state regulatory authorities that aquaculture facilities were causing impairments to water quality or designated water uses. This follow-up analysis provided a national overview on the scope and relative severity of pollution associated with aquaculture from the perspective of state regulatory agencies. In numerous cases, state reporting included only speculations about pollution from aquaculture facilities.

The credibility of AETF was strengthened by the participation of several professional societies (Aquaculture Engineering Society, United States Aquaculture Society, Fish Culture and Fish Health Sections of American Fisheries Society) that supported the process of integrating scientific information and technical expertise into federal rule making. Significant involvement came in the form of a book published by the United States Aquaculture Society summarizing scientific literature related to aquaculture and the environment as a scientific contribution to the process (Tomasso 2002). The societies carefully avoided lobbying activities or interfering with USEPA's legal policy-making role. Establishing a clear distinction between contributing scientific knowledge and formulating policy created an acceptable detachment that was important to their participation.

The AETF leadership conducted a midpoint evaluation of progress toward fulfillment of its stated objectives and an assessment of overall performance and satisfaction. This internal evaluation, done among diverse stakeholders, identified several areas that needed improvement, including nongovernmental organization participation, outreach projects, communication among technical subgroups, cost of meeting locations, the need for teleconferences, turnaround time on technical reviews, farmer participation, and guidance to develop outputs. This self-evaluation exercise helped improve core AETF activities and assess overall effectiveness.

The incorporation of consensus science, accurate industry profiles, participatory stakeholder opportunities, and current state regulatory requirements helped mitigate USEPA and stakeholder polarization regarding regulatory options under consideration. The establishment of professional conduct and operating standards, technical competency, and transparency of work was essential to keep USEPA actively engaged with AETF. The USEPA solicited public input and received comments from many sources during the public rule-making process. However, AETF was engaged throughout the entire rule-making process and played a significant role in contributing the collective expertise and knowledge from its technical subgroups and scientific reports. The USEPA acknowledged the AETF as an instrumental group that provided comments, expertise, and information (Federal Register 2004). The AETF continued communications among interested stakeholders to help develop the compliance guide for permit writers and facility operators on the CAAP facility effluent limitation guideline (USEPA 2006).

### *Highlights of the USEPA Rule-Making Process*

The first major milestone by USEPA was publication of the proposed CAAP rule for public review and comment in September 2002 (Federal Register 2002a). To develop the proposed rule, USEPA used information provided by the AETF and its own research. The USEPA conducted a two-phase effort to collect additional data from aquaculture producers. A screener questionnaire was used to collect general facility information from all known aquatic animal producers (Federal Register 2000, 2001; USEPA 2001a). The screener questionnaire data, AETF assistance, and the national census of aquaculture (USDA-NASS 2000) were the primary sources of information for the proposed CAAP rule. The USEPA prepared additional supporting documents and released data relating to guidance and economic and environmental impact analyses (USEPA 2002a, b, c). The proposed rule elicited 300 public comments, including form letters.

The next milestone was publication of the Notice of Data Availability (NODA) that summarized the data received and described how USEPA might use the data for the final rule (Federal Register 2003a). The NODA explained an intensive second phase of technical data collection through a detailed questionnaire completed by about 200 facilities (USEPA 2001b). The detailed data from select facilities allowed USEPA to revise methods to estimate costs and economic impacts. Better information helped establish baseline levels of control technologies and operational measures at aquaculture facilities. The USEPA narrowed the regulatory options being considered for the final rule. The NODA also included postproposal data, results from site visits and additional sampling data. After the NODA was published, only about 20 public comments were received, signifying broader support for the direction of rule options under consideration by USEPA. Initially, there was a wide range of treatment options under consideration by USEPA, from stringent end-of-pipe numeric limits for specific pollutants to continuation of the status quo for all aquaculture production systems and facility sizes.

In developing the final rule, USEPA conducted a variety of public outreach activities to solicit input and educate affected and interested stakeholders on the status of the rule-making process (Federal Register 2002b). These activities included site visits and sampling trips, AETF meetings, public meetings during public comment periods, participation in aquaculture conferences, meetings with other federal agencies, and posting materials on the USEPA and AETF websites.

The Small Business Regulatory Enforcement Fairness Act (Public Law 104-121) addresses the concerns and potential impacts of federal regulations on small businesses. Because the aquaculture industry is dominated by small businesses (defined as less than $750,000 annual gross revenue; USDA-NASS 2006), USEPA convened a small business review panel. Key participants on the panel were aquaculture producers representing diverse systems and species and representatives from several federal agencies, including

USEPA. A report included comments and recommendations from aquaculture producers and the panel's findings and recommendations (USEPA 2002d). Recommendations from this process and analyses influenced the facility size threshold (45,454 kg or more, annual production) established in the final rule.

Federal agencies are stakeholders in federal rule making. The Office of Management and Budget (OMB) oversees an internal federal interagency regulatory review and planning process (Federal Register 1993). This interagency regulatory review step also engaged technical expertise and political management of different federal departments with an interest in the outcome of the final rule. Numerous agencies in the Departments of Agriculture, Commerce, and Interior were actively engaged in consultations with USEPA on technical issues and OMB on policy matters; the Office of Advocacy of the United States Small Business Administration also played a significant role in this process.

Finally, the CWA allows judicial review of the final rule by the United States Circuit Court of Appeals. In the case of the aquaculture final rule, no petition was filed requesting court-mediated dispute resolution. The absence of a court challenge by stakeholder organizations or individuals was a clear indicator of broad acceptance or indifference for the effluent limitation guideline and concomitant regulatory oversight by authorized state governments. In cases of disputes with environmental regulations, arbitration or litigation may be an option for resolution based on the applicability of laws to the facts of a specific case. This course of action can be costly for litigants in reaching a legal outcome from extended delays through the appeals process or out-of-court settlement agreements.

The final rule established a national effluent limitation guideline and new source performance standards for the CAAP point-source category in commercial (for profit) and noncommercial (public) facilities (Federal Register 2004) and marked the end of a nearly 4-year rule-making process.

### *The USEPA Aquaculture Regulation*

The aquaculture effluent limitation guideline was published with a complete description of the applicable legal authorities, environmental requirements, and rationale for the final rule (Federal Register 2004). The technology-based regulation applies to CAAP facilities with annual production of 45,454 kg (100,000 pounds) or more, with exemptions for inland pond systems, alligator farms, and open-water shellfish systems. The definition of a CAAP facility for coldwater structures with annual production of 9,090 kg (20,000 pounds) or more under NPDES permitting regulations was increased to 45,454 kg, based on economic achievability and affordability criteria for this new regulation (40 CFR §122.24 and Subpart D Appendix C). The USEPA estimated that compliance for this regulation will impact about 240 facilities nationwide. The majority of the estimated total annual compliance cost of $1.4 million falls on public hatcheries. The number of facilities in scope of the regulation is low compared to the estimated total of 4,300 aquaculture farms in the United States (USDA-NASS 2006). There are currently a limited number of recirculation-system farms above the production threshold and affected net-pen operations. Most facilities directly impacted employ flow-through raceways for production of coldwater species (primarily salmonids).

The types of production systems or subcategories were narrowed to include a combined subcategory for flow-through and recirculation systems and a separate subcategory for net pens and submerged cages. Effluents discharged and confined to private property are exempt. Discharges into sewers flowing into publicly owned treatment works (POTWs) are not covered because of the low mass loading of pollutants. The POTWs must develop local limits for users if the mass loading from a facility causes a violation in the NPDES permit. The effluent limitation guideline did not recognize fish, including nonnative species, as a pollutant for regulation under the CWA and NPDES permit system.

Many point source dischargers are required to comply with numeric effluent limits established for specific pollutants. However, USEPA recognizes that BMPs can be an important part of the NPDES permitting process to prevent releases of pollutants. Over the years, BMPs for many types of facilities (metal finishing; organic chemicals, plastics and synthetic fibers; textile manufacturing; pulp and paper manufacturing; pharmaceuticals manufacturing; and petroleum refining) have been developed. Case studies have demonstrated the success and flexibility of the BMP approach in controlling releases of pollutants to receiving waters. Pollution prevention practices have become part of the NPDES program, working in conjunction with BMPs, to reduce potential pollutant discharges. Pollution prevention methods reduce costs and pollution risks through source reduction and recycling/reuse techniques (USEPA 1993). The effluent limitation guideline for concentrated animal feeding operations also included guidance for conservation and pollution prevention practices (BMPs) that may improve production efficiency and protect the nation's waters (USEPA 2004).

The core requirement for flow-through and recirculation systems is development of a facility BMP Plan that specifies how the permittee will 1) employ efficient feed management and feeding strategies; 2) minimize discharges of accumulated solids during routine cleaning, inventorying, grading, or harvesting aquatic animals; 3) remove and dispose aquatic animal mortalities on a regular basis; 4) ensure proper storage of drugs, pesticides, and feed to prevent spills; 5) implement procedures for proper containment, cleaning, and disposal of spilled material; 6) maintain the containment structure with inspections to identify and promptly repair damage and conduct regular maintenance to ensure proper system operation and functioning; 7) maintain records to calculate feed conversion ratios and document frequency of cleaning, inspections, maintenance, and repairs; and 8) train all relevant personnel to ensure proper clean-up and disposal of spilled material, spill prevention and emergency response, operation and cleaning of production and wastewater treatment systems, and feeding procedures and equipment use.

For the net-pen or submerged cage system category, the same annual production threshold of 45,454 kilograms or more applies. The exception is native species released after a growing period of no longer than 4 months to enhance commercial or sport fisheries. Facilities in this subcategory must meet the same BMPs for mortality removal, materials storage, maintenance and inspection of the production system, record keeping, and training as the flow-through and recirculation system subcategory. However, feed management strategies must minimize the accumulation of uneaten food beneath pens through active feed monitoring and management practices or good husbandry practices approved by the permitting authority. Waste management and disposal specifically refer to feed bags, packaging material, waste rope, and netting. Special attention is directed to transport or harvest discharge of aquatic animal blood, viscera, and carcasses or transport water containing blood.

The aquaculture effluent guideline applies to CAAP facilities located in the territorial seas (Mean Low Water to 12 nautical miles) and the Exclusive Economic Zone (12 to 200 nautical miles). Net-pen (or cage) facilities operating in the Exclusive Economic Zone are considered to be point sources subject to new source performance standards and NPDES permit requirements. This scope of coverage is important because there are currently no model aquaculture facilities operating within this area. The federal government has proposed a regulatory framework for aquaculture facilities in these federal waters (Bush Administration 2004; NOAA 2006).

The renewed federal interest to develop national effluent limitation guidelines for aquaculture gained nationwide attention. It influenced numerous states to review their CAAP facility discharge regulations and induced several producer organizations to take proactive steps to develop reasonable state regulatory options. The approach preferred by numerous states and producer organizations was a BMP program that was system-, species-, or site-specific to mitigate potential environmental risks. Some states used BMPs as a regulatory model while others used end-of-pipe numeric limitations for some production systems, such as flow-through raceways.

Numeric discharge limits for a specific pollutant of concern and BMPs are two regulatory options that may be used to meet common CWA objectives. BMPs provide flexibility for producers to incorporate evolving science and innovation based on site-specific factors to achieve a desired environmental outcome. Numeric limits define a maximum concentration or discharge of a specific priority pollutant determined by periodic monitoring and testing of end-of-pipe discharges. The limits can be determined based on the performance of best available technologies.

### *Federal Assistance for Conservation-Related Programs*

Federal agencies administer a variety of financial assistance programs that may assist landowners with voluntary conservation, meeting requirements of government regulatory programs and aiding government-industry partnerships to promote sound environmental management. In the case of USEPA, Section 319 of the CWA directs states to submit assessment reports that demonstrate intergovernmental coordination and public participation in implementing BMPs or other management options for pollution sources. States prepare management programs for controlling pollution from nonpoint and point sources into navigable waters within the state and improving the quality of such waters. To assist states in implementing these programs, USEPA administers a grant program to provide cost-share financial assistance. This can support demonstration of aquaculture BMPs or other eligible activities (training and publications, for example). Funds are available to state agencies, colleges and universities, and nonprofit organizations on programs to prevent, control, and/or abate nonpoint source water pollution. Florida has taken advantage of these funds to hold statewide producer education sessions and install educational signage that illustrates BMPs at some university aquaculture research facilities.

The USDA's Natural Resources Conservation Service (NRCS) administers the Environmental Quality Incentives Program (EQIP) as a voluntary conservation program for farmers and ranchers to promote agricultural production and environmental quality. The EQIP offers limited financial and technical assistance to eligible participants to install or implement structural and/or management practices on agricultural land. Fish or other animals raised by aquaculture are included under the definition of livestock (Federal Register 2003b). The EQIP offers contracts as incentive payments and cost sharing to implement conservation practices. Conservation practices are implemented according to a farm-specific conservation plan, developed in conjunction with the producer, that addresses the landowner's natural resource goals and objectives. Landowners receiving cost-share assistance must implement practices according to NRCS technical standards and specifications adapted for local conditions. The EQIP funds are distributed through a competitive process based on state ranking criteria. These federal cost-share funds have supported limited conservation practices for shellfish farming in several New England states and installation of a wetland filtering system for an aquaculture facility in Wisconsin.

The NRCS has partnered with several state initiatives to develop aquaculture BMPs referenced to NRCS production codes with common interests in promoting sound conservation practices (NRCS 2004; LSU AgCenter 2003; FDACS 2005). The NRCS publishes conservation standards and specifications in the state Field Office Technical Guide. A noteworthy spin-off by the NRCS Massachusetts office was development of an interim Conservation Practice Standard, Shellfish Aquaculture Management Code 706. The purpose of the Code is to enhance the sustainability of aquaculture; minimize adverse impacts of shellfish farming on water, plant, animal and human resources; ensure dependable quantity and quality of water to support shellfish production; and ensure adequate quantity and quality of food to support shellfish production.

Amendments to the Coastal Zone Management Act (Public Law 104-150) in 1996 allowed the Secretary of Commerce to provide development grants to states to prepare management programs. It also established a grant program for states to regulate aquaculture facilities. This amendment was recognized as an important national priority (NRC 1992) to support the development of policies and practices for marine aquaculture in state waters. States have the opportunity to recognize aquaculture as a priority area for inclusion in management programs with financial support under provisions of this Act.

Federal programs support development of environmental codes of practice and BMPs for aquaculture in partnership with industry and university stakeholders (Howerton 2001; PCSGA 2001; WFGA 2002; Leavitt 2004; Malison and Hartleb 2005). Within the broad public interest and responsibility to regulate and enforce conservation and protection laws for natural aquatic resources, numerous government programs fund projects often through universities and producer organizations. Federal funding with state partners contributes scientific information and aquaculture extension programs to support development of relevant and practical BMPs as an acceptable option for policy programs and industry adoption. Public investments in science and technology, state regulatory initiatives, and continuous innovations and improvements by industry provide important baseline data, scientific information, and field experiences to assist governmental regulators in developing aquaculture-specific effluent regulations and BMPs.

## State Government Best Management Practices Programs

State governments have a significant role in environmental regulatory programs, especially states authorized by USEPA to administer the NPDES permit program. In these cases facilities apply to the approved state agency for an NPDES permit to discharge into state waters. The USEPA retains an oversight role for NPDES program implementation and can interject during the issuance of a permit. Some states have extensive experience issuing NPDES permits for aquaculture facilities and acknowledge the important role of BMPs as guidance or the primary requirement for a discharge permit. In other cases aquaculture facilities may be required to have a BMP plan as one of several conditions for a discharge permit. Numerous state permitting requirements are more stringent than the national effluent limitation guideline for CAAP facilities, especially for marine finfish aquaculture in open water net pens and enclosures.

Regional reviews on the status of state permitting for aquaculture facilities revealed considerable variations, mixed concerns, and challenges because of previous lack of a national effluent guideline and reliance on the best professional judgment of state permit writers (Floyd et al. 1991; Davis 1993; Wypyszinski et al. 1994; Ewart et al. 1995). The NPDES permitting regulation definition of a CAAP facility in 1983 was not relevant for floating net pens in open marine waters. Emerging net-pen facilities were confronted with NPDES permit requirements in the late 1980s. There was no general NPDES permit template or permitting experience for these new systems in state coastal waters. This situation created significant burdens on state regulatory programs and permit applicants. The ongoing legal and regulatory environment continues to be a major constraint for marine aquaculture development (DeVoe 1999). Shellfish farming is generally considered an established, traditional activity in most coastal states and recognized as a legitimate activity in federally approved state coastal zone management plans (Nelson et al. 1999).

Five states (Arizona, Florida, Hawaii, Idaho, and Maine) had taken the initiative to use BMPs for voluntary guidance or mandatory regulations prior to 2000. The USEPA's decision to develop an effluent limitation guideline for CAAP facilities, including BMPs as a regulatory option, influenced numerous state programs and industry associations to take proactive steps using the BMP approach. Some states took a wait-and-see approach because of the uncertainty about the requirements in USEPA's final rule. From the perspective of state regulatory programs, despite differences in NPDES permitting requirements, there was limited concern about significant pollution impacts from aquaculture facility discharges covered under existing effluent regulations. However, the cost and complexity of permit compliance were significant to some commercial sectors and public hatcheries impacted by site-specific factors and type of production system (Floyd et al. 1991). Increased engagement by environmental advocacy organizations in some state regulatory programs and periodic cases of costly litigation (Nash 2001) created uncertainties for operational practices and financial risks. Renewed federal attention catalyzed north-central and northeastern regional efforts to assess critical environmental issues and provide guidance to facility owners and regulators (Mugg et al. 2000; Westers 2003).

Twenty-one of 50 states responded to our national questionnaire soliciting current information about state agency regulatory programs and voluntary initiatives associated with BMPs and aquaculture facilities. These states represent geographical areas where aquaculture is an important activity. Numerous state agencies have developed and implemented programs. Other states were developing BMPs, completing general guidance, encouraging BMPs for improved production practices, or requiring animal husbandry practices to protect farms from nuisance lawsuits under an existing right-to-farm law. Several states expressed interest in developing BMPs.

State regulatory programs provide models for BMPs, and in conjunction with USEPA's support for BMPs, should stimulate broader BMP application by state regulators and industry groups. Maryland passed legislation to form a coordinating council to draft BMPs for aquaculture operations. California passed legislation regulating marine finfish aquaculture in state waters that requires operators to establish lease-site BMPs for disease, escape, and environmental stewardship (2006 California Senate Bill 201 *Marine Finfish Aquaculture: Leases*). The following highlights programs and initiatives led by state agencies, often in partnership with industry stakeholders and academia.

### *Voluntary Programs*

For cases in which aquaculture operations are below the thresholds for mandatory effluent regulations, state agencies have collaborated with stakeholders to develop BMPs as guidance for voluntary adoption. These are proactive steps intended to safeguard the environment through improved environmental management practices. They also function as trials to determine effectiveness in lieu of mandatory prescriptive requirements. Many of these voluntary BMPs are relatively new, but continued monitoring of their effectiveness will likely determine long-term acceptance and broader adoption in other states.

#### *Alabama*

The Alabama Department of Environmental Management (ADEM) recommends the application of voluntary BMPs to prevent and/or minimize possible environmental impacts. Each BMP consists of a definition, explanation of why and how an environmental effect may arise, list of suggested practices or combination of practices to mitigate or prevent environmental effects, and additional information (implementation notes) to efficiently achieve the desired environmental protection outcomes. In the event of a demonstrated in-stream water quality effect from a facility, ADEM has already determined it would use BMPs as a regulatory baseline to add new permit requirements.

#### *Massachusetts*

The Department of Agricultural Resources encourages the development of shellfish aquaculture BMPs as an industry-driven activity. In addition to sanctioning BMPs, the department encourages broad application and implementation of these practices. The shellfish BMPs are a set of voluntary procedures focused on maintaining or increasing production while minimizing impact on the environment and improving relations with other coastal resource users. This voluntary initiative exemplifies state-level interest (farmers and agencies) to exceed federal requirements supported by a partnership with the USDA Risk Management Agency (Leavitt 2004).

#### *Maryland*

Legislation enacted during 2005 created the Maryland Aquaculture Coordinating Council (MACC) consisting of 17 members from industry, academia, regulatory, and political organizations. Among other responsibilities, the MACC was charged with the development of voluntary Best Management Practices (BMPs) for all forms of aquaculture.

To accomplish this task, the MACC created six subcommittees chaired by MACC members, with additional membership provided by MACC members, agency and producer representatives, and aquaculture extension specialists. During the summer and fall of 2006, the subcommittees met and formulated drafts. Subcommittee meetings were open to public participation.

The BMPs consist of existing state and federal laws and regulations as well as production system designs and practices and conservation practice standards from NRCS, Southern Regional Aquaculture Center, and other aquaculture extension publications that will "minimize, so far as practicable, pollution or environmental disruption" (MACC 2006). Topics addressed include water resources and management; production systems; shellfish culture; nonnative species; aquatic animal health; and shipping, transport, and sale. The MACC will review the BMPs and all laws and regulations pertaining to aquaculture in Maryland on a regular basis.

#### *Michigan*

The Michigan Right-to-Farm Act provides farmers with protection from nuisance lawsuits. This state statute authorizes the Michigan Commission of Agriculture to develop and adopt Generally Accepted Agricultural and Management Practices (GAAMPs) for farms and farm operations that include aquaculture species (Michigan Commission of Agriculture 2006). The GAAMPs are reissued annually with updates as needed. These voluntary practices are based on available technology and scientific research to promote sound environmental stewardship and help maintain a farmer's right-to-farm. Aquaculture GAAMPs are used to promote proper animal husbandry and care practices. The GAAMPs were developed with input from the Michigan Aquaculture Association, Michigan State University, and Michigan Departments of Agriculture and Natural Resources. They are revised as new scientific discoveries and changing economic conditions dictate. The aquaculture GAAMPs are not related directly to the CWA or Michigan environmental regulations, although there were requests that water quality related GAAMPs be developed for aquaculture.

### ***Regulatory Programs***

States that employ BMPs in NPDES permits generally adhere to the CWA definition of a BMP as a schedule of activities, prohibitions or practices, maintenance procedures, and other management practices to prevent or reduce the pollution of waters of the United States. The BMPs also include treatment requirements, operating procedures, and practices to control site runoff, spillage or leaks, sludge or waste disposal, or drainage of raw material storage (40 CFR §122.2).

States with approved NPDES program authorities generally have adopted two approaches with BMPs: 1) prevent or reduce nutrients and sediments in effluents and/or 2) address local issues that may include species-specific management practices, construction, water sources, nonnative species, genetics, aquatic animal health, mortality disposal, and chemical and drug use. State regulators were concerned with farmer practices that might cause degradation of public waters, soils, vistas, or unique ecotypes not easily mitigated in cases of significant pollution. Those states also created mandates for compliance monitoring and reporting. Although most of this chapter is focused on commercial aquaculture, public hatcheries have a history of developing and implementing BMPs and performance standards for hatchery operations to comply with discharge regulations and minimize discharges (USFWS 2000).

### *Idaho*

Idaho is one of the five states not approved by USEPA to administer the NPDES permit program. The USEPA Region 10 has developed a general permit for aquaculture facilities in Idaho to satisfy the NPDES permit requirement (USEPA 1999b). The Idaho Department of Environmental Quality (IDEQ) performs much of the on-the-ground work under contract to USEPA that includes facility inspections. A central feature of the general permit is a requirement for producers to develop a waste management plan with BMPs to prevent or minimize the generation and discharge of wastes and pollutants and ensure disposal or land application of wastes in such a way as to minimize adverse environmental impact. Pollution prevention and recycling are encouraged. The USEPA specifically advises permit applicants to create and adopt BMPs to address capture and disposal of solids and biological wastes; detoxification of chlorine or other chemicals; feed management; drug, disinfectant or other chemical storage, use or disposal; pond or raceway cleaning; maintenance to prevent overflow or bypass events; and staff training.

University of Idaho Extension, Idaho Department of Agriculture, IDEQ, and the aquaculture industry developed a publication to assist aquaculture (trout) producers develop waste management plans (IDEQ, undated). The guidelines provide design criteria for construction of waste management systems; owner, operator, agency and community education relative to aquaculture waste management systems; and BMPs to meet the NPDES general permit requirements. The USEPA advises producers that their BMP plan must be consistent with the general permit and guidelines.

### *Maine*

In 1994, the University of Maine suggested biosecurity audits might be helpful to the farmed salmon industry to reduce disease risk. This introduced the concept of collective best management practices (BMPs) to the industry. In cooperation with the university, an auditing program was initiated in 1995. In 1997 the Maine Aquaculture Association (MAA) developed a code of containment that established standards for equipment and operations designed to reduce the escape of farmed fish. That code ultimately formed the basis of the Containment Management System (CMS) (Ostergard et al. 2002). The CMS is an externally audited set of BMPs embedded in a hazard analysis and critical control point-based risk management system designed to minimize fish farm escapes. The lease contracts of the Maine Departments of Environmental Protection (DEP) permit and Marine Resources require growers to submit a CMS plan for agency review and approval. The DEP permit also requires an annual audit of each farm for CMS compliance.

In 2001, the Maine Department of Environmental Protection was authorized by USEPA to administer the NPDES permitting program. During 2003, the Board of Environmental Protection promulgated a salmon aquaculture general permit containing extensive monitoring requirements and water quality standards. The general permit includes a husbandry practice BMP and specific BMPs for facility operation, disease control, and spill control and prescribes BMPs in a CMS . The husbandry BMP specifies stocking densities and site fallowing. Facility operation BMPs include mortalities, chemical and solid waste, biofouling, predator nets, mooring systems, and unusual events that may lead to significant environmental impacts. The disease control BMP includes drug labels, drug use notification, investigational new animal drugs, drug discharge, and facility signage. Spill control BMPs are prescribed within a spill prevention and control plan that includes petroleum and hazardous chemical inventory, discharge and cleanup procedures, equipment inventory, spill event reporting, employee training, and federal regulations.

### *Florida*

In 1999, a state statute and associated administrative rule established an application procedure for an annual aquaculture certificate of registration and BMPs to establish minimum standards to protect and maintain water quality, fish, wildlife, and natural systems. Producers must apply for a certificate from the Florida Department of Agriculture and Consumer Services (FDACS) and agree to abide by the BMPs or acquire all other applicable permits from government agencies. A manual of BMPs was developed through advisory committees and a public rule-making process. The manual is a dynamic document with four editions implemented over 7 years to accommodate technical and scientific advancement. The manual includes BMPs for water resources, construction, nonnative and restrictive nonnative species, marine shrimp culture, sturgeon culture, live rock culture, aquatic plants, health management, mortality removal, preventing wildlife depredation, shipment, transport and sale, aquaculture chemical and drug handling, and aquatic animal welfare (FDACS 2005).

The BMPs in the manual are used to preserve environmental integrity while eliminating cumbersome, duplicative, and often confusing environmental permitting and licensing requirements. The practices were developed specifically for Florida aquaculture and represent a mutually beneficial relationship between commercial aquaculture production and natural resource protection. Florida aquaculturists following the BMPs meet the minimum standards necessary for protecting and maintaining offsite water quality and wildlife habitat. Farms certified through this program are presumed to be in compliance with state groundwater and surface water standards. The Florida Department of Environmental Protection is not authorized to institute proceedings against any certified facility to recover costs or damages associated with groundwater or surface water contamination or the evaluation, assessment, or remediation of contaminated groundwater or surface water. The FDACS enforces and verifies BMP implementation through unannounced farm inspections. Farms that do not implement or maintain the BMPs are violating state law and are subject to written notice, fines, suspension/revocation of the aquaculture certificate of registration, and potential misdemeanor charges.

### *New Jersey*

In 1993, the New Jersey Department of Agriculture (NJDA) and producers began the process of developing agricultural management practices (AMPs) for aquaculture to anticipate environmental regulations and take proactive steps to protect the environment and conserve wild stocks (Rutgers University 2004). The NJDA is the lead agency for AMP development, approval and oversight. The AMPs are goal-oriented management practices linked to acquiring and retaining a compulsory aquatic farmer license. The practices assist farmers in complying with environmental regulations and facilitate the permitting process. They emphasize good production practices that can yield economic benefits and improve profits. The AMPs can protect the natural environment and native fish stocks, reduce disease and mortality, improve the quality of farm-raised products, potentially lower the cost of permitting, and reduce the cost of remediation and rehabilitation. Many of the core concepts to develop AMPs were based on New Jersey Department of Environmental Protection permit requirements. No aquaculture facilities in New Jersey meet the facility requirements for an NPDES permit under the national effluent limitation guideline.

### *Texas*

During 1998, the Texas Commission on Environmental Quality (TCEQ) approved a general permit for aquaculture discharges into or adjacent to water in the state by all aquatic animal production facilities. Facilities that meet the definition of a CAAP under the NPDES permit regulation and coastal shrimp research facilities that exceed specified discharge limits must obtain an individual permit. The general permit includes BMPs to abate the discharge of suspended solids or other pollutants (TCEQ 2006). The BMPs were developed as an outcome of administrative hearings that included input from producers, Texas Parks and Wildlife, and Environmental Defense. The BMPs include treatment requirements, operating procedures, and practices to control site runoff, spillage or leaks, sludge or waste disposal, drainage from raw material storage, or the abatement of nuisance odors and conditions. The BMPs are reasonable and necessary measures to achieve performance or quality standards. Furthermore, they are intended to protect air quality, surface water quality, and potential uses of groundwaters. Through implementation of the BMP plan, the permittee is expected to prevent or minimize the generation and release of pollutants to waters of the state.

The TCEQ also identifies management practices and standard operating procedures that should be addressed: 1) modification of equipment, facilities, technology, and procedures; 2) improvement in management or general operation of the facility; 3) inspections and records; and 4) reporting of BMP incidents. Regional office guidance includes specific BMPs to control solids; storage of drugs, pesticides, and feed; spill management; structural maintenance; record keeping; training; and pond aeration. While there is no formalized public process to create or modify BMPs, modification of the BMP plan by the applicant is required with any change in the facility or facility operation or when TCEQ finds a failure to achieve the general objective of preventing or minimizing the generation of pollutants and their discharge. The TCEQ's regional offices complete annual inspections to examine BMP plans and verify implementation and compliance. The Texas A&M University Sea Grant College Program published an in-depth regulatory guide to clarify the complex regulatory environment (Treece 2005).

### *Arizona*

The 1986 Arizona Environmental Quality Act was enacted to protect surface and groundwater quality from point and nonpoint source discharges following discharge permit administration approval by USEPA. Arizona has focused on decreasing nitrate concentrations in groundwater as the primary objective of its groundwater pollution prevention programs. In state legislation, aquaculture is recognized as a component of agricultural production and a potential source of nitrate contamination to groundwater. Aquaculture operations are defined as concentrated animal feeding operations, which are regulated to minimize environmental effects. Arizona provides industry-wide regulation through the use of agricultural general permits. These permits allow farms to operate and discharge, without an individual NPDES permit, when the operation implements BMPs. These practices may be applied before, during, and after discharges to reduce or eliminate the introduction of pollutants into receiving waters. Economic, institutional, and technical factors are considered in developing BMPs.

Arizona's BMPs consist of three general goals that address the importance of properly 1) harvesting, stockpiling, and disposing of animal manure; 2) controlling and disposing of nitrogen contaminated water; and 3) closing operations. A variety of guidance practices (GPs) provide owner/operators with methods to implement the BMP goals. The GPs represent state-of-the-art technologies available to the owner/operator. The actual GPs chosen for adoption may vary because their environmental effectiveness depends on such factors as soil type, available farm equipment, water quality impacts, land ownership, facility siting, and related economic criteria. The aquaculture GPs were developed by the University of Arizona and then reviewed by representatives from the Arizona Department of Environmental Quality, producers, and Arizona Department of Game and Fish (Fitzsimmons 1999).

### *Hawaii*

Hawaii is an approved state by the USEPA to enforce the CWA. The authorized agency for granting the permit in Hawaii is the Department of Health. Following a 6-year effort funded by the USDA Center for Tropical and Subtropical Aquaculture to characterize effluent discharges, the Center developed a BMP manual (Howerton 2001). The BMPs are simultaneously voluntary and a compulsory part of two permit processes. The BMPs are voluntary in that the state extension/advisory program recommends their use to farmers for farm operations. The BMPs are required in the issuance of the NPDES permit by the Department of Health and the issuance of the conservation district use permit by the Hawaii Department of Land and Natural Resources (DLNR). In the case of the DLNR, they are called Management Plans. With respect to the mandatory BMPs, the Departments of Health or Land and Natural Resources use previous experience and work interactively with permit applicants to develop the permit BMPs on a project-by-project basis. The process of negotiating required BMPs with permit applicants has become more efficient. The BMPs are more relevant, reasonable, and realistic; agency personnel gained experience with aquaculture and farmers gained experience with what agency personnel wanted. Required BMPs are enforced through the permit and ongoing project monitoring and reporting to the regulatory agencies. Site inspections are carried out to review farm operations.

### *Missouri*

During 2003, the Missouri Department of Natural Resources added a requirement that farmers develop and implement BMPs for general NPDES permits required for coldwater and warmwater species. One permit covers impoundments, tanks, or recirculation production systems, and another addresses flow-through systems. Initially, the Missouri Aquaculture Council introduced the concept of adding BMPs to the general permits. The council is composed of state agencies, industry, and university representatives and cochaired by the Missouri Departments of Agriculture and Conservation. After some discussion, the permits were drafted and made available for public comment.

The BMP requirements for both permits instruct the farmer to develop an operation and maintenance plan that employs BMPs for preventing the discharge of solids from the facility. The plan includes a list of management practices on reducing solids discharge, drug and chemical usage, and feed and fertilizer storage (MDNR 2002a, b). The Department of Natural Resources has the authority to inspect farms for permit compliance.

### *Oklahoma*

Aquaculture facilities defined as CAAPs under the NPDES permitting regulation must acquire a general permit from the Oklahoma Department of Environmental Quality and use BMPs. Twenty-three aquaculture BMPs were developed based on university research and demonstration projects (Langston University 2002). The BMPs are intended to minimize pollutant loading to aquatic environments and include treatment requirements, operating procedures, and practices to control plant site runoff, spillage or leaks, sludge or waste disposal, or drainage from raw material storage. The BMPs are focused on minimizing nutrient and sediment discharges by specifying practices to reduce discharge turbidity; improve sediment settling; keep discharge and drug use records; create settling basins; reuse collected sediments; prevent erosion (pipe placement and revegetation); use in-pond harvest basins; manage and store stormwater, fertilizers, and feeds; aerate; and harvest. Operators of aquaculture facilities who do not require NPDES permits or monitoring must adopt seven prescribed BMPs and may choose any combination of the remaining BMPs, or devise their own, to achieve the goal of environmental protection.

## Producer Initiatives

State and regional producer organizations have developed codes of practice and BMPs as proactive steps for responsible environmental stewardship. These actions demonstrate commitments to environmental stewardship for purposes of minimizing potential adverse impacts from aquaculture production. Producer initiatives gained credibility through relevant research and strong backing by aquaculture producers. Significant farmer input has been critical to create BMPs that are practical, effective, and minimize unreasonable costs. Aquaculture associations in Alabama, Alaska, Arkansas, Maine, and two regional shellfish farmer organizations sought partnerships with Land Grant universities or Sea Grant college programs to collaboratively develop BMPs.

### *Quality Assurance Programs*

Development of voluntary quality assurance programs was an early initiative of several producer associations. Catfish, trout, and hybrid striped bass associations developed quality assurance programs with BMPs as guidance to prevent potential hazards related to food safety (Brunson 1993; USTFA 1994; Jahncke et al. 1996). A generic shellfish quality assurance program addressed BMPs in the context of shellfish issues (Canzonier 2002). Producer associations administer these programs as a benefit and service to members. These food safety-oriented initiatives became less important after the United States Food and Drug Administration required seafood processors and importers to comply with mandatory seafood Hazard Analysis Critical Control Point (HACCP) regulations (Federal Register 1995). However, these programs trained producers to adopt good practices in the chain-of-custody from farm to processor as the first critical control point for unprocessed farm products.

### *Alabama Catfish Producers*

Alabama Catfish Producers voluntarily partnered with the Alabama Department of Environmental Management (ADEM) and NRCS to formalize voluntary BMPs that were in use and to develop new BMPs that addressed issues identified by Auburn University during an environmental impact assessment funded by the Alabama Catfish Producers. Auburn University researched, developed, evaluated, or updated BMPs that would avoid or minimize adverse environmental impacts. Producers, Auburn University research and extension personnel, ADEM, USEPA, NRCS, Alabama Farmers Federation, and various other individuals reviewed the initial practices. The draft BMPs were formally presented to the Alabama catfish farmers to gather additional comments. After revision, the final BMPs were produced as 21 NRCS conservation practice guide sheets (Boyd and Hulcher 2001; Boyd et al. 2004).

### *Alaskan Shellfish Growers Association*

During 2001, the University of Alaska and the Alaskan Shellfish Growers Association drafted voluntary BMPs to ensure that operations were conducted to protect the natural marine environment to the greatest extent possible. This includes minimizing adverse environmental effects and maximizing beneficial effects, and minimizing impacts of shellfish farming operations on neighbors and other users of Alaska's marine waters. The environmental code presents objectives, strategies, and performance measures to address and mitigate potential adverse environmental impacts from shellfish aquaculture and provides the means for monitoring compliance in implementing these strategies.

Farmers are encouraged to "take stewardship into their own hands and go above and beyond regulatory requirements" by improving upon and adding their own policies to enhance the value of the code to their operations. The code consists of five sections:

introduction; environmental health; general shellfish aquaculture practices; integrated pest management and predator control practices; and shellfish cultivation operations and practices. Each section provides in-depth discussion for appropriate BMPs and a rationale for their implementation. The BMPs are voluntary and not required by Alaska regulatory agencies.

### *Arkansas Bait and Ornamental Fish Growers Association*

In 2001, the Arkansas Bait and Ornamental Fish Growers Association, in cooperation with the University of Arkansas at Pine Bluff (UAPB), developed BMPs for bait and ornamental fish farms (ABOFGA, undated). The impetus for producing voluntary BMPs was a concern by producers that additional regulatory and monitoring costs would further contribute to declining numbers of fish farms in the state, and growing member awareness that larger environmental impacts are possible from small local sources.

The BMPs focus on water conservation, erosion prevention, and solids and nutrient management. In-depth narratives for each issue describe current, sensible practices and suggestions to conserve water and prevent off-farm releases of solids and nutrients. The BMPs are summarized, and a signature block includes the statement that the farmer agrees to voluntarily implement the practices.

Technical assistance is available from UAPB extension specialists to implement BMPs but there is no formal process to verify implementation. Financial assistance is not available for implementation. Anecdotal evidence suggests a high implementation rate, especially for practices with economic benefits (water conservation). Extension specialists have field-tested and proved that some BMPs are not appropriate and no longer recommend their implementation or have modified recommendations for specific conditions. As examples, the BMP to plant grass along pond edges to reduce erosion is no longer recommended because this practice created habitat that favored aquatic snails, which serve as intermediate hosts for several fish parasites (N. Stone, University of Arkansas-Pine Bluff, personal communication, December 2005). Specific site analysis is also needed before recommending the use of vegetated ditches to capture suspended sediments (Frimpong et al. 2004).

### *Maine Aquaculture Association*

The Maine Aquaculture Association (MAA) developed a code of containment that established BMPs and standards for equipment and operations designed to reduce the escape of farmed fish. That code ultimately formed the basis for the Containment Management System (CMS). In 2000 MAA hosted an international meeting of growers' associations focused on codes of practice, BMPs, and their design and implementation. This meeting and review of codes of practice formed the basis for the MAA code of practice (MAA, undated). This is an overarching code for compliance by all association members. It is linked to two species group subdocuments, the MAA finfish bay management agreement (MAA 2002) and the MAA shellfish biosecurity and shellfish health agreement. The latter document is still under development.

The MAA's original BMPs, the CMS, and industry code of conduct were developed in cooperation with state and federal agencies and environmental nongovernmental organizations. The MAA Code of Conduct was developed by MAA staff and reviewed by members and external reviewers including the United Nations Food and Agricultural Organization and World Wildlife Fund (MAA, undated).

The MAA writes BMPs and works to get members vested in their implementation by 1) involving members in BMP technical drafting, 2) conducting member BMP training seminars and educational meetings, and 3) working with regulators to ensure that BMPs in regulations actually achieve intended effects. The MAA also defined key terms prior to developing codes, systems, and practices. The BMP review and revision are a continual process driven by producers. The MAA has a finfish bay management committee and a shellfish working group to review, revise, and recommend BMPs. A steering committee advises on the implementation of the CMS. This steering committee consists of all relevant state and federal agencies, the industry, Conservation Law Foundation, Trout Unlimited, and the Atlantic Salmon Federation.

### Washington Fish Growers Association

The Washington Fish Growers Association (WFGA) developed BMPs to foster and maintain high facility operating standards in the salmon net-pen industry (WSGA 1991) followed by a voluntary code of conduct (WFGA 2002). The BMPs stressed best practices related to introduction of fish stocks, feed and feeding, mortality removal and disposal, net cleaning and changing, predator control, harvesting, medical and chemical application, spill prevention and chemical storage, solids waste collection and disposal, sanitary facilities and waste disposal, maintenance and repair of facility and equipment, environmental monitoring and reporting, navigation aids, safety, aesthetics and noise, and employee training and public education. The codes of practice were developed under the code and guidelines for responsible aquaculture and practices of the Food and Agriculture Organization of the United Nations (FAO 1995, 1997). The code was developed and published in collaboration with and financial support from the Department of Commerce, National Oceanographic and Atmospheric Administration (NOAA).

### Pacific Coast Shellfish Growers Association

The Pacific Coast Shellfish Growers Association (PCSGA) established an environmental management system for West Coast farmers. Growers recognized that increased scrutiny of their operations, due largely to the Endangered Species Act and Essential Fish Habitat rules under the Magnuson-Stevens Fishery Conservation and Management Act (Public Law 65), had the potential to impact their farming operations. Consumers are also increasingly demanding environmentally sustainable seafood. The PCSGA's environmental management system was designed to address these concerns (Dewey 2000).

The PCSGA's approach included an overarching environmental policy (general operating principles) and detailed environmental codes of practice with sets of recommended BMPs for culture activities associated with molluscan species produced on the West Coast. The process for developing the policy and codes involved grass-roots level engagement. Eight shellfish growing areas in Alaska, Washington, Oregon, and California were designated as regions for the purpose of holding small group growers meetings to develop the environmental policy followed by environmental codes and BMPs.

The policy consists of five components: 1) environmental stewardship and responsible management, 2) environmental excellence, 3) regulatory compliance, 4) waste management, and 5) sharing resources (PCSGA 2001). With the environmental policy as a foundation, the environmental codes and BMPs were developed with the goal of minimizing adverse environmental impacts and maximizing benefits to the extent possible, utilizing the best available science. The codes were developed by a steering committee with one representative shellfish farmer from each of the eight regions. The steering committee and the regions also included Sea Grant College Program representatives. During a 2-year effort, culture practices and their potential effects on the environment, positive and negative, were identified. A list of recommended BMPs was developed and designed to minimize negative impacts and magnify positive impacts. Experts in marine biology, regulation, and policy from the Pacific Shellfish Institute, PCSGA, and state Sea Grant Programs drafted documents. These drafts were reviewed by each region and revised to accurately represent regional shellfish production practices and environmental conditions. The initial BMP draft was reviewed by federal and state resource agencies and environmental nongovernmental organizations.

The BMPs adopted by the PCSGA consist of 13 sections, including the purpose of environmental code of practices; background on the shellfish industry; shellfish aquaculture interactions in the marine environment; shellfish aquaculture operations; general management principles; pest, predator, and disease control; integrated pest management; hatchery and nursery operations; cultivation operations and practices; processing and shipping operations; industry regulations; a template for individual farm management plans; and a research bibliography. The environmental code of practice includes a template farm plan designed to simplify growers' development of their own farm plans. Currently, the BMPs are voluntary.

### *East Coast Shellfish Growers Association*

The East Coast Shellfish Growers Association (ECSGA) supports the need to adopt voluntary BMPs that minimize negative interactions with the environment and other user groups and prepare growers to deal with natural disasters. The BMPs outline the benefits and impacts of shellfish cultivation and where these methods are most appropriate. The BMPs help growers and managers address animal husbandry issues such as disease and predator control. The ECSGA is collaborating with the USDA Northeastern Regional Aquaculture Center on a project to develop an environmental code of practice and BMPs for shellfish growers on the East Coast that will also engage extension specialists in the region similar to work led by PCSGA for shellfish growers on the West Coast.

## University Initiatives

The Louisiana State University Agricultural Center (LSU AgCenter) initiated discussions with the NRCS and Louisiana Farm Bureau to develop BMPs prior to the imposition of total maximum daily loads as required by the CWA and other regulations. Several agricultural commodities were identified for BMP development, including aquaculture. The LSU AgCenter led a collaborative effort with input from NRCS, Louisiana Department of Environmental Quality, Louisiana Farm Bureau Federation, and the Louisiana Department of Agriculture and Forestry to produce a BMP manual (LSU AgCenter 2003). The manual includes eight chapters: introduction, finfish pond production, crawfish pond production, crawfish nutrient management, intensive production systems, soil and water management, pesticide management, and general farm BMPs. The soil and water management chapter includes references to specific NRCS production codes for each BMP. Information about this program was distributed to the aquaculture farming community through industry newsletters, producer meetings, and website updates.

The BMPs are voluntary and can be verified through farm visits by LSU extension specialists. The LSU AgCenter is under contract with the Louisiana Department of Environmental Quality to develop in-depth written guidelines, fact sheets and how-to publications to assist crawfish farmers with the adoption of BMPs. The BMPs will be revised and updated by the LSU AgCenter based on recommendations by the original participants and an initial recommendation to revisit the BMPs after 5 years. The LSU AgCenter also conducted research to support some of the BMPs, especially for crawfish aquaculture (Parr 2002).

The National Sea Grant College Program provided funds to develop an aquaculture BMP educational manual. The manual offers guidance for current and prospective aquaculturists and regulatory agencies in Wisconsin and the Great Lakes region. The BMPs are defined as management guidelines or approaches designed to minimize or prevent any adverse environmental impacts, maximize the health and well-being of the organism being raised, and encourage efficient and economical production. A small team of authors wrote an in-depth narrative with BMPs highlighted throughout the text. The manual consists of nine chapters: overview of aquaculture; water; management and beneficial reuse of aquaculture wastes and effluents; fish health; aquaculture and fish biology, species, strains and genetics; interactions with nonfish species; flow-through systems; recirculating systems; and pond systems. An appendix includes current Wisconsin environmental, resource, and fish health regulations. A committee composed of industry, regulatory agency, academics, and environmental organization representatives, provided review and comments. Aquaculture specialists are advised to add electronic copies of their respective state regulations for distribution across the region (Malison and Hartleb 2005).

## Creating a Participatory Process of Regulatory Development

An underlying goal of participatory regulatory development must be to actively recruit and mobilize diverse stakeholders who will identify problems, participate in the regulatory development process in good faith, and offer solutions for the broader public benefit. A constructive, holistic, multisectoral dialogue about an environmental issue can improve understanding of uncertainties from different perspectives and clarify options for decision making (Luoma and Löfstedt 2007). However, when environmental issues are complex, unconstructive advocacy, a narrow focus, and exclusion of selected parties from decision making can erode public trust in science and lead to cynicism about the policies of government and the private sector (Luoma and Löfstedt 2007).

Full consensus on highly charged and emotional issues is difficult when widely opposing views are held or divergent solutions are proposed. Disagreement is commonplace in public policy forums with complex environmental dilemmas, but trust may be best served by a focus on why disagreements exist rather than who is right (Luoma and Löfstedt 2007). Input of diverse opinions is an essential part of participatory policy making if the process is to be effective and legitimate. Divergent thinking assures consideration of a range of solutions and can provide opportunities for creativity and innovation (Joldersma 1997). Involvement of interest groups with divergent points of view also legitimizes the process by assuring the public that a broad range of stakeholder positions were considered during deliberations.

This is especially true for environmental issues like the USEPA effluent guidelines effort that involve complex technological or socioeconomic questions. The successful development and broad acceptance among stakeholders of environmental codes of practice, regulatory BMPs, or voluntary guidance for environmental stewardship relied on transparent stakeholder participation. Creating stakeholder respect for a transparent decision making process facilitates compromises that can mollify divisive ideologies. Those affected by policies or regulations are more likely to work with regulators when they are comfortable with the working relationship and perceive that everyone is working toward a mutual and well-defined goal with clear criteria.

### *Stakeholders in Regulatory Development for Aquaculture*

Stakeholders in the USEPA rule-making process used to develop an environmental regulation of aquaculture effluents included affected producers, various federal and state regulatory agencies, scientists, and environmental nongovernmental organizations (NGOs). In the sections below, the perspective and role of each stakeholder is described, with emphasis on identification of areas of divergent interests or disagreement among stakeholders. In the AETF approach—as in nearly all participatory rule-making processes—each stakeholder operated in its own self-interest, but remained open to consider perspectives of other participants in the process. This rationality, which is called "inducement of shared perspective" by Joldersma (1997), is essential for convergence on true consensus.

No single stakeholder can adequately provide the resources, technical expertise, or regulatory authority needed to develop a balanced and effective outcome. Partnerships of stakeholders facilitate the identification of key strategic actions and the means to leverage limited resources from different programs for the broader public good. During nearly every effort to develop aquaculture BMPs at the state level, affected producers, regulators, university scientists, environmental organizations, and the public created partnerships to gain the needed expertise and engender broad support.

Recruiting experts and other stakeholders to openly share their knowledge and field experiences can be challenging for national regulatory initiatives. Individuals may have working, professional, or statutory responsibilities to public or private programs or a paying clientele. Without direct monetary compensation, the incentive for some stakeholders to participate voluntarily may be driven by 1) relative importance of the issue (locally and nationally); 2) sense of peer support; 3) status of participating organizations; 4) prior commitment of in-kind resources; 5) perceived or actual risk of liability; or 6) confidence in the organizational structure, process, and leadership. During the development of national effluent guidelines, dozens of scientists and stakeholders contributed considerable time and effort to attend meetings, develop industry reviews, respond to USEPA questions, or otherwise participate in the rule-making process.

### *Industry representation*

Most industry organizations consider participating in policy decisions as an interest group as an essential, if not primary, function of the organization (Furlong and Kerwin 2005). The incentive to organize is based on the enhanced political power of a large group relative to the diffuse influence of individuals. When governmental entities consider developing new or revising existing environmental regulations or policies, the stakeholder community most often directly impacted includes producers and companies whose practices or technologies are under scrutiny. Environmental regulations are often perceived by this stakeholder group as an unnecessary financial burden. In the case of pollution-control regulations, producers are in essence asked to internalize the cost of pollution control in situations where that cost was previously borne by society at large. Thus, producers are inclined to resist change because regulation is perceived to adversely affect profitability, particularly in business situations were profit margins are small.

Most United States aquaculture is conducted in earthen ponds that have historically been viewed by environmentalists and aquaculture scientists as having little negative impact on the environment, especially relative to other land uses and industries. Producers using pond systems perceived that criticism of the environmental performance of aquaculture was unfair because their record of environmental stewardship was good. Other producers believed that existing regulations, particularly those in certain states, were already adequate to address concerns about aquaculture effluents.

Despite these reservations, producers, as represented by leaders of producer associations, were actively engaged in the AETF-sponsored process. Producer organizations representing aquaculture are smaller and much less well developed as political interest groups than organizations representing terrestrial agriculture. With few exceptions, these organizations consist mainly of farmers growing a particular species or species group.

The various groups representing aquaculture producers rarely interact. The initial broad scope of the USEPA national effluent guideline created a rare event that unified the diverse United States aquaculture industry because of a common issue. More than ten regional and national aquaculture associations had representation throughout the entire USEPA regulatory process. They played critical roles in communicating progress and needed actions to their respective members as an important outreach function. All appointed at least one member to serve a liaison role with the AETF.

In numerous cases, there are strong local (state), regional, or national producer associations that have financial resources and the will to be actively engaged in public policy processes. However, this is not always the case. Critical representation may be diminished by logistical and financial constraints in prolonged, costly policy-making processes and distant meeting locations. National issues may receive less attention compared to local issues because of a poor understanding of potential direct on-farm impacts and uncertainty of how to effectively participate in a national public policy process. Local issues are best addressed by local producers and associations, with support from local programs and backing from regional or national producer associations as needed. In numerous states, producer associations play key roles in developing BMP regulatory and voluntary programs with their experience and knowledge as key ingredients for success.

Innovation is a continuous process of on-farm experimentation and pioneering discoveries that are critical for today's producers to operate successfully within a mix of economic challenges, including compliance with environmental regulations. Most small- and medium-size farm operations are fully occupied by day-to-day issues and have limited resources of time and finances to expend on participation in a regulatory development process. However, proper representation of farm-level practices, conditions, and experiences are critical to accurately understand the on-farm consequences of options under consideration by regulatory authorities and other interested stakeholders. Producers are needed to articulate the reasonableness and economic achievability of compliance alternatives and propose recommendations based on their understanding of a regulatory objective and knowledge of farming practices and technologies. Ultimately, producers are the environmental stewards who rely directly on the well-being of aquatic resources for their livelihood. They have daily managerial roles over the use of best practices and taking responsible actions to help sustain the environmental integrity of aquatic resources for the broader public good.

### *Federal agencies*

The role of federal agencies in a multistakeholder process of regulatory development is central and straightforward. Agencies of the United States government are responsible for administering programs and enforcing regulations within their domain. With respect to the desirability of regulations, federal agencies are subject to policy direction from elected and appointed officials of the executive branch of government. Depending on the policy inclinations of these officials, the federal government has imposed a greater or lesser regulatory burden on affected businesses and industries as a whole. Ideally, the role of federal agencies is to balance the concerns of all stakeholders by developing regulations within existing policy frameworks that, in the case of aquaculture effluents, provide effective environmental protection without an unreasonable burden on small businesses. The role of USDA and NOAA representatives was critical to the success of the AETF process, primarily acting in key leadership roles as facilitator and catalyst. In the AETF process, the federal government, specifically the USEPA, was acting in response to a need to satisfy the terms of the Consent Decree with the NRDC to enforce provisions of the Clean Water Act, so the threat of further legal action was a strong incentive to develop a meaningful regulatory process that would satisfy critics of the federal government's enforcement of the CWA.

Beyond the direct role of federal agencies, society benefits immeasurably when publicly funded research integrates objective scientific, economic, and technical analysis into policy-making decisions. Numerous agencies and programs within the Departments of Agriculture, Commerce, and Interior provided support for research, extension, technical assistance, stakeholder meetings, publications, and communications. The USDA's regional aquaculture centers funded numerous research projects since the late 1980s to characterize effluents, improve environmental management, and understand environmental interactions. This includes an interregional initiative focused on coordinated research, education, and public policy projects. Numerous USDA agencies (Agricultural Research Service, Cooperative State Research, Education and Extension Service, Natural Resources Conservation Service, and the Risk Management Agency) contributed to national-, regional- and state-level BMP development projects. The NOAA National Sea Grant College Program was particularly supportive of regional initiatives to develop environmental codes of practice and BMPs for shellfish aquaculture and aquaculture producers in the Great Lakes Region. The USEPA administers numerous competitive grant programs and the National Center for Environmental Research has funded aquaculture projects (Jin et al. 2003).

### *State regulatory agencies*

Although often not perceived as such, state regulators are also stakeholders in the policy-development process. Their principal objective is to address their mandate to protect and conserve natural aquatic resources, which may require stronger environmental protection than provided in the federal framework. State regulatory agencies are often at the forefront of federal regulatory enforcement. Very often, new federal regulations are developed without additional federal support for enforcement. Thus, state regulatory agencies may oppose the development of new federal regulations because they are seen as an unfunded mandate from the federal government that imposes a financial burden on the budgets of state governments. Additionally, agency representatives from states with significant aquaculture were familiar with the environmental performance and regulation of aquaculture within their state and believed that additional regulation was not warranted based on their experiences.

Many state regulators are strong advocates for BMPs as a regulatory option. Environmental management programs based on BMPs usually involve one or more state agencies with the authority to administer discharge regulations for aquaculture facilities. These regulatory agencies have numerous options available for regulating discharges from aquaculture facilities, and many choose to experiment with BMPs or codify them into state law. State agencies can provide in-kind contributions of technical expertise and assistance, guide applied research to create or improve environment management practices and waste management technologies, and in some cases, provide resources for cost-sharing BMP implementation.

### *University scientists*

University scientists play an important role in the policy development process by providing factual knowledge that can serve as the scientific underpinnings of environmental regulation. In this way, university scientists function more as information providers, rather than advocates of a particular policy position. In the AETF process, most university scientists that participated in the AETF process were affiliated with Land Grant institutions, which historically have strong research and extension partnership programs with agriculture, and, in this case, aquaculture interests. Thus, university scientists may be perceived by some representatives of environmental NGOs as not entirely objective because of this close association. However, university research and extension programs played critically important roles in organizational leadership, conflict resolution, communications, applied research, scientific expertise, technical assistance, publications, and educational programs to support the development of BMPs at local, state, regional, and national levels. Land Grant, Sea Grant, and other university programs have made significant contributions to developing successful BMP initiatives. University programs can contribute practical research and field demonstrations of BMPs. They also provide technical assistance to facility operators in adopting BMP plans or customizing BMPs to site-specific conditions.

#### *Environmental nongovernmental organizations (NGOs)*

Environmental nongovernmental organizations (NGOs) can be extraordinarily vocal and have financial resources to mobilize their membership and the public at large to exert influence on public policy decisions (Tiersch and Hargreaves 2002). The role of environmental NGOs as contributing partners in developing BMPs has varied, depending on the intensity of opposition to a specific issue or aquaculture setting (e.g., salmon farming in net pens). Environmental NGOs were invited to participate in an open, solutions-oriented manner to identify potential and actual adverse environmental effects and offer reasonable recommendations. Several national environmental NGOs agreed to participate and submitted independent, formal comments to USEPA that identified areas where the environmental performance of aquaculture could be improved. Most wanted to be informed about planned AETF activities, but some hesitated to be recognized as named participants. Hesitation sprang from the perception that active participation might dilute their influence through alternative approaches and would suggest unqualified endorsement for the AETF-sponsored process. There was some distrust based on the perception that the AETF favored industry positions. However, the AETF and environmental NGOs benefited from information exchanges at AETF public meetings. The experience of many state-level activities is exemplified by those in Maine and Florida, where BMPs were developed through stakeholder technical advisory committees consisting of agency-invited farmers, and representatives from the relevant state agencies, university extension services, and environmental NGOs.

### *Forms of Stakeholder Input*

Active engagement of all stakeholders, even in the initial stages of the process, can expand the range of opinions and technical expertise available to develop effective environmental management programs. All interested parties should have ample opportunity to provide input throughout the public rule-making process. In the case of the USEPA national regulation, public input consisted of a mix of information, data, recommendations, and opinions from diverse stakeholders. To be effective, stakeholders must be willing to sustain active participation for the duration of policy development.

In recognizing the important role of stakeholder input, the motivation to support or oppose an issue varies widely. In some states, the decision to issue a permit or license requires local citizen input. This can lead to decisions influenced by parochial self-interest (e.g., an unobstructed ocean view). The intensity of opposition by local stakeholders can often deter aquaculture development, especially in populated coastal areas. A participatory stakeholder process must accommodate a variety of social dimensions during regulatory development.

As one example of the results of a process with broad stakeholder participation, the governor of Maine became a stakeholder through submission of a white paper that addressed the need for state-level policy decisions amid mixed stakeholder support for aquaculture (Apollonio 2004). The Texas BMPs were developed by the Texas Commission on Environmental Quality as an outcome of administrative hearings and input from Texas Parks and Wildlife and a national environmental organization. The Missouri Aquaculture Council introduced the concept of adding BMPs to the Missouri general aquaculture permits. The council consisted of state agencies, industry, and university representatives and was cochaired by representatives from the Departments of Agriculture and Conservation. The Florida BMPs were initially developed by the public and academic technical advisory committees, reviewed internally by the lead agency, and then submitted to an administrative rule development process that included public comment and legislative review.

The development of new or revised environmental regulations by the USEPA under the CWA requires public review and comment. This also applies to the process of issuing new and renewed NPDES permits (Federal Register 2006). Although statutory public comment plays an important role in allowing open participation in policy making, soliciting comments is a passive procedure that may not provide adequate or representative input to assist with policy development.

Although open participation is essential to any policy-development process, stakeholders with entrenched ideologies or philosophies may become overly influential and science can become marginalized. The result, unless the input is balanced, can be unreasonable criteria or ad hoc approaches for reaching a critical decision. Stakeholders who have assumed a public identity but are motivated by self-interest can misrepresent the public interest because of a priori positions. The burden of proof may then, by default, become the responsibility of a business or industry potentially impacted by a regulation or proposed regulatory option (i.e., precautionary principle). Those affected by decisions must take positions, accept the outcome of scientific inquiry, and be fully engaged in supporting environmental protection and conservation through responsible actions to gain broad public support.

## The Role of Science in Policy Development

Throughout this chapter, terms such as *science, scientific, sound-science, science-based, best available science,* or *peer-review* have been used to signify information or data produced by objective, testable, hypothesis-driven analysis of physical and biological phenomenon that has undergone independent evaluation by knowledgeable peers. Unfortunately, these phrases, which are highly valued in the scientific community, have been put to questionable use to achieve political goals (Mooney 2005). Misuse of these terms and other related issues have triggered thoughtful commentaries by fishery professionals (Lackey 2004; Hilborn 2006). The term *consensus science* implies a preponderance of scientific evidence for which there is wide or general agreement. Even *best* available science can suggest selectivity or value judgment regarding what is best within the body of scientific information on a particular issue. In extreme cases, scientific information may not even be scientifically valid. Public trust in science is the greatest resource at stake in the dialogue about complex environmental or health risks. The best science might be judged by how well it considers the full scope of the relevant literature and the complete scope of the issue. It is a challenge to fully understand all the ingredients of a constructive dialogue on science, especially those that optimally generate public trust and effective policy (Luoma and Löfstedt 2007).

The process of regulatory development should use the best available scientific knowledge to guide and support decision making. Some stakeholders may consider current science inadequate or there may be limited scientific information to inform policy. Scientific uncertainties create difficulties for environmental policy makers. Agreement must be attained to accept scientific information that will lead a reasonable, objective person to reach a credible conclusion. This may present a dilemma if scientists disagree on the interpretation of the available information or the need for additional studies. The debate can become *whose* science is valid or *which* interpretations of complex studies or data should be accepted. An initial agreement on the ground rules for how science will be used in any policy-making process can be helpful, in addition to a mutually agreeable peer-review process to validate recommendations and gain broader trust.

Most environmental programs that assess new regulatory options include a review of current scientific and technical literature. Knowledgeable individuals familiar with the literature are most effective in accomplishing this task. The determination of state-of-the-art knowledge provides opportunity to identify critical information gaps on regulatory questions and determine relevance on specific issues. For some issues there may be insufficient information or lack of tested science. Much of the theoretical and applied research conducted in the United States was not designed in consultation with regulatory authorities to use approved sampling methodologies, sample chain-of-custody, laboratory procedures, quality controls, or other standards that are acceptable in a court of law under the legal framework of "good laboratory practices." This has little if anything to do with the quality of the science, but can result in challenges to the interpretation or acceptance of research findings in the context of regulatory development.

Within a diverse mix of stakeholders engaged in public rule making, there is commonly wide disagreement on the analysis of environmental impacts and desired outcomes. During the early phases of rule making, knowledge levels can differ widely among stakeholders, who may have strongly held perceptions rather than facts. Technical contributions by recognized experts can facilitate a more comprehensive understanding of the issues among diverse stakeholders and allow the attainment of reasonable and mutually acceptable outcomes. Science can provide validated baselines of data and actual or projected environmental effects based on modifying variables in reliable simulation models. Scientifically developed and validated tools can help evaluate potential and actual environmental benefits.

For USEPA, the goal of using "sound science" is clearly stated in agency strategic plans. Numerous state agencies and BMP advocacy organizations also stress the need for science to develop effective and relevant BMPs. The AETF functioned under the principle of using the best available scientific knowledge to inform policy options. The role of science in federal programs related to aquaculture development has been reviewed from a historical perspective (Tiddens 1990; Jensen, in press). Value systems of society or advocacy organizations and political management ideologies can be critical factors that determine the relative role of science in public policy making. Public benefits from federally funded science can be increased significantly when the resulting knowledge is used to formulate science-based policies.

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# Chapter 5

# Development, Implementation, and Verification of Better Management Practices for Aquaculture

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## Introduction

The purpose of better management practices (BMPs) for aquaculture is to provide an on-farm management system designed to minimize adverse environmental and social impacts or assure food safety. BMPs, as an approach to achieve environmental protection or conservation goals and an alternative to prescriptive regulations, have been promoted by public agencies and farm organizations in the United States since the late 1990s.

Although the impetus for creating BMPs has ranged from altruistic self-governance to legislative mandate, the process to develop, implement, or verify BMPs has many commonalities. Presented here are the cumulative experiences and observations of those activities that have resulted in workable and effective programs, which continue to evolve.

Aquaculture affects a diverse group of stakeholders that includes producers; input suppliers; fish processors; seafood buyers; consumers; government agencies; members of affected communities; and environmental, social, and consumer advocates. Representatives of each group should be involved in the process of formulating BMPs. It is essential to reach a consensus among stakeholders about the issues to be addressed by BMPs. Some stakeholder concerns might seem irrelevant to scientists and other technical experts, but all concerns must be openly discussed among stakeholders to create a credible and transparent process that will lead to an effective suite of practices that will be acceptable to all affected parties.

Once the issues of concern have been agreed on, technical experts should be given responsibility by the stakeholder group to prepare draft BMPs that address each issue. Of course, the entire range of stakeholders, and especially producers, should be involved in revising draft BMPs. It is essential for the BMPs to address all major issues, but they also must be practical, implementable, effective, and acceptable to the stakeholders.

The rate of adoption of BMPs and the degree of benefit accrued from their use should be documented. Of course, compliance with governmentally mandated BMPs must be

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verified by the appropriate agency. Adoption of BMPs in a certification program requires independent, third-party verification.

The purpose of this chapter is to provide an overview of the general process that should be followed in developing, implementing, and verifying BMP programs for aquaculture. This process should be viewed as continuous and iterative. Based on the results of the monitoring program to verify performance, BMPs can be adjusted or new BMPs developed for implementation.

## Uses for BMP Programs

A program based on BMPs offers substantial flexibility to achieve environmental protection goals. The BMP approach does not dictate specific methods, but offers a range of options that can be selected and adapted by producers to site-specific conditions. Adoption of BMP programs can be voluntary or mandatory. Voluntary programs are intended to provide environmental protection while enhancing market opportunities for producers. Mandatory programs are used by governments to achieve environmental protection as an alternative to prescriptive numerical limits.

### *Voluntary Adoption*

Voluntary adoption of BMPs is the most desirable form of implementation because it signifies that producers understand the importance of responsible aquaculture and are willing to expend the effort and bear the costs necessary to attain it. However, in reality, voluntary adoption of BMPs probably is the most uncertain method of implementation. There are several reasons for this. Producers may assess their operation and simply declare that their farms already are in compliance with the better practices. For example, the Global Aquaculture Alliance (GAA) developed a series of BMPs for voluntary adoption by shrimp farms. A self-graded evaluation sheet with a scoring system was provided. Many producers self-graded at 90% or higher out of a possible score of 100%. A similar response indicating high levels of BMP implementation was received from catfish producers in Alabama. The senior author also heard several individuals from Alabama and other states declare that essentially all catfish producers were in compliance with the BMPs. In both examples, there were few, if any, producers who were actually in total compliance with the BMPs.

#### *Investment and credit screens*

It is not uncommon for principals in proposed or existing aquaculture projects to seek investors or loans. Commitment to implementation of BMPs would demonstrate environmental and social stewardship and should be attractive to cautious investors or lenders. Studies showing that BMPs are cost effective would be particularly valuable to those considering investments or loans to aquaculture facilities. The International Finance Corporation (IFC) often makes loans to large aquaculture projects in developing countries. The IFC asks their clients to comply with some environmental regulations. In the future, adoption of BMPs may become a common requirement for farms seeking investors or loans.

### *Use by seafood buyers*

Many seafood buyers are interested in providing products with a history of responsible production. The Label Rouge (Red Label) program in France is one example. Although this program emphasizes product quality and freshness, it also has some environmental requirements with which the producer must comply. Several large supermarket (e.g., Whole Foods, Wal-Mart) and restaurant chains (e.g., Darden Foods/Red Lobster) seek seafood products that are produced with "environmentally friendly" and "socially responsible" techniques. A few of these organizations have formulated specifications for their producers and hired employees to source products from responsible producers.

Consumers have grown increasingly concerned about seafood safety, especially the accumulation of mercury and other persistent bioaccumulative toxins, antibiotic residues, and other potentially harmful substances in seafood. Producers who implement BMPs are not likely to be sources of contaminated produce. Such producers are heavily favored by buyers.

### *Environmental sustainability certification programs*

The Global Aquaculture Alliance (GAA) has developed certification standards for shrimp aquaculture and licensed these standards to the Aquaculture Certification Council (ACC). The GAA currently is developing standards for fish aquaculture certification. The World Wildlife Fund (WWF) is developing certification standards for the most common aquaculture species in international trade (Boyd et al. 2005) and Environmental Defense is developing shrimp aquaculture standards. These standards have specific numerical criteria and record-keeping requirements. For example, the GAA has an effluent standard with water quality limitations for pH, dissolved oxygen, biochemical oxygen demand, total suspended solids, ammonia nitrogen, total phosphorus, and chloride. At the farm level, the most feasible way of obtaining compliance with the standards is through the adoption of BMPs. Of course, each farm is different, and the actual combination of BMPs necessary for compliance with certification standards will differ among farms.

## ***Mandatory Adoption***

Several states and industry organizations have taken steps to develop voluntary BMP programs. These BMP programs are voluntary in principle, but local regulators can make them mandatory for facilities that are currently exempt from the national effluent limitation guideline because of system type or annual production level. This situation puts pressure on facilities that use voluntary environmental codes of practice that include BMPs to demonstrate BMP program effectiveness as an option over mandated requirements.

### *Government regulations*

Governments develop various regulations applicable to aquaculture to include restrictions on siting, exotic species, antibiotic and chemical use, wildlife depredation deterrence, water use, effluent composition and volume, and possibly others. Compliance with these regulations obviously will affect the range of practices that can be used at an aquaculture facility and can, potentially, increase the costs of production. For example, if a particular nuisance species of bird or marine mammal cannot be killed, a variety of more costly nonlethal techniques may be required. Laws to protect wetlands will eliminate the practice of building farms partially or totally in areas delineated as wetlands. This may limit farm size, require the acquisition of additional land for the construction of compensatory wetlands, or require the purchase of more expensive land.

Water pollution control is a major goal of many governments, and discharge permits may be required for aquaculture. The new aquaculture effluent rule in the United States (Federal Register 2004) implemented by the United States Environmental Protection Agency (USEPA) is a good example. This rule requires National Pollutant Discharge Elimination System (NPDES) permits for concentrated aquatic animal production facilities, but it does not specify effluent limitation guidelines. This leaves individual NPDES-delegated states free to determine the conditions required in NPDES permits for aquaculture. In some cases, states will likely require implementation of the BMPs, or similar BMPs, as described by the USEPA (see Chapter 4). Other states may specify certain limitations on effluent water quality concentrations or a combination of effluent water quality criteria and BMPs. Even where BMPs are not specifically required, producers will need to implement better practices in order to comply with water quality restrictions for discharges.

One long-term concern is that resource-strapped government agencies will indiscriminately adopt sets of BMPs developed for other locales or culture conditions, and make them mandatory without regard to applicability. The model of "one size fits all" is too inflexible for unique facility conditions and sites; BMPs may be available but not necessarily relevant to local conditions. The BMPs may be practices that a regulator believes a farmer should follow irrespective of the availability of data demonstrating that an environmental benefit will be realized or that implementation and maintenance costs are reasonable. Real-world experience may yield unexpected results that can be remedied by revising a BMP, but regulatory programs must be sufficiently flexible to accept change.

## Development of Better Management Practices

There has been much effort toward developing documents containing BMPs for a number of aquaculture species (see Chapter 4) and especially for marine shrimp (Boyd 2003a), rainbow trout (*Oncorhynchus mykiss*) (MacMillan et al. 2003), and Atlantic salmon (*Salmo salar*) (Brooks et al. 2002). Individual farms and local producer groups also have become interested in improving management practices. For example, the Alabama Catfish Producers (ACP), a group of mainly channel catfish producers in a five-county area of west-central Alabama, followed a formal procedure to develop BMPs (Boyd et al. 2003). The ACP is cooperating with Auburn University, the United States Department of Agriculture Natural Resources Conservation Service (NRCS), and the Alabama Department of Environmental Management in developing aquaculture effluent regulations based on BMPs (Boyd and Hulcher 2001). Moreover, the ACP is currently working with WWF to use the BMPs as the basis for an environmental certification program for channel catfish. Supermarket chains and other large purchasers of seafood have expressed interest in aquaculture species produced by good practices. In response to this potential market, WWF, the ACC, and Environmental Defense in the United States, and several European organizations are considering programs for certification of several aquaculture species.

Two other notable examples are the development of a Code of Conduct by the Maine Aquaculture Association that was reviewed by members and external reviewers, including the United Nations Food and Agricultural Organization (FAO) and WWF. Significant portions of the Code, over time, have been adopted into state regulations with a management committee consisting of industry, federal and state agencies, and nongovernmental organizations to prevent, control, and manage the escape of farm-raised salmon.

The Pacific Coast Shellfish Growers Association, with the input of growers from eight self-described shellfish regions in Alaska, California, Oregon, and Washington, has engaged in an environmental certification process. This has occurred through a stepwise effort that initially created a code of conduct followed by BMPs. In turn, this has led to planning for an environmental certification process managed through a market-chain supported organization. (See Chapter 4 for a complete description of the Alabama Catfish Producers, Maine Aquaculture Association, and Pacific Coast Shellfish Growers Association efforts.) There is likely to be a proliferation of efforts to develop BMPs and possibly certification programs for many aquaculture species.

Agency-driven efforts to develop BMPs as an environmental protection or conservation effort are public processes that require, to a greater or lesser degree depending upon federal or state laws, direct stakeholder involvement. Stakeholder involvement by state agencies in the United States has generally been organized through the creation of technical advisory committees with membership comprised of commercial producers, aquaculture extension specialists, agency representatives, and environmental organizations. They begin their work by either debating and refining a state agency draft document or creating an original draft through a collaborative effort. An innovative risk analysis process was used to develop agency-adopted BMPs to mitigate potential risks (i.e., genetic, ecological, and disease) of culturing exotic species (Zajicek and Metcalf 2002).

If finalized BMPs are to become regulation, a formal review process for congruence with constitutional guidelines and existing laws will occur internally within the lead agency followed by an announcement to elicit public comment. Regulatory development can be lengthy and time consuming, with controversial provisions triggering opposition by agencies other than the lead agency, or public opposition that will play out in public workshops or hearings and may, if unresolved, result in a challenge through an administrative hearing process for resolution by an impartial hearing officer.

Increasingly, many states in the United States are adopting a BMP approach to environmental protection because of generally effective results and an inherent flexibility to encompass small and large operations. This reflects the experience that the development of aquaculture-related BMPs in the United States has not resulted in confrontational legal action or interagency “turf” battles. BMPs created and adopted into regulation in Hawaii, Florida, Louisiana, New Jersey, and other states (described in Chapter 4) are examples of the outcomes of these processes.

The suggested process for developing BMPs is summarized in a flowchart (Fig. 5.1) and described in more detail below.

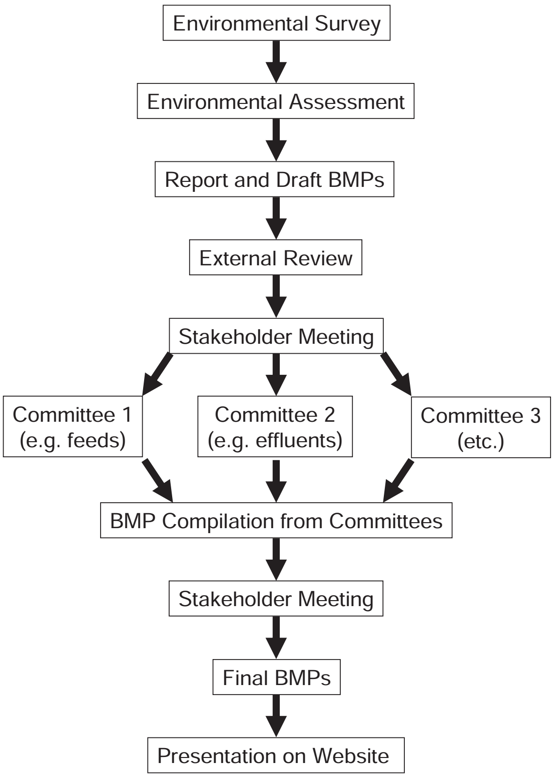

**Fig. 5.1.** Flowchart for BMP development.

## *Environmental Survey*

The initial step in developing BMPs for production of a particular species in a given area is to conduct a survey of production activities and their potential effects on the environment and nearby communities. There may be so many producers that a sample of farms must be selected for the study. The sample should be a random selection of farms to assure that it is broadly representative of the production activity. The survey probably should include farms accounting for 10 to 25% of total production within the area of interest.

The survey should be conducted by a small team of individuals with collective expertise in aquaculture, environmental science, and social science. These individuals should be responsible for designing the survey instrument for capturing the information needs listed in Table 5.1. The return on surveys through postal or electronic mail is low. Therefore, the investigators should visit each farm and use direct interviews with producers to fill in the survey instrument.

## *Environmental Assessment*

The findings of the environmental survey should be summarized in a report because the information will be used in later stakeholder meetings. The report should describe the

**Table 5.1.** Suggestions for information to be obtained from aquaculture producers for use in developing BMPs.

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**General information on the aquaculture activity**

Species, total area in production, total annual production, value of production, size of farms, employment opportunities, major milestones, future prospects, and climate information

**Specific information for individual farms**

- Site and farm
  - Location
  - Significant features—terrain, soils, elevation, vegetation, nearness to neighbors, possible natural disasters, likelihood of pollution from other land and water users
  - Area in production
  - Source of water
  - Culture species
  - Annual production
- Production system
  - Type—e.g., ponds, raceways, cages, etc.
  - Description of system
  - Water use
  - Water intake and distribution
  - Water release—frequency, volume, quality
  - Retention time
  - Water discharge—frequency, volume, quality
  - Condition of facilities—maintenance of facilities, erosion control, general tidiness
- Production methodology
  - Species
  - Source of seed and stocking density
  - Fertilizers and liming materials—types, amounts, application frequency
  - Feed—type and protein, fishmeal, phosphorus content
  - Feeding—frequency, amount per day, method of application, amount per crop
  - Mechanical aeration—type of aerators, amount of aeration per pond, operating schedule
  - Water exchange—method of application, amount per day, use in response to water quality emergencies, total water use
  - Species health management (including information on the use of therapeutants)
  - Water quality management (e.g., copper sulfate, zeolite, sodium chloride, etc.)—doses, frequencies, methods of application
  - Harvest data—harvest method and harvest statistics (survival, net production, FCR, etc.)
- Effluents
  - Annual volume and frequency of discharge
  - Average quality and maximum concentrations of nutrients, suspended solids, biochemical oxygen demand, dissolved oxygen, pH
  - Annual loads of N, P, TSS, and 5-day BOD
  - Treatment of effluent before final discharge
  - Conditions around final discharge point
  - Receiving waters—area, volume, flushing rate, quality, other users, other pollution sources
  - Permit conditions and monitoring
- Miscellaneous
  - Use of pesticides
  - Predator control method
  - Storage of materials—feeds, fertilizers, liming materials, fuels, etc.
  - Waste disposal—mortalities, used oil, expired or unwanted chemicals, refuse, sewage, etc.
  - Observations of surrounding environment—evidence of eutrophication or sedimentation in receiving water body, damage caused by improper waste disposal, ecological nuisances, etc.
- Community and worker relations
  - Procedures used to communicate with community leaders
  - Assistance provided to local communities
  - On-going conflicts (conflict resolution?)
  - Origin of workers
  - Pay scale and incentive pay for workers
  - Living conditions on farms
  - Medical care
  - Recreational activities

aquaculture sector and how it has been superimposed on landscapes and communities. Production facilities and methods should be described. Published research findings and extension recommendations on feed use efficiency, aeration, effluents, and other aspects of production with potential environmental impacts should be summarized. A careful description of water use within the culture facilities is necessary. There should be thoughtful analysis of resource availability, competing uses, and possible environmental impacts in which wasteful and environmentally harmful aquacultural practices are identified. In addition, the possibility of negative social aspects of farms should be ascertained. Investigators should prepare lists of BMPs that could be useful in preventing wasteful use of resources and each negative environmental and social impact. The BMPs also should include practices for preventing contamination of aquaculture products at the farm level.

The report should be sent to three to five external reviewers (not local stakeholders) and the reviewers' comments incorporated in the final draft. Examples of reports on the environmental status of aquaculture industries are available for marine shrimp farming in Thailand (Tookwinas 1996) and channel catfish farming in Alabama (Boyd et al. 2000).

### *Stakeholder Meetings*

The credibility and effectiveness of BMPs are increased greatly by the involvement of a variety of stakeholders. These stakeholders should include producers, local extension specialists, local environmentalists, regulatory agencies, and representatives of communities situated near farms or facilities. In addition, the team responsible for the environmental survey and report, aquaculture specialists, representatives of international NGOs, officials from processing plants, and possibly others should be invited. Typically, the most contentious exchanges in multi-stakeholder meetings have occurred between environmentalists and industry representatives concerning the environmental and social impacts of aquaculture. These debates are characterized by polarized arguments pertaining to the types and magnitude of the environmental impacts of aquaculture, resulting in extreme views and little compromise. It is interesting to note that, within the aquaculture community, some of the staunchest opponents of the claims of environmentalists are trying to address environmental impacts through BMPs and codes of conduct. In doing so, the interests of the aquaculture community and environmentalists are synchronized; thus, it is quite sensible to involve environmentalists more formally in BMP development processes.

The number of participants can be limited according to the judgment of the organizers, but 20 to 25 participants would be a typical group. In some cases, a smaller subset of the main stakeholder group can serve as a technical advisory committee for initial BMP development. Restricting participation in stakeholder meetings is very difficult because many stakeholders have a vested interest in the BMPs being developed. Thus, meeting planners and facilitators should have a good, general understanding of the individuals and groups who would be most affected and interested in the particular type of aquaculture being discussed. In many cases, consultants and professional facilitators are hired to do this specific job. Nevertheless, the issues should be thoroughly deliberated because exclusion of a concerned party may be detrimental to the credibility of the BMP program in the future.

The discussion at the first stakeholder meeting, in which all representative stakeholders are present, should be reserved for scientific considerations on the identification of the most important issues. It is helpful to maintain a workshop setting and record concerns as they are articulated to provide some assurance to stakeholders that their concerns are being legitimately considered. A certain level of trust needs to be established among participants of multi-stakeholder meetings, and if this is achieved sufficiently early in the process, a sense of teamwork and unity-of-purpose often develops.

It is unlikely that mutually agreeable BMPs can be developed in a single meeting. Committees should be given assignments related to the process, and these committees could work separately to prepare material for discussion by all stakeholders in finalizing BMPs.

### *Guidelines for Writing BMPs*

In developing BMPs, it is most convenient to consider several categories of potential environmental impacts and provide a range of BMP options to address a particular impact under each category. Producers could then select the BMPs appropriate for individual sites and operations. For example, Boyd and Hargreaves (2004) suggested eight categories of BMPs for channel catfish aquaculture: site selection and pond construction, liming and fertilization, feeds and feeding, solids management and disposal, use of drugs and chemicals, mortality removal and disposal, management of escapees, and general facility operation and maintenance. However, the Alabama catfish farming BMP effort (Boyd et al. 2003) required 15 categories in order to satisfy all stakeholders. Several of these categories were added specifically at the request of the state agency with responsibility for environmental protection.

The environmental assessment report provided to stakeholders should have BMPs arranged by categories. However, this presentation of BMPs should be considered preliminary and the basis for further discussions that will lead to the final BMPs. The categories can be altered according to the judgment of the stakeholders, and individual BMPs can be selected or rejected based upon the opinions and experience of the group.

Previous studies about the effects of various treatments and management strategies for the particular aquaculture activity should be considered in selecting appropriate BMPs. The input of producers is especially important because they can provide opinions on the degree of difficulty and costs of implementing individual practices. On occasion, established producers may suggest BMPs to a BMP technical advisory committee that would be difficult or costly for new producers to adopt and implement. It is unclear whether these BMPs are innocently proposed based on experience gained with production systems or species or as an indirect means to deter competition, but the involvement of objective aquaculture extension specialists and knowledgeable agency representatives can serve as a way to assess the value of such proposals.

The goal of BMPs is to reduce environmental and social impacts, and where possible, estimates of benefits should be quantified, including estimates of performance variation and uncertainty. For example, calculations of reduction of nutrient loads in effluents resulting from improving feed conversion through the use of better feed management can be calculated. The likely effect of sedimentation basins on effluent quality also can be calculated. Many stakeholders will want assurances that the proposed practices will have positive effects on the environment; thus, there should be a scientific basis for effectiveness or experience from previous applications of practices in other kinds of aquaculture, in agriculture, or in unrelated industries to support efficacy.

Examination of BMPs recommended in other types of aquaculture can be especially useful. Boyd (2003b) discussed farm-level issues in environmental management of aquaculture effluents. He emphasized the need to categorize BMPs and gave an example of BMPs for preventing erosion of pond watersheds, embankments, bottoms, and discharge canals that may be a significant source of suspended soil particles in effluents. Boyd (2003b) also provided a list of BMPs that could be adopted to minimize nutrient loads in aquaculture effluents and reduce the likelihood of eutrophication in receiving water bodies.

### *Presentation of BMPs*

The final BMP document should explain the environmental, social, or conservation problem that each category of BMPs will address and provide either guidance to producers for implementing practices or a directed educational effort by the responsible agency or active partnership with aquaculture extension programs (Box 5.1). The final draft BMPs should be placed on a website and published as a manual.

## Implementation of BMPs

Compared to BMP implementation, the task of developing BMPs is relatively simple because the major negative environmental impacts and the methods for preventing these impacts are easily identified. The main difficulty is obtaining agreement among stakehold-

### BOX 5.1
### An Example Format for Presentation of BMPs

Each category of the Alabama catfish farming BMPs (Boyd et al. 2003) was presented according to the following format:

**Title:** The name of the BMP category, e.g., feed management or worker safety.
**Definition:** A paragraph to define the environmental, social, or safety problem being addressed by the BMP category.
**Explanation:** Several paragraphs to elaborate on information provided in the definition and to explain why and how the problem should be solved.
**List of practices:** The BMPs for the category are listed.
**Implementation notes:** Suggestions to help the producer decide which of the BMPs are appropriate for a particular operation and to provide specific details on implementation of the BMPs.
**Selected references for further reading**

ers about issues where differences of opinion arise about the costs and benefits of changing or prohibiting longstanding production practices. The implementation of BMPs is a much more challenging task. Many producers are asked to alter production practices according to guidelines provided in a document prepared by selected stakeholders, and producers may be reluctant to expend the time, effort, and money necessary to implement BMPs correctly. Voluntary adoption of BMPs depends on the extent to which those BMPs affect farm profitability.

Nussbaum et al. (2003) describe a process of phased implementation of BMPs for forestry that could be adapted for aquaculture. The forestry BMPs are implemented in generic modules that address legal, technical, environmental, and social issues. In the phased approach, BMPs that achieve a minimum or baseline level of performance are addressed first. The implementation process has three components: 1) an initial review to assess the current situation; 2) development of an action plan to improve practices, including a timetable; and 3) implementation of the action plan.

### *Programs to Facilitate Implementation*

The implementation of BMPs can be a technologically complex process. Thus, programs that assist producers with implementation of BMPs are valuable. Organizations preparing BMPs for voluntary adoption, use in governmental regulations, or use in certification programs should dedicate resources to programs that facilitate and encourage adoption of BMPs. These include a range of outreach and education programs, economic incentives, cost-benefit analysis, and applied research.

Broad acceptance and adoption of BMP programs beyond regulatory requirements require incentives and leadership by industry organizations in partnership with regulators. There are few states or industry organizations with dedicated financial resources to accomplish outreach activities. States that lack strong industry associations or extension education programs will have difficulty providing outreach activities to communicate benefits of the BMP approach. States that lack resources for monitoring, verification, and enforcement are vulnerable if problems occur with the BMP approach to improve environmental quality. Partnerships at the local level with state governments, federal assistance programs, and university extension programs can play critical roles to leverage limited resources to support BMP implementation.

#### *Education programs*

Educational and outreach activities are essential to promote adoption of innovative technology and practices at aquaculture facilities. Where possible, workshops should be convened to provide technical assistance to producers interested in implementing BMPs. Owners or managers of large farms may hire private consultants to help install BMPs and conduct monitoring, but small farms need government or university education programs to provide on-site technical assistance.

Producer meetings can be used to explain the benefits of BMPs and provide advice on their adoption. For example, southeast Massachusetts shellfish farmers were introduced to BMPs through meetings and announcements linked to state and federal incentive programs for BMP implementation. The Texas Commission on Environmental Quality presented permit and BMP information during aquaculture association meetings and through the permitting process. Maine farmers learn about BMPs and their implementation through Maine Aquaculture Association (MAA) activities and the state agency permit and leasing processes. The education and outreach activities of the Maine Aquaculture Association are funded through membership fees. The New Jersey Department of Agriculture includes farmer education as a component of compliance site visits.

Many entities have developed collections of voluntary BMPs for aquaculture, but few include specific details on how to install BMPs. Written instructions or detailed technical guidance manuals should be part of any BMP education program (Box 5.2). Examples include the *Idaho Waste Management Guidelines for Aquaculture Operations* developed by the Idaho Division of Environmental Quality through the efforts of a stakeholder advisory committee (IDEQ, undated). This technical manual is available on the Internet (www.deq.idaho.gov/water/prog_issues/waste_water/pollutant_trading/aquaculture_guidelines.pdf) to assist producers to develop a waste management plan composed of effective BMPs suitable for the farm location, size, and design. In addition, the University of Wisconsin Sea Grant Institute has published a manual entitled *Best Management Practices for Aquaculture in Wisconsin and the Great Lakes Region* as a flexible document that can be modified for each state in the region with the regulatory requirements for that state

### BOX 5.2
### A Format for BMP Technical Guidance

The California Stormwater BMP Handbook (California Stormwater Quality Association 2003) contains technical guidance for treatment-control BMPs to manage nonpoint source pollution from stormwater runoff in the form of fact sheets. Each fact sheet is assembled in the following format:

Name
General description
Experience
Advantages
Limitations
Design and sizing guidelines
    Construction considerations
Performance
Siting criteria
Design guidelines
Maintenance and inspection activities
Costs
    Construction cost
    Maintenance cost
References and additional sources of information
Drawings/illustrations

(Malison and Hartleb 2005). The Pacific Coast Shellfish Growers Association (see Chapter 4) has provided specific guidance for BMP installation. Installation of BMPs that involve infrastructural or management changes may be complex. For example, a feed management BMP may state that feed should be applied conservatively to avoid overfeeding and uneaten feed. Many producers may not know the most widely agreed-upon procedures for preventing overfeeding, and they would not apply the best available practices. Clear instructions on methods of installing infrastructural and management changes necessary to comply with BMPs are a necessary part of implementation.

As an example of an integrated educational effort, the Florida Department of Agriculture and Consumer Services (FDACS) partnered with the University of Florida Department of Fisheries and Aquatic Sciences to hold producer meetings and workshops. Explanatory signs that illustrate and describe BMPs have been installed at four university aquaculture demonstration and research facilities (shellfish, food and bait fish, shrimp, and ornamental fish and aquatic plants). The FDACS also publishes a free newsletter to notify farmers, agencies, legislators, and other interested parties about BMP developments or revisions.

### *Economic incentives*

Together with education programs, economic incentives can promote adoption of BMPs, particularly those for which the incentive of improved profitability is not present. Traditionally, these take the form of cost-share programs, direct subsidy payments, or tax benefits. In the United States, there are no dedicated public funds available to assist aquaculture producers with programs to adopt, implement, or construct BMPs that require equipment, structures, or farm remodeling. As a notable exception, shellfish producers in Massachusetts successfully applied for state funds and funding from the Environmental Quality Incentives Program (EQIP), a program administered through the NRCS of the United States Department of Agriculture. The funds were used to implement a shellfish Conservation Practice Standard that was adopted by NRCS as a result of producer efforts to create shellfish farming BMPs.

### *Cost-benefit analysis*

Demonstrating economic benefits can stimulate widespread adoption of BMPs. Boyd and Tucker (1995) and Engle and Valderrama (2002) evaluated production practices used in channel catfish farming in the United States and concluded that 1) the better practices appeared to be the most sustainable and profitable and 2) BMP adoption is most successful where there are strong economic incentives to do so. Studies that demonstrate the cost effectiveness of BMPs would be a great help for inducing producers to voluntarily adopt better practices.

Development, implementation, and verification of BMP facility plans represent a cost in money, labor, and physical resources that may or may not result in measurable economic benefits to producers from improved operational efficiency or improved environmental quality. In any case, these costs can be more easily absorbed by larger operations that realize greater efficiencies through economies of scale. Producers cannot pass increased production costs on to processors and distributors. Implementation costs can be burdensome and, in extreme cases, force closure of small businesses. However, BMP programs can minimize the loss of small farms because time and costs can be reasonable compared to overly prescriptive regulatory options. BMPs provide flexibility, with more options across a range of farm sizes, to achieve desired environmental protection outcomes.

Some BMPs are easier or less expensive to implement than others. A BMP for conserving water and reducing overflow after rainfall requires pond managers to maintain storage volume in ponds by leaving water levels about 15 cm below the overflow elevation when replacing seepage and evaporation. This BMP costs nothing and is obviously effective and simple. On the other hand, considerable effort and cost will be required to plant grass or provide stone cover around the edges of a pond to prevent erosion. Thus, producers may implement those BMPs that seem convenient and omit the others. Partial implementation of BMPs is better than no implementation, but great improvement cannot be expected from such a procedure.

As a regulatory option, BMP programs can protect natural resources, maximize environmentally beneficial outcomes, minimize impacts on neighbors, and reduce regulatory costs and burdens. The formation of industry-academic-regulatory partnerships or other coalitions among industry organizations can assure that BMPs and regulatory requirements address real environmental concerns rather than impose burdensome regulations with limited environmental benefit. Programs to monitor and document environmental benefits and costs of voluntary BMP programs will help justify this approach as a regulatory option. Lack of quantitative data may create questions about the effectiveness of BMPs, thereby justifying other, more rigid regulatory options such as end-of-pipe numerical limits.

### *Applied research*

Adequate research and demonstration infrastructure is needed to support the dynamic progression of improved practices and adoption of innovations for environmental management. The diversity of aquaculture species, production systems, and geographic locations creates a matrix of choices and potential environmental effects that require science and applied knowledge. BMPs for new species and systems are likely to evolve in the future. There is a need to build upon applied research to determine environmental effects of aquaculture and to create, test, and improve BMPs for aquaculture.

New scientific tools are creating knowledge about aquatic ecosystems that may generate new issues and concerns. The protection of natural aquatic resources is a benefit to the general public, so publicly funded research plays a significant role in developing BMPs. The public also gains benefit from this investment when new information is integrated into the development of public environmental policies. Aquaculture likewise benefits from research discoveries that protect natural aquatic resources. As states continue to assess the quality of public waters, more water bodies are likely to be categorized as impaired, and much stricter end-of-pipe total maximum daily load limits may be applied to specific pollutants. Water use restrictions, legal access rights, and water availability are becoming critical issues in some locations as well. These situations will require new BMPs and technologies to conserve, reuse, or recycle culture water.

Many states recognize the need to revise and update BMPs based on new knowledge. The BMPs should be flexible and revised based on regulatory, judicial, operational, scientific, and environmental developments. Two states have repeatedly revised their aquaculture BMPs and created new ones. Florida has produced four editions of their BMP manual. The Maine Aquaculture Association code of conduct is the source for many BMPs that are now components of NPDES permits for marine net pens. The Association continually revises their finfish BMPs and is creating BMPs for shellfish biosecurity and aquatic animal health. The United States Army Corps of Engineers is considering the PCSGA environmental codes, and growers' individual farm plans, as components of a general nationwide permit the Corps will issue for shellfish culture activities in navigable waters of the United States.

Information to support the effectiveness of some BMPs may be lacking, and it may be necessary, as was the situation in developing BMPs for Alabama catfish farming, to conduct special studies. For example, studies of sedimentation (Ozbay and Boyd 2003, 2004), persistence of copper residues (McNevin and Boyd 2004), effects of sodium chloride treatment (Tavares and Boyd 2003), estimation of water budgets and effluent pollution loads (Boyd et al. 2000), and impacts of farm effluents on streamwater quality (Silapajarn and Boyd 2005) were made to support the selection of BMPs for Alabama catfish farming. BMPs will also need to be refined for specific species, production systems, or soil types, as proven in Arkansas for baitfish effluent treatment using vegetated ditches (Frimpong et al. 2004).

## Verification of BMP Effectiveness

The most difficult aspect of a program to improve the environmental and social performance of aquaculture likely is demonstration of the program's effectiveness. One objective of verification is to confirm that producers have implemented BMPs or that they are in compliance with governmental regulations or certification standards. Even more importantly, the objective of verification is to determine whether compliance with the program is providing effective environmental protection. If it is not, the BMPs, standards, and regulations are not achieving their desired effect and should be improved. Verification is accomplished through a compliance monitoring program, site inspections, or audits of facility records. In forestry, BMP effectiveness has been assessed using literature reviews, the number of citizen complaints, the resources committed to BMP implementation, interdisciplinary field surveys, direct monitoring, aquatic habitat measures, and modeling (Ice et al. 2004).

### *Forms of Verification*

Verification of BMPs can be accomplished by producers (first-party verification), an external organization with a relationship to producers (second-party verification), or an organization that is independent of producers or the standards-development organization (third-party verification) (Wessels et al. 2001).

#### *Internal verification*

Producers can monitor their operations to determine and self-declare that BMPs are having the desired effect. Standards of compliance can be developed by an outside group or by the farm or facility itself. Self-evaluation, or *first-party verification*, can be highly effective if a producer is willing to make changes to practices if desirable and intended results are not being achieved. However, producers who voluntarily adopt BMPs often do not properly install the improved practices and are unlikely to be critical of their own efforts.

### *External verification*

Verification of compliance by an external body with some relationship with the farm or facility being certified is called *second-party verification*. For example, an industry association can create standards and support compliance monitoring and BMP performance verification of its members through inspections and audits.

### *Independent verification*

Ideally, compliance with standards and requirements of lending agencies and certification standards should be verified by *third-party inspection*. The organization that sets performance standards should be independent of producers and marketers. In a certification program, the inspector should be completely independent of the producer and should not be directly employed by the certifying organization. The inspector can be from an accredited certifying agency, a private consulting firm, or independent agents. The certifying organization would be required to train the inspectors and specify their assignments. The producer should pay an inspection fee to the certifying body and this body would pay the inspector. Furthermore, the certifying organization should be independent of the group that develops the standards.

## Compliance Monitoring and Effectiveness Evaluation

Successful best management practices must be economically and socially beneficial, easily adapted and adopted, and environmentally effective (Watson et al. 1994). A comprehensive BMP program is an iterative, adaptive, and continuous process of BMP development, implementation, and evaluation. The success of BMP programs is related to educational efforts and subsidies that support implementation and monitoring to assess effectiveness. Compliance monitoring programs are used to estimate BMP implementation rates, refine BMPs, or target technical assistance programs (Prud'homme and Greis 2002). Although many BMPs have been proposed and developed for aquaculture, the effectiveness of most of these improved practices has not been evaluated formally through controlled research studies or informally through surveys or site inspections.

The experiences of BMP programs developed to evaluate the effectiveness of BMP programs designed to control nonpoint source pollution from forestry, agriculture, and stormwater runoff are illustrative to aquaculture. The performance of BMPs can be assessed by measures of effectiveness, efficiency, and performance (Strecker et al. 2001). Effectiveness is a measure of the extent to which a particular BMP or BMP system (i.e., integrated set of BMPs) meets stated improvement goals. Efficiency is a measure of the extent to which BMPs remove particular pollutants or mitigate adverse effects. Performance is a combined measure of effectiveness and efficiency that quantifies the extent to which a particular BMP or BMP system meets a stated environmental improvement goal relative to the maximum potential reduction at a particular location.

The main component of effectiveness evaluation is a program of compliance or implementation monitoring. This monitoring program can include inspections or facility audits that result in a certification of compliance. Nussbaum et al. (2003) describe a process of verifying BMP implementation that consists of three main activities. First, a baseline assessment of the farm or facility should be conducted. This assessment will serve as the basis for comparison with the results of future assessments. Second, the monitoring program should confirm some minimum level of improved performance. Third, the monitoring program should confirm a trajectory of improved environmental performance.

Studies that evaluate the effectiveness of BMPs in other domains have been hampered by the lack of consistent methodological design and standardized reporting protocols (Strecker et al. 2001; Prud'homme and Greis 2002). One attempt to standardize reporting is represented by the online database of stormwater BMP effectiveness (www.bmpdatabase.org). This may be a good model to collate the experiences with implementation of aquaculture BMPs.

Questions of appropriate scale (e.g., pond, farm/facility, watershed/basin, region) and variation in sampling techniques limit the utility of many findings. Monitoring programs are more rigorous than site surveys because they assess specific and quantifiable chemical (e.g., water quality) or biotic impacts. Some programs use bioassessment to evaluate in-stream effects and report results in terms of various habitat quality indexes. Other programs assess BMP effectiveness with comparative studies conducted before and after implementation, upstream and downstream of the BMP, or input-output studies conducted in paired watersheds. Compliance surveys or visual quality assessments to gauge the level of implementation are another option, but these are much more qualitative than formal monitoring programs because they simply indicate whether a particular practice is being implemented and the number of practices implemented. Various scoring methods can be used to gauge the implementation of BMPs, including presence/absence, pass/fail, and degree of compliance as a proportion of full implementation (Husak et al. 2005).

### *Compliance Monitoring in Aquaculture*

Implementation of BMPs and compliance with governmental regulation or certification standards will not always prevent negative environmental effects. Confirmation of effectiveness must be found through environmental and social monitoring programs that include evaluation of off-site effects. Such programs have been rare in aquaculture because neither governments nor the private sector are often willing to bear the costs. A shrimp farm in Madagascar funded a study to determine the effects of farm effluents on water quality in the receiving bay (McNevin 2004). A tilapia farm with cage culture operations in lakes in Honduras and Indonesia sought the senior author's assistance to initiate a program to monitor water quality in the lakes. The Alabama Catfish Producers provided funds to determine the effect of catfish farm effluents on stream flow and water quality (Silapajarn and Boyd 2005). Some government agencies in several countries have conducted limited water quality monitoring in coastal areas with extensive areas of aquaculture.

The State of Florida employs a staff of four BMP compliance officers that have Master of Science degrees in fisheries, aquaculture, biology, or environmental sciences and an annual performance goal of at least two unannounced, on-farm compliance visits annually. Discharge permits for aquaculture usually require reporting according to a specified timeline. In some cases, producers are allowed to make the analyses, but more often, a consulting firm or laboratory approved by the government must make the effluent analyses. Verification of compliance with mandated BMPs may be done unannounced by a government official or by a certified professional approved by the government. An in-depth discussion of BMP verification by a variety of state governments in the United States is provided in Chapter 4.

In many countries, the government will make rules about aquaculture, but not have adequate personnel to inspect the facilities. Producers will know whether this is the situation, and if it is, they will tend to ignore the regulations. Even in developed nations such as the United States, facilities may not be checked for compliance with some environmental regulations unless the public makes a complaint. In some nations, corruption is common, and environmental regulations are mainly a means for governmental officials to obtain bribes.

Guidelines for conducting monitoring studies should be developed and more effort devoted to this important issue. However, such studies often are difficult to interpret because background data are seldom available, aquaculture is not the only source of pollution, and the expense to monitor certain production systems and environments (e.g., open ocean net pens) may hinder the development and implementation of practical and cost-effective monitoring (Alston et al. 2006).

### *Record Keeping*

Record keeping is necessary even for voluntary BMP programs. However, they are most critical for discharge permits with numerical limits and for certification programs. Governments usually require monthly or quarterly reports of concentrations of water quality variables measured to verify compliance with discharge permits, chemical and drug use, wildlife control, aquatic animal health certifications, and sales records for restricted species. Such record keeping is relatively simple compared to that required by certification programs. These programs require records of the sources and numbers of animals stocked in ponds; amounts of fertilizers, feeds, and other chemicals added; and the disposition of the harvest.

Certified products must have a bar code on each package that will allow them to be traced back to the pond or other culture unit of origin. The farm records must be sufficient to determine the origin of the stock and all of the substances used during culture.

Large farms are able to assign the responsibility for record keeping to one or more specific individuals. Small, family-operated farms may find record keeping to be a major effort.

### *Review and Correction for Noncompliance*

Environmental management systems always include the requirement for periodic review and correction for noncompliance. The same should be included in all programs for promoting environmentally and socially responsible aquaculture. Records should be audited and farms inspected, and failure to comply within a specified period would result in loss of the rights given by the government (e.g., use of water, discharge of water, operation of aquaculture facility, etc.) or loss of certified status. Inspections should be random and unannounced so that facilities are less likely to relax their attention to BMPs and standards until time for inspection is near. In instances of noncompliance, certifiers should clearly state the reason(s) and explain the corrections that must be made to regain compliance.

In the United States, state departments of environmental protection or federal agencies have jurisdiction over nonpoint source pollution control programs and make decisions about the consequences of noncompliance with BMP programs, usually dependent on the severity of the violation. The NPDES program is administered by EPA regional offices or delegated to states for enforcement in a manner that provides for remediation before punitive action. The GAA certification standards stress continual improvement. Annual review of records is essential for achieving this goal.

Although punitive or corrective action may be necessary in the event of noncompliance, it is important to understand the reasons and motivations for noncompliance. Involving producers in the development of BMPs is critical to assuring compliance. In particular, producers may perceive or experience a conflict between profitability and implementation of BMPs, reinforcing the need to develop cost-benefit analyses for BMPs. Furthermore, during BMP implementation, education and outreach programs need to communicate the full range of benefits, beyond environmental protection, of BMP implementation.

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## Chapter 6

# Better Management Practices for Freshwater Pond Aquaculture

*Craig S. Tucker, John A. Hargreaves, and Claude E. Boyd*

## Introduction

Most of the fish and crustaceans produced in world aquaculture are cultured in ponds. In the United States, ponds are used to grow channel catfish (*Ictalurus punctatus*) and crayfish (*Procambarus* spp.), which together comprise almost 80% of the country's annual aquaculture production by weight. Ponds are also used to grow economically important crops of baitfish, hybrid striped bass, freshwater ornamental fish, and penaeid shrimp. Overall, approximately 125,000 ha of ponds are used for aquaculture in the United States.

Aquaculture ponds can be operationally defined as confined bodies of standing water that are managed to produce a crop of the target aquatic organism. Ponds are usually envisioned as being constructed entirely of soil, but that is not a necessary part of the definition. Some ponds, for example, may be lined with plastic to reduce seepage.

With respect to possible environmental effects of pond aquaculture, ponds can be functionally defined as aquatic systems where, by virtue of long hydraulic residence times, suitable water quality for production is primarily controlled by natural physical, chemical, and biological processes. In contrast, suitable water quality is maintained by continuous water exchange in flow-through and net-pen systems and by discrete unit water treatment processes in recirculating systems. This is an important distinction because it suggests that much of the waste loading to ponds is removed from water prior to discharge.

All aquaculture ponds bear a superficial similarity, yet potential environmental impacts and "sustainability" may vary considerably. Factors affecting the environmental performance of pond culture systems include culture intensity, pond hydrological type, and the species cultured.

## Pond Culture Intensity

Culture system intensity is an imprecise typology based on a continuum of management inputs and crop yield. The term is often used to classify culture system types; for example,

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fish production in cages is generally considered more "intensive" than production in ponds. Culture intensity is also used to describe production characteristics within a system type—particularly for pond aquaculture. Extensive pond culture systems have limited water exchange, rely mainly on production of natural foods to support growth of the culture species, and consequently have relatively low crop yields. At the other extreme, intensive pond systems may have higher rates of water exchange, rely on manufactured feeds (often with high levels of animal protein) to promote rapid fish or crustacean growth, and have relatively high crop yields. Semi-intensive systems are intermediate between these intensity extremes.

The relationship between culture intensity and sustainability is not direct. Superficially, extensive aquaculture might seem more sustainable. However, measures of resource use efficiency in production (such as land, water, fossil fuel energy, and nutrient inputs) are important indexes of environmental sustainability, and efficiency varies among culture systems depending on the particular index examined. For example, production per unit fossil fuel energy input is lower in intensive than in extensive systems, but production per unit land area in extensive systems is much lower than in intensive systems. Although it is difficult to combine the various efficiency measures used to quantify sustainability, intermediate levels of culture intensity are thought to be the most sustainable. Environmental sustainability must be evaluated across a spectrum of criteria and should not be based on a simple set of operational features. Furthermore, sustainability includes economic and social domains, as well as an environmental domain. Extensive pond aquaculture systems generally are not economically sustainable in the United States and all commercial pond aquaculture is based either on semi-intensive culture of "commodity" products (e.g., catfish) or intensive culture of high-value products (e.g., ornamental fish).

## Pond Hydrology

### *Pond Hydrological Types*

Classification of aquaculture ponds by hydrological type is important because water use, effluent volume, and, to a lesser degree, effluent quality are impacted by pond hydrology. Pond hydrology also affects effluent management practices and the degree to which effluents can be controlled.

Embankment ponds (Fig. 6.1) are the most common type of pond used in aquaculture and are constructed in flat areas by scraping soil from the pond bottom and using that soil to form embankments around the pond perimeter. Alternatively, the original bottom elevation is maintained for most of the pond area, and the soil used to construct embankments is removed from a trench excavated adjacent to the embankment. Catchment areas are small, consisting only of the pond surface and the inside embankment slopes, so there must be a source of pumped water to fill ponds and maintain water levels during droughts.

Excavated ponds are similar to embankment ponds with respect to general construction and primary water source, but they are usually smaller and the pond bottom is further below the original ground level than in embankment ponds. In some areas with high water

**Fig. 6.1.** A large tract of embankment ponds used to grow channel catfish in northwest Mississippi. Ponds vary in size from 2 to 5 ha.

**Fig. 6.2.** Two watershed ponds used to grow channel catfish in Alabama. The larger pond is approximately 8 ha. Photograph courtesy of Auburn University Department of Fisheries and Allied Aquacultures.

tables, excavated ponds may extend below the water table and be partially filled with groundwater inflow. Water may have to be pumped from excavated ponds to empty them.

Watershed ponds (Fig. 6.2) are built in hilly terrain by damming a temporary or permanent stream. The major source of water is runoff from the drainage basin above the dam, although a source of pumped water is often available to help maintain water levels during droughts. The fourth pond type is a hybrid between embankment and watershed ponds. These ponds may have two or three sides consisting of embankments (actually low dams) across a relatively small, shallow drainage basin. A significant amount of water may be obtained from runoff, but a source of pumped water also must be available because the catchment area above the pond is relatively small. Hybrid watershed-embankment ponds are built in regions with gently rolling topography that is not ideally suited for embankment ponds or watershed ponds.

Embankment and excavated ponds have much less overflow than watershed ponds, with the overflow volume from hybrid ponds being intermediate. Also, the quality of effluents from watershed ponds may be affected (either positively or negatively) by upstream water quality, which is, in turn, affected by land-use practices in the catchment area.

### *Water Budgets*

Water budgets can be used to identify and describe the magnitude of inflows, outflows, and changes in water level in ponds. The basic water budget can be described as: change in storage (pond depth) = inflows − outflows. For ponds, the budget may include some or all of the following: inflows = precipitation, runoff, stream inflow, groundwater inflow, and regulated inflow; outflows = evaporation and evapotranspiration, seepage, overflow, consumptive use, and regulated discharge.

Water budgets are influenced mainly by climatological variables, particularly rainfall and temperature. Most pond water budgets have been developed to estimate discharge volume because of interest in the possible impacts of effluents on downstream ecosystems. However, the general hydrological equation can easily be rearranged and solved for estimates of water use, rather than overflow. Water budgets have been prepared for excavated or embankment ponds (Boyd 1982; Pote et al. 1988; Teichert-Coddington et al. 1988; Green and Boyd 1995; Nath and Bolte 1998; Braaten and Flaherty 2000) and watershed ponds (Shelton and Boyd 1993; Boyd et al. 2000).

Accounting for water in aquaculture has two significant implications. First, water is a resource that must be used wisely to assure sustainable development. Second, water budgets can be used to estimate effluent volume and develop options for managing discharged water. This is important because water discharged from ponds may impact the water body receiving the effluent and the extent of that impact is greatly influenced by effluent volume.

These two issues—conservative water use and minimizing effluent volume—are intimately linked. Water that is discharged from a facility is a loss process on one side of the water budget equation. By decreasing the magnitude of that loss, less water will be needed on the other (input) side of the equation. In this section we discuss water budgets for aquaculture ponds, with the goal of pointing out how water can be used more efficiently and how effluent volume can be reduced.

### *Water Sources for Ponds*

The main water sources for aquaculture ponds are precipitation, runoff from watersheds, and regulated additions of water from groundwater aquifers or surface water bodies (e.g., streams and reservoirs). Precipitation and runoff are the most important water sources for watershed ponds; precipitation and regulated inflows from groundwater or surface water are the primary water sources for embankment and excavated ponds.

### Precipitation

Precipitation falling directly into a pond can be a significant source of water in humid climates. The increase in pond water level from direct precipitation is equal to rainfall. The frequency distribution of precipitation events is approximately log-normally distributed: there are many more precipitation events of low amount than of high amount.

In the lower Mississippi River valley, average annual precipitation is about 125 to 150 cm and ranges from about 6 to 9 cm/month in the fall to about 14 to 16 cm/month in the spring. Long-term average rainfall obscures seasonal variability and rainfall extremes. The range of monthly rainfall among years is great, particularly during winter and early spring. Variability in rainfall is greater in the summer than in the spring. Most tropical areas are characterized by distinct rainy and dry seasons, which have profound impacts on pond water budgets.

Providing storage volume in ponds to capture rainfall (or runoff) will minimize the need for pumped water, particularly during the summer, and reduce effluent volume released during pond overflow. Many producers make some effort to capture this free water source. Boyd and Gross (2000) recommend maintaining a water storage capacity equal to the normal maximum daily precipitation.

### Watershed runoff

Once the capacity of soil to hold moisture (infiltration capacity) is exceeded, water will begin to flow across the land surface. Watershed ponds are constructed to capture overland flow from the surrounding watershed, especially if groundwater or surface water availability is not reliable or predictable. The volume of runoff will depend on watershed characteristics, particularly slope, type and extent of vegetative cover, soil type, and antecedent moisture. The volume of runoff is also a function of rainfall amount and intensity. Methods for estimating the proportion of rainfall that is converted to runoff are reviewed by Yoo and Boyd (1994).

Across the United States, runoff averages 28% of precipitation. In the southeast United States, overland flow is about 21 to 29% of rainfall from November to March, but very little runoff occurs from April to October (Yoo and Boyd 1994). The total annual runoff from various soil areas of Alabama ranges from 46 to 65 cm (Yoo and Boyd 1994).

Approximately 6.5 to 9.8 ha of watershed is recommended to support 10,000 $m^3$ of water storage in the southeastern United States (USDA-SCS 1982). Many ponds in west Alabama and east Mississippi are constructed as a combination of watershed and embankment ponds, and many catfish farms in this area have wells to supplement inflow from runoff. Fluctuations in water level in watershed ponds will exceed those in levee ponds because runoff is a much more important source of water for watershed ponds than levee ponds. During droughts, water levels in ponds supplied only by runoff may decline to dangerously low levels.

### Regulated inflows

Regulated inflows of water are provided to fill ponds initially, replace losses from evaporation and seepage, and exchange water to manage water quality. The main sources of regulated inflow water are groundwater aquifers and surface water supplies. Water can be added by pumping or gravity flow.

#### *Groundwater*

Groundwater has favorable and unfavorable characteristics for use in aquaculture ponds, but on balance it is an excellent source of water for pond aquaculture. Groundwater is usually free of the chemical and biological contaminants that may be present in surface waters. Groundwater is usually not subject to the same fluctuations in availability as surface waters. However, groundwater is usually cooler than surface waters, has no dissolved oxygen, and may have elevated concentrations of reduced substances that are toxic to fish.

Groundwater aquifers are underground reservoirs of water that are usually associated with pervious alluvial layers of soil. Favorable attributes of groundwater aquifers that are suitable as a water supply for aquaculture ponds include shallow depth to aquifer surface, high transmissivity and hydraulic conductivity, abundant alkalinity and hardness, separation from potential surface contamination by an impervious layer, and recharge that maintains aquifer volume. These attributes are characteristic of most aquifers that supply water to ponds in the main catfish growing areas in Mississippi, Arkansas, and Louisiana, as well as the main crayfish growing areas of south Louisiana.

#### *Surface waters*

Water can be pumped into ponds from streams and rivers to supplement groundwater and runoff sources. However, surface waters are undesirable from many standpoints. Generally, the seasonal availability of surface waters does not correspond to demand for pond aquaculture. In the southern United States, peak stream discharge occurs during winter to early spring, yet the demand for surface water, particularly as a supplemental water source, is maximum during the summer when stream discharge is near the annual minimum. The seasonal and year-to-year availability of surface waters is extremely variable. In extremely dry years, insufficient surface water may be available to supplement other water sources. In extremely wet years, flooding of streams and rivers may damage pond levees and drainage structures. Overtopping of levees by floodwaters may result in escape of cultured stock. Surface waters are also undesirable because they are sources of contamination by wild fish, potential disease pathogens, agricultural pesticides, fertilizers, and sediment. Finally, in the United States, surface waters are considered Waters of the State and are therefore subject to potential regulatory constraints that may limit withdrawals for pond aquaculture.

### ***Water Losses from Ponds***

Water loss from ponds results from evaporation, seepage, and overflow that occurs when inflows exceed pond water storage capacity. The sum of evaporation and seepage represents consumptive water use because this water is not available for downstream uses. Water is also lost when ponds are intentionally drawn down or drained for harvest, pond renovation, or in the case of crayfish culture, to stimulate crayfish burrowing and prepare ponds for planting vegetation. Water that overflows or is intentionally discharged is available for other purposes and thus does not represent a consumptive use.

Evaporation is controlled by climatic forces beyond the control of the culturist. However, seepage can be reduced by good site selection and pond construction practices, overflow can be minimized by maintaining water storage capacity and not managing water quality with water exchange, and losses from draining can be minimized by reducing the frequency of pond draining.

### *Evaporation and evapotranspiration*

Pond evaporation is the loss of water from the pond surface to the atmosphere. The rate of evaporation increases as wind speed and the difference in vapor pressure between water and air increases, and decreases as the latent heat of vaporization and water density (both a function of water temperature) increases. Evaporation rates tend to follow annual temperature cycles, so evaporation rates are maximum during summer and minimum during winter in the temperate zone.

As a practical matter, pond evaporation is difficult to measure directly because decreases in pond water stage are due to the combined effects of evaporation and seepage, which cannot be easily differentiated. Accordingly, pond evaporation rates are estimated indirectly by multiplying the evaporation rate determined with a class A evaporation pan by 0.81 (Boyd 1985a). Measurements from class A evaporation pans (sometimes simply called *pan evaporation*) can be obtained from weather monitoring stations located throughout the world. Average monthly pan evaporation in the southeastern United States ranges from about 2.8 cm/month (0.9 mm/day) in January to 19.7 cm/month (6.6 mm/day) in June (Boyd and Tucker 1998). Over the period 1962 to 1986, maximum daily pond evaporation rates in the lower Mississippi River valley during June ranged from 8.9 to 11.4 mm/day (Pote et al. 1988). Pond evaporation from excavated ponds in Panama was 1.4 to 8.4 mm/day (Teichert-Coddington et al. 1988). In Thailand, pond evaporation from brackishwater ponds was 3.1 mm/day (Braaten and Flaherty 2000) and from freshwater ponds was 4.5 mm/day (Nath and Bolte 1998).

In some ponds, rice or other vegetation is planted or grows naturally as a forage base for the culture of crayfish. Transpiration by vegetation increases the water loss compared to evaporation by open ponds. In practice it is difficult to separate evaporation from transpiration, so the two processes are grouped together. Coefficients that depend on the vegetative growth stages of rice are applied to evapotranspiration from a reference crop (grass or alfalfa). When a crop is first planted, nearly all of the evapotranspiration is from evaporation. At full cover, about 90% of evapotranspiration is from transpiration. Estimated evapotranspiration rates for crayfish ponds range from 1.2 mm/day in December to 5.4 mm/day in August (Parr 2002).

### *Seepage*

Ideally, ponds should be constructed in soil that is impervious to water movement. In practice, however, water moves into or out of all ponds unless they are lined with a watertight material, such as plastic. Although water may move into ponds from the surrounding soil when local water tables are near the soil surface, the net movement of water through most pond soils is generally outward, and this loss is called *seepage* or *infiltration*. Seepage is difficult to measure because soils are not uniformly impervious across the pond bottom and evaporative losses are difficult to partition from seepage losses. Generally, seepage is estimated by subtracting pond evaporation from total losses measured by decrease in water stage.

Embankment ponds in the Mississippi River valley are constructed in montmorillonite clay soils that are dense and swell when wet, becoming nearly impervious to water flow. Seepage from rice fields and crayfish ponds constructed in these soils is 0.38 mm/day (Pringle and Pennington 1991). Limited measurements from embankment ponds constructed in the lower Mississippi River valley indicate that seepage is <1.3 mm/day (Pote et al. 1988). Seepage from ponds constructed in the Black Belt soil edaphic region of east-central Mississippi and west-central Alabama is 1.5 mm/day (Parsons 1949). Seepage was calculated for excavated ponds in Thailand (4.4 mm/day) and Honduras (5.8 mm/day) (Nath and Bolte 1998) and for brackishwater shrimp ponds on the central plain of Thailand (5.2 mm/day) (Braaten and Flaherty 2000). Boyd (1986) classified seepage rates as low (0 to 5 mm/day), moderate (6 to 10 mm/day), high (11 to 15 mm/day), and extreme (>15 mm/day). About 87% of the water lost from ponds at a research station in Panama was from seepage, which ranged from 19 to 58 mm/day (Teichert-Coddington et al. 1988).

Excessive seepage is undesirable because it increases the need for pumped water. Also, excessive seepage can pose a threat to the pristine quality of underground water supplies because uncharged substances or anions such as nitrate can percolate through soils with seepage water. Seepage also has a profound effect on the amount of water lost as overflow. In ponds with low seepage rates, a proportionally greater volume of water is discharged as overflow. In ponds with high seepage rates, water is lost to infiltration and overflow rates are low.

### *Overflow*

Overflow occurs when pond inflows exceed pond storage capacity. Overflow is intentional when water quality in ponds is managed with water exchange. Overflow is unintentional when inflows from rainfall and runoff exceed pond storage capacity. In embankment ponds, the volume of unintentional overflow depends on the capacity of the pond to store precipitation. In a year with average precipitation in northwest Mississippi, overflow from ponds managed with 15 cm of storage capacity is about 33 cm (Tucker et al. 1996). Estimated overflow ranges from 20 to 38 cm for ponds managed with 15 to 46 cm of storage capacity (Tucker et al. 1996; Hargreaves et al. 2001). The volume of unintentional overflow from watershed ponds is much greater (235 to 380 cm) because of the much greater contribution of runoff to the water budget of watershed ponds (Boyd et al. 2000).

Most unintentional pond overflow occurs from fall to mid-spring, the cooler, wetter part of the year in the southeast United States, when precipitation exceeds losses from evaporation and seepage. In years with normal rainfall, 72% of overflow from watershed ponds occurs between December and April (Shelton and Boyd 1993). Very little overflow occurs during the dry summer months when evaporation often exceeds precipitation. Pond overflow volume can be reduced by maintaining some storage capacity for rainfall and runoff.

Water exchange is no longer used to manage water quality in most ponds for finfish in the United States. However, water exchange is used to manage dissolved oxygen in the shallow ponds used for crayfish culture. From 1 to 9 water exchanges (or 50 to 450 cm) may be used during one crop cycle.

### *Pond draining*

Ponds are drained to facilitate harvest, adjust fish inventory, remove accumulated sediment or lime pond soil, and repair embankments. The volume of water discharged when ponds are drained is equivalent to that added when ponds are filled. Thus, from the perspective of water use, there is no net loss of water as a result of filling and draining ponds. However, from the perspective of effluents, substantial changes in water quality occur during culture, with substances either accumulating during the culture period, reaching an equilibrium in response to feeding, or reflecting conditions in the short period prior to discharge.

Long term, the volume discharged from pond draining is a function of draining frequency, which varies by species, phase of production, and hydrological pond type. Most foodfish production ponds for channel catfish are drained every 3 to 15 years. Shallow (50 cm) crayfish ponds are drained annually to stimulate crayfish burrowing, an essential part of the production cycle. Ponds for the culture of phase I hybrid striped bass are drained after 45 to 60 days.

With channel catfish, fingerling ponds are drained annually, broodfish ponds are drained every 1 to 5 years, and foodfish ponds are drained every 3 to 15 years (USDA-APHIS 2003). Although fingerling ponds are about 13% of the total area in catfish production, they contribute 47% of the total volume discharged from ponds when ponds are drained. Because fingerling ponds represent an inordinate share of the water discharged from catfish ponds, considerable scope for water conservation and reducing the volume of effluent in channel catfish aquaculture may be derived by improving water management in fingerling ponds.

Embankment or excavated ponds represent over 90% of the ponds used for catfish culture (USDA-APHIS 1997). Final fish harvest occurs only when ponds need to be drained for renovation or adjustments in fish inventory are deemed necessary. In contrast, watershed ponds may be partially or completely drawn down to facilitate fish harvest. Partial drawdown occurs about every 6 years and complete drawdown occurs about every 15 years. In 15 years, there will be two drawdowns of 50% of the pond volume and one drawdown of 100% of the pond volume (total = 2 pond volumes).

For embankment or excavated ponds drained annually or more frequently, the volume of water discharged from pond draining can exceed that discharged by unintentional overflow. For ponds with a long interval between draining, such as foodfish catfish ponds, most of the effluent is discharged from unintentional overflow. Thus, one obvious way to minimize effluent volume is to extend the interval between pond drainings.

## Major Species Cultured in Ponds

Ponds are used to grow a wide range of species, including channel catfish, baitfish, ornamental fish, hybrid striped bass, bluegill (*Lepomis macrochirus*), largemouth bass

(*Micropterus salmoides*), walleye (*Sander vitreus*), trout, crayfish, penaeid shrimp, freshwater prawns (*Macrobrachium rosenbergii*), and many other freshwater and saltwater aquatic animals. Potential environmental impacts can vary widely depending on culture species, husbandry practices, and pond hydrology. In fact, culture conditions and potential impacts of peneaid shrimp culture differ to such an extent that shrimp ponds are considered in a separate chapter (Chapter 7).

The diversity of species and culture methods employed in pond aquaculture make the development of generic environmental management practices particularly challenging. A reasonable practice for one species may be totally inappropriate for another, and some practices are more appropriate for a particular facility than other practices. Furthermore, practices may be combined in unique ways to achieve the goal of pollutant reduction. The following sections will present brief overviews of the most important species cultured in ponds, focusing on water use, discharge frequency, and effluent volume.

### *Channel Catfish*

Other than perhaps rainbow trout, more is known of the biology and culture of channel catfish than any other aquaculture species grown in the United States. Moreover, environmental management of catfish farming has been more thoroughly studied than that of any other species. General aspects of catfish farming are thoroughly reviewed in Tucker and Robinson (1990) and Tucker and Hargreaves (2004). Catfish pond effluents are characterized by Boyd (1978), Tucker and Lloyd (1985), Tucker and van der Ploeg (1993), Schwartz and Boyd (1994), Shireman and Cichra (1994), Tucker et al. (1996), Boyd and Tanner (1998), Boyd and Gross (1999), Boyd et al. (2000), Tucker et al. (2002), and Hargreaves et al. (2005a, b). General pond ecology and identification and management of environmental impacts of catfish farming are described by Schwartz and Boyd (1996), Tucker (1996), Boyd and Tucker (1998), Boyd et al. (2000), Tucker et al. (2002), Hargreaves and Tucker (2003), and Tucker and Hargreaves (2003).

Channel catfish are grown commercially in at least 35 states, although more than 95% of all United States catfish production is derived from farms in Alabama, Arkansas, and Mississippi. Within those states, production occurs in two well-defined geographic regions: 1) the Mississippi River floodplain in northwest Mississippi and southeast Arkansas and 2) the Blackland Prairie region of west-central Alabama and east-central Mississippi. These two catfish-growing regions are separated by about 250 km and have similar climates, but pond hydrology and water use differ considerably between the two regions.

About 50,000 ha of ponds are used for catfish aquaculture in the Mississippi River Alluvial Valley. Nearly all the catfish fingerlings used in catfish farming are grown in this region. The land is flat and ponds are constructed on clay soils that have low infiltration rates (<0.1 cm/day). Embankment ponds are universally used for aquaculture in the region, and they are built by removing soil from the area that will be the pond bottom and using that soil to form embankments around the pond perimeter. Ponds range in size from 2 to 6 ha and are 1 to 2 m deep. Water for filling ponds is pumped from the Mississippi River Alluvial Aquifer. After ponds are initially filled with groundwater, water levels are maintained by inputs of precipitation and pumped water. Abundant rainfall in the region significantly reduces the requirement for pumped water after ponds are filled (Pote et al. 1988).

An additional 25,000 ha of catfish ponds are located in west-central Alabama and east-central Mississippi, mostly in the western portion of the Blackland Prairie soil edaphic region. The land is nearly flat to moderately hilly. High-yielding aquifers in the Blackland Prairie are considerably deeper than the Alluvial Aquifer along the Mississippi River, and this is reflected in water-use patterns and pond types in the prairie region. Whereas all catfish ponds in the Mississippi River floodplain are embankment ponds filled with groundwater, about 75% of the commercial catfish ponds in the Blackland Prairie are watershed ponds that use mainly rainfall and storm runoff for filling and maintaining water levels. Ponds are designed to maintain a minimum water level with average rainfall. The remaining 25% are embankment ponds similar to those used in the Mississippi River floodplain. These ponds are filled with pumped water from wells or surface water from adjacent creeks. Some ponds in the Blackland Prairie are hybrid watershed-embankment ponds built with two or three embankments that confine water against a slope in a broad water catchment area. After initial filling, pond water levels are maintained with precipitation, runoff, and pumped water, depending on availability.

Catfish aquaculture is usually practiced in four discrete phases: 1) broodfish are held in ponds at relatively low standing crops and allowed to randomly mate each spring; 2) fertilized eggs are taken from the broodfish pond to a hatchery where they hatch under controlled conditions; 3) fry are transferred from the hatchery to a nursery pond where they are fed a manufactured feed for about 6 months; 4) fingerlings are moved from the nursery pond to foodfish production ponds where they are fed a manufactured feed until they reach 0.7 to 1 kg. In the southeastern United States, 18 to 30 months (two or three growing seasons) are required to produce a food-size channel catfish from an egg.

Water use varies considerably with each phase of catfish farming. Broodfish ponds (which represent about 2% of the total pond area devoted to catfish production) are typically drained every 2 to 5 years for inspection and replacement of broodfish. Hatcheries operate only from late April through early July, corresponding to the natural catfish breeding cycle. Catfish hatchery water use and effluent characteristics are described by Tucker (2005). Fingerling nursery ponds (about 13% of total catfish pond area) are usually drained every year after fish have been harvested and moved to foodfish ponds.

Foodfish-production ponds constitute about 85% of the total pond area used to raise catfish. Most foodfish ponds are used for several years before being drained. Market-sized fish are selectively harvested using large-mesh seines and fingerlings are added to replace the harvested fish (Fig. 6.3). The process of selective harvest and "understocking" can continue for many years without draining the pond. Some producers use a variation of this cropping system in which as many fish as possible are harvested after a growing season without draining the pond. The pond is subsequently restocked with fingerlings and grow-out continues. Foodfish grow-out ponds are usually drained only when pond levees need to be renovated or when there is need to adjust fish inventory by completely harvesting the crop. Commercial foodfish ponds remain in production for 3 to 15 years, or more, without being drained; the average time between pond drainings is more than 9 years (USDA-APHIS 2003). Intentional water exchange (flushing) is not routinely practiced in catfish ponds.

Catfish standing crops and feeding rates are relatively high in foodfish ponds. Annual production ranges from 6,000 to 7,000 kg/ha (5,000 to 6,000 pounds/acre), and feed inputs during the summer are routinely in the range of 100 to 150 kg/ha per day. That level of

**Fig. 6.3.** Catfish in most embankment-style ponds are harvested without draining. Small fish swim through the large-mesh seine while larger fish are retained. Harvest without draining conserves considerable water and reduces the volume of effluent discharged. Photograph courtesy of Danny Oberle.

production is possible in ponds with limited mechanical aeration and no water exchange only because natural physical, chemical, and biological processes within the pond assimilate or remove wastes that are generated as a result of nutrient input from feeds. Although catfish production has steadily increased over the last 40 years, it appears that the loading limits of the production system as currently configured and managed have been reached. Factors affecting the loading limits of catfish ponds are detailed by Hargreaves and Tucker (2003).

## *Red Swamp Crayfish*

Culture of the red swamp crayfish (*Procambarus clarkii*) and white river crayfish (*P. zonangulus*)—collectively referred to as *crawfish* in the southern United States—ranks second only to channel catfish in terms of area devoted to aquaculture ponds in the United States. In 2005, there were about 47,000 ha of crayfish ponds in Louisiana (Lutz and Romaire 2005) and since the mid-1990s the production area has ranged from 45,000 to 52,000 ha (Avery and Lorio 1999). Crayfish farms in Louisiana produce about 90% of the crayfish in the United States. Less than 3,000 ha of crayfish ponds are located outside of Louisiana (McClain and Romaire 2004), with most of that area in Texas, Florida, and South Carolina. The main crayfish growing areas of the coastal plain and river alluvial valleys of southwest and south-central Louisiana overlap with the main rice-growing areas. The basic aspects of crayfish biology and culture are reviewed by Huner and Barr (1991), Avery and Lorio (1999), and Eversole and McClain (2000). Crayfish pond effluents were characterized by Orellana (1992) and effluent mass discharge was modeled and measured by Parr (2002). Specific environmental management practices for crayfish farming have been compiled by Lutz et al. (2003).

**Fig. 6.4.** Crayfish ponds in Louisiana. The pond in the foreground is approximately 12 ha. Note earthen baffles that direct water from the well (lower-left corner) to the outlet (upper-right corner) of the pond in the foreground. Photograph courtesy of the LSU AgCenter.

Production of crayfish in Louisiana is unique to pond culture in the United States because ponds are operated at low intensity, with yield strongly related to the development of a detrital food web based on natural plant forage and factors affecting natural crayfish recruitment. Unlike most pond culture of finfish in the United States, manufactured feeds are not applied to crayfish ponds. Hatcheries are not necessary for production of juveniles. Crayfish are not harvested by seine, but are captured gradually over the course of the production season in baited traps. Average production is low, around 600 kg/ha, with annual yields ranging widely from 100 to 1500 kg/ha because of variation in type and biomass of forage, the availability of and ability to manage water, and factors affecting natural recruitment of young crayfish.

Water is managed to mimic the hydrological cycles to which natural populations of crayfish are exposed. Water use and management is dependent on the type of production system used for crayfish culture. With permanent ponds, crayfish are cultured in ponds constructed specifically and solely for crayfish culture. Typical ponds are 4 to 8 ha in surface area with a shallow water depth that ranges from 20 to 60 cm (Fig. 6.4). A forage crop such as rice is planted in summer, or naturally occurring moist-soil plants are allowed to grow. The pond is flooded in October and crayfish are harvested from late fall to late spring. Permanent ponds are drained in late spring or early summer and the cycle repeated. With rotational ponds, agronomic crops such as rice and soybeans are planted in rotation with crayfish. Water management in rotational ponds represents a compromise between the demands of the crops in the rotation. For example, in the rice-crayfish-rice rotation, rice is planted in spring and the pond flooded to a depth of 20 to 25 cm. The pond is drained in late summer to allow mechanical rice harvest. Forage produced from the remaining rice stubble—the ratoon crop—is used as the forage base for crayfish culture. Ponds are flooded in October and crayfish are harvested from late fall to early spring, when ponds are drained in preparation for rice planting. Yields from rotational ponds tend to be lower than those from permanent ponds because forage biomass is usually lower and the duration of crayfish harvest is shorter. In both permanent and rotational ponds, ponds are drained annually over 10 to 14 days, usually in the spring. Ponds are deliberately drained slowly to promote the construction of crayfish burrows that are sufficiently deep to avoid drought during summer and enhance survival of burrowed crayfish.

Much more water is used for water exchange than for initial pond filling because water exchange is commonly used to manage water quality in crayfish ponds. When ponds are first flooded in October, decomposition of vegetation can lead to dissolved oxygen depletion, a condition that is managed as necessary by exchanging pond water with pumped surface or groundwater. Depending on the density of vegetation and the severity and duration of low dissolved oxygen concentration, as many as 7 to 9 pond volumes may be exchanged over a production season (Avery and Lorio 1999). Alternatively, crayfish farmers can manage dissolved oxygen by recirculation and aeration of pond water with paddlewheel aerators in ponds configured with internal baffle levees and access to electrical power. The cost of electricity or fuel for pumping is a major expense in crayfish farming, so there is a strong economic incentive to reduce the use of pumped water to manage water quality.

### *Baitfish*

Baitfish farming is a significant aquaculture industry in the United States, with perhaps 15,000 ha of ponds devoted to baitfish production. Although many species are raised for bait and culture conditions vary widely, three species (golden shiners, fathead minnows, and goldfish) constitute over 90% of overall sales and culture practices for those three species are somewhat standardized. Golden shiners (*Notemigonus crysoleucus*) and fathead minnows (*Pimephales promelas*) are used as fishing bait, while goldfish (*Carassius auratus*) and larger fathead minnows are primarily sold as food for carnivorous ornamental fish. Reviews of baitfish farming are provided by Stone (2000) and Stone et al. (2005). Baitfish pond effluents are characterized by Bodary et al. (2004) and Frimpong et al. (2004).

Baitfish may be captured from the wild or cultured in ponds. About half of all baitfish sold are wild-caught and in some regions of the upper northeast and midwestern United States, the percentage of wild-caught bait is much higher. Harvesting baitfish from the wild may impact natural fish communities by overharvesting or by depleting forage for game species, although the greatest concern is the widespread transportation of baitfish and the potential for introducing species into ecosystems where they are not indigenous. Farm-raised fish are a substitute for wild fish and therefore reduce the possible impacts of obtaining bait from the wild. Farming provides a reliable source of a few species that are already widely distributed and generally innocuous.

Most farm-raised baitfish are grown in managed ponds in the southeastern United States. In 1998 (the latest figures available) there were 275 baitfish farms in the United States (USDA-NASS 2000) with total annual sales exceeding $40 million (Collins and Stone 1999). Arkansas is the largest producer of farm-raised baitfish, accounting for more than 60% of total sales.

Most baitfish are grown in levee-style earthen ponds that are hydrologically similar to catfish ponds in the Mississippi River floodplain. Ponds for golden shiners and fathead minnows are 2 to 10 ha and ponds for feeder goldfish are usually less than 1 ha. Water is supplied from wells because surface waters contain wild fish and disease organisms. Ponds often are filled only to a depth of 25 to 50 cm for best egg hatch or fry survival. Water from adjacent ponds is then added to seed the new pond with plankton. After ponds are filled, water is added only to replace evaporation and seepage. Intentional water exchange is rare because dilution will reduce the abundance of natural foods, which are an important source of nourishment for baitfish, even if manufactured feeds are being used. Serious groundwater supply issues in the major baitfish-producing region of Arkansas during the 1980s and 1990s prompted most baitfish farmers in that region to adopt water-conservation practices that include formal pond water-level management to capture rainfall and reusing pond water discharge whenever possible.

Fathead minnows and golden shiners are usually harvested multiple times over the growing season to supply bait markets. Some ponds are drained each year to make room for the next year's crop. Some ponds are not drained because fish are needed to meet spring and early summer demand for bait. These ponds are stocked by transfer of fish from overcrowded nursery ponds. Feeder fish production is different because ponds must be totally harvested over a short period before fish become too big for the feeder market.

Standing crops of baitfish in ponds are low compared to catfish aquaculture. Maximum standing crops of golden shiners and fathead minnows may be 400 kg/ha, or less than one-tenth of the biomass in catfish ponds. Maximum standing crops of goldfish are higher than for other baitfish and may be as high as 800 kg/ha. Waste generation in baitfish ponds is therefore relatively low compared with other pond aquaculture.

### *Hybrid Striped Bass*

Interest in culturing striped bass and its hybrids for food was stimulated by dramatic declines in the Atlantic coast wild fishery for striped bass (*Morone saxatilis*) during the 1980s. Striped bass are an esteemed foodfish along the Atlantic seaboard and striped bass aquaculture grew steadily from the mid-1980s to fill established commercial markets. Popularity of the fish has also increased in response to the greater availability provided through aquaculture. In 2005, 5,400 tonnes of hybrid striped bass were produced in the United States, with about 3,200 tonnes produced in approximately 600 ha of ponds, primarily in Texas, Mississippi, and North Carolina. Most of the remainder was produced in intensive flow-through tanks or recirculated aquaculture systems in the northeast, midwest, and west. Although there may be more than 70 facilities growing hybrid striped bass in the United States, production is highly skewed toward only a handful of large operations. In 2000, 60% of the total annual production was grown by only three operations.

Striped bass are not a particularly good fish for pond aquaculture, and all commercial production uses hybrids made by crossing striped bass with white bass (*Morone chrysops*). The original cross, or palmetto bass, is made by crossing female striped bass with male white bass. The reciprocal cross, or sunshine bass, is most commonly used in aquaculture and is made by crossing female white bass and male striped bass. Both hybrids grow faster and tolerate aquaculture conditions better than either parent. Compilations of information on the biology and culture of hybrid striped bass are available in Harrell et al. (1990), Kerby (1993), Harrell (1997), Kohler (2000), and Woods (2005).

Pond culture of hybrid striped bass consists of several distinct phases, beginning in early spring when white and striped bass are crossed in a hatchery. After 2 to 4 days in the hatchery, fry are transferred to fertilized rearing ponds where they remain for 30 to 45 days. Fish are fed a finely ground manufactured feed during the last half of this period to reduce cannibalism and to wean fish (called *phase I fingerlings*) onto manufactured feed. Fingerlings are then harvested as 1-g fingerlings, graded to uniform size, and restocked in phase II ponds for further growth. Waiting longer to harvest and grade phase I fish results in poor survival due to cannibalism. Relatively few operations produce feed-trained phase I fingerlings and those that do supply most of the industry.

Most farmers buy feed-trained, size-graded fingerlings and grow the fish to market size in either one or two steps. When grown in one step, farmers stock fingerlings at 1,200 to 2,000 fish/ha and fish are fed and grown to market size (0.5 to 1 kg) over a 15- to 18-month period. In the second, and more common, production option, farmers allocate about 25% of the farm's pond area to an intermediate step where phase I fingerlings are stocked at high densities (6,000 to 12,000 fish/ha), fed, and grown until fish are 1 year old and weigh 100 to 150 g/fish. Fish from phase II culture are then harvested, graded to uniform size, and restocked into ponds at 1,200 to 2,000 fish/ha for growth to market size (phase III culture).

Embankment-type ponds initially filled with well water are used for all posthatchery culture phases. Ponds used in phase I culture are 1 to 2 ha and 1 to 2 m deep; ponds used for phase II culture and final grow-out are usually larger (2 to 5 ha). A major difference between ponds used for catfish culture and those used for hybrid bass culture is the increased reliance on water exchange to maintain good water quality in ponds used for phase II and III culture (or for final grow-out in the two-step process). Water exchange is particularly common toward the end of final grow-out when feeding rates are highest. Pond managers often use a predetermined water-quality criterion (such as total ammonia-nitrogen levels or water temperatures) to initiate flushing, but water may be exchanged whenever the pond manager feels that fish health is threatened. Water use varies greatly among ponds and among facilities. Based on anecdotal reports, ponds may be flushed several times during grow-out, with overall water use totaling one or two pond-volumes per year.

Ponds are always drained between crops of phase I and phase II fish, and most managers drain ponds between crops of foodfish. However, foodfish ponds on at least one large hybrid striped bass farm are not drained between crops as a water conservation and time-saving measure. On that farm, ponds are used for 4 to 8 years without draining and fish remaining in ponds between crops are killed using a piscicidal chemical.

### *Ornamental Fish*

The trade in ornamental fish for use as pets in home aquaria is an important global industry. The worldwide value of the aquarium hobby exceeds $5 billion annually, and the United States is the largest importer of ornamental fish and is second only to Singapore as the largest supplier. Florida is the center for ornamental fish supply in the United States, providing more than 90% of the aquarium fish sold in the United States. Most of the fish sold from Florida are imported from overseas and redistributed. However, a significant aquaculture industry exists in that state for certain species and the 2003 farm-gate value exceeded $47 million. In addition to "tropical" fish cultured mainly in Florida, ornamental goldfish and koi for display in water gardens and landscape pools are grown on small facilities throughout the United States.

Hundreds of ornamental fish species are grown in the United States and it is impossible to summarize the wide variety of production techniques. Some of the commonly cultured groups are in the families Cyprinidae (barbs, danios, goldfish, koi), Characidae (tetras), Callichthyidae (armored catfishes), Loricariidae (plecostomus), Poeciliidae (livebearers), Cichlidae (cichlids), and Belontiidae or Osphronemidae (gouramis) (Hill and Yanong 2006). Information on ornamental fish aquaculture has been summarized by Chapman (2000), Watson and Shireman (2002), and Hill and Yanong (2006). Many of the production practices used on ornamental fish farms were developed by trial and error and are closely guarded business secrets.

Depending on the species raised, indoor facilities may be used for breeding and larviculture; earthen ponds are commonly used for grow-out of juveniles to market size. About 600 ha of ponds are used to produce ornamental fish in Florida. However, ever-increasing land values and dwindling water resources in Florida have lead to increased interest in using intensive, water-recirculation technology for all phases of production. Intensive indoor culture technology also reduces the risk of fish loss to predation and sudden decreases in water temperatures during winter months.

Ornamental fish ponds are much smaller than ponds used for other species. Typical ponds are 25 m long by 6 m wide and 2 m deep (Fig. 6.5). Ponds are usually excavated in sandy soil or, in south Florida, coral bedrock. Ponds are often excavated below the water table and must be pumped dry between crops. Most ponds are also supplied with well water.

Prior to stocking with fish, producers usually fertilize ponds with an organic fertilizer, such as cottonseed meal, to stimulate primary production and development of appropriate zooplankton communities that serve as forage for juvenile fish. Commercial feed is applied daily to the ponds, although it is unknown to what extent tropical ornamental fish derive

**Fig. 6.5.** Small, 0.04-ha ornamental fish ponds in Florida. Photograph courtesy of Jimmy Avery.

their nutrition directly from the feed or indirectly through the activity of the feed as a source of fertilizer. Most ponds are aerated continuously with small surface aerators and are drained (or pumped dry) between crops. Relative to other pond-raised fishes, ornamental fish grow rapidly to "market size." Ponds are typically filled and drained three times a year to initiate and end individual grow-out cycles.

## Site Selection

There is perhaps no greater predictor of the potential success and environmental impact of an aquaculture operation than site selection. Site selection criteria can be divided into two broad categories. First are those factors that constrain construction and operation of ponds in particular locations. Second are those factors that make sites more or less suitable for pond aquaculture. These include the various physical and environmental factors that influence the suitability of a particular site.

More broadly, site selection can include factors such as proximity to hatcheries, fingerling suppliers, feedmills, fish processing plants, and suppliers of other farm inputs; access to transportation, electrical, and communications infrastructure; and access to skilled and unskilled labor in support of fish production and processing. Despite the inclusion of such a wide range of criteria in site selection, this discussion will focus on the physical and edaphic factors of site selection that have a strong effect on the environmental performance of pond aquaculture. These include the availability of suitable terrain and soils in which to construct ponds and water of appropriate quality and quantity to fill ponds and maintain water levels.

Most of the siting criteria important in reducing environmental impacts of pond aquaculture are also critical in assuring profitability of the farm. For example, selection of sites with proper soils and protection against floods will reduce long-term expenses associated with water use and replacement of escaped stock, while also protecting the environment by reducing water use, reducing infiltration of pond water into groundwater supplies, and preventing escaped animals from entering nearby water bodies. As such, careful site evaluation should be made prior to construction regardless of the legal requirements. Identification of potential problems before construction and either addressing those problems or locating an alternative site is much less expensive and environmentally benign than solving problems by implementing mitigation measures after construction or, in the extreme, having to close the farm and abandon the site.

Until recently, the tools available for site selection consisted of aerial photographs and soil, topographic, and flood maps. Coupled with site-specific investigations and interviews with local residents, these site selection tools were basic. More recently, site selection has become more sophisticated with the advent of geographic information systems (GIS) that can synthesize and weigh relevant factors and site constraints in the form of overlay maps or coverages for each criteria. Areas of each coverage can be weighted according to subjective criteria of relative importance and the final site selection map coded to indicate sites according to relative suitability. Site selection using GIS can be done at a coarse scale and low resolution (1 to 10 km) or at a fine scale and high resolution (10 to 100 m). Examples of site selection using GIS are summarized by Nath et al. (2000).

From the standpoint of environmental impacts, particularly from pond effluents, information about soil and water resources is most important. Other criteria may have a greater effect on farm profitability (proximity to input sources and markets, for example), but soil and water resource characteristics have a strong effect on the environmental performance of pond aquaculture. Better management practices for site selection described here are based on rating criteria developed for soil and water resources by Hajek and Boyd (1994). Depending on the value of each criteria, limitations are categorized as slight, moderate, or severe. For purposes of the practices discussed below, site selection criteria for soil and water with only slight limitation are considered characteristic of "best" sites. The United States Department of Agriculture (USDA) Natural Resources Conservation Service has published a set of conservation practice standards, useful in site selection and pond construction, that are available on the Internet (www.nrcs.usda.gov/technical/standards/nhcp.html).

## *Better Management Practices for Site Selection*

### *Do not site ponds in wetlands or protected areas*

Although the availability of water and the flat topography of wetlands makes them attractive sites for pond aquaculture, wetland soils often contain high concentrations of organic matter (>10%) that are not suitable for the construction of stable embankments. Organic soils are difficult to work with machinery, resulting in relatively high pond construction costs. Organic soils are elastic, which are difficult to compact properly, suggesting that water loss from seepage may be severe. The elasticity of organic soils also means that they have low load-bearing capacity, so embankments built with organic soils will have difficulty supporting vehicles and machinery. Some wetlands have acid-sulfate soils, which can require very high application rates of lime before they are suitable for pond aquaculture.

Riparian wetlands are susceptible to seasonal flooding. In the United States, constructing ponds in wetlands requires a permit from the United States Army Corps of Engineers. Siting aquaculture ponds in wetlands often results in increased costs of production and long-term management problems. Furthermore, the long-term intrinsic ecological value of natural wetlands (Costanza et al. 1997) may exceed that derived from conversion to aquaculture ponds. However, natural or constructed wetlands can be used to treat the effluent from aquaculture ponds before release to receiving waters.

### *Do not site ponds in areas prone to regular flooding*

The best sites for the construction of aquaculture ponds are those with slopes less than 2% and often these areas correspond to riverine floodplains or valley floors that are subject to periodic inundation in the absence of flood-protection levees. Floods that overtop aquaculture pond levees can result in loss of cultured animals, contamination of ponds with feral aquatic animals, mixing of potentially poor quality floodwaters with pond waters, and damage to pond embankments and other farm infrastructure. Aside from the possible escape of nonnative animals, the major impact of floods will usually be catastrophic for the farmer but benign to the environment since pond waters will be greatly diluted by floodwaters.

In the United States, the local USDA Natural Resources Conservation Service provides information on historic flood levels and recurrence interval, guidance on avoiding sites in flood-prone areas, and suggestions for siting ponds to minimize flooding of adjacent lands caused by pond construction. Best sites are those where the frequency of flooding is 0 to 5 times in 100 years (Hajek and Boyd 1994). In areas with no flood-protection levees, the top of perimeter pond embankments should be 50 cm above historic flood levels.

### *Do not site ponds near urban areas, near industrial pollution sources, or in sites with contaminated soils*

Aquaculture producers with ponds located in peri-urban areas have a distinct advantage of proximity to large markets of urban consumers and sources of farm inputs. However, the risks associated with contamination are increased relative to ponds sited in rural areas or where zoned for agricultural uses. Effluents and runoff from urban wastewater treatment plants and industrial facilities can contaminate surface waters used for aquaculture ponds. Seepage from improperly constructed hazardous waste holding ponds at industrial facilities can contaminate groundwater resources. Ponds should not be sited near utility right-of-ways because these areas are often sprayed with herbicide to control vegetation. Aquaculture ponds should be sited at least 3 km from urban areas or potential pollution sources.

Soils previously exposed to certain agricultural, industrial, or urban activities may be contaminated with harmful chemicals that may affect the health of the cultured species or accumulate in tissues that will affect product quality or safety. Contaminants may negatively affect natural waste removal processes within ponds or be discharged with effluents. Soils that are being considered for construction of aquaculture ponds should be tested for residual contamination if there is a history of pesticide use in the area. Often, contaminants will accumulate in topsoil, which should be excavated and removed from the site in preparation for pond construction.

### *Do not site ponds where regulatory or other restrictions apply*

Several state or federal agencies may have jurisdiction over land use and pond construction. Contact the local office of the USDA Natural Resources Conservation Service for guidance. Additional site review may be required by the United States Army Corps of Engineers, which administers and enforces provisions of Section 404 of the Clean Water Act. Section 404 regulates, among other activities, conversion of wetlands to farming, including aquaculture ponds. In some areas, land-use zoning may preclude agriculture in general or aquaculture in particular. Ponds cannot be constructed in national, state, or local parks, forests, conservation areas, or monuments.

### *Select sites with suitable topography for pond aquaculture*

Site topography should allow construction of ponds and any required treatment facilities. Typically, ponds are constructed in low-gradient landscapes with average slopes <5%, and the best sites are those where the slope is <2% (Hajek and Boyd 1994). Costs for embankment pond construction on low-gradient slopes are relatively low because less soil must be moved to construct levees than on higher-gradient slopes. For watershed ponds, good sites have a topography of gently sloping ridges with a broad valley behind. Best sites are those where the greatest volume of water can be impounded for the least volume of earth fill for the embankment.

### *Select sites with suitable hydrology for pond aquaculture*

It goes without saying that sufficient water must be available to support pond aquaculture. Water requirements depend on the culture methods appropriate for a particular species or life stage, soils and pond construction techniques, and climatic conditions, particularly precipitation and evaporation. Sites with losses from evaporation and seepage that cannot be replaced by available water resources should be avoided. Sites should be selected that make good use of available rainfall as a water source. Best sites have a climate where the sum of losses from evaporation and seepage minus water added from precipitation is less than 25 cm/year (Hajek and Boyd 1994). Furthermore, sites where rainfall is highly seasonal should be avoided unless surface waters are available. Best sites are those where the interval between appreciable rainfall is less than 5 days. Monthly and annual averages, minima, and maxima precipitation and evaporation should be determined for each site to estimate water losses and gains. Absolute values as well as year-to-year variation should be assessed.

Water should be available in sufficient volume to support pond aquaculture. At minimum, sufficient water should be available to fill a pond within 10 days, or 250 L/minute per ha (25 gallons/minute per acre). Water can be obtained from surface waters by gravity or pumping, or pumped from groundwater aquifers. Surface waters are less desirable than groundwaters because availability tends to be seasonal, or the water can be contaminated with pollutants or contain wild fish or organisms that are pathogenic to cultured fish. Surface waters should be filtered or screened when used as a water supply for aquaculture ponds. The water quality of surface waters can be widely variable, especially during floods. Groundwaters have few of these limitations, although groundwater quality is usually not suitable for direct use in aquaculture ponds without aeration. The temperature of groundwaters is usually less variable than that of surface waters, and it is cooler than surface waters in summer and warmer than surface waters in winter. The depth to the aquifer surface, potential well yields, and water quality should be determined if groundwater is used as a water source. This information can be obtained from local maps, well drillers, or the United States Geological Survey.

### *Select sites with consideration of the downstream impacts of pond construction*

The diversion of large streams to supply water to aquaculture ponds should be avoided. Construction of facilities and access roads should not alter natural water flows needed to maintain surrounding habitats and downstream environments such as wetlands and groundwater aquifers. The potential disruption caused by pond construction and operation to downstream multiple-use resources should be considered. Pond construction should not have a negative impact on downstream cultural or historical resources.

Construction of aquaculture ponds can mitigate or exacerbate flooding by alterations to the natural hydrological regime, particularly watershed runoff, depending on the size (i.e., storage volume) and position of the ponds in the watershed and physical alterations to natural drainage patterns from pond construction. Although ponds can be constructed in rolling or hilly terrain, embankments will be necessarily large and, unless spillways are constructed properly, are at increased risk for failure during storms.

Watershed ponds should not be located where embankment failure could result in loss of life or damage to residences, industrial buildings, main highways, or railroads, or interruption of public utilities. Design and construction of embankments should be supervised by a qualified engineer or reputable pond construction company. Embankments should be constructed in compliance with local or state dam safety regulations.

### *Select sites where water supplies are free from contamination*

Water supplies for pond aquaculture should be free of substances that may cause poor water quality in ponds and pond effluents, cause excessive stress or disease in cultured animals, or accumulate in tissues and affect product quality or food safety. Local aerial pesticide applicators should be notified of the location of aquaculture ponds, and measures to prevent contamination of ponds with pesticide drift should be discussed.

The quality of runoff entering watershed ponds will depend on land uses in the drainage area. Drainage basins above watershed ponds should be protected against erosion by maintaining vegetative cover and land terracing if slopes are steep. Drainage areas that are in pasture or forest are best. Alternatively, a 10- to 15-m wide vegetated buffer strip to intercept sediment in runoff can be maintained around pond margins. Additional information can be obtained in USDA Natural Resources Conservation Service Conservation Practice Standard 393 (Filter Strip).

### *Select sites where soils are suitable for pond construction*

Soil is the material used to construct embankments that contain water, and when properly formed and compacted, provide a barrier to the movement of water from the pond as seepage. Negative environmental impacts associated with ponds constructed in unsuitable soils are caused by excessive seepage of pond water, excessive water level fluctuation that requires greater surface or groundwater withdrawals to maintain water level, and sediment loading of receiving waters from embankment erosion. Properly constructed embankments and sufficiently compacted bottom soils will effectively prevent seepage and minimize erosion.

Soil texture is the most important physical characteristic of soils for pond construction. Texture depends on the sizes and shapes of particles and the distribution of those varied particles in a soil. Soils contain coarse-grained particles (e.g., gravel and sand), fine-grained particles (i.e., silts and clays), organic matter, and water. Texture class and grain-size distribution should be determined prior to pond construction.

A good soil for construction of embankments is said to be well graded, meaning that it has a wide range of particle sizes that are capable of good compaction. Previously, Hajek and Boyd (1994) recommended that soils for pond construction have a clay content >35%, although this recommendation has since been revised (Boyd et al. 2002). Soils with a high clay content can be difficult to work with machinery because they are highly plastic and cohesive. A clay content of 15% is preferred although soils with a clay content as low as 5 to 10% can be used to construct embankments if soils are well graded.

Water content has a profound impact on the engineering properties of fine-grained soils. As water is added to a soil, it transitions from solid to semisolid to plastic to liquid states. Soils with a water content greater than the liquid limit should be dried prior to construction of embankments. Conversely, soils may be too dry to compact properly and water may need to be added.

The depth, thickness, composition, and extent of the impervious base layer should be determined. Often this corresponds to the B soil horizon, which should be 30 to 45 cm thick throughout the impounded area. Other edaphic factors affecting seepage include the thickness of the organic layer, which should be <50 cm, and the depth to hardpan or bedrock, which should be >150 cm (Hajek and Boyd 1994). Pond areas with sand lenses or former stream channels can be sealed by replacement with clay, although such measures can be expensive.

Soil texture, water content, and other soil properties should be evaluated in soil samples from cores and test pits throughout the construction area. For watershed ponds, soil investigations should be done along the centerline of the dam, at the location of the spillway, and in the planned borrow area.

## Pond Construction

Every effort can be made to select a suitable site, but if ponds are poorly constructed, the inherent advantages of the site cannot be fully realized and the potential for negative environmental impacts increases. Poorly constructed embankments and inadequately compacted pond bottoms can result in excessive seepage losses that can contaminate groundwater aquifers or surface water supplies. Embankments that are not properly constructed are also subject to erosion that can contaminate surface water supplies with suspended sediment. Reducing seepage losses with proper pond construction can reduce the environmental impact of lost water, reduce water level fluctuation, and reduce the requirement for water from external sources.

### *Better Management Practices for Pond Construction*

#### *Prepare the site prior to pond construction*

Before construction, land should be cleared of all vegetation, roots, stumps, and other obstructions. The upper 5 to 10 cm of topsoil should be removed and stockpiled for use after levee construction is complete to cover embankments in preparation for seeding and other erosion-protection measures. This stockpiled soil should be surrounded by a sediment curtain or hay bales to prevent erosion during pond construction. Any coarse-grained pervious soils, such as can be found in existing stream channels, should be removed, replaced with well-graded soils, and compacted. The soil surface upon which embankments are to be constructed should be scarified to facilitate the creation of a good bond between existing soil and material added to form embankments.

### *Construct ponds according to specific design criteria*

The long axis of ponds should be oriented to avoid erosion of levees during the period of strongest winds. In the southeast United States, the strongest winds occur during winter, and a north-south orientation should be avoided. For ponds 4 ha or less, the long axis should be oriented parallel with the prevailing wind direction. For ponds larger than 4 ha, the long axis should be oriented perpendicular to the prevailing wind direction.

Pond bottoms should be smooth and flat to allow efficient seine-harvesting of fish. The pond bottom should be constructed with a slope toward the drain of 0.2 to 0.3%. The bottom should be tilled with a disc, leveled, and compacted.

Embankment and excavated ponds for most finfish should be 1 to 2 m deep; crayfish ponds should be 30 to 60 cm deep. Ponds may contain a harvest basin 30 to 45 cm deeper than the pond bottom, or, in deeper ponds, a harvest bench that will allow workers to move easily in the pond to harvest fish.

Embankment top widths should be 6 to 7.5 m on primary levees and 5 to 6 m on secondary levees. The minimum inside slope should be 3 : 1 with a maximum inside slope of 4 : 1; outside slopes should be 3 : 1. The minimum freeboard should be 30 cm for ponds <4 ha and 60 cm for ponds 4 to 8 ha. Freeboard height should be increased above the minimum by the following amounts based on fetch:

| Fetch (m) | Freeboard Increase (cm) |
|---|---|
| <100 | 10 |
| 100–200 | 30 |
| 200–400 | 40 |
| 400–1600 | 60 |

Embankments for watershed ponds should include a cutoff core trench in the embankment foundation. Soil in the cutoff trench should be tightly compacted. The core trench should extend to the height of the permanent water elevation.

Watershed ponds should not have watershed areas larger than necessary to keep ponds full, because excessively large watersheds increase runoff into ponds and result in high discharge. The watershed area required to maintain water level is much greater in arid areas than humid areas. The USDA Natural Resources Conservation Service recommends a watershed area of 13.1 $m^2$ for every $m^3$ of storage or about 20 ha for a 1 ha pond that is 1.5 m deep. For watershed ponds in west-central Alabama, about 10 ha of land is required to maintain the water level for 1 ha of pond water surface (Yoo and Boyd 1994). The ratio between annual runoff volume and pond volume should not exceed 3 : 1 to 4 : 1 to avoid excessive flushing (Hajek and Boyd 1994). Pond design will vary with climate, topography, soil type, and plant cover in the watershed.

Ponds should be constructed with properly designed drainage structures. Drainpipes should be 20 cm in diameter or be able to handle the runoff from a 10-year, 24-hour storm, whichever is greater. Most commercial catfish ponds have 25-cm diameter drainpipes. Drainpipes should be installed by excavating a trench after embankment construction is complete. Drainpipes should extend well past the outside toe of the levee to minimize embankment erosion during pond draining (Fig. 6.6). In watershed ponds, anti-seep collars should be added to drainpipes. Soil placed around the pipe barrel should be thoroughly

**Fig. 6.6.** Improper and proper installation of embankment pond drains. Erosion around the improperly installed drain (top) has washed approximately 5 $m^3$ of soil into the receiving stream. The properly installed drain (bottom) extends beyond the foot of the embankment into the receiving steam. Photographs courtesy of Danny Oberle.

compacted with vibratory tampers up to 60 cm above the pipe. Risers that control water level can be placed inside or outside pond embankments. Trash racks or screens should be placed on internal pipe risers unless the watershed does not contain debris that would clog the outlet.

Spillways constructed for watershed ponds where runoff is the primary water source should be able to accommodate the runoff from a 10-year, 24-hour storm event. Spillways should be flat at the spillway entrance, allowing for a shallow flow of water from the pond, and vegetated to limit erosion. Beyond the flat entrance, the spillway should be constructed with a drop to prevent wild fish from entering the pond.

In the United States, the local USDA Natural Resources Conservation Service has developed conservation practice standards for pond design and construction and can provide specific technical guidance in these areas. Consult NRCS Conservation Practice

Standards 378 (Pond), 397 (Aquaculture Ponds), and 402 (Dam) for additional guidance (www.nrcs.usda.gov/technical/standards/nhcp.html). Specific guidance regarding large earthen dam construction can be found in NRCS Technical Release 60 (Earth Dams and Reservoirs).

### *Compact pond embankments and bottoms properly*

Compaction of well-graded soils increases close packing of soil particles, reduces air voids (porosity), and increases the dry density of soil. The objectives of compaction are to decrease future settling, increase shear strength, and—most importantly for aquaculture ponds—decrease permeability. When properly compacted, well-graded soils will result in embankments that are stable and resist erosion and a pond bottom with low hydraulic conductivity to limit seepage.

Compaction is a function of soil dry density, water content, compactive effort, and soil type. Perhaps most importantly, effective compaction of clay soils depends on water content. When water content is low, soils are hard and firm; when water content is high, soils are plastic and difficult to compact. For soils with high clay content, the best compaction occurs at a water content slightly less than the plastic limit. Optimum compaction can be achieved with a water content of 10 to 20%, although 10 to 15% is best.

Clays require greater compactive effort because soils are cohesive. Thus, embankments formed with these soils may not be stable or have a good weight-bearing capacity when wet. Swelling of clays is greater and soils are more rigid and stronger when compacted on the dry side of the optimum water content than those compacted on the wet side of the optimum water content. The main reason for these observations is that the particle structure of compacted soil tends to be more random on the dry side, whereas particles tend to be more oriented, or parallel, on the wet side.

Well-graded soils can be worked with a combination of kneading and static weight compaction. For fine-grained soils, kneading compacters such as sheepsfoot rollers or tamping-foot rollers are best. Rubber-tired (pneumatic) rollers are suitable, but steel drum rollers are not. The compaction provided by the dirt pans used to scrape soil from borrow areas and deliver it to embankments is acceptable. Soil should be placed in 15 to 20 cm (6 to 8 inch) layers (or *lifts*) and compacted. Depending on soil type, 2 or 3 passes with a tamping foot roller, or 4 to 6 passes with a sheepsfoot roller are sufficient to compact soil. A settlement allowance of 5 to 10% should be considered during pond construction to achieve the design embankment height.

### *Control erosion during and after pond construction*

Construction of pond aquaculture facilities involves dramatic disturbance of the original landscape. Large areas are laid bare as soil is moved to construct embankments, roads, and support infrastructure. Unless denuded areas are protected, rainfall and runoff will erode the bare soil and contribute to downstream eutrophication and cause sedimentation in receiving streams. Erosion control involves using vegetation, stone, gravel, or other structural practices to protect the soil surface from the impact of rainfall and flowing water.

### *Protect pond embankments from erosion*

Erosion of embankments is caused by rainfall and the scouring action of wind-driven waves inside the pond. Erosion that occurs on the inside slopes of the embankment does not have an immediate environmental impact, but sedimentation of eroded soils reduces the useful life of a pond, requiring more frequent renovation. Water released during renovation can have a negative environmental impact if suspended sediment loads are high. Erosion that occurs on the outside slopes of the embankment can enter receiving waters directly or accumulate in the farm drainage system, depending on pond location relative to receiving streams and configuration of the drainage system. In both cases, it is important to protect embankments from erosion as quickly as possible after construction. In a study of sedimentation in commercial catfish ponds, the greatest sedimentation rates occurred within the first year of pond construction (Steeby et al. 2004), suggesting that erosion of unprotected embankments is a major contributor to initial sedimentation.

Embankments can be protected by seeding the embankment with herbaceous vegetation. Selected plants should be well-adapted to the region and resistant to diseases or insect pests. A perennial, low-statured grass with flexible stems and a rhizomatous, spreading root system, such as Bermuda or centipede grass in the southeast United States, is most appropriate. Following construction of embankments, any topsoil that was removed in preparation for pond construction should be spread over embankment tops and slopes and tilled. If necessary, soil should be limed and fertilized in association with seeding. The site should be protected from grazing or from compaction by vehicular traffic until vegetation is established. Once vegetation is firmly established, embankments should be mowed regularly during the growing season to prevent tree growth. Trees can compromise embankment integrity because roots provide channels for water loss. Burrowing animals should not be allowed to become established and should be trapped or killed humanely.

The effect of erosion on internal embankment slopes caused by wind-driven waves can be minimized by a combination of good construction practices and in-place protection measures. Pond orientation should consider prevailing wind direction and speed, and pond size. The minimum freeboard height is 30 cm, with additional freeboard depending on pond fetch (see above). Embankments should be constructed with 3 : 1 slopes and soil should be properly compacted during construction. Riprap is not normally placed inside aquaculture pond levees, but some areas prone to excessive scouring may be protected by the addition of erosion-resistant material at the pond waterline. However, riprap should be placed on the outlet side of pond drains to prevent excessive scouring during pond draining. Additional information can be found in the USDA-NRCS Conservation Practice Standards 322 (Channel Bank Vegetation), 580 (Streambank and Shoreline Protection), and Technical Releases 56 (A Guide for the Design and Layout of Vegetative Wave Protection for Earth Dam Embankments) and 69 (Riprap for Slope Protection Against Wave Action). For protection of exterior embankment slopes and drainage systems from erosion, additional guidance is provided in NRCS Conservation Practice Standard 412 (Grassed Waterway).

### *Construct drainage ditches to minimize erosion*

Ditches should be sufficiently large and of proper cross section and slope to convey farm discharges without the occurrence of excessive current that can cause bottom scouring and erosion of the sides. Controlling the flow rate of effluent from ponds can minimize ditch erosion. Extending drainpipes beyond the toes of pond embankments reduces erosion at the point of discharge. In addition, riprap can be placed on the embankment opposite the point of discharge to deflect scouring flows.

### *Eliminate steep slopes on farm roads and cover roads with gravel*

Steep grades should be avoided on farm roads, and roads should follow contours whenever possible. A 2- to 6-inch layer of gravel should be applied on farm roads.

### *Avoid leaving ponds drained in winter, and close valves once ponds are drained*

Rain falling on drained or partially constructed ponds can cause serious erosion of internal embankments and pond bottoms, sedimentation in deeper areas of ponds, and loss of suspended solids through the open drain. Refilling ponds promptly and keeping drain valves closed in empty ponds are practices that can protect the pond infrastructure and reduce suspended solids loads to farm ditches and finally to receiving streams. If rains occur during construction or renovation, accumulated rainwater can be held for 1 to 2 days prior to discharge to allow any suspended solids to settle before discharge.

## Pond Renovation

Over time, erosion of pond embankments will increase the risk of embankment failure. Soil eroded from internal embankments will accumulate as sediment on the pond bottom, decreasing pond depth and harvest efficiency. Ponds should be renovated before embankments can no longer support vehicular traffic safely. Aquaculture pond renovation techniques are reviewed by Steeby et al. (1998). The basic approach to renovation is to dry pond sediments sufficiently to allow bulldozers to enter the pond to replace material eroded from embankments. Replacement of material from the pond bottom to embankments should restore the original levee top width and cross-sectional profile with interior slopes of at least 3 : 1.

In a technique outlined by Steeby et al. (1998), pond renovation is accomplished in phases. Initially, after ponds are drained, a perimeter trench is excavated with a dragline to allow water to drain from accumulated sediment. Next, a bulldozer is used to cut channels into the accumulated sediment and pile it into rows parallel with the long axis of the pond. Further drainage can occur through the channels. Once the sediment has dried to the proper moisture content (<25%), the material piled in rows can be pushed onto the existing embankments and compacted. Pond embankments should be revegetated as quickly as possible to extend useful pond life.

The major environmental impact of pond renovation is associated with the discharge of sediment from within the pond that is produced while the pond is drained and heavy equipment is operated. Reducing the environmental impact of sediments produced during pond renovation represents a compromise between timely renovation and minimizing sediment release. Specifically, water that drains through the perimeter trench and sediment channels will reduce the water content of accumulated sediment, but may carry elevated sediment loads.

### *Better Management Practices for Pond Renovation*

#### *Use sediment from within the pond to repair embankments rather than disposing of it outside of ponds*

Ponds are unlike other aquaculture systems because solids derived directly from aquatic animal fecal matter are not the major constituent of the material that accumulates as sediment in the system. Fecal matter produced by animals is quickly decomposed in ponds and the nutrients released in the mineralization process support the growth of aquatic plants—usually phytoplankton—which constitute the majority of suspended solids in most ponds. The organic matter that settles to the bottom rapidly decomposes, especially in warmwater aquaculture ponds, and annual rates of organic matter decomposition nearly match rates of organic matter deposition (Box 6.1).

Nearly all of the sediment that accumulates in earthen aquaculture ponds consists of inorganic solids derived from erosion of pond embankments or erosion on the watershed. The sediment deposition rate can be quite high, especially in large ponds with long fetches for wave generation by wind. For example, Steeby et al. (2004) showed that sediment accumulates in large commercial catfish ponds as a function of pond age according to this equation: accumulation (cm) = $12.51(x)^{0.46}$, where x = years of continuous pond use. For a pond in continuous use for 9 years (the average for channel catfish foodfish production ponds; USDA-APHIS 2003), an average of 30.4 cm of sediment accumulates in pond bottoms. Most sediment is deposited in deeper areas of the pond, typically the end with the drainage structure. This sediment is a valuable resource that is needed to restore proper pond morphology when the pond is repaired.

Solids also accumulate in settling basins, constructed wetlands, or vegetated ditches that capture solids during pond draining. Accumulated solids will eventually reduce the volume

## BOX 6.1
### Accumulation Rate of Organic Matter in Pond Sediments is Low

In a typical catfish culture pond, about 30 kg/ha of organic matter in the form of fish feces is produced daily during the summer growing season. Daily net photosynthetic fixation of carbon by phytoplankton corresponds to about 100 kg/ha per day of organic matter production. If the total organic matter produced over the 200-day growing season accumulated without loss in the upper 5 cm of soil, the organic content of the bottom soil should increase by roughly 1% per year. Actual measurements of sediment organic matter accumulation in catfish ponds range from no accumulation over time (Boyd 1985b; Steeby et al. 2004) to about 0.2% per year (Tucker 1985).

of the basin or ditch, affecting hydraulic retention time and the efficiency of solids removal. These solids should be removed or compacted periodically to maintain treatment efficiency.

### *Reduce discharge of sediments during renovation*

During renovation activities, pond drains should remain closed. After activities cease, sediment should be allowed to settle for 1 to 2 days before drains are reopened to release water. Water should be allowed to accumulate in the pond during rainfall events because these can cause sediment suspension and erosion from the exposed pond bottom. Water can be released by opening the drain after a period of settling following a rainfall event.

### *During pond renovation, excavate to increase operational depth*

Increasing depth during renovation can increase water storage, permit greater fluctuation in water level without compromising aquaculture production, and reduce the volume of effluent. Using deeper ponds also extends the useful life of ponds by allowing a longer period for sediment accumulation before ponds become too shallow and require renovation. Increasing depth will, however, substantially increase the cost of pond construction.

### *Properly dispose of solids removed from settling basins*

This will be a site-specific practice. Accumulated solids are unlikely to contain toxic concentrations of metals or other chemicals and therefore can be used without concern as fill material.

## Overflow Effluents

Ponds have two types of effluents. One type occurs when water overflows from ponds when rainfall exceeds pond storage capacity or when water is pumped into the pond for intentional water exchange (called *flushing*). The other type occurs when water is discharged intentionally when ponds are drained. The two effluents differ in quality, volume, and discharge frequency. Overflow effluents are discussed here; draining effluents are discussed in the next section.

Concentrated animal feeding operations (CAFOs), such as cattle feedlots, must be designed to contain all animal waste plus runoff from storm events. Depending on the size, location, and design of the facility, runoff must be contained from a 24-hour, 25-year rainfall event or from all storms, even those exceeding the hypothetical 24-hour, 25-year event (Federal Register 2003). Discharge from CAFOs is prevented by constructing retention ponds to retain wastewater and runoff. Water in the retention structure is either lost by evaporation or applied to land as part of a facility-specific nutrient management plan.

Most pond aquaculture in the United States is conducted in the southeast—a region with abundant rainfall. Using retention ponds to prevent discharge from aquaculture ponds does not appear generally feasible in that region. Most aquaculture farms occupy larger land areas than CAFOs and, consequently, the amount of water discharged from ponds during storm overflow may be much greater than that discharged from CAFOs. For example, Boyd and Queiroz (2001) calculated that 1.53 ha of retention pond would be needed to retain the overflow from a 1-ha embankment pond after a 25-year rainfall event in Alabama. For a typical watershed pond, 11 ha of retention pond would be needed for each hectare of production pond. Therefore, aquaculture ponds in the southeast and other areas where rainfall is relatively abundant cannot be operated profitably without effluent because of the costs of committing more land area to retention ponds than for production. Furthermore, the reduction in potential pollutant loading from the construction and operation of retention ponds to treat overflow effluents from aquaculture ponds is far less than those used to treat runoff from CAFOs.

When rainfall exceeds pond storage capacity and causes ponds to overflow, the rate of water exchange during the event is usually low because the volume of most ponds is large relative to the volume of water added (except, however, for small ponds or prolonged, heavy rains). Therefore, the quality of most overflow effluents is similar to or dilute compared with water in the pond prior to the event causing overflow. Solids in overflow effluent are principally phytoplankton, phytoplankton-derived detritus, and finely divided clay derived from pond bank and watershed erosion. Since ponds act as their own settling basins and solids that settle rapidly are constantly removed from pond water, the solids that remain in overflow effluent have poor settling characteristics and are difficult to remove in postdischarge treatment. Reducing mass discharge is best accomplished by reducing effluent volume, reducing erosion, and using efficient feeding practices to reduce internal waste loading.

## *Better Management Practices for Overflow Effluents*

### *Reduce or eliminate intentional water exchange*

Water exchange, or flushing, was commonly used in the past to improve pond water quality. Water exchange was thought to remove toxic fish metabolites and excess phytoplankton and add oxygen or desirable natural foods. Many times, water exchange was used as a desperation measure during fish kills when other measures failed to resolve the problem. As research progressed and the various causes of fish kills in aquaculture ponds were identified, there was less justification for water exchange as a pond management practice.

If freshwater ponds are managed within their assimilative capacity for waste nutrients, there should be few (if any) times when water exchange is needed to improve water quality. That is, in fact, part of the definition of pond aquaculture. When waste loading exceeds the capacity of physical, chemical, and biological processes to eliminate or transform the wastes, water exchange is needed to prevent water quality deterioration. At that point, the system transitions from a pond to a flow-through facility.

For large ponds, such as those used in channel catfish aquaculture, incoming water is greatly diluted by pond water, and it is unlikely that enough water can be exchanged in a sufficiently short period of time to have a beneficial effect during acute water quality crises. Research (McGee and Boyd 1983) and practical experience have shown that routine water exchange at rates possible in large catfish culture ponds (less than 5% of total pond volume daily) has little or no effect on pond water quality or fish production.

Water exchange is, however, widely practiced as a dissolved oxygen management tool in crayfish culture, where as many as 7 to 9 pond volumes may be exchanged over a production season (Avery and Lorio 1999). Flushing ponds is commonly practiced when crayfish ponds are first flooded in the fall, when the decomposition of abundant vegetation places a substantial demand on dissolved oxygen, leading to critically low concentrations. In this situation, ponds should be filled to 30 cm depth, drained to a depth of 10 to 15 cm and then refilled with new water to 30 cm depth (Lutz et al. 2003). When temperature declines and dissolved oxygen concentration improves, ponds can be filled to normal operating depths (35 to 45 cm). In this way, ponds are drained and filled at separate times, improving the effectiveness of water exchange.

Water exchange is also considered an essential part of the final phase of hybrid striped bass culture, although there has been no systematic research to support the practice. Intentional water exchange is rare in baitfish and ornamental fish culture because flushing with new water reduces the abundance of natural foods, which are an important source of nourishment for those fish.

Displaced pond water represents a pollution load to receiving waters and consumptive use of a valuable resource. Furthermore, pumping requires energy and adds to the cost of growing the aquaculture crop. Accordingly, high rates of water exchange should not be used unless absolutely necessary. If water exchange is practiced as a dissolved oxygen management tool, pond aeration or mixing should be considered as a preferable option. Where technically feasible, discharged water should be circulated between a treatment or reservoir pond and production ponds.

### *Manage ponds to capture rainfall*

Although most aquaculture ponds cannot be operated economically without some water being discharged during unusual precipitation events, the volume of water discharged can be greatly reduced by keeping the pond water level below the level of the drain so that rainfall is captured rather than allowed to overflow. This method of reducing effluents, originally modeled as a water-conservation practice for catfish ponds (Pote et al. 1988; Pote and Wax 1993), is known as the *drop-fill scheme*.

In drop-fill schemes, pumped water is not added until evaporation and seepage cause the pond water level to fall to a predetermined level below the level of the pond overflow device. At that point water is added to replace losses, but the pond is not refilled completely. For example, a *10–4 drop-fill scheme* means that pumped water would not be added until the pond water level falls 10 inches (25 cm) below the level of the overflow device. Then, 4 inches (10 cm) of water would be added, bringing the water level to 6 inches (15 cm) below the overflow level. This 6 inches (15 cm) of storage will retain considerable rainfall, thereby reducing overflow and pollutant mass discharge, as well as offsetting the need for pumped water (Tucker et al. 1996) (Box 6.2).

Another approach to reducing effluent volume is based on the use of some ponds on a farm for both fish production and water storage. The combined production-storage pond is constructed 0.25 to 1 m deeper than typical production ponds to provide additional volume for storage of rainfall. The production-storage pond is linked via culverts to 1 to

## BOX 6.2
## "Drop-Fill" Water Management

The effectiveness of the 10-4 drop-fill scheme as an effluent management and water conservation practice was evaluated under commercial catfish aquaculture conditions over 3 years in northwest Mississippi (Tucker and Hargreaves 2006). Mass discharge of nitrogen, phosphorus, and organic matter was reduced by more than 60%, and average annual groundwater use was only 18 cm in managed ponds while 45 cm of water was added to ponds not managed with the drop-fill scheme. Water-level management is particularly effective at reducing discharge during the summer. For example, total phosphorus discharge from drop-fill ponds was reduced by over 90% during summer months, but only by 40% in winter months. Winter rainfall is greater and more frequent in northwest Mississippi and ponds usually stay near the overflow level for long periods. As such, most winter rainfall was lost as overflow from both sets of ponds. Average annual fish harvest was 6,425 kg/ha in drop-fill ponds and 6,250 kg/ha in ponds without water-level management, demonstrating that the simple practice reduces pollutant discharge and water use in catfish ponds without affecting fish production.

The 10-4 scheme used in the study above is an extreme version of drop-fill, requiring ponds deep enough to allow a 10-inch (25-cm) water-level drop without affecting fish culture practices. Most catfish ponds are 1.25 to 2 m deep, and can be operated with 6- to 12-inch (15- to 30-cm) drops without affecting fish growth or culture practices. Hargreaves et al. (2001) modeled drop-fill schemes for embankment ponds with drops ranging from 2 to 18 inches (5 to 45 cm) and fills ranging from 2 to 6 inches (5 to 15 cm). Significant reductions in overflow discharge volume were obtained with drops as low as 6 inches (15 cm) and fills of 3 inches (7.5 cm). As such, the drop-fill scheme can be used in relatively shallow ponds without serious impacts on fish production practices.

3 production ponds so that overflow from all ponds in the linked system drains into the production-storage pond. Overflow occurs only when the storage capacity of the linked system is exceeded. Mathematical modeling using a 26-year climatological record for northwest Mississippi showed that the effluent discharge from linked ponds can be reduced by 40 to 90% (depending on rainfall) relative to single ponds refilled to the top of the overflow device every time the water level drops 7.5 cm (Cathcart et al. 1999).

### *Optimize the ratio of watershed-to-pond area*

Watershed ponds should not have watershed areas larger than necessary to keep ponds full because excessively large watersheds increase runoff into ponds and result in high discharge. Optimal pond design will vary with climate, soil type, and watershed use. Consult representatives of the local office of the USDA Natural Resources Conservation Service for assistance with pond design. See the specific recommendations in the section on pond construction above.

### *Use drains with surface-water intakes*

Although shallow embankment ponds temporally stratify during the day, convective heat loss at night causes destratification and mixing of the water. Water mixing by wind and aeration also counteracts thermal stratification. The quality of water in embankment ponds is, therefore relatively homogeneous with depth, and except for brief periods at the beginning and end of pond draining, effluent quality does not differ significantly if waters are discharged from either the surface or bottom of the pond. However, deeper ponds may stratify for long periods during warmer months, and water quality can vary from the surface to the bottom. Bottom water has lower dissolved oxygen concentrations and higher dissolved nutrient and suspended solids concentrations. The quality of effluent discharged as overflow from the surface may be better than that discharged from the bottom. Pipe sleeves, dam board configurations, or other structures that allow the withdrawal of water from deeper layers should not be used. In ponds managed with intentional water exchange, water can be discharged from the pond bottom if it is recirculated or treated in a reservoir pond or wetland prior to discharge.

### *Control erosion on pond watersheds and pond levees*

Vegetative cover will reduce erosion of watershed soils and the loading of suspended solids to ponds in runoff. In watersheds used for grazing, livestock stocking rates appropriate for the forage base will allow maintenance of sufficient plant cover. In degraded watersheds or those subject to erosion, streamside management zones (SMZs) or buffer strips adjacent to water supply streams should be maintained. Seed pond levees with a cover crop, such as Bermuda or centipede grass, shortly after pond construction. Planting a cover crop will limit sedimentation of the pond, thereby extending the interval before renovation is required.

### *Divert excess runoff from large watersheds away from ponds*

Runoff and supply streams can be diverted by constructing temporary low-elevation embankments or ditches running across slope on watershed areas adjacent to ponds. This practice can divert turbid runoff where it is not possible to provide erosion control on watersheds. Diversion can extend the production interval between draining and renovation in watershed ponds by minimizing reduction in pond depth caused by deposition of sediment derived from turbid runoff. Less water passing through ponds will reduce erosion of embankments and farm ditches, and the output of suspended solids will be less.

### *Whenever possible, prevent water discharge from ponds during fish kills*

If the fish kill was caused by deleterious water quality, preventing water discharge during fish kills will limit the release of potentially poor-quality water. Furthermore, preventing water discharge from ponds during fish kills will limit the release of potential fish pathogens. Drainage structures can be temporarily plugged or blocked to prevent overflow.

### *Use effluents to irrigate terrestrial crops*

Under certain conditions, the water discharged as intentional overflow or from pond draining may have value as irrigation water for agronomic crops. The primary goal of integrating aquaculture and terrestrial agriculture would be to make productive use of pond effluents by supplementing the water supply for irrigation. Nutrients in pond effluent might also be beneficial to the crop (Box 6.3). However, there are a number of practical considerations that severely restrict the utility of this seemingly attractive management practice.

The primary impediment to using pond effluents for crop irrigation is that crop water requirements seldom correspond to the availability of pond effluents. Peak water demand for irrigation occurs during dry periods when there is little or no overflow from ponds. Also, many fish farmers object to draining ponds during the summer growing season because they lose valuable production time when ponds are empty. Most farmers prefer to drain ponds in autumn or winter, during which time there is little demand for irrigation water. Because irrigation demands do not correspond to water availability from rainfall overflow or intentional pond draining, the only way to provide water for irrigation is to intentionally pump water into the pond to generate overflow.

In some types of irrigation (such as flooding of rice fields) water is needed quickly, in relatively large volumes, and at a specific time—which may or may not correspond to the availability of water from fish ponds. For example, a crop of rice requires about 1 to 1.5 m of water, which corresponds to nearly the entire volume of most fish ponds for an equivalent area of rice. Low rates of water exchange do not improve water quality in fish ponds (McGee and Boyd 1983), so using pond water for irrigation would not benefit fish production. Further, the need for large water volumes delivered quickly means that gravity flow from pond discharge devices may not be sufficient to provide the flow rates that are needed. Rapid delivery of large water volumes would require installation of large pumps and water

## BOX 6.3
## Low Fertilizer Value of Pond Effluents

The agronomic benefit of the nutrients in pond effluents is usually overestimated because effluents from aquaculture ponds are, in fact, quite dilute with respect to dissolved forms of major plant nutrients. For example, nitrogen is usually applied to rice as a top dressing at 30 to 60 kg/ha. Assuming a total inorganic nitrogen concentration of 1 mg/L in pond water, roughly 3 to 6 m of water would be needed to supply the amount of nitrogen usually applied to rice as fertilizer. Thus, the contribution of nutrients in catfish pond water to the irrigated crop is small. The lack of benefit of the nutrients in catfish pond water to the irrigated crop was verified in an unpublished study conducted at Stoneville, Mississippi, where rice fields were irrigated over a 3-year period using water pumped from a catfish pond. Rice yield across several nitrogen fertilization practices did not differ when using catfish pond water or groundwater as a source of irrigation water.

distribution systems to convey water where it is to be applied in the required amounts. The high suspended solids concentration of some aquaculture pond effluents can clog the water distribution orifices of some kinds of irrigation equipment. Thus, use of pond effluents with some types of irrigation equipment would require filtration, a process that would remove a significant proportion of the nutrients contained in the effluent.

## Effluents from Pond Draining

The quality, volume, and frequency of water discharged when ponds are drained is different from that discharged as overflow following rains or from intentional water exchange. Overflow effluent is unpredictable and discharge volume and frequency varies depending upon weather. Pond draining, on the other hand, is predictable and usually varies with the culture cycle. When ponds are drained, there are periods (often quite brief) when solids from the pond bottom are discharged along with pond water. Accordingly, water discharged during pond draining may temporarily have much higher concentrations of solids, nutrients, and organic matter than overflow effluents.

Frequency of pond draining (and, therefore, annualized effluent volume) depends primarily on the species or phase of culture. For some species, such as ornamentals and baitfish, crops are completely harvested annually (or more frequently) and ponds are drained to facilitate harvest and prepare the pond for the next crop. Ponds used to grow crayfish and juvenile phases of channel catfish and hybrid striped bass also are drained annually. In contrast, ponds used to grow food-sized channel catfish may be operated without draining for many years.

Pond hydrological type also affects discharge frequency and effluent quality. Embankment ponds used to grow food-sized channel catfish are relatively shallow (1- to 2-m deep) and there is no need to partially drain ponds to facilitate fish harvest. Ponds may be operated without draining for many years by selectively removing market-sized fish and restocking the pond with fingerlings. When the pond must be drained after years of use, a seine is pulled through the pond one or more times to capture fish before draining. In contrast, deep watershed ponds are difficult to harvest without partially drawing down the water level. Watershed ponds may need to be partially or completely drained each year.

Most embankment ponds for channel catfish are equipped with fixed drains that extend from the deepest part of the pond through the embankment. A screened extension is fitted to the end of the pipe (usually 25 to 30 cm in diameter) inside the pond, with a riser and an “alfalfa” valve on the outside. The height of the riser determines pond depth (Fig. 6.7). Draining is initiated by removing the riser extension. Then, after the water level in the pond has dropped at least half way, the valve at the bottom of the drain is opened and the remaining water in the pond is drained. When draining is initiated, shear forces generated by water moving into the drainpipe scour the pond bottom around the entrance to the drainpipe. The initial flush of water discharged, therefore, consists of pond water and a slurry of sediment that has accumulated over the screen inside the pond. During this first flush of sediment-laden water, concentrations of solids, organic matter, and nutrients can be very high. Depending on the depth of sediment around the drain, the effluent clears in 5 to 30 minutes and all water subsequently discharged is pond water with little or no material derived from the sediment (Hargreaves et al. 2005a). Although concentrations of

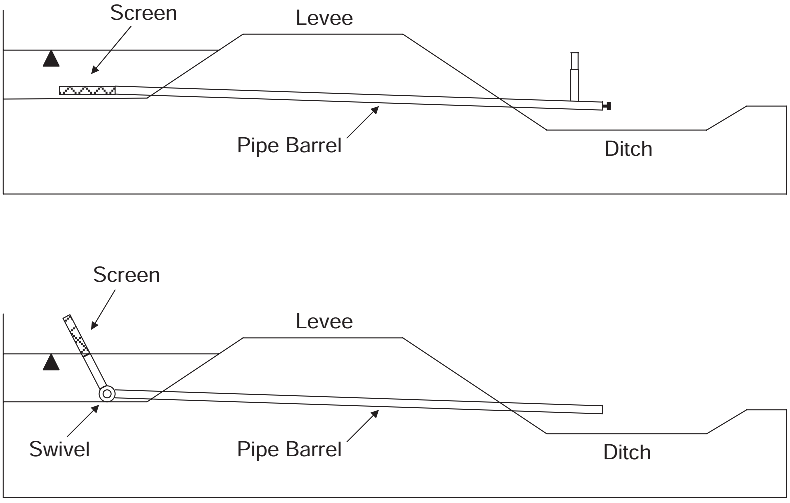

**Fig. 6.7.** Cross sections through pond embankments showing a fixed drain with external riser (top) and a swivel drain (bottom).

potential pollutants can be high in the first-flush effluent, the duration of elevated concentration is relatively brief and, therefore, the proportion of pond volume (and total pollutant mass) discharged during that period is small (Hargreaves et al. 2005b).

Some watershed ponds are too deep to allow fish harvest unless the pond is partially drained before the seining operation begins. In those ponds, effluent quality is more or less constant during discharge of the initial 80 to 90% of the pond volume (the draining phase). Following discharge of most of the pond water, fish are harvested by repeatedly seining the water remaining in the pond. Disturbance of the sediment by harvest activities and fish movements in shallow water causes nutrient, organic matter, and suspended solids concentrations to increase dramatically during the last 10 to 20% of discharge volume (Boyd 1978; Schwartz and Boyd 1994).

Mass discharge from pond draining can be minimized by reducing the volume of draining effluent, primarily by extending the interval between pond drainings. If possible, this should be the first approach. Next, the water quality of the effluent from pond draining can be improved by practices that vary depending on hydrological pond type. The least practical approaches are those where effluent is treated after discharge.

## *Better Management Practices for Effluents from Pond Draining*

### *Reuse water for multiple crops*

It is impossible to conduct pond aquaculture without occasionally draining the pond. Most commonly, ponds are drained to facilitate complete harvest of the aquaculture crop. Production schemes have, however, been developed for some species that allow multiple crops to be grown without draining the pond. Using such systems dramatically reduces effluent volume. Therefore, whenever possible, ponds should be constructed with uniform, relatively shallow (1 to 2 m) bottoms that allow harvest without draining.

## BOX 6.4
## Increasing Hydraulic Retention Time Improves Pond Effluents

When natural microbial and physicochemical processes act over the long hydraulic retention time (months or more) characteristic of most fish ponds, a large proportion of the total waste loading to the pond is removed before water is discharged. For example, Boyd (1985b) estimated that in-pond processes removed 90% of the waste N and P and 95% of the organic matter added to catfish ponds over 1 year. If water is retained in ponds for multiple years, further increases in waste treatment efficiency can be realized. In fact, catfish ponds can be operated continuously for 15 years or longer without year-to-year accumulation of nutrients and organic matter in the water column (Zimba et al. 2003). So, if it is feasible—from a fish culture standpoint—to use ponds for longer intervals between drawdowns, better use is made of the waste treatment capability of the pond ecosystem because more time is provided for natural processes to remove wastes before water is discharged. For example, compared to ponds drained each year, annualized waste discharge is reduced by approximately 30% when ponds are used for 3 years before draining and by 45% when ponds are not drained for 5 years (Tucker et al. 1996).

In multiyear production systems, such as that used to grow food-sized channel catfish, ponds are drained only when renovation is needed or when there is need to adjust fish inventory by completely harvesting the crop. Wind-driven waves, acting over several years, can erode levees to the point where levee integrity is compromised. Material eroded from levees also accumulates as sediment on the pond bottom, making the pond bottom uneven and difficult to seine-harvest. It is also difficult to maintain accurate records of fish inventory in multiyear production systems, and farmers sometimes harvest and drain ponds simply to "zero-out" the inventory and start a new production cycle. The interval between pond drainings can therefore be increased by managing ponds to reduce erosion of earthwork and by improving inventory control through efficient harvest and better record keeping.

Using ponds for several years without draining and refilling is possible, in large part, because natural microbial and physicochemical processes continually remove nutrients and organic matter from pond water. The rate at which these processes act is such that fish ponds (at least in the southeastern United States) can be used for many years without significant long-term accumulation of nutrients and organic matter in the water column or sediment, despite large inputs of metabolic waste resulting from fish feeding practices (Box 6.4).

### *Reuse or recirculate water that is drained from ponds*

Rather than draining ponds for harvest, it may be possible to pump water to adjacent ponds where it can be reused in the same or other ponds. To facilitate this practice, ponds can be constructed with higher levees than normal or water levels can be maintained with more freeboard to provide greater storage capacity for water pumped from a nearby pond. Water from one pond can be transferred to another with a low-head lift pump and then, where topography permits, returned to the empty pond by siphon. Alternatively, drained water can be lifted to a large reservoir pond for treatment prior to recirculation to culture ponds by gravity. If topography of the landscape allows, ponds can be constructed in such a way to allow draining of one pond into adjacent, lower-elevation ponds.

Reusing pond effluent is commonly practiced on baitfish farms in the Grand Prairie region of eastern Arkansas. Water reuse practices have been widely adopted because of the dwindling groundwater supply, the lower cost of pumping water from pond to pond compared with pumping water from deep wells, and a desire to not waste the "old water" that contains abundant natural foods for baitfish.

### *Drain water from the pond surface*

The quality of pond surface waters is often better than that near the pond bottom. Using drainage structures that allow control over the depth from which water is discharged controls, to some extent, the quality of water discharged. Examples of flexible-level drainage structures include swivel drains (Fig. 6.7) and drainage monks managed with progressive removal of dam boards as ponds drain. These drainage structures allow the discharge of pond water in stages. The last 10 to 20% of water can be held until solids settle and then discharged.

### *Allow solids to settle before discharging water*

Some watershed ponds must be partially drained to facilitate fish harvest. In those instances, water should not be discharged during seining to avoid the discharge of sediment suspended by harvest activities. After seining, the last 10 to 20% of water can be held without discharge to allow solids to settle. Holding water for 2 or 3 days after seining can greatly reduce the discharge of solids, organic matter, and nutrients (Schwartz and Boyd 1994). Holding water for more than 3 days can result in an increase in solids concentration as phytoplankton blooms develop in response to the nutrients released during harvesting.

### *Treat pond effluents in constructed wetlands prior to discharge*

Using wetlands to treat wastewaters is based on removal of nutrients and solids as the water is slowly passed through a shallow (30-cm deep), vegetated impoundment (Fig. 6.8). Nutrients are assimilated by wetland plants, removed by physicochemical processes, such as precipitation and adsorption reactions in the soil, and transformed and removed by biological reactions associated with the vast surface area provided by plant roots and above-ground plant biomass. Solids are removed by settling as water slowly passes through the system (Box 6.5).

The disadvantage of constructed wetlands for treating wastes from channel catfish ponds is the large area necessary to provide adequate hydraulic retention time when the process is used on large farms. In particular, the relationship between the pond area and wetland area needed for effective effluent treatment during the high-discharge winter periods is

**Fig 6.8.** Constructed wetlands used to treat effluents from a fish pond. Water enters the center cell near the bottom of the photograph, flows through the emergent vegetation, and exits the cell in the distance.

## BOX 6.5
## Improving Effluent Quality with Treatment Wetlands

Schwartz and Boyd (1995) designed a treatment system where effluent from a catfish pond was passed through a constructed wetland consisting of two cells planted with emergent aquatic vegetation. Concentrations of potential pollutants were much lower in effluent from the wetland than in water discharged directly from the catfish pond. Overall performance of the wetland was best when operated with a 4-day hydraulic retention time during the growing season, but good removal of potential pollutants was achieved with shorter retention times. The wetland was relatively efficient in improving water quality even in late fall and winter when vegetation was dormant.

not known. Also, the usefulness of wetlands to treat pond effluents in colder climates is suspect.

An alternative to using wetlands designed to treat all effluents from a farm would be to construct a small wetland to treat only the most concentrated effluents released when ponds are drained in the drier seasons—the time of greatest potential environmental impact because of low rates of dilution by effluent-receiving streams. In other words, effluents released during peak discharge would not be treated because of the low nutrient concentration of most of the effluent volume, the large wetland area needed to provide an effective hydraulic retention time, and the great dilution provided by high receiving stream flows. This approach would minimize the land needed for constructed wetlands and significantly improve effluent quality during dry periods. However, the overall reduction in mass discharge of nutrients and organic matter, and the costs associated with this scaled-down approach, are unknown.

### *Treat pond effluents in settling basins prior to discharge*

Settling basins are easier to construct and operate than wetlands because they do not require the establishment of plants. More important, Boyd et al. (1998) showed that settling basins may be nearly as effective as constructed wetlands at removing potential pollutants from effluents discharged during pond draining, which often contain high concentrations of solids dislodged from the pond bottom by fish harvest activities. Sedimentation of synthetic pond effluents (designed to simulate waters released during the final stages of pond draining) for 8 hours removed more than 75% of suspended solids and total phosphorus and more than 40% of the 5-day biochemical oxygen demand ($BOD_5$) and turbidity. Removal of these substances is rapid because much of the phosphorus and organic matter in this particular kind of pond effluent is associated with inorganic suspended solids, primarily suspended soil particles, which settle quickly (Box 6.6).

For watershed ponds that must be partially drained to facilitate fish harvest, the production pond can be used as its own settling basin. As discussed above, when ponds are

## BOX 6.6
## Treating Pond Effluents with Settling Basins

The settling basin volume needed to treat only pond draining effluent is much smaller than that required to treat draining and overflow effluent, because typically only one or two ponds on a farm are drained at any one time whereas overflow from excess precipitation is derived simultaneously from all ponds. Boyd and Queiroz (2001) calculated settling pond areas needed to treat draining effluent or draining effluent plus storm overflow for catfish farms of various sizes. Assuming that settling ponds are 1.5-m deep, percentages of the farm area devoted to settling ponds for draining effluent from levee ponds ranged from 0.7% for a 200-ha farm to 14% for a 10-ha farm. The corresponding range for watershed ponds is 0.8 to 15%. In contrast, settling ponds to treat overflow from a 25-year storm on farms greater than 25-ha would require a much larger area—7% of the farm area for levee ponds and 43% of the farm area for watershed ponds. Aside from constraints related to the land area required for settling basins, a serious practical limitation to using settling basins would be the need to design and construct a drainage system on the farm so that effluent from as many ponds as possible (preferably all ponds on the farm) could be directed to one common settling basin. Reconfiguring drainage patterns on existing farms would be difficult and expensive.

## BOX 6.7
### Farm Drainage Ditches Act as Settling Basins for Pond Effluents

Hargreaves et al. (2005b) studied the settling characteristics of draining effluents from typical levee-style catfish ponds and used that data to design sedimentation basins to remove effluent solids. Based on the discharge rate for the ponds studied (5.7 to 7.6 $m^3$/min), removing 95% of the solids requires a basin area ranging from 95 to 126 $m^2$. They also measured changes in water quality as pond-draining effluent flowed down a 0.5- to 1.5-m wide, low-gradient (0.04%) vegetated ditch. After the effluent traveled 120 to 220 m downstream, effluent solids concentration was less than the bulk pond water, meaning that all of the solids generated during draining and even some of the phytoplankton and inorganic solids in the pond water had been removed. The distance that the effluent traveled downstream before most of the solids were removed (120 to 220 m) is consistent with the results of the design example described above, where 95 to 126 m of a 1-m-wide ditch was estimated as sufficient to remove most solids from initial effluent.

drained, the final volume of water may be held in the pond for 2 to 3 days to allow solids to settle before draining completely. Alternatively, the last 20% of water discharged from ponds can be held in farm drainage ditches for settling prior to final discharge.

*Release pond effluents into low-gradient drainage ditches*

Low-gradient ditches, particularly those with natural or planted vegetation to impede flows, can function as effective settling basins for rapidly settling solids released during pond draining (Box 6.7)

## Water Conservation

Water conservation is a commendable goal because it helps ensure the sustainability of aquaculture. In pond aquaculture there are additional incentives to conserve water. Water for most pond aquaculture requires pumping, either from underground aquifers or surface waters. Pumping can be expensive, depending on the hydraulic head, distance the water must be moved, and energy or fuel costs. So, water conservation reduces production costs. There is also a direct link between water conservation in pond aquaculture and effluent volume. Every liter of water that is discharged must be eventually replaced, either by rainfall or pumped water. So, water conservation also reduces effluent volume.

In many parts of the world, aquaculture must compete for water with other forms of agriculture, industry, and household uses. In arid and drought-prone regions, conservative and intensive water management is the only way pond aquaculture can be conducted. For example, baitfish and catfish aquaculture in the Grand Prairie region of eastern Arkansas and ornamental fish culture in south Florida are severely constrained by lack of suitable groundwater supplies caused by long-term overdrafts by other forms of agriculture (rice and cotton in the case of Arkansas) or urban development (in the case of Florida). In the face of this critical resource constraint, pond aquaculturists in those regions have developed innovative practices to conserve water without significantly affecting production.

Losses of water from ponds include evaporation, transpiration, seepage, overflow, and draining. Little can be done to reduce water lost to evaporative processes, but other losses can be controlled to some degree. Most water conservation practices are addressed in other sections of this chapter and will be mentioned only briefly here. See the sections "Pond Hydrology" for a discussion of water budgets and water loss processes, "Site Selection" and "Pond Construction" for aspects of siting applicable to reducing seepage losses, and "Overflow Effluents" and "Effluents from Pond Draining" for practices that can reduce water lost in effluents.

### *Better Management Practices for Water Conservation*

#### *Select sites with soils that are suitable for pond construction*

Soils vary widely in their ability to retain water. Well-graded soils with a range of particle sizes and a moderate clay content will compact well during construction and have negligible seepage. Permeable soils with high sand content or soils with lenses of sand or gravel will seep excessively. Also, thin soils over fractured bedrock (especially over limestone) can seep excessively. Proper site selection will largely prevent excessive water loss to seepage. Landowners should consult with the local USDA Natural Resources Conservation Service (NRCS) office before building ponds. The NRCS has soil surveys with information on soil properties and their suitability for pond construction. Core samples from a proposed pond site will help identify areas of high permeability.

#### *Construct ponds properly*

Construction practices that can reduce water loss to seepage include proper preparation of the land before construction, proper pond design (which will be site-specific), adequate compaction of soil during pond construction, and installation of properly designed drainage structures. The USDA Natural Resources Conservation Service has developed practice standards for pond design and construction and can provide specific technical guidance in these areas. Consult NRCS Conservation Practice Standard 378 (Pond), 397 (Aquaculture Ponds), and 402 (Dam) for additional guidance. Specific guidance regarding large earthen dam construction can be found in NRCS Technical Release 60 (Earth Dams and Reservoirs).

#### *Reduce or eliminate intentional water exchange*

Water exchange is believed to improve pond water quality by removing toxic fish metabolites and excess phytoplankton, and adding oxygen or desirable natural foods. Although water exchange is considered essential in some types of pond aquaculture, reduction or elimination of this practice is probably feasible in all cultures. Displaced pond water increases effluent volume and is a consumptive use of a valuable resource. Pumping also requires energy and adds to the cost of growing the aquaculture crop. If water exchange is practiced as a dissolved oxygen management tool, pond aeration or mixing should be considered as an option. Where technically and economically feasible, discharged water can be circulated between a treatment or reservoir pond and production ponds to conserve water.

### *Manage ponds to capture rainfall*

Ponds can be designed and operated to retain rainfall, which will offset future needs for pumped water. Building and operating ponds with extra freeboard and using the drop-fill scheme to capture water (see the section "Overflow Effluents") can greatly reduce the need for pumped water (Pote et al. 1988; Pote and Wax 1993; Hargreaves et al. 2001; Tucker and Hargreaves 2006).

### *Reduce water lost during pond draining*

Although it is impossible to conduct pond aquaculture without occasionally draining the pond, production schemes have been developed for some species that allow multiple crops to be grown without draining the pond for many years. These production systems dramatically reduce effluent volume. Therefore, whenever possible, ponds should be constructed with uniform, relatively shallow (1 to 2 m) bottoms that allow harvest without draining. Additional practices that allow for longer intervals between draining include reducing erosion on the watershed, building deeper ponds (Steeby et al. 2004), and using management practices that allow better tracking of pond inventories.

### *Reuse or recirculate water that is drained from ponds*

Rather than draining ponds for harvest, it may be possible to pump water to adjacent ponds where it can be reused in the same or other ponds. Water from one pond can be transferred to another with a low-head lift pump and then, where topography permits, returned to the empty pond by siphon. Drained water may be lifted to a large reservoir pond for treatment prior to recirculation to culture ponds by gravity.

### *Use water efficiently by increasing production intensity*

Water use in pond aquaculture can be described in absolute terms (volume/time), but a better index is water efficiency (fish production/water volume). As production intensity increases, water efficiency correspondingly increases. Extensively managed ponds are comparatively wasteful of water because production is low relative to the volume of water used. Intensively managed ponds use water efficiently, although the quality of water is degraded during culture in comparison to that in extensively managed ponds. Intensification of pond aquaculture can be achieved by increasing stocking density and feeding rates, which requires corresponding increases in aeration, mixing, and occasionally water exchange. Water efficiency can also be increased by reusing water for multiple crops before draining. In areas where water is scarce, conservation and production objectives can be achieved through intensification.

## Feeds and Feeding

Although some ponds are fertilized in the early stages of production to stimulate natural food production, most finfish aquaculture in the United States relies on manufactured feeds to promote rapid fish growth. Feeds used for catfish and hybrid striped bass culture are manufactured from high-quality ingredients and formulated to meet all nutritional requirements of the fish. Nevertheless, even under the best conditions only about 10 to 20% of the carbon, 20 to 30% of the nitrogen, and 25 to 35% of the phosphorus in the feed is removed in fish at harvest. The remainder is excreted by fish into the pond. Feed nutrient assimilation efficiency is even lower in baitfish and ornamental fish culture because these fish often do not eat all the feed offered. Dissolved and particulate nutrients and organic matter excreted by cultured animals and derived from applied feeds constitute the waste load to pond water. Nutrients from uneaten feed and fish metabolic waste products stimulate the production of large amounts of phytoplankton, which constitute most of the suspended solids in pond water.

The total amount of a substance discharged from aquaculture facilities (*mass discharge*) is the product of concentration and total effluent volume. In "open" systems, such as flow-through and net-pen culture systems, effluent volume is more or less fixed and mass loading is primarily related to the interactions among feed composition, feeding rate and frequency, and fish bioenergetics. Therefore, one of the best ways to reduce waste mass discharge is to improve feed nutrient assimilation efficiency so that less waste is produced within the system. Although there is a general relationship between nutrient input via feed input and pond water quality (Tucker et al. 1979; Boyd 1985b; Cole and Boyd 1986; Southworth et al. 2006), the relationship between feed input and effluent mass loading is much less direct than it is in open systems.

Two factors disconnect internal waste loading from waste discharge in pond aquaculture. First, most ponds discharge water intermittently and mass discharge is usually more sensitive to changes in pond draining frequency and overflow effluent volume than it is to changes in pond water quality. The second factor that disconnects waste loading from mass discharge is the cumulative effect of various natural, within-pond processes that transform and remove a large majority of the waste load before water is discharged. These physical, chemical, and biological processes are well known in limnology and wastewater treatment, and are not unique to aquaculture ponds (see Boyd 1985b; Hargreaves 1998; Boyd and Tucker 1998; and Hargreaves and Tucker 2003 for discussions of these processes).

The overall effects of these two factors (discharge volume and internal waste removal) on waste discharge are interrelated because the degree to which the wastes are treated in ponds before discharge depends primarily on hydraulic retention time and water temperature, both of which vary considerably depending on pond hydrological type, culture species and life stage, individual farm management practices, season, and geographic location. For example, most ponds used to raise food-sized catfish are not drained between crops, are operated with no intentional water exchange, and water temperatures are warm throughout much of the year. Under those conditions, well over 90% of the nitrogen, phosphorus, and organic matter added as fish metabolic waste is removed from water prior to discharge (Tucker et al. 1996). Draining ponds between crops and using intentional water exchange will reduce hydraulic retention time and afford less time for natural processes to remove nutrients and organic matter before water is discharged.

Because biological activity within the pond and physical factors such as hydraulic retention time and pond draining frequency have such a large impact on waste mass discharge from ponds, feed management offers less opportunity for control of potential pollution than it does in "open" culture systems. In ponds, reducing waste discharge by reducing effluent volume is easier and more effective than trying to reduce pollutant concentrations through feed management. Improved feed nutrient utilization in ponds does, however, provide other important benefits. Feed represents the largest single variable cost (typically about half) of aquatic animal production and efficient use of feeds can improve farm profitability. Also, operating ponds within the assimilative capacity of the pond ecosystem will improve water quality inside the pond and provide a better environment for aquatic animal growth. Feed management is therefore one of the most important aspects of pond aquaculture.

Aquatic animal nutrition and feeding practices are active areas of research, and technology is constantly evolving. An important research goal is to improve the efficiency of nutrient utilization by the animal under culture, thereby enhancing economic returns and reducing waste production. Because technology is rapidly changing, BMPs for feed management should be flexible so that newer and better practices can be implemented as they become available.

## *Better Management Practices for Feeds and Feeding*

### *Use feeding practices that maximize the efficiency of feed use*

Most feeds used in commercial aquaculture are manufactured to high quality standards and formulations are based on many years of research into the nutrient requirements of the cultured animal. Nevertheless, poor feeding practices can negate the benefits offered by these feeds. In fact, for channel catfish, hybrid striped bass, and marine shrimp, there is much greater opportunity for reducing waste loading in ponds by improving feeding practices than by making incremental improvements in feed formulation. For example, improving the feed conversion ratio (weight feed fed/fish weight gain) from 2.2 to 1.8 in channel catfish farming results in almost 25% less waste nitrogen added to the pond. Reductions in waste loading of this magnitude are possible by using improved culture practices, but are difficult to achieve simply by improving current feed formulations (but see Box 6.8). Regrettably, much more research has been conducted on nutrient requirements and feed formulation than on feeding practices, and there is no standard feeding practice for any commercially important species grown in ponds. In that regard, feeding fish in ponds is more skill than science. Developing the skill to feed fish efficiently takes experience to acquire a feel for how fish appetite, as an aggregate population effect, changes in response to variations in weather and pond water quality.

Feeding fish in ponds is not as simple as feeding terrestrial animals because it is often difficult or impossible to observe underwater feeding activity, especially in turbid ponds.

## BOX 6.8
## Diet Composition and Pond Effluent Quality

The effects of diet modifications on pond water quality (and, therefore, the quality of potential effluents) are somewhat ambiguous, at least for channel catfish fed at relatively high rates. Two studies (Gross et al. 1998; Tucker et al. 2005) evaluated the effect of improving phosphorus utilization by catfish on effluent water quality. The following approaches were evaluated: 1) using feeds with the lowest possible phosphorus supplementation to meet the dietary requirements; 2) using water-insoluble phosphorus supplementation (defluorinated rock phosphate); and 3) using microbial phytase to improve the bioavailability of plant phytate phosphorus. Modifications of dietary phosphorus did not reduce waterborne phosphorus concentrations or phytoplankton abundance and, therefore, will not reduce phosphorus or organic matter mass loading in pond effluents. Lack of effectiveness was attributed to the high "background" nutrient loading from phosphorus contained in practical feed ingredients combined with high internal phosphorus loading (recycling) within ponds. These factors overwhelm the effect of small changes in external phosphorus loading associated with diet modification. Two other studies (Li and Lovell 1992; Robinson et al. 2004) evaluated the effect of feed protein level on nitrogenous waste compounds in catfish pond waters. Reductions in feed protein for fish fed to satiation resulted in approximately proportional reductions in total nitrogen concentrations in pond water. For example, in the study by Robinson et al. (2004), reducing feed protein from 36 to 28% (a 22% reduction) reduced average pond water total nitrogen from 5.0 to 3.6 mg/L (a 28% reduction). Overall, it appears that reducing protein levels in practical catfish feeds significantly reduces nitrogen loading in pond effluents while quantitative and qualitative modifications of dietary phosphorus have little effect on effluent quality.

Also, environmental conditions in ponds change more rapidly than in other aquaculture systems, and those changes cause fish appetite to vary from day to day in a largely unpredictable manner. Feeding response can be best gauged when extruded (floating) feeds are used. Pelleted (sinking) feeds do not allow observation of fish feeding activity and are generally not recommended for finfish aquaculture in ponds.

Daily feed allowances can be based either on subjective evaluation of fish feeding response or on schedules computed from fish size and biomass, expected feed consumption, and water temperature. It is difficult to use scheduled feeding in ponds because fish feeding response varies unpredictably with environmental conditions and because fish biomass may not be accurately known in ponds. Therefore, feeding fish in ponds should be based on subjective evaluation of feeding response rather than schedules based on expected feed consumption (Garrard et al. 1990).

Fish growth is usually best when fish are fed one or more times daily to satiation. On the other hand, nutrient retention improves, up to a point, when ration is restricted. The best compromise between growth and feed conversion for commercial pond aquaculture is attained when fish are fed to just short of satiation (Minton 1978). It is, however, difficult to judge when fish are fed to that level in ponds because fish appetite varies from day to day and from pond to pond. As such, there is no way to know what will constitute satiation until that point is reached. Experienced culturists who pay close attention to feeding activity can, however, judge with fair accuracy when the point of just short of satiation is reached. Healthy, actively feeding fish should be satiated within 20 to 30 minutes of feeding, and feeding fish more than they can consume in this relatively short period is wasteful and results in poor feed conversion. The previous discussion points out the importance of carefully feeding fish. However, logistical considerations associated with feeding a large number of ponds on large farms often mean that fish are not fed with the care and attention that would result in improved feed conversion and profitability. In this case, it is important to weigh the potential gains associated with improved feed conversion and increased production against the costs associated with additional labor for feeding carefully.

Other examples of efficient feeding practices include feeding from the upwind side of ponds, broadcasting feed across as large an area as possible, and taking time to observe fish feeding behavior. Feeding rates should be adjusted with season, with lower feeding rates used in winter.

### *Base feeding regimes on the capacity of the pond to assimilate waste nutrients and organic matter*

Water quality deteriorates when the waste load derived from feeding exceeds the capacity of the pond to assimilate waste nutrients and organic matter. Impaired water quality stresses aquatic animals and reduces the efficiency of feed conversion and production. High stocking and feeding rates also lead to effluents with a greater pollution potential, although the impact of feeding rates on effluent quality depends on when effluent is discharged relative to the time of maximum feeding rates. Nevertheless, stocking and feeding at profit-maximizing rather than yield-maximizing rates is more efficient (Losinger et al. 2000) and the likelihood of water pollution by effluents is less. There is no set value for pond assimilative capacity, which can vary greatly depending on water temperature, pond size and depth, amount of supplemental aeration, water exchange rate, and other factors (Hargreaves and Tucker 2003). Assimilation capacity can be loosely determined empirically by monitoring fish feeding response. A reduced feeding response that cannot be attributed to infectious disease may indicate that pond assimilative capacity has been exceeded.

In practice, maximum sustained feeding rates in ponds are determined by the availability of dissolved oxygen, which in turn is a function of the amount of mechanical aeration. By enhancing dissolved oxygen concentrations, aeration increases the capacity of ponds to assimilate organic matter by aerobic processes. Higher dissolved oxygen concentrations also increase the nitrification rate of ammonia to nitrate, which is then lost from the pond through denitrification in the large volume of anoxic sediment. Aeration and water circulation also affect rates of phosphorus loss from pond water. Formation of oxidized ferric phosphates and phosphorus occluded in ferric oxyhydroxide coatings on soil particles in the surface layers of sediment are important sinks for orthophosphate from the overlying water. In addition, the thin layer of oxidized surface sediment functions as a barrier that prevents the release of orthophosphate from deeper, anaerobic layers of mud into the overlying water (Masuda and Boyd 1994a, b).

In general, long-term daily feeding rates in summer months should not exceed about 30 kg/ha in ponds without mechanical aeration. Long-term average daily feeding rates can be increased to 110 to 140 kg/ha per day in ponds provided with efficient mechanical aerators at 2.5 to 3.5 kW/ha. Higher amounts of mechanical aeration may allow for higher feeding rates, but these more intensive pond systems may require periodic water exchange or additional energy inputs for continuous mixing to allow nutrient inputs to be sustained at that level. Maximum daily feeding rates of 300 kg/ha are possible with 4.25 to 8.50 kW/ha aeration and 30% daily water exchange. Obviously, the discharged water represents a potential pollution source that should be treated on-farm before reuse or discharge.

Despite the clear benefits of aeration, excessive aeration and circulation can have deleterious effects. Erosion of pond bottoms and embankment by strong water currents produced by certain types of aerators can suspend large amounts of particles and potentially increase the suspended solids concentration in pond effluents. Zones of scouring and deposition create an uneven pond bottom profile that renders harvesting fish with seine nets difficult and inefficient.

### *Use high-quality feeds*

Using high-quality feeds improves feed nutrient retention, thereby reducing amounts of metabolic waste and uneaten feed. Bulk or bagged feeds should be manufactured to contain a minimum amount of fines, or dust. Fish feeds are more fragile than feeds for livestock and poultry and will naturally contain 3 to 5% fines. Fines should not be fed from bagged feeds and it may be possible to screen fines from bulk feeds. Feeds should be stable in water long enough so that pellets remain intact until eaten. The dry matter retention after 1 hour, an index of water stability, should be >90%. Compared with floating feeds manufactured by cooking extrusion, steam-pelleted (sinking) feeds fracture more easily during shipping and handling and disintegrate more rapidly in water. Although more expensive, extruded feeds are therefore recommended for most pond aquaculture situations.

Feeds should be formulated to meet the nutritional requirements of the cultured species and should be formulated using practical ingredients that have high dry matter and protein apparent digestibility. Formulations should be designed to enhance nitrogen and phosphorus retention efficiency and reduce metabolic waste output (Box 6.8). Feeds should contain sufficient dietary energy to spare dietary protein (amino acids) for tissue synthesis. Feed protein levels should be as low as possible without causing adverse effects on fish growth, health, processing yield, or fillet quality. To a large extent, feed protein requirements reflect the trophic position of the cultured animal, with higher levels required for carnivorous species and lower protein levels for herbivorous or omnivorous species. Generally, higher levels of feed protein are also required for culture of the early life stages of aquatic animals. Available phosphorus levels should be slightly in excess of the dietary requirements of the cultured species for each life-history stage, and the formulation should be designed to minimize the difference between total feed phosphorus levels and available feed phosphorus levels. Consult a qualified aquatic animal nutritionist or feed manufacturer for information regarding feed formulation.

### *Use feeds with the least amount of fishmeal and other animal protein as possible*

Cultured fish do not have a requirement for fishmeal, having only a requirement for specific essential amino acids, minerals, and fatty acids. Fishmeal is an excellent source of these nutrients, with amino acid profiles similar to that of the requirements of cultured finfish. Fishmeal is also an excellent source of energy and is highly palatable. The protein and energy in fishmeal is highly digestible, implying that waste loading from fish fed diets with high levels of fishmeal is low. However, fishmeal is an expensive practical ingredient and cost usually limits the level of incorporation in the diet. Given that feeds are the single largest variable cost in most pond aquaculture operations and that fishmeal is the most expensive component of aquaculture feeds, there is a strong economic incentive to reduce feed costs and reduce the level of fishmeal in feeds formulated with practical ingredients. Fishmeal replacement remains one of the most active areas of aquaculture nutrition research.

Environmental advocates have criticized the use of fishmeal in aquaculture (Naylor et al. 2000), claiming that the production of fish in aquaculture using fishmeal derived from capture fisheries for small pelagic species represents a net loss of protein. These arguments have been refuted on the basis of the differences in the ecological efficiency of carnivorous fish growth in natural and aquaculture production environments, and on the greater efficiency of protein production in aquaculture compared to terrestrial livestock production, where feeds include fishmeal. However, the use of fishmeal in aquaculture feeds remains controversial. Other studies (Hites et al. 2004) have indicated that levels of environmental contaminants in fishmeal are variable, but they can accumulate and concentrate in cultured fish. Thus, reducing the level of fishmeal in aquaculture feeds, particularly from sources with high levels of environmental contaminants, is desirable from the standpoint of food safety and product marketing.

Meals made from the rendered by-products of beef or pork processing are nutritionally good substitutes for fishmeal in feeds for most pond-raised fish. Although animal protein sources other than fishmeal are good sources of dietary energy, protein, and minerals for fish, some consumers may be concerned about fish grown on feeds containing by-products of ruminant livestock slaughter because of a perceived link with “mad-cow” disease (bovine spongiform encephalopathy or BSE). In response to consumer concerns, the European Union Commission on Food Safety and Animal Welfare strengthened the European Union’s BSE control measures in June 2000 by requiring all member states to remove ruminant animal by-products from all animal feeds, including fish feeds. The United States Food and Drug Administration bans the use of most rendered mammalian proteins in feeds for ruminant animals but allows their use in feeds for nonruminants, including poultry, swine, and fish because there is no evidence of transmission of BSE from ruminants to nonruminant animals (Matthews and Cooke 2003; Ingrosso et al. 2006).

In summary, the reasons for reducing the amount of fishmeal and animal protein in aquaculture feeds are related to 1) incentives to reduce the cost of production, 2) negative consumer perceptions about the incorporation of animal protein in general and fishmeal in particular into aquaculture feeds, and 3) perceived or real environmental impacts on natural ecosystems of which small pelagic fish species are a key component.

Feeds for omnivorous species such as channel catfish and herbivorous species such as tilapia do not require animal protein to meet dietary amino acid requirements. Nonetheless, some fishmeal (up to 4%) and fish oil (as a top dressing) is included to increase the palatability of the feed. Feeds for omnivorous and herbivorous species should not include animal protein from the by-products of the slaughter of ruminant livestock.

### *Handle and store feeds to maintain feed quality*

Feeds for commercial aquaculture are formulated and manufactured to have low amounts of inedible fines and to remain stable until they are used. Feeds must, however, be handled and stored properly to prevent deterioration and to maximize the efficiency of feed use by the cultured species. Bagged feed should never be handled roughly because abrasion of feed within the bags can produce large amounts of fines that will not be consumed by fish and therefore will add directly to the waste load within the pond. Bulk and bagged feeds should be stored in cool, dry areas. Because this may not be possible with bulk feed stored in bins on the farm, bulk feed should be purchased in amounts that will be used quickly so that storage time in minimized. Use feeds on a first-in and first-out basis so that older feed in bins or bags is used before using more recently purchased feed. Improperly stored feed or feed stored for too long may become moldy. Never feed moldy feed to fish because molds reduce the nutritional quality of the feed and may produce toxins detrimental to fish growth and health. Barrows and Hardy (2001) present an excellent detailed account of proper feed handling and storage, particularly for bagged feeds.

## Pond Fertilization

Chemical or organic fertilizers are applied to some ponds to increase aquaculture production. Chemical fertilizers provide essential plant nutrients that stimulate phytoplankton growth; organic fertilizers provide nutrients and organic matter that stimulates plant and bacteria growth. Phytoplankton and bacteria then serve as the base of food webs that provide natural food organisms—such as zooplankton and insects—for fish or crustaceans. Pond fertilization is common throughout the world in the culture of fish and crustaceans that are capable of efficiently using natural food production. In the United States, pond fertilization is most commonly used in sportfish ponds and aquaculture ponds used for bait and ornamental fish culture. Combinations of organic and chemical fertilizers are also used in ponds for the early life stages of hybrid striped bass, channel catfish, and other foodfish. Fertilization is also used to promote phytoplankton blooms that prevent the growth of nuisance weeds and to stimulate production of a vegetative forage crop that serves as the base of a detrital food web in commercial crayfish ponds.

When used correctly, fertilization can be an ecologically efficient, cost-effective approach to pond aquaculture. Misuse of fertilizers can, however, be wasteful of a valuable resource and increase the risk of environmental degradation inside and outside the pond.

## *Better Management Practices for Pond Fertilization*

### *When used to promote phytoplankton blooms, apply fertilizers only as needed*

Ponds receiving large inputs of nutrients from other sources should not be fertilized. For example, plant nutrients derived from fish wastes via manufactured feed will usually promote abundant phytoplankton growth without fertilization. Likewise, ponds with watersheds in pastures of agricultural cultivation may receive nutrient-enriched runoff that encourages adequate phytoplankton growth without additional nutrient input. In either case, fertilization may cause excessive phytoplankton growth; greater oxygen demand; and higher concentrations of organic matter, nitrogen, and phosphorus in effluents. An exception is the use of fertilizers to encourage rapid phytoplankton growth for aquatic weed control immediately after ponds are filled. Fertilization for aquatic weed control in pasture ponds or ponds with feeding can be stopped once a phytoplankton bloom develops. The bloom will then be sustained by nutrients derived from feed or runoff.

### *Use fertilizers efficiently*

Inefficient use of fertilizers is wasteful, economically unsound, and may result in excessive phytoplankton growth and elevated nutrient and solids concentrations in pond effluent. Regrettably, efficient pond fertilization practices are difficult to determine because response to fertilizers varies depending on water source (particularly hardness and alkalinity), texture and chemistry of pond bottom soil, watershed land use, pond morphology and hydrology, climate, past fertilization history, and a host of other factors. Fertilization recipes are available for ponds in some regions but these recommendations are, at best, only guidelines that may need to be changed depending on the response in a particular setting (Box 6.9). Boyd and Tucker (1998) summarize pond fertilization programs and also discuss factors affecting pond fertilization success. Private consultants or experts at

### BOX 6.9
### Algal Bioassay for Efficient Fertilizer Use

In general, algal growth is limited by phosphorus in freshwater and nitrogen in brackishwater, although exceptions to this generality abound. To use fertilizers efficiently, it is important to identify the nutrient that limits algal growth. Knud-Hansen (1998) described a simple algal bioassay procedure that identifies nutrient requirements and the associated nutrient input rates. Fish (tilapia) yield in ponds managed with a fixed-input fertilization regime were significantly greater but more variable than that in ponds fertilized using the algal bioassay procedure (Knud-Hansen et al. 2003). The nitrogen utilization efficiencies of the two treatments were similar, but phosphorus was used more efficiently when applied according to the algal bioassay procedure. Overall fertilization efficiency and profitability was greater using the algal bioassay approach than with the fixed-input regime.

universities can provide advice on fertilization practices applicable to specific regions and culture species. Basic soil and water testing can indicate the need for specific nutrients and appropriate types, rates, and frequency of fertilizer application.

### *Apply agricultural limestone to ponds with total alkalinity below 20 mg/L as $CaCO_3$*

Acidic, low-alkalinity water is perhaps the most common cause of poor response to pond fertilization and inefficient fertilizer use. Acidic bottom soils adsorb fertilizer phosphorus, making it unavailable to phytoplankton. Low-alkalinity waters are also deficient in carbon, an essential plant nutrient. As a general rule, fertilizers are not effective in promoting phytoplankton growth in pond waters with total alkalinities below 20 mg/L as $CaCO_3$. The problem is easily corrected by applying agricultural limestone to increase alkalinity (Boyd and Tucker 1998).

### *Do not use animal manures for fertilizers*

Organic pond fertilizers include composted vegetation, hay, grain and oilseed meals, or animal manures. Organic materials added to ponds slowly decay and release nutrients that are then available to support phytoplankton growth. Organic detritus produced during decomposition may also be consumed by zooplankton, macroinvertebrates, and even by the cultured fish or shellfish. Organic fertilizers often make use of low-quality organic material that would otherwise be considered a waste product. Combined with chemical fertilizers, organic fertilizers promote a stable and diverse plankton community that is particularly desirable in the culture of larval fish and juvenile fish (Ludwig 2004).

Organic fertilizers are not widely used in the United States, the exception being grain and oilseed meals used as part of fertilization programs for the early life stages of some foodfish. Most organic materials have low fertilizer value and are less convenient to use than chemical fertilizers. Organic fertilizers also create an oxygen demand as they decompose and release humic substances during decomposition that may stain the water.

When organic fertilizers are needed, grains or oilseed meals are preferred to manures or other wastes. Animal manures may contain antibiotics or other drugs that could contaminate effluents or fish flesh. Animal manures are also nutrient-poor organic fertilizers and may cause oxygen depletion when used in amounts necessary to promote rapid phytoplankton growth. Other aesthetic and sanitary concerns related to the use of manures argue against their use in foodfish aquaculture, despite their widespread use in low-input aquaculture throughout the world.

### *Do not exchange water after fertilization*

Water exchange reduces the effectiveness of fertilization by flushing and diluting nutrients and natural food organisms. Water exchange also increases mass discharge of organic matter and nutrients by increasing effluent volume. Fertilization rates, frequency of fertilizer application, and mass discharge of nutrients and organic matter can therefore be reduced by minimizing pond overflow. Practices for reducing pond overflow are discussed in the section "Overflow Effluents."

### *Do not fertilize ponds 1 or 2 days before significant precipitation events*

Concentrations of plant nutrients are highest a day or two after chemical fertilizers are applied to ponds. If pond overflow occurs at that time, the nutrient concentration in effluent will be greater than normal. Runoff following heavy rains can also muddy ponds and impair response to fertilization because of inadequate light for phytoplankton growth. Clay particles in turbid runoff sequester phosphorus and remove the nutrient from water as clay particles settle to the bottom or are washed out of the pond. Although it is difficult to predict short-term weather, attention should be paid to official forecasts and pond fertilization should be postponed if there is a significant chance that heavy rainfall will cause overflow or muddy conditions in the pond.

### *Store fertilizers properly*

Fertilizer storage areas should be separate from other uses. Store fertilizers on pallets in a cool, dry place. The storage area must be covered and protected from rain and runoff. Preferably, the storage area should be a building with an impermeable floor. Store fertilizers away from pesticides or other agricultural chemicals and purchase fertilizers in amounts that will be used relatively quickly so there is no carryover from year to year. Spills or ripped bags should be immediately swept up and stored in barrels or buckets and used first during the next scheduled application.

## Fish Escape

Fish can escape when aquaculture ponds become hydrologically linked to adjacent receiving waters. In most aquaculture ponds under normal operating conditions this connection is intermittent because water is discharged only when ponds are drained or overflow after heavy rains. However, hydrological connection can occur as a result of design, construction, or operational failures. Ponds may be improperly sited in flood-prone locations, where fish may escape when floodwaters overtop pond embankments that were not constructed sufficiently high. If ponds are not properly constructed, embankments or drainage structures may fail, leading to the release of fish. Fish can also escape during routine farm activities, especially when fish are handled during stocking, grading, or harvesting. Fish can also escape through predation or vandalism.

The cumulative risks of escape must be considered in terms of the hazards or consequences associated with escape and the probability of each hazard occurring. The main hazards associated with escape include displacement of native species through direct predation, competition for food or spawning sites, or habitat alteration; transmission of pathogens to natural populations; and potential changes in allele frequencies within populations of native conspecifics. In the case of channel catfish culture in ponds in most of North America, the geographic extent of pond aquaculture overlaps with the native range of the species, and so the consequences of escape to natural populations are relatively benign. In the case of ornamental fish culture in Florida, virtually all species cultured are not native, and at least 20 of the 32 nonnative fish species that have been released or escaped are now established in that state.

Nonnative fish that escape, persist, and cause environmental and economic harm when they escape are described as invasive. Invasive species have characteristics or a combination of characteristics that facilitate their survival and establishment: broad water quality tolerance limits, omnivory, rapid growth rates, early maturity, high fecundity, and a lack of natural competitors or predators. Invasive species can have negative effects on biodiversity, habitat quality, and ecosystem functioning. Regrettably, the record of species that have escaped from pond aquaculture facilities and established reproducing populations is not good. There are notable examples of the establishment of invasive species that were introduced to a watershed by escape from aquaculture ponds. In the United States, the establishment of grass carp, bighead carp, and silver carp in the Mississippi River and its main tributaries is attributed, in part, to escapes from commercial pond aquaculture facilities. A variety of species have been purposefully stocked as gamefish by public agencies that may also have escaped commercial culture, such as common carp; brown and rainbow trout; largemouth bass; and various sunfishes, pikes, salmonids, and catfish. Escaped fish represent an undesirable loss of potential revenue to pond culturists, so there is a strong economic incentive to prevent the occurrence of escapes. Thus, the practices discussed below focus on measures that can be implemented to prevent escapes and not measures to contain the spread of fish once escape has occurred.

### *Better Management Practices for Preventing Escapes*

#### *Consider the risk of flooding in site selection*

Selecting sites that are subject to flooding increases the risk of escape if the elevation of floodwaters exceeds that of the top of pond embankments. Sites should be selected above the 100-year flood elevation as determined by the USDA Natural Resources Conservation Service or an equivalent natural resource regulatory agency. The elevation of the top of pond embankments should be 50 cm above the 100-year flood elevation. Selected sites may experience 0 to 5 floods every 100 years.

#### *Construct and maintain pond embankments to prevent failure*

Standards for pond design and construction as outlined in the pond construction section should be followed. Pond embankments should be constructed with 3 : 1 side slopes to minimize erosion and scouring by floodwaters. Embankments should be compacted properly. Embankments that are subject to erosion from wind-driven waves should be armored with riprap or other protective measures. Embankments should be vegetated shortly after construction and grass cover maintained by mowing. Burrowing animals should be controlled by trapping or hunting. Documented levee inspections should occur at least monthly and following each severe storm event.

#### *Include barriers to escaped fish in drainage structures and ditches*

Barriers to the escape of fish should be considered optional for species that are cultured within their native range, but essential for nonnative species. No single barrier will prove sufficient and a redundancy of barriers should be built and maintained to ensure effectiveness. Barriers must be sufficiently open to allow water to flow through, but sufficiently closed to retain the smallest life stage (e.g., egg, larvae, fry, or fingerling) in the pond. Debris must be regularly cleared from all barriers and screens to prevent clogging and barrier overtopping during overflow.

Pipe culvert barriers can be placed over inlet or outlet ends of drainpipes or the pipe risers that control water level. For fry, 5-mm (3/16-inch) mesh, and for fingerlings, 13-mm (1/2-inch) mesh can be secured to pipes with a coupling band or clamp. This barrier is appropriate for flows to 1.7 $m^3$/minute (1 cubic foot per second).

Spillway barriers consist of a metal framework with horizontal bars or expanded metal mesh extending the full width of the spillway and 1 m above the normal high-water level. The barrier should be constructed to withstand a 20-year flood. The horizontal bars can be 9.5- to 25-mm (3/8- to 1-inch) diameter metal bars or PVC pipe. To retain grass carp, bars should be spaced 25 to 38 mm (1 to 1.5 inches) apart. Gabion filters (rock screen) consist of various-size rocks (10 to 20 cm; 4 to 8 inches) and gravel encased in wire mesh or chain-link fencing that is placed on the spillway. Gabion filters that are 2 m wide × 3 m long can accommodate water flow rates less than 1.7 $m^3$/minute (1 cubic foot per second).

Drainage ditch screens consist of flattened, expanded metal mesh welded to an angle-iron frame that extends across the full width of a drainage ditch. The barrier should be placed flush against ditch side slopes. Barrier height should be sufficient to handle intermittent flows to 3.4 $m^3$/min (2 cubic feet per second). If on-farm ditches or stormwater retention ponds hold water year-round, they should be stocked with native predaceous fish that will consume escaped fish.

### *Prevent escape during fish transfers*

Production of most species in pond aquaculture is accomplished in phases, necessitating movement of fish between one culture unit and another. For example, channel catfish fry are stocked into nursery ponds from a hatchery and then harvested and stocked into foodfish production ponds. At harvest, foodfish are graded, loaded into transport trucks, and hauled to a processing plant. At each point where fish are handled, there is opportunity for escape. In particular, fish can escape with outflowing water when ponds are drained for harvest if drainage structures are inadequately screened. Knowledge of the behavior of fish in response to flowing water can help determine what type of barrier is appropriate. Fish escape during transport can be avoided by maintaining harvest and transport equipment in good working order through periodic inspections and restricting operation of loading equipment to trained personnel. An HAACP-type evaluation can assess the steps in the production process where the probability of escape is elevated, leading to implementation of a preventive program to minimize that probability.

### *Deter nuisance wildlife*

Active nuisance wildlife deterrence is an essential component of an escape prevention program. Burrowing animals, such as muskrat, nutria, and beaver, can excavate tunnels in embankments, increasing the risk of washout, and undermining the structural integrity of the embankment. Emergent aquatic plants, especially those with starchy tubers, that provide food and cover should be eliminated from pond margins. Keeping embankments well mowed or periodic spot applications of approved herbicides can control emergent aquatic plants. Burrowing animals can be captured with traps set in den openings, runways, or slides. After animals are removed, the area of the embankment around the burrow opening should be excavated to the full extent of the burrow, refilled with soil, properly compacted, and promptly revegetated to minimize erosion.

Although not as serious a potential problem as escapes caused by burrowing animals, some birds can carry live fish from ponds. Most of the bird species that are most problematic from the standpoint of fish predation consume fish at the point of capture. However, some raptors (e.g., ospreys and eagles) and owls capture fish swimming near the pond surface by grasping and holding with talons and flying off to a perch to consume the fish. Struggling fish may be dropped into receiving waters outside the facility boundaries. Although a limited number of some species of birds can be killed under permits, raptors are protected by legislation, and so conventional, nonlethal scare tactics are the only option. Effective nonlethal methods include frightening devices (e.g., propane cannons, pyrotechnics) in combination with harassment patrols. Nuisance birds can be excluded from small ponds by overhead wires, nets, or other barriers. In the United States, the USDA Animal and Plant Health Inspection Service (APHIS), Wildlife Services program provides technical assistance on appropriate control methods for nuisance wildlife.

### *Do not culture invasive species in ponds without rigid safeguards*

Pond aquaculture of potentially invasive species should only be undertaken after thorough study and consultation with knowledgeable fisheries and aquaculture specialists and federal and state regulators to determine risks and benefits. It is rare that the potential benefits of culturing an invasive species will outweigh the costs associated with escape and invasion. Due diligence should be documented when deciding whether culture of an invasive species is appropriate. Producers should demonstrate that adequate protection measures are in place and that the risk of escape and establishment is low. Producers should review the fish life history, habitat and food preferences, and the history of invasion elsewhere of a particular species to assess the risk of establishment.

State fish and wildlife resource management agencies usually administer permits to culture nonnative species. The United States Fish and Wildlife Service can designate invasive species that have become established and caused ecological and economic harm as injurious, which limits their importation into the United States and prohibits interstate transport.

Beyond physical barriers, producers of nonnative species should make a conscientious effort to prevent escape and mitigate postescape effects of nonnative species. For some species, sterile (triploid) fish or monosex fish can be cultured. A plan should be in place in the event of invasive species escape to contain, recover, or eradicate them. Recapture equipment or sufficient quantities of approved piscicides should be in place for a rapid response, if this approach is warranted and allowed by law.

## Predator Control

High concentrations of fish and crustaceans in outdoor aquaculture facilities provide attractive foraging opportunities for certain species of birds, reptiles, mammals, and fish. Relative to other aquaculture production systems, ponds are especially vulnerable to wildlife depredation. Ponds may extend over large areas that are difficult or impossible to protect using barriers or enclosures. Pond aquaculture facilities are usually located in rural or isolated areas that already support diverse and abundant wildlife, and many of these animals will be attracted to the concentrated food resources available in ponds. Ponds constructed in the flyways for migratory birds offer convenient foraging opportunities and, in areas with extensive aquaculture development, the attraction of a year-round food supply may even cause birds to change foraging behavior and migration patterns and linger near farms for longer periods of time (Glahn and King 2004).

The effect of predators on aquaculture production can range from insignificant to catastrophic. Mammals (such as otters [*Lontra canadensis*], mink [*Mustela vision*], and nutria [*Myocaster coypu*]) and reptiles (such as snakes and alligators) may be a nuisance, but they rarely cause significant economic losses in pond aquaculture. Predacious fish can cause serious losses, especially in the early phases of production. Birds are the most important predators in pond aquaculture, although impact varies with species and number of birds. Certain birds, such as the great egret (*Ardea alba*), feed primarily on weak or diseased fish found near pond banks and their economic impact is probably minor. In contrast, double-crested cormorants (*Phalacrocorax auritus*) are highly adapted to foraging on live fish in open water and often visit aquaculture ponds in large flocks. Cormorant depredation may therefore cause serious economic hardship in areas with abundant populations.

In addition to direct losses to predation, predators indirectly affect aquaculture production by serving as vectors for infectious diseases. Birds and other animals may move infected fish from one pond to another or spread pathogens in regurgitated stomach contents or fecal material. The importance of animals as mechanical vectors of disease is, however, largely unknown. On the other hand, birds also serve as obligate hosts for certain digenetic trematode fish parasites and are therefore integral in the spread of these disease organisms among water bodies. Digenetic trematodes have complex life cycles in which fish may act as either intermediate hosts that harbor an immature stage of the parasite or as final hosts in which the adult trematodes are found. Trematodes using fish as intermediate hosts usually involve fish-eating birds as final hosts and mollusks, usually snails, as first intermediate hosts.

Predator control practices should minimize the interaction between wildlife and cultured animals to protect wildlife and minimize production losses. Predators may not only cause direct loss of fish, but the mere presence of predators, especially birds, around aquaculture facilities can keep fish in a perpetual state of fright, resulting in increased physiological stress and poor feed conversion. Direct and indirect effects on production will reduce resource-use efficiency and increase waste generation. Limiting access of predators to moribund and dead fish minimizes the potential spread of pathogens into wild fish populations.

Given the abundance of wildlife, especially birds, associated with aquaculture ponds, it is highly unlikely that predator control practices in pond aquaculture will negatively impact natural populations of wildlife. In fact, the conversion of agricultural land to aquaculture ponds has created additional habitat for wading birds, waterfowl, and other species that has helped support healthy populations in the face of wetland and other habitat loss elsewhere (Huner 2000). Nonetheless, aquaculture ponds are visited by birds that are classified as threatened or endangered by the United States Fish and Wildlife Service, and aquaculturists must be aware of the legal and ethical limitations on predator control methods for threatened and endangered species.

Predation of cultured fish or crustaceans can be eliminated only through total exclusion, which is impractical on all but the smallest pond facilities. Also, many predators quickly learn to avoid or ignore management efforts. Effective management usually relies on a combination of management approaches. Overall, the best approach is one based on principles of Integrated Pest Management where predators are identified, the type and level of damage is assessed through regular monitoring, and control methods are chosen that are appropriate for the predator and level of damage.

## Better Management Practices for Predator Control

### Assess predator impact

The potential impact of predation determines whether management efforts are economically justified. Predatory mammals tend to be nocturnal and elusive, and often the only signs of predation are tracks, scat, and chewed or partially eaten fish on pond embankments. Although birds often swallow fish whole, leaving few signs of damage, predation by birds is easy to confirm because the important fish-eating birds, except for pelicans, forage during daylight hours. Problems can be initially confirmed by observing actively feeding birds or birds loafing or roosting near ponds.

Regrettably there are no simple quantitative tools to assess the economic impact of wildlife damage on aquaculture farms, and there is no way to predict whether a small problem will become a major problem if action is not taken. It is therefore prudent to seek advice and assistance from experts as soon as a problem is suspected. Technical assistance and information on wildlife predation control at aquaculture facilities can be obtained by contacting the nearest USDA Animal and Plant Health Inspection Service, Wildlife Services office. To find the nearest Wildlife Services office, contact your local county Extension agent or call the USDA-APHIS/WS Operational Support Staff Office in Riverdale, Maryland, at (301) 734-7921.

Problems with digenetic trematodes are a special case because widespread infections of fish may occur with little or no evidence of bird involvement. Birds that serve as final hosts for adult trematodes need not feed on fish in a pond to initiate an infection. If a single trematode-infected bird flies over a pond and defecates, thousand of trematode eggs will be dispersed into the pond. If the pond contains the correct snail and fish intermediate hosts, the life cycle can be completed and fish will become infected. Moreover, American white pelicans (*Pelecanus erythrorhynchos*)—the final host for the *Bolbophorus damnificus* trematode that infects channel catfish—often forage at night and farmers may be unaware that pelicans are visiting or flying over their farm. Risks of trematode infections are best assessed by frequent monitoring of the fish population for clinical signs of infection. Farmers should also be aware of early, population-level signs of the disease, such as an unexplained reduction in fish feeding response (Wise et al. 2004).

### *Identify the predator responsible for losses*

Identification of the species responsible for predation is necessary to assess the potential impact of predation and formulate a management plan (Fig. 6.9). Species identification is also critical because wildlife management is regulated by federal and state laws. Field guides to birds and other wildlife are available at local libraries and bookstores. Technical assistance can be obtained from USDA Wildlife Services using the contact information above.

### *Check with appropriate regulatory authorities*

All fish-eating birds are protected under the Migratory Bird Treaty Act and may not be killed without a depredation permit or depredation order. The United States Fish and Wildlife Service (USFWS) has regulatory authority for managing migratory birds. If fish-eating birds are causing problems at an aquaculture facility, the USFWS may issue a depredation permit that allows the producer to kill a limited number of some species to reinforce the effectiveness of nonlethal control measures. Some fish-eating birds also are protected by the Endangered Species Act. For example, wood storks (*Mycteria americana*) found east of the Mississippi-Alabama border receive this protection. No lethal or nonlethal control activities can be used to control any bird species using aquaculture facilities in this region if wood storks are nearby. The Bald and Golden Eagle Protection Act further protects eagles and prohibits all hazing activities near bald (*Haliaeetus leucocephalus*) and golden eagles (*Aquila chrysaetos*), except with special permission from the USFWS.

**Fig. 6.9.** Fish-eating birds can cause considerable economic loss but most are protected under one or more laws. These are great egrets (*Ardea alba*), one of the most common fish-eating birds seen on catfish ponds in the southeastern United States. Egrets feed mostly on diseased or dead fish along the shore and, as such, are not considered a major predator problem. Photograph courtesy of Les Torrans.

Federal and state laws may also pertain to other wildlife, and the first step when considering managing predation problems on aquaculture facilities should be to contact USDA Wildlife Services using the contact information above. Operational support staff at Wildlife Services can assist with identifying the problem and recommending legal control methods.

### *Design facilities to reduce predation losses*

Physical characteristics of farms can affect the extent of predation losses and the effectiveness of predator-control practices. Isolated farms and farms near loafing or roost sites are especially vulnerable to bird predation. Small fish are more susceptible to wildlife predation than larger fish, and on farms with both fingerling and foodfish ponds, fingerling ponds can be located near the farm headquarters or other areas with more human activity. Birds and other wildlife tend to avoid close proximity to humans, and ponds closer to headquarters will also be more convenient to patrol and manage for wildlife control. Large ponds tend to suffer greater bird predation losses because birds feel safer on large ponds and management is more difficult. For example, birds harassed from one embankment or one end of a large pond often simply fly across the pond and resume feeding. Using smaller ponds—particularly for small, vulnerable fish—can reduce losses to wildlife.

It may not be practical to redesign or relocate existing facilities to address predation problems, but even relatively minor changes can help reduce losses or make management efforts more effective. For example, removing weed and brush around ponds, keeping embankments mowed, and selectively removing nearby trees that serve as loafing, hiding, or roost sites can reduce predation pressures. Assuring all-weather access to ponds is also important so that harassment efforts can continue without interruption regardless of weather.

### *Use frightening or harassment techniques*

Frightening and harassment techniques use sound, sight, or both to discourage birds and other wildlife from feeding, roosting, or loafing near ponds. Passive frightening and harassment programs (those not requiring human presence to function) employ a wide variety of devices, including exploding or whistling pyrotechnics, automatic propane cannons, flashing lights, human effigies (scarecrows), flash tape, and even old vehicles parked on pond levees. Programs should be initiated before birds arrive and establish feeding habits. For example, on southern aquaculture farms visited every year by overwintering double-crested cormorants, deterrence programs should start in fall when birds first begin arriving from northern breeding grounds.

Harassment must be aggressive and persistent to be effective. Most passive techniques discourage predation only for a short time because birds quickly lose their initial fear and become habituated to the deterrent device. Periodically changing the location of the devices or alternating the type of device can enhance long-term effectiveness. However, even the most aggressive passive deterrence program rarely eliminates wildlife predation and may quickly become ineffective in areas with heavy predation pressure. Active patrols employing nonlethal or lethal measures to reinforce passive measures are usually required for effective, long-term control, especially on large farms.

When all measures to disperse birds using nonlethal techniques have been exhausted, farmers may consider using limited killing of birds to reinforce the fear of nonlethal measures. Depredation permits are required from the United States Fish and Wildlife Service and, in some states, from the state wildlife agency to kill almost any species of bird. For currently applicable laws, contact the nearest USDA Wildlife Services or United States Fish and Wildlife office.

### *Discourage birds from areas near the farm*

Fish-eating birds usually focus daily activities around night roosts or daytime loafing sites within a short flight to feeding areas. Dispersing birds from roosts or resting sites can augment on-farm deterrence activities, although the value of off-farm dispersal varies with species and intensity of the management effort. Cormorants, for example, usually have night roosts within a few miles of foraging areas, and regionally coordinated roost dispersal activities can significantly reduce numbers of cormorants visiting catfish farms (Tobin et al. 2002). Pelicans may forage near their daytime loafing areas, but foraging activities range over a much greater area than cormorants and are more difficult to manage.

Dispersing cormorants from roosting and loafing areas may require teams working in a regionally coordinated effort. Teams should enter the roost shortly before sunset and fire pyrotechnics into the roost to prevent birds from settling. Roosts should be dispersed on several successive nights. If there are several roosts in the immediate vicinity of a farm where damage is occurring, all the roosts should be dispersed simultaneously so that birds do not simply fly to another nearby roost.

American white pelicans use shallow water areas such as rice fields, waterfowl impoundments, flooded fields, and abandoned catfish ponds as daytime loafing areas. Loafing areas can be made less attractive by patrolling daily and harassing birds to ensure that they are dispersed. Abandoned fish ponds should be drained to eliminate them as habitat for fish-eating birds.

### *Use exclusions, impediments, or barriers*

Total exclusion is the only means of eliminating predatory wildlife and may be justified on small farms raising valuable crops, such as ornamental fish. Exclusion structures are usually made of netting, which should be a dark material rather than clear monofilament to reduce chances that birds will inadvertently fly into the netting and become entangled. Netting should also be checked frequently to remove any trapped birds. Exclusion structures should be installed by knowledgeable professionals to assure ease of maintenance and resistance to damage by ice and wind. Relatively inexpensive polypropylene or nylon netting that is specifically manufactured for predator exclusion from aquaculture facilities can be installed (Fig. 6.10). Depending on the size of the facility and the durability of the structure, netting enclosures may require a relatively large initial investment, but the cost can be amortized over a relatively long period.

Complete exclusion of predators is not possible on ponds larger than 1 to 2 ha and is not economically feasible on large farms, regardless of pond size. Partial exclusion or

**Fig. 6.10.** Close-up of bird-exclusion netting over a small ornamental fish pond in Florida. Photograph courtesy of Jimmy Avery.

deterrence using impediments such as wires, lines, or fencing may be more cost-effective on larger facilities. Such devices do not prevent bird predation, but rather reduce predation by discouraging birds from landing or wading into ponds. Overhead lines and wires suspended in one direction or in a crossing pattern are particularly effective in reducing depredations by birds with long takeoff distances, such as cormorants. Lines can be widely spaced (10 to 20 m) and should be highly visible to the birds to be effective. Adding brightly colored streamers or Mylar balloons increases the effectiveness of these systems. Major constraints to using such impediments are cost and interference with pond culture practices, especially fish harvesting.

Wading birds, such as herons and egrets, prefer to land on solid ground and walk into the pond. Fencing or perimeter netting will discourage wading birds from walking into the pond. Perimeter fences may not be effective if the pond margins are shallow because birds can land and forage on the water side of the barrier.

Exclusion devices are expensive and there are numerous options. Before making an investment in a particular technique, farmers should obtain technical assistance from the nearest USDA Wildlife Services office using the contact information above.

### *Prevent the introduction of predatory fish*

Predatory fish accidentally introduced into aquaculture ponds can cause large losses, especially in ponds used to raise bait or ornamental fish or in nursery ponds for juvenile catfish or hybrid striped bass. Aside from direct losses attributable to predation, wild fish can also serve as vectors for infectious disease organisms. The key to managing losses to predacious fish is to prevent their introduction, because it is difficult and expensive to selectively remove wild fish from culture ponds using piscicidal chemicals.

Unwanted fish most commonly enter ponds with the water supply, as contaminants during stocking, or through unsecured pond drainage structures. Additional routes include floodwaters that overtop pond embankments and fish transported from one water body to another by wildlife. Many of the practices applicable to controlling accidental escape of the culture species are also applicable to controlling accidental introduction of predacious fish. Ponds should be properly constructed in areas not prone to flooding, drainage structures should include barriers to prevent fish movement into or out of the pond, and nuisance wildlife should be deterred. The risk of accidentally introducing wild fish can be reduced by using groundwater to fill ponds. If surface waters are used, inlets should be screened to prevent introduction of fish or eggs. Any undesirable fish in the pond can be eliminated by draining and drying the pond before refilling for the next culture cycle. Fish in puddles remaining when the pond is drained can be eliminated by applications of quicklime. Fry and fingerlings should be purchased from reputable sources and inspected for contamination with unwanted fish before stocking.

## Aquatic Plant Control

Aquatic plants are essential components of pond aquaculture systems. In cultures relying upon natural food organisms to support aquaculture production, plants are the base of the food web and their growth is often encouraged through fertilization to increase aquaculture yield. Plant communities are also important in pond cultures receiving manufactured feed, even though plant-based food webs are of minor importance to the nutrition of animals in those cultures. Some plant growth is necessary because plants function with other components of the pond ecosystem to help maintain adequate environmental quality for aquaculture production. For example, oxygen produced in plant photosynthesis is usually the major source of dissolved oxygen in ponds.

Despite the importance of plants in aquaculture ponds, some plant communities interfere with pond management (especially harvesting and feeding), endanger the well-being of the animal under culture, or impair the quality of the aquaculture product. Such communities are undesirable, and aquaculturists often attempt to prevent them from developing in ponds or try to eradicate them if they become established. Aquatic plant management is a common practice in pond aquaculture and involves a variety of practices, all of which have potential environmental impacts both in and outside the pond. The overall goal of plant management should be to control undesirable vegetation in a way that is compatible with maintaining a well-functioning environment for fish production with minimal or no effects on nontarget organisms inside and outside the pond.

Effective, environmentally sound management of aquatic plant communities can be difficult because the ecology of aquatic plants is complex. Effective management, especially when using herbicides, requires experience and training. Consult with aquatic plant control experts at local universities or with lake-management consultants before undertaking treatment. Plant identification keys and management guidelines are available in Westerdahl and Getsinger (1988) and Petty (2005). Excellent online resources for aquatic plant management include websites managed by Texas A&M University's Aquaplant (aquaplant.tamu.edu) and the University of Florida's Center for Aquatic and Invasive Plants (aquat1.ifas.ufl.edu).

### *Better Management Practices for Aquatic Plant Control*

#### *Prevent weed problems whenever possible*

Almost any plant can be tolerated as long as it does not become so abundant that it interferes with producing the aquaculture crop. It is, however, difficult to predict whether a small infestation of weeds will spread and become a problem, so most control measures are implemented only when fairly large stands of weeds have already become established. At that time, using chemical herbicides is usually the fastest way to eradicate weeds and reestablish a phytoplankton community, which is usually the most desirable plant form in aquaculture ponds. Chemical weed control is, however, risky in aquaculture ponds because water quality deteriorates when dense stands of weeds are killed. Certain practices can reduce the probability of weed problems, thereby reducing chemical use.

Most noxious weeds start growing in the shallow areas of ponds where light penetrates to the bottom. Deepening the edges of ponds will discourage the establishment of emergent or submersed weeds, although this may not be possible in large ponds subject to rapid pond bank erosion. Ponds should have an adequate supply of water and be filled as quickly as possible. If several ponds are served by a common water supply, it is better to fill them one at a time rather than to slowly fill several ponds at once. By increasing water depth as quickly as possible, plants that grow from the pond bottom have less opportunity to become established. Excessive water flow through ponds flushes plant nutrients from the water, favoring rooted weeds that can obtain nutrients from bottom soils. Ponds should not have watershed areas larger than necessary to maintain water level and excess runoff from large watersheds should be diverted away from ponds.

An effective fertilization program can encourage the development of a phytoplankton bloom. A well-established phytoplankton community competes with other types of plants for light and nutrients, and usually prevents growth of submersed and emergent plants in all but the most shallow water. Fertilization should only be used to prevent weed infestations; if noxious stands of weeds are already established, fertilization will make conditions worse by stimulating further weed growth.

Removing weeds mechanically or by hand may reduce the possibility of having to use other measures to control plants. Routine mowing of pond banks will help prevent the establishment of dense growths of shoreline plants such as willows and will also reduce habitat for snakes. Manual removal of plants is feasible only in small ponds. Plants should be removed immediately as small areas become infested, because it is time consuming and laborious to manually remove established stands of weeds. Care should be taken to remove as much of the rootstock or rhizome as possible to minimize regrowth. Preferably, manual removal should be undertaken in the beginning of the plant-growing season.

#### *Identify the weed problem*

Correct identification of weeds is critical because potential impacts and management differ for each plant. Strategies effective on one species may be ineffective even on similar species. In particular, herbicides are selective (some much more than others), and effective control depends on matching the weed with the most appropriate herbicide. Private consultants or experts at local universities can help identify the weed problem. Plant identification keys are available in the publications and websites listed above.

### *Make management decisions based on site-specific conditions*

Environmentally sound and cost-effective management depends on the type of plant, the extent of plant coverage, the species and life stage of fish or crustaceans in the pond, water quality, time of year, and weather. Understanding these interactions, which differ for each weed problem, is largely a matter of experience. Until that experience is gained, seek advice from private consultants or experts at universities.

### *Use only those herbicides labeled for use in aquaculture*

Although hundreds of chemicals are used for weed control in the United States, only about ten active ingredients are labeled for use in aquaculture. Herbicide trade names and the status of herbicide label clearances change over time, so be sure to review the most current herbicide information for proper use and restrictions.

### *Carefully follow herbicide labels*

Herbicides sold in the United States must be registered with federal and state regulatory agencies. The printed information accompanying the herbicide container is called the *label* and constitutes a legal document. Failure to use herbicides according to label instructions can lead to severe penalties. From a practical standpoint, misuse of herbicides can result in poor weed control; risks to people, the aquaculture crop, or wildlife; or herbicide residue problems in the aquaculture product.

The label provides information on the active ingredient, directions for correct use on target plant species, warnings and use restrictions, and safety and antidote information. Remember, state and local regulations may be more restrictive than federal regulations. Certain products are registered as Restricted Use herbicides and can be legally applied only by trained and certified applicators or by people under their direct supervision. Be sure to check federal, state, and local regulations prior to using herbicides.

Herbicide treatment rates are based on pond area or pond volume. Miscalculation will result in either overtreatment or undertreatment (which may require additional treatments to eradicate the weed). In either case, more chemical than needed will be applied to the pond. Carefully measure pond dimensions and keep up-to-date records of pond size and depth. Pond surface area tends to increase and pond depth tends to decrease over time because of erosion of embankments and sedimentation of pond bottoms. The only way to be certain of average pond depth is to measure water depth before treatment at several dozen random locations.

### *Handle herbicides safely*

Although aquatic herbicides are relatively safe to handle, it is nevertheless important to keep exposure to an absolute minimum, especially for applicators. Herbicide labels and material safety data sheets advise what protective clothing and equipment should be worn, any precautions the handler should follow, a statement of practical treatment in case of poisoning, statements concerning hazards to the environment, any physical or chemical hazards, and directions on proper storage and disposal. By law, copies of labels and any supplementary labels must be in the possession of the applicator at the application site for each herbicide used. Anyone who handles a pesticide must read and understand all label statements prior to using the product. Herbicide safety is reviewed by Avery (2003).

### *Be aware of the consequences of herbicide use*

With the notable exceptions of copper-based algicides and the methylamine formulations of endothall, herbicides registered for use in United States aquaculture are of low toxicity to most aquatic animals and, when used at recommended rates, seldom cause direct toxicity problems. However, the use of herbicides in ponds has risks because treatment of a plant-infested body of water with any phytotoxic chemical can cause a dramatic change in environmental conditions that may endanger cultured animals. In particular, decay of plants killed by the herbicide may lead to dissolved oxygen depletion. The extent to which water quality is affected depends on the amount of plant material killed, the amount of plant material unaffected by the herbicide, the rate death occurs, water temperature, and other factors. Obviously, the risks of herbicide treatment are greatest when treating dense stands of weeds during hot weather because the dead plant material is rapidly decomposed and the solubility of oxygen in water is low. It is usually inadvisable to use herbicides under such conditions, but if treatment is absolutely necessary, the pond should be divided into halves or thirds and only one portion of the pond treated at one time. After waiting a few days, another portion can be treated, and so on. With this method, there may not be enough vegetation killed at any one time to cause an oxygen depletion. In any case, supplemental aeration should be available to prevent fish kills caused by low dissolved oxygen concentration resulting from plant decomposition.

### *Dispose of herbicide containers properly*

Improper disposal of herbicide containers can cause contamination of soil and water and may result in fines or loss of an applicator's license. Empty herbicide containers must be triple rinsed, with each rinsing drained into the herbicide mix tank. If no mix tank is used, the rinse water from the container should be applied to the pond in the same manner as the herbicide in the container. Containers must then be punctured or crushed so that they cannot be reused. Empty bags must be rinsed or shaken clean and cut so that they cannot be used for other purposes. Laws regarding disposal of rinsed containers vary among states, so be sure to follow all state and local regulations regarding pesticide container disposal.

Two aquatic herbicides, 2,4-D and endothall, are regulated as hazardous materials under federal law, and any waste generated during their use must be disposed of as hazardous waste. Triple-rinsed containers can be disposed of as with any other pesticide container. Any rinse water from cleaning of containers or application equipment must be applied as if it were the herbicide or disposed of at a hazardous waste disposal facility.

### *Use sterile grass carp for weed control*

Grass carp (*Ctenopharyngodon idella*, also called white amur) (Fig. 6.11) are nonnative fish that feed primarily on submersed and emergent vascular plants, which are the most

**Fig. 6.11.** A large grass carp captured when harvesting catfish. Using grass carp to control weeds can be an excellent alternative to chemical herbicides, but care must be taken to assure that this nonnative fish does not escape from ponds. Photograph courtesy of Danny Oberle.

common weed problems in aquaculture ponds. For control of particular aquatic weed problems with grass carp, proper plant identification is critical because the plant preferences of grass carp are variable. Grass carp stocking density is a function of weed species and extent of plant cover. Grass carp can be a highly effective weed management tool and when used properly, their use obviates the need for chemical control. However, grass carp are banned or regulated in most states. Even where it is legal to use the fish, discretion should be used and every effort made to prevent their escape into natural waters (see the section on prevention of fish escape). To further diminish the likelihood that grass carp will reproduce and thrive in natural waters, use only sterile triploid fish even in areas where use of diploid fish is allowed. Control of established stands of weeds by grass carp may require a year or more, so it is usually best to use the fish early, before the weed problem becomes widespread. Lower numbers of fish are needed when used this way, which reduces the risk associated with escape.

## Mortality Removal and Disposal

Animal mortality in ponds is unpredictable and highly variable among ponds and among farms. Numbers of animals dying range from chronic losses of a few per day over long periods to catastrophic losses caused by acute environmental stress or infectious diseases. Dead fish may float or sink, depending mainly on water temperature. In warmwater, nearly all fish that die will float for several days before decomposing and sinking. In cold water, most fish sink after dying. Although there are benefits to timely removal of dead animals from culture ponds, routine removal from large-scale farms is difficult and costly, and may not even be physically possible. Fortunately, most aquaculture ponds can be operated as self-contained hydrological units during fish kills, which will prevent the discharge of carcasses, infectious agents, or products of decomposition into receiving water bodies. Natural pond processes have considerable ability to assimilate the products of fish decomposition, so mortalities do not have a lasting effect on water quality within the pond or on effluents released after the die-off. Nonetheless, depending on the number of fish that die, removal of mortalities may improve water quality by minimizing dissolved oxygen depletion associated with carcass decomposition and may limit the transmission or release of fish pathogens.

### *Better Management Practices for Mortality Removal and Disposal*

#### *Follow recommended aquatic animal health management practices*

Proper aquatic animal health management is the best method of managing mortalities in ponds. Reducing the incidence of loss will reduce the need to deal with dead animals. Most states offer aquatic animal health services to aid in diagnosis and treatment of disease problems. General guidance on health management can be found in Chapter 12.

#### *Take measures to ensure that dead animals are not discharged with overflow*

Screens or trash racks installed on overflow structures will prevent carcasses from being discharged with overflow.

#### *If practical, remove dead animals from ponds for sanitary disposal*

Dead aquatic animals may be deposited in a permitted landfill, incinerated, composted, rendered, or ground up and applied to fields as fertilizer. The best disposal method will be site-specific and may depend on local or state regulations. Consult NRCS Conservation Practice Standard 316 (Animal Mortality Facility) for additional guidance on sanitary disposal of dead animals.

## Facility Operation and Maintenance

Pond aquaculture facilities are expensive to build and operate. Protection of the investment by operating farms in a sustainable and economically efficient fashion is in the best interest of both farm owners and environmental protection. Facilities that are well-maintained, managed efficiently, and operated in compliance with all applicable laws and regulations will simultaneously improve long-term economic performance and reduce environmental impacts. As such, all of these management practices are simply part of good farm management.

### *Better Management Practices for Facility Operation and Maintenance*

#### *Maintain all equipment in good working condition*

Use the best equipment affordable and develop a maintenance program to assure that equipment is always in good repair. Maintain a file on each major piece of equipment that contains maintenance logs, operating manuals, and warranty information. Maintain an on-site inventory of frequently used repair and replacement parts for critical equipment. All personnel should be familiar with equipment operation and the location of backups, tools, spare parts, and other materials that may be needed if equipment fails.

### *Inspect pond drains and water supply lines frequently and repair when needed*

Drains that leak can significantly increase water use and long-term effluent volume, especially when totaled for many ponds on large farms. Drains can leak through faulty valves and improperly compacted soil around drainpipes that extend through pond embankments. Most drains can be inspected for leakage during routine farm activities. Leaking drains can also be tentatively identified by excessive water use in a pond relative to adjacent ponds.

Water supply pipelines can deteriorate over time and leak. Heavy equipment on levee roads may also damage underground pipe that is buried improperly, especially during wet weather when soils are soft. Leaky pipes can usually be identified by wet areas that appear during periods of dry weather.

### *Use and store petroleum products to prevent contamination of the environment*

Petroleum leaking from storage tanks or farm equipment wastes a valuable resource and can contaminate surface or underground water supplies. Pond aquaculturists should also be aware that petroleum products are highly odorous and small amounts in water can cause a disagreeable off-flavor to aquatic animals. For example, as little as 1 L of diesel fuel in a 2-ha pond can cause a detectable taint in fish. That amount of fuel can be released in just one day from a fuel line leaking one drop every second. Petroleum storage in aboveground and underground tanks is regulated by federal and state laws, and information can be obtained from State Departments of Commerce, State Departments of Environmental Quality or Protection, or from regional EPA offices. A protective containment berm that retains leakage or tank contents in the event of failure can be constructed around storage tanks. Fuel storage tanks should be located at least 50 m and downslope from groundwater wells and surface waters. Underground fuel storage tanks should be avoided because it is difficult to detect leaks. Aquaculturists should also implement a regular maintenance schedule for tractors, trucks, and other equipment to prevent oil and fuel leaks. Used oil should be properly stored in a designated waste oil container until recycled.

### *Use and store chemicals to prevent contamination of the environment*

The most common chemicals used in pond aquaculture are fertilizers, liming materials, and herbicides. These materials will have no adverse effects on the environment when used properly. They should be used only when needed and only for the specific purpose for which they are intended. Herbicide use is regulated by federal and state laws, and farmers are responsible for using products according to label instructions and disposing out-of-date chemicals and empty containers according to applicable state and federal regulations. All chemicals should be stored in secure, well-ventilated, watertight buildings.

### *Develop a response plan for spills of petroleum products, pesticides, and other hazardous materials*

Reporting significant spills of petroleum and pesticides is required by state and federal law, and farmers should be aware of all applicable regulations. Farmers should develop an emergency response plan for all hazardous materials on the farm and all farm employees should be aware of the plan.

### *Collect and dispose of solid waste on a regular basis and in a responsible manner according to all applicable state and federal regulations*

Solid waste containers should be installed in convenient locations on the farm. Containers should be emptied regularly and the waste disposed of in a permitted landfill or county-operated dumpster.

### *Develop a record-keeping system*

Good record keeping is the hallmark of a well-operated aquaculture facility. Records, such as feeding, chemical and therapeutant use, water quality, serious weather conditions, culture operations, and animal inventory (e.g., stocking density, mortality, harvest number) facilitate improvements in the efficiency of farm input use. Paper copies of records should be maintained for archival purposes; computerized record-keeping tools can be used for trend analysis and forecasting. Records should be reviewed periodically to determine whether they are useful and to provide insight into opportunities for improvement of farm operation.

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# Chapter 7

# Better Management Practices for Marine Shrimp Aquaculture

*Claude E. Boyd*

## Introduction

Marine shrimp are a high-value product cultured primarily in tropical, developing countries for the export market. Global marine shrimp production was 6.08 million tonnes in 2004, with 2.46 million tonnes, or 40%, originating from aquaculture (FAO 2006). The major shrimp farming countries are, in order: China, 850,000 tonnes; Thailand, 387,000 tonnes; Vietnam, 236,000 tonnes; Indonesia, 185,000 tonnes; India, 133,000 tonnes; Brazil, 76,000 tonnes; Mexico, 62,000 tonnes; Ecuador, 56,000 tonnes. Farmed shrimp production in the United States was only 4,731 tonnes in 2004, and most of this production was from Texas. Several species of marine shrimp are cultured, but the two most common species are Pacific white shrimp (*Litopenaeus vannamei*) and black tiger shrimp (*Penaeus monodon*). The Pacific white shrimp is the primary species cultured in the United States and other countries in the Americas. This species also has been introduced into Asia and is becoming increasingly popular there. In 2004, 1.4 million tonnes of *L. vannamei* and 0.7 million tonnes of *P. monodon* were produced by aquaculture.

Marine shrimp are cultured primarily in ponds in coastal areas, but there is increasing interest in producing them in inland areas where saline water is available. Inland culture of marine shrimp is of particular interest in the United States because coastal sites for farms tend to be excessively expensive and highly regulated. There has been more environmental concern over shrimp culture than for other types of pond aquaculture. This chapter focuses on marine shrimp culture, but most of the topics apply equally to the production of other species in ponds supplied by seawater or brackishwater.

The basic procedures for culturing marine shrimp are similar worldwide for all major species (Fast and Lester 1992). Postlarval shrimp are stocked in ponds filled with saline water. Shrimp are cultured in waters ranging in salinity from 1 ppt to more than 40 ppt. Postlarvae once were caught from the wild. This was gradually replaced by the practice of obtaining broodstock from the wild and producing postlarvae in hatcheries. Farm-reared broodstock often are used in hatcheries today.

Ponds typically are treated with fertilizer during the first few weeks to enhance natural productivity and assure plenty of natural food for small postlarvae. Commercial shrimp

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feed usually is applied throughout the 4- to 6-month crop period to allow higher levels of shrimp production than possible in ponds that are only fertilized. Nutrients from fertilizers and feeds promote phytoplankton growth, and water exchange and mechanical aeration may be applied to avoid water quality deterioration. Antibiotics may be incorporated in feeds when shrimp diseases become troublesome. Shrimp production ranges from less than 500 kg/ha in extensive ponds that are only fertilized to over 10,000 kg/ha in highly intensive ponds that receive initial fertilization, large daily feed inputs, heavy mechanical aeration, and daily water exchange. Most shrimp farms produce between 1,000 and 5,000 kg/ha per crop. In tropical areas, two crops or more are produced annually. Ponds are completely drained for harvest, and bottoms are allowed to dry out between crops. Agricultural limestone or lime may be applied to neutralize sediment acidity, bottoms may be tilled to enhance aeration of the sediment, and sediment is removed if accumulation is excessive.

In inland shrimp culture, ponds are filled with saline water from wells or brine solution from seawater evaporation ponds is mixed with freshwater to provide adequate salinity (Smith and Lawrence 1990; Limsuwan et al. 2002; Boyd and Thunjai 2003). Imbalances in major ions in saline well water and especially low potassium and magnesium concentrations often must be corrected by additions of mineral salt amendments to ponds (McNevin et al. 2004; Boyd et al. 2007a, b). Water supply for inland farms usually is limited, and water exchange is either not used or is applied by recirculation of water between ponds and a reservoir. Otherwise, shrimp culture in inland ponds relies on the same methodology used in coastal ponds.

Shrimp culture is a small industry in the United States and it is not expected to increase greatly in the future. The main reasons are the high cost of coastal land, the inability to produce more than one crop per year in subtropical or temperate climates, and regulations about the use of land and water. Shrimp farms in the United States that discharge 30 or more days per year, except for excess runoff, and produce over 45,454 kg (100,000 pounds) harvest weight must comply with the United States Environmental Protection Agency (USEPA) aquaculture effluent rule (Federal Register 2004). Most domestic shrimp farming is conducted along the Texas coast and that state has developed discharge requirements and mandated BMPs that are more restrictive than the USEPA rule. Inland shrimp producers in Florida must comply with BMPs promulgated by the Florida Department of Agriculture and Consumer Services (FDACS 2000), and in Alabama, discharges from inland shrimp farms must not cause in-stream chloride concentrations to exceed 230 mg/L (Boyd et al. 2006).

There has been great concern over the negative environmental and social effects worldwide of shrimp farming. These negative impacts include conversion of coastal ecosystems to farms, adverse effects on biodiversity through capture of wild postlarvae for stocking ponds and of adults for broodstock, water pollution, excessive use of antibiotics and other chemicals, salinization of land and water, and deprivation of access to coastal ecosystems by local communities and other social conflicts. These impacts are discussed in Chapter 1. The purpose of this chapter is to consider the practices that should be used to lessen the negative environmental impacts of shrimp culture in ponds. The discussion has an international perspective because there is little shrimp farming in the United States.

## Site Selection

Poorly planned shrimp farms developed at sites with serious deficiencies obviously are likely to fail. Experience also reveals that poorly sited projects are likely to cause negative environmental and social impacts (Boyd and Clay 1998; Clay 2004). Sites for shrimp aquaculture projects should be subjected to thorough analyses to identify soil and water limitations (Hajek and Boyd 1994), likelihood of negative environmental impacts, and possible conflicts with other land and water users (Boyd 1999). Unless the potential problems identified in the site evaluation and environmental impact assessment can be mitigated or avoided through cost-effective methods, the site should be rejected. It is better not to build a shrimp farm than to build one doomed to failure and negative environmental or social consequences. Nevertheless, many shrimp farms already have been constructed on sites with serious limitations, and negative environment impacts and conflicts are common. This increases the challenges of mitigating negative aspects of shrimp culture.

### *Better Management Practices for Site Selection*

Ponds are built along the coast or beside the estuarine reaches of rivers where there is a suitable supply of good quality seawater or brackishwater. The best areas for coastal ponds are above the tidal zone on flat or gradually sloping terrain. Former agricultural land often presents excellent sites, and salt flats located behind mangrove areas usually are suitable locations. The worst sites are mangrove forests or other coastal wetlands. It usually is impossible to construct ponds properly in wetlands because land cannot be adequately drained and dried (Massaut 1999). Wetlands should not be destroyed because of their inherent ecological value and because they protect the coastline from storm damage (Mitsch and Gosselink 2000). Sites for inland culture of marine shrimp also should be restricted to those where salinization of soil and water can be avoided (Boyd et al. 2006).

#### *Do not alter local hydrology*

Coastal farms must have continuous access to seawater or brackishwater. However, they must also discharge into estuaries or the sea to avoid salinization of freshwater. Roads, embankments, and other farm infrastructure must not alter salinity patterns by changing local hydrology. For example, roads at shrimp farms sometimes restrict tidal flow into coastal marshes, depriving them of normal saline water influx.

In many places, coastal areas may flood during heavy rains. Flood elevations should be determined and pond embankments built high enough to avoid overtopping by floodwaters. Storm surges also must be considered in farm construction to avoid inundation of ponds. This issue is especially important in the Gulf Coast area of the United States where hurricanes often cause large surges.

**Table 7.1.** Tsunami events in four areas where shrimp farms may be located along the coast during the period 1950–2003.

| Area | Number of Events | Gauging Stations Impacted/Event[a] | Average Increase in Water Height (m) |
|---|---|---|---|
| Caribbean | 7 | 2.6 | 0.32 |
| Ecuador | 10 | 1.0 | 0.43 |
| Philippines | 8 | 4.9 | 3.93 |
| Indonesia (1968–2003)[b] | 15 | 6.6 | 5.24 |

*Source:* www.ngdc.noaa.gov

[a] Distances between gauging stations were not available.

[b] Data do not include the massive tsunami that struck Sumatra on 26 December 2004.

### *Consider climatological, meteorological, and geological conditions*

Climatological and geological records applicable to a particular site should be evaluated to determine the likelihood of floods, droughts, severe storms, earthquakes, and other potentially destructive natural phenomena. Many coastal areas with shrimp farms along the Pacific and Indian Oceans have a high probability for seismic activity. Earthquakes have caused damage to the infrastructure of some shrimp farms. Tsunamis resulting from earthquakes also may destroy shrimp farms, as dramatically illustrated in Indonesia, Thailand, India, and Sri Lanka in December 2004. Although the December 2004 tsunami was particularly devastating, it should not have been a total surprise. Selected data on tsunamis between 1950 and 2003 for four areas with shrimp farming revealed that these events were most common in Indonesia and that the extent and water height was particularly great in that nation (Table 7.1). The water height of tsunamis in Indonesia and Philippines suggests that any shrimp farm constructed near the coast could be damaged by the average tsunami regardless of construction methods used. However, the average water height is much less in the Caribbean region and in Ecuador (Table 7.1), and likelihood for inundation of ponds with water can be lessened by constructing embankments higher than maximum anticipated water levels.

The Intergovernmental Panel on Climate Change (IPCC) predicts that the frequency and intensity of hurricanes (or typhoons) and the variability in rainfall will increase in response to global warming (www.ipcc.ch). This suggests that the use of historical climatic data may underestimate the risks of storm damage and aberrations in rainfall at a particular site. Thus, it might be wise to provide a greater margin of safety when planning projects in coastal areas.

Hurricanes form over the oceans and often pass through coastal areas. The number of hurricanes and severe storms are provided in Table 7.2 for four selected shrimp farming areas. Texas in the United States and the Yucatan area of Mexico were struck by more than one hurricane every 2 years, and Belize was struck with slightly less than one hurricane every 2 years. In the Philippines, there are four to eight hurricanes annually with an average of nearly six per year. In these four areas, and in many other places, hurricanes and severe storms are commonplace, and shrimp farms should be constructed and designed to withstand strong winds, unusually high tides, and storm surges.

Heavy rainfall can be harmful to shrimp farms by causing extended periods of low salinity. Salinity at shrimp farms typically declines during the rainy season (Fig. 7.1), but

**Table 7.2.** Hurricanes and severe storms by decade in four areas where shrimp farms are located along the coast.

| Decade | Texas (US) | Yucatan (Mexico) | Belize | Philippines |
|---|---|---|---|---|
| 1950s | 7 | 8 | 4 | 44 |
| 1960s | 6 | 6 | 4 | 43 |
| 1970s | 8 | 7 | 7 | 67 |
| 1980s | 7 | 4 | 1 | 54 |
| 1990s | 5 | 7 | 3 | 80 |
| 2000–2003 | 4 | 7 | 2 | 20 |
| Average/year | 0.70 | 0.74 | 0.40 | 5.81 |

*Source:* weather.unisys.com/hurricane.

**Table 7.3.** Rainfall during the rainy season (October to March) at a shrimp farm in Madagascar.

| Rainy Season | Total Rainfall (mm) | January Rainfall (mm) |
|---|---|---|
| 2000–2001 | 1,605 | 820 |
| 2001–2002 | 720 | 210 |
| 2002–2003 | 1,150 | 550 |
| 2003–2004 | 1,590 | 560 |

*Source:* Ken Corpron, personal communication.

during a year with especially heavy rainfall, the salinity may fall below 1.0 ppt for periods long enough to stress or kill shrimp.

Tropical regions are known to have high variation in rainfall between years as illustrated in Table 7.3 for a shrimp farm in Madagascar. In that nation, heavy rainfall usually is associated with cyclones from the Indian Ocean. Nearly 1 m of rainfall fell during January 2001, normally the wettest month. The next year only 210 mm of rain fell in January. In the United States, extremely heavy rainfall usually is associated with hurricanes, and records of rainfall available for all coastal areas may be used to estimate the maximum amounts of rainfall that can be expected from these events.

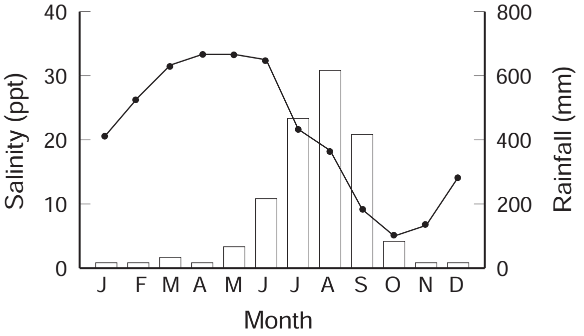

**Fig. 7.1.** Relationship between rainfall (bars) and salinity (line) at a shrimp farm in a tropical region with well-defined wet and dry seasons. Redrawn from Boyd (1990).

In South and Central America, rainfall during the rainy season also varies greatly from year to year associated with the so-called El Niño Southern Oscillation (ENSO) of oceanic currents. In an El Niño period, the ocean currents coming from the south along the South American coast weaken to allow warmer water from the tropical region of the western Pacific Ocean to migrate eastward. The warmer than normal ocean water offshore during El Niño years results in greater rainfall. El Niño events often alternate with La Niña events, in which water offshore is cooler than normal and there is less rainfall. Although these events tend to alternate, there is no cycle with a specific time between events. Shrimp farm operators along the Pacific coast of South and Central America should plan for alternating heavy and light rainy seasons. The United States also is impacted by the El Niño phenomenon, and farm water supplies should be selected with attention to minimizing fluctuations in salinity resulting from alternation in rainfall.

Ponds should be operated to conserve salinity when heavy rainy seasons are anticipated. Freshwater and saline water in estuaries do not mix well, and the higher salinity water will be near the bottom. At some sites, the intake of freshwater can be avoided by installing pumps for deeper intake.

Heavy rainfall also causes greater turbidity in estuaries. When water with high concentrations of suspended solids is transferred to water supply canals or ponds, the solids settle rapidly. Excessive accumulation of sediment in canals and ponds reduces volume, and in ponds, soft sediment interferes with feeding and harvest activities.

Rivers running into estuaries and channels within estuaries may occasionally change course during years with especially great rainfall. There have been cases where it was necessary to relocate pump stations for shrimp farms because changes in river courses increased catchment areas resulting in more freshwater and unacceptably low salinity. Heavy rainfall can be beneficial in flushing estuaries where water exchange with the sea is weak.

### *Confirm suitable terrain and soil characteristics*

Embankments for ponds must be high enough to avoid overtopping by unusually high tides, storm surges, and floods. Thus, water must be lifted several meters above sea level for transfer to canals and ponds. Pumping costs and energy use will be excessive if the land is more elevated than necessary. Thus, flat areas that are above the highest tide level should be favored for shrimp farm sites.

Site soils should be sampled to at least the maximum depth of excavation for ponds and canals. The best procedure is to delineate the area for construction and take core samples to the necessary depth at intersections of a 50-m, or smaller, grid superimposed over the site. The minimum requirement is to take samples from the surface, mid-depth, and bottom of the cores. These samples should be analyzed for at least particle size distribution, pH, and organic matter concentration. It also is desirable to determine whether potential acid-sulfate soils exist at sites. This can best be done by making sulfur analyses of samples. Soils with more than 0.75% sulfur are potentially highly acidic when dried (Hajek and Boyd 1994). The contractor also should be consulted about the desirability of measuring other soil properties such as liquid, plastic, and shrinkage limits and coefficient of linear expansion for use in designing earthworks and planning construction activities. Sites with sandy soils or high percentages of clay should be avoided in favor of sites with a wide range of soil particle sizes. Ponds built on sandy sites often seep excessively, and heavy clays may not form stable embankments, as illustrated in Fig. 7.2. Sites with organic soils and potential acid-sulfate soils also should be avoided. Organic soils decompose when exposed to air and cannot be used to make stable embankments. Acid-sulfate soils can be used in aquaculture, but control of low pH will be a continuing and expensive effort.

Soils at most sites will not be uniform. Thus, knowledge of soil characteristics over the entire site can be useful in determining whether special attention must be given to particular areas or whether some areas should be excluded from the farm layout.

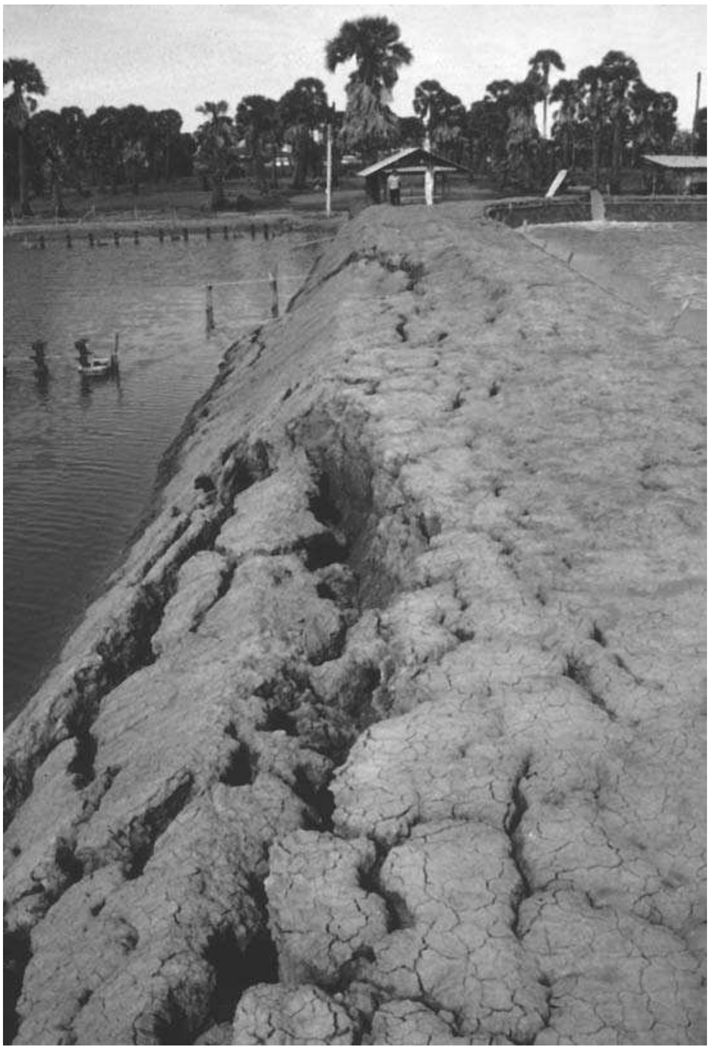

**Fig. 7.2.** Embankments made of heavy clay soils must have adequate side slopes or they will slip. Also, cracks occur when embankments of heavy clay dry.

#### *Avoid sensitive habitats*

An appropriate site for a shrimp farm should not present a high probability for degrading natural ecosystems. In particular, farms should not be sited in mangrove forests or other sensitive coastal wetlands or near seagrass beds, coral reefs, or protected marine areas.

#### *Avoid conflicts with other resource users*

Site evaluation should include an assessment of natural resource use in the area by local communities. Farms should not interfere with traditional hunting, fishing, and gathering activities by coastal inhabitants. Much conflict has resulted when farms blocked traditional passageways and access to resource areas. Most conflicts can be avoided if shrimp farm developers and local community leaders collaborate in developing procedures that minimize interference in traditional resource use patterns.

## Shrimp Farm Design and Construction

Shrimp farms should be designed and constructed in a responsible manner. Design features and good construction methods should be used to overcome site limitations and to prevent or mitigate negative environmental and social impacts. Construction should be done by reliable firms using standard and proven techniques.

Farms should not be constructed in ecologically sensitive places or in places where it is impractical to correct site-related problems such as highly acidic, organic, or permeable soils. It is especially important to design and construct aquaculture facilities in a way to avoid possible negative environmental impacts identified in the environmental impact assessment. Moreover, the construction project itself should not be the source of negative social and environmental impacts.

The basic requirements for responsible shrimp farm design and construction are similar to those recommended in Chapter 6 for freshwater aquaculture farms. Thus, to avoid duplication, the following discussion will focus on issues of particular concern in shrimp farm design and construction.

### *Better Management Practices for Shrimp Farm Design and Construction*

#### *Reduce or eliminate impacts on mangroves*

Shrimp farming has been accused of destroying large expanses of mangrove forest. Mangroves have been cut for many purposes, and shrimp farming has destroyed less forest than often reported (Macintosh and Phillips 1992; Menasveta 1996; Boyd 2002). Nevertheless, special attention should be given to mangrove conservation because many people still relate shrimp farming to mangrove destruction.

New shrimp farms should not be developed within mangrove ecosystems. Some mangroves must be removed for canals, pump stations, and other purposes when new aquaculture projects are sited behind mangroves. There should be a goal of no net loss of mangrove through replanting more mangrove trees than were cut for necessary reasons. A shrimp farm owner usually will not be able to replant mangrove on site for lack of suitable habitat. Also, shrimp farmers are unlikely to have knowledge of mangrove restoration techniques. It seems preferable that a financial contribution or other direct support be made to a mangrove reforestation program in which there is a greater opportunity for success of replantings.

Farm operations should not have negative impacts on mangrove. Mangrove vegetation should not be cut or deprived of natural water movements necessary for its survival (Field 1996; Mitsch and Gosselink 2000). Sediment should not be discharged into mangrove areas, and they should not be dumping sites for shrimp farm refuse. Mangrove areas on farms should be regularly inspected to verify that conservation measures are preventing negative impacts.

Mangrove ecosystems usually are an important resource for coastal communities. They are sources of firewood and construction poles, and they serve as hunting and fishing areas. Shrimp farmers should cooperate with local communities to assure sustainable use of mangrove resources.

### *Protect earthwork from erosion*

All earthen infrastructure on shrimp farms should be constructed to avoid erosion of above-water portions by rainfall and runoff and below-water portions by water currents. Erosion control protects the earthen infrastructure of farms. It also is an important environmental practice because erosion can be a major source of suspended solids in pond effluents. Suspended solids increase turbidity in water and coarse particles settle to cause negative impacts on benthic communities.

A major erosion control practice is attention to soil characteristics in the design of side slopes, embankments, channel cross sections and bottom slopes, intersections of canals, and outfalls. If side slopes of embankments, canals, and other earthwork will not withstand the impact and velocities of water to which they are exposed, excessive erosion will occur. The relationships among soil properties, design, and erosion are too complex to reduce to simple BMPs and a competent engineer should be consulted. Nevertheless, some suggestions for embankment and channel design are provided for illustration.

Recommended side slopes for embankments for different soil materials are presented in Table 7.4. Allowable side slopes and erosion coefficients for various channel materials are provided in Table 7.5.

**Table 7.4.** Recommended side slopes for embankments.

| | Slope (*Z*) | |
|---|---|---|
| Material | Wet Side | Dry Side |
| Clay, clayey sand, clayey gravel, sandy-clay, silty-sand, and silty gravel | 3 | 2 |
| Silty clay and clayey silt | 3 | 3 |
| Well-graded soil | 1 or 2 | 1 or 2 |

*Source:* Yoo and Boyd (1994).

**Table 7.5.** Allowable side slope factors and erosion coefficients (G) for various channel materials.

| Soil Type | $Z$ | Side Slope (degrees) | G |
|---|---|---|---|
| Sandy loam | 3.0 | 18.4 | 2.0 |
| Silty clay | 3.0 | 18.4 | 2.5 |
| Silty sand | 2.0 | 26.5 | 2.5 |
| Soft shale | 2.0 | 26.5 | 3.2 |
| Stiff clay | 1.5 | 33.7 | 3.5 |
| Soft sandstone | 1.5 | 33.7 | 3.5 |
| Riprap lining | 1.0 | 45.0 | — |
| Concrete lining | 0.5–1.0 | 63–45 | — |
| Peat | 0.25 | 76.0 | — |
| Rock | 0.0 | 90.0 | — |

*Source:* United States Bureau of Reclamation (1952).

The best hydraulic section for a trapezoidal channel is:

$$b = 2y(\tan\theta / Z) \tag{7.1}$$

where $b$ = channel bottom width (m), $y$ = depth of flow in channel (m), and $Z$ = side slope. The tangent of $\theta = 1/Z$, and $\theta = \tan^{-1}(1/Z)$. Maximum velocity to present scouring of earthen channels and minimum velocity to avoid sedimentation in channels can be calculated as follows:

$$V_{\max} = 0.305\mathrm{G}\,(y^{0.2}) \tag{7.2}$$

$$V_{\min} = 0.192(y^{0.64}) \tag{7.3}$$

where $V_{\max}$ = maximum permissible velocity (m/sec), $V_{\min}$ = minimum permissible velocity (m/sec), and G = erosion coefficients (Table 7.5).

Canals may be designed to avoid scouring of sides and bottom, but serious erosion can result where one canal discharges into another or where canals discharge into natural water. Stone riprap can be installed to lessen the force with which water strikes earthen areas to reduce erosion.

Earthwork should be compacted properly. This requires that the earth fill be compacted at the optimum moisture content as determined by the standard Proctor test (McCarthy 1998). Typical optimum moisture contents for compaction of different soil materials are

| | |
|---|---|
| Sand | 6 to 10% moisture |
| Sands and silt | 8 to 12% moisture |
| Silt | 11 to 15% moisture |
| Clay | 13 to 21% moisture |

Attention to design and compaction of earthwork and reinforcement of potential problem areas with stone or other material will not prevent erosion caused by rainfall. Rainfall erosion can be controlled through installation of grass or other cover over exposed earthwork. In shrimp farming, pond embankments and above-water portions of other infrastructure are exposed to salty water. Thus, salt-resistant species or strains of grass must be used.

Mechanical aerators frequently are used in shrimp ponds. Water currents produced by these devices may cause erosion if they impinge strongly on embankments or pond bottoms. This problem usually can be avoided if aerators directed at embankments are at least 50 m away, aerators directed parallel to embankments are 5 m away from the toes of these structures, and aerators are not installed in water less than 1 m deep. Where necessary, stone riprap or geotextile material may be installed at critical places to prevent erosion by aerators.

### *Avoid ecological damage and noise at pumping stations*

Pumps used to obtain water to use in shrimp farms create a strong suction and can impinge on fish and other aquatic organisms. Coarse screens with openings 1 or 2 mm often can be installed across entrances to pump intakes to avoid impingement of larger aquatic organisms. Pumps often are driven by diesel engines that make a loud noise. Trees or other tall vegetation planted around pumping stations can provide a degree of noise control.

### *Prevent negative impacts during construction*

Construction activities for building new shrimp farms and renovating existing ones can lead to negative environmental impacts. Removal of vegetation and disturbance of soil should be limited to the actual farm area as much as possible. Silt fences and detention basins should be provided on the downslope perimeters of construction areas to retain solids eroded from denuded and disrupted areas. Roads into the construction area should be protected from erosion as well.

Cut and fill construction methods should be used to the extent possible. Nevertheless, it often will be necessary to either remove some soil from the site, obtain fill material from outside the site, or both. When construction has been completed, spoil piles and barrow pits should be contoured and grass established to prevent erosion and other ecological nuisances.

Construction sites often have living quarters, kitchens, toilets, shops, fuel storage areas, and other facilities. The sites should be operated in a manner to assure sanitation and avoid soil and water pollution. Waste materials should be burned, put in a landfill, or disposed of by other appropriate techniques. Trash piles should not be left by the construction crew.

## Sourcing of Broodstock and Postlarvae

In the early days of shrimp farming, coastal water was pumped into ponds or transferred to ponds by tidal flow, and the shrimp contained in this water were raised to a larger size and harvested. In order to increase production, farmers in Ecuador and some other countries began to capture shrimp postlarvae and stock them in ponds (Sonnenholzner et al.

2002). As technology improved, hatcheries were established to produce postlarvae, but the broodstock was captured from the sea. The capture of wild postlarvae and broodstock is considered detrimental to natural shrimp fisheries and biodiversity. In Asia, natural broodstock for black tiger prawn has become scarce and very expensive. Shrimp farming possibly contributed to falling natural stocks of this species, but commercial shrimp fishing also has taken a toll.

## *Better Management Practices for Sourcing Broodstock and Postlarvae*

### *Use only farm-reared broodstock and hatchery-produced postlarvae*

The shrimp culture industry should be encouraged to use only farm-reared broodstock in hatcheries and to stock only hatchery-produced postlarvae in production systems. This practice is becoming more common because it allows for the development of pure lines of shrimp that grow faster, are free of certain pathogens, or have other desirable characteristics. Nevertheless, some will argue that hatchery-produced shrimp are genetically altered because they have been bred from specific strains, and others fear that hatcheries will begin to genetically alter shrimp through gene transfer techniques.

### *Purchase only specific pathogen-free (SPF) broodstock or postlarvae*

Hatcheries often purchase broodstock, and farms without hatcheries purchase postlarvae. Although vendors may claim that their broodstock or larvae are free of pathogens, purchasers should require a health certificate from a reputable source stating that the animals have been tested and found free of specific pathogens.

### *Use stress tests to evaluate postlarvae*

Stress tests such as exposure to a weak concentration of formalin or to a change in salinity can be used to determine whether postlarvae are strong enough to survive stocking into ponds (Box 7.1). Of course, where the pond salinity is significantly lower than that of the hatchery, postlarvae should be acclimated to pond water salinity before stocking.

### *Comply with import regulations for broodstock and postlarvae*

Many countries allow trade in broodstock and postlarvae. When animals are sourced from another country, all import regulations should be strictly obeyed. Quarantine of animals often is necessary, but even if it is not required by the government, farms should voluntarily quarantine imported animals until sure that they do not have disease.

### *Destroy diseased broodstock and postlarvae*

Diseased broodstock or postlarvae should be disposed in a sanitary manner to prevent the transfer of disease. They can be incinerated or treated in a 1 or 2% chlorine solution to kill all pathogens.

## BOX 7.1
### Stress Tests to Evaluate Post-Larval Shrimp Quality

There are several simple stress tests that can be used to evaluate postlarval vigor, including temperature, pH, salinity, and formalin. Two tests should be used for each batch of postlarvae. The salinity and formalin tests are the easiest to perform and are described here. Postlarvae of different ages can withstand different levels of stress, so the test should be performed on 6-day-old shrimp to standardize the results. Each test will require 300 6-day-old postlarvae.

**Salinity test:** Dilute seawater with distilled water to 5 ppt and fill three 15-L containers. Aerate the water gently and place groups of 100 postlarvae in each container. Record survival after 1 hour.

**Formalin test:** Add formalin to seawater for a concentration of 150 to 200 ppm and fill three 15-L containers. Aerate the water gently and place groups of 100 postlarvae in each containers. Record survival after 1 hour.

If the average from the three replicates is lower than 60%, the postlarvae should not be stocked or their quality further evaluated. Record and archive the stress test results so that a correlation can be established between postlarval survival in stress tests and performance in the nursery and grow-out phases.

## Feeds and Feeding

Manufactured feed can greatly increase production and the economic feasibility of aquaculture. Feeds also are the source of two major concerns about aquaculture. First, environmental groups are concerned about the efficiency with which marine fishmeal and fish oil are used in aquaculture feeds (see Chapter 1). Shrimp feeds contain especially large amounts of fishmeal and fish oil, so this issue is particularly important in shrimp aquaculture. Second, feeding leads to high concentrations of nutrients and organic matter in pond waters. Effluents from aquaculture ponds usually have greater concentrations of nitrogen, phosphorus, total suspended solids, particulate organic matter, and 5-day biochemical oxygen demand than natural water into which ponds discharge (Boyd and Tucker 1998).

Shrimp nibble feed pellets and consume them slowly. They drop many small particles of feed, and the feed pellets may disintegrate before they are consumed. Typically, 20 to 40% of pelleted feed offered to shrimp is not consumed but settles to the pond bottom to decompose (Ruttanagosrigit 1997). By contrast, fish ingest feed pellets quickly and 95 to 100% of pellets are consumed if fish are not overfed. Additional wastes enter pond water in feces and metabolites. Phosphorus pollution is of greater concern in shrimp culture than in fish culture. Shrimp feeds contain as much or often more phosphorus than fish feeds, but less feed phosphorus is recovered in shrimp biomass than in fish biomass at harvest because shrimp do not have bones and contain much less phosphorus than fish (Boyd and Teichert-Coddington 1995; Gomes and Boyd 2003).

Feed is expensive and it should be used efficiently to reduce production costs and conserve fish and plant meals and oils that are used to make it. Good feeds and feeding practices also are important steps toward reducing waste loads in shrimp farm effluents. Freshwater pond culture and culture of marine shrimp in ponds do not differ greatly with respect to best management practices for feeds and feed management. For sake of brevity, information provided in Chapter 6 will not be repeated here, and reference will be made only to issues of particular concern in efficient use of feeds in shrimp culture.

### *Better Management Practices for Feeds and Feeding*

#### *Use high-quality feed*

The shrimp grower should implement good practices that begin with purchasing a high-quality feed, storing it in a cool, dry place to prevent mold and other biological contamination, and using the feed before its quality deteriorates as a result of oxidation and other processes that occur during storage.

Feed manufacturers have an important role in responsible shrimp culture. They should work toward reducing amounts of marine fishmeal and marine oils in feeds. Feed pellet stability is a particularly important issue because unstable pellets fall apart quickly, increasing the amount of feeding waste. Feeds also should contain no more nitrogen and phosphorus than needed by shrimp. Large shrimp farms can contract with feed producers to provide feed with specific characteristics, but small-scale shrimp farmers must use feed available in the market. Shrimp usually are produced on small farms in Asia, and feed producers are almost entirely responsible for the characteristics of feed.

#### *Use efficient feeding practices*

Feed management practices should assure that shrimp consume as much of the feed as possible to avoid uneaten feed that decomposes in ponds to impair water and sediment quality. Feeding rates should be determined from standard feeding rate curves and adjusted for shrimp biomass, appetite, and pond conditions. Feeding trays are widely used in shrimp farming to monitor feeding and prevent under- and overfeeding. Some shrimp producers offer all feed on trays, but the extra labor cost for this practice probably exceeds the benefits. Shrimp feeds should be offered two to five times per day and widely distributed throughout the ponds. Careful records should be maintained on feed input to each pond so that the feed conversion ratio can be calculated.

#### *Maximize the contribution of natural productivity to shrimp growth*

Pelleted feed cannot be used as efficiently by small shrimp larvae as by larger shrimp. Thus natural productivity is important to shrimp production in ponds with feeding and especially during the first 6 to 8 weeks of culture. Producers should develop procedures for establishing natural productivity through liming and fertilization before stocking postlarvae in ponds. Maintenance of natural productivity will improve the efficiency of feed use in shrimp ponds.

#### *Do not use raw fish or other animal waste as feed*

In Asia some shrimp farmers apply raw, cut fish and invertebrates to ponds as feed. This practice should be discouraged because it can spread diseases and foul pond waters.

## Effluents

Shrimp farms discharge effluents in response to heavy rainfall, water exchange, and pond draining for harvest. Effluents from shrimp farms tend to have elevated concentrations of nutrients, suspended solids, and organic matter relative to receiving water bodies. However, overflow after rainfall and in response to water exchange usually is less concentrated in potential pollutants than water discharged when ponds are drained for harvest. The last 20 to 25% of effluent discharged at harvest is of particularly low quality (Teichert-Coddington et al. 1999). Effluent discharged from shrimp farms also is a potential avenue for the spread of pathogens to other shrimp farms or to wild shrimp. When effluents are discharged, they are mixed into coastal waters and eventually flushed into the sea and transported away. Natural factors influencing this process include freshwater inflow, morphometry of coastal areas, tidal action, and long-shore currents (McNevin 2004). Human factors also are involved, such as intensity of shrimp farming in an area and other sources of pollution. Water pollution from shrimp farming is most likely when a large shrimp farm is located in a small estuary that does not exchange water rapidly with the sea.

Adoption of BMPs for site selection, farm design and construction, feeds and feed management, and pond dry-out will provide water quality benefits within shrimp ponds that should improve effluent quality. However, BMPs for reducing the volume of effluent and removing solids before final discharge can also be beneficial in preventing water pollution by coastal shrimp farms. Application of good practices only reduces the load of potential pollutants in farm effluents, and water quality monitoring could be used to verify the benefits of good practices.

### ***Better Management Practices for Effluents***

#### *Comply with applicable effluent standards*

Governments in some nations have imposed limits on concentrations of selected water quality variables and other conditions for effluents. For example, the effluent regulation in Thailand requires a settling basin equal to 30% of farm volume, no discharge of black water, and a 5-day biochemical oxygen demand of 10 mg/L or less (Tookwinas 1996). Government regulations on effluent water quality can be an important means of preventing pollution of coastal waters.

The Global Aquaculture Alliance (GAA) prepared an effluent standard with water quality limits for use in the Aquaculture Certification Council (ACC) shrimp pond certification program (Table 7.6). There is an initial standard and a target standard to be

**Table 7.6.** Effluent limitation guidelines of the Global Aquaculture Alliance shrimp certification standards.

| Variable (units) | Initial Standard | Target Standard | Measurement Frequency |
|---|---|---|---|
| pH (standard units) | 6.0–9.5 | 6.0–9.0 | Monthly |
| Total suspended solids (mg/L) | 100 or less | 50 or less | Quarterly |
| Soluble phosphorus (mg/L) | 0.5 or less | 0.3 or less | Monthly |
| Total ammonia nitrogen (mg/L) | 5 or less | 3 or less | Quarterly |
| 5-day biochemical oxygen demand (mg/L) | 50 or less | 30 or less | Quarterly |
| Dissolved oxygen (mg/L) | 4 or more | 5 or more | Monthly |
| Salinity (ppt) | No discharge of water above 1.5 ppt salinity into freshwater[a] | No discharge of water above 1.5 ppt salinity into freshwater[a] | Monthly |

*Source:* Aquaculture Certification Council (www.aquaculturecertification.org).

[a] Freshwater is defined as water less than 1 ppt salinity or specific conductance less than 1,500 µmhos/cm.

achieved after 5 years. Conservation International feels that the total suspended solids limit is too high, and GAA is studying data from certified farms to determine whether a lower total suspended solids limit could be adopted. Measurement frequencies for the analyses also are provided in Table 7.6, and data on sampling and analytical procedures can be found on the GAA websites (www.gaalliance.org and www.aquaculturecertification.org).

There are cases where the incoming water at a shrimp farm exceeds the GAA effluent standard for one or more variables. This usually is not a problem for total suspended solids, because ponds serve as sedimentation basins. It usually is not possible to greatly reduce the concentrations of other variables in water used in shrimp ponds. The GAA effluent standard has an option for use at farms where the source water has higher concentrations of one or more water quality variables than allowed by the initial criteria. In this option, demonstration that the variable concentrations do not increase (or decrease for dissolved oxygen) between the source water and farm effluent is an acceptable alternative to compliance with the criteria. This option does not apply to chloride.

It is likely that other certification programs also will have an effluent standard. Wal-Mart, a major shrimp buyer, reached an agreement with ACC to purchase certified shrimp (Chamberlain 2005, 2006). Other major shrimp buyers probably will make environmental commitments and also purchase certified shrimp. It seems likely that a considerable amount of shrimp may soon be produced on certified farms that must comply with an effluent standard.

### *Reduce water exchange*

At many coastal shrimp farms, water availability depends more on pump capacity than hydrological factors. The traditional way of solving water quality problems in shrimp farms has been to flush nutrients, plankton, and organic matter from ponds using water

## BOX 7.2
## Reducing Water Exchange in Shrimp Ponds

Water exchange has been used traditionally in shrimp farming to manage water quality, although the efficacy and economic value of the practice is questionable. The pollutant mass loading from shrimp ponds is directly related to water exchange rate, so any technique that reduces effluent volume can reduce the pollution potential of shrimp aquaculture. In a series of experiments at the Waddell Mariculture Center in South Carolina, USA, the effect of reduced water exchange on shrimp production, water quality, and mass discharge was evaluated. In one study (Hopkins et al. 1993), ponds were stocked with *Litopenaeus setiferus* postlarvae at 44/m$^2$ and managed with daily water exchange rates of 25, 2.5, or 0%. Shrimp production from ponds stocked at 44/m$^2$ and managed with 25 or 2.5% daily water exchange was similar (5.7 to 6.4 tonnes/ha). In this study, survival was poor in ponds managed without water exchange at this stocking density. Reducing daily water exchange from 25 to 2.5% reduced the mass loading of total suspended solids (including effluent from draining ponds for harvest) from 2.0 to 1.0 kg solids per kg shrimp.

In another study (Hopkins et al. 1995), ponds managed without water exchange were stocked with *L. vannamei* postlarvae at 39 or 78/m$^2$ and fed either a 20 or 40% protein feed. Ponds were aerated at 20 kW/ha (low-density ponds) or 40 kW/ha (high-density ponds). Shrimp production ranged from 5.8 to 8.2 tonnes/ha. Commercial application based on results of this research was described by McIntosh (2001), Boyd and Clay (2002), and Burford et al. (2003). Commercial ponds were lined and intensively aerated (21 to 45 kW/ha). Shrimp yields range from 11 to 15 tonnes/ha per crop with 2.5 crops produced annually, and water is used very efficiently (1 to 2.3 m$^3$/kg shrimp).

from outside the facility. Average water exchange rates of 10 to 20% of pond volume per day over a shrimp crop were not uncommon, and emergency exchanges of 40 to 50% of pond volume in 1 day have been used. Water exchange rates have been reduced drastically at many shrimp farms either to comply with effluent regulations or as a disease control measure because diseases may enter farms with the intake water. This practice also reduces pumping costs and lessens the discharge of pollutants (Box 7.2).

Ponds have a natural ability to assimilate feeding wastes through a variety of physical, chemical, and biological processes. Less water exchange lengthens hydraulic retention time in ponds and increases their capacity to assimilate wastes. Water exchange should not be used to manage dissolved oxygen concentrations. This practice is ineffective and aeration is a much more efficient way of providing oxygen to ponds.

### *Recirculate water on the farm during shrimp grow-out*

The natural capacity of individual ponds to assimilate wastes can be enhanced by pumping pond water though settling basins or constructed wetlands and then reusing the water in

## BOX 7.3
## Water Reuse on a Shrimp Farm: A Case Study from Texas

Water reuse can be combined with other practices to dramatically reduce mass pollutant discharge and water use in shrimp farming. In 1995–1996, managers of a 170-ha Texas shrimp farm developed an environmental management system to address stricter effluent discharge regulations (Hamper 2000; Treece and Hamper 2000). The system consisted of practices to eliminate water exchange, improve on-farm waste removal, and reduce in-pond waste loading. Farm drainage ditches were widened and deepened to reduce water velocity so that ditches functioned as sedimentation basins rather than solely as water-conveyance structures. Weirs and baffles were strategically placed in the ditches to enhance the settling of solids. Aerators were then placed in the ditches to enhance organic matter decomposition and removal of waste nitrogen (Fig. 7.3). After the 6.5-km system of farm ditches was modified, pumps were installed to lift water from the ditches back into ponds rather than allowing it to be discharged from the farm. In-pond waste loading was reduced by reducing shrimp stocking rates from 50 to 36/m$^2$, using lower protein feeds, and feeding more frequently (as many as 4 times/day) to increase efficiency of feed use by shrimp. Mechanical aeration in ponds was increased from 15 to 19 kW/ha to meet the increased oxygen demand associated with reduced water exchange and to improve in-pond waste treatment.

The farm originally used daily water exchange rates of 10 to 20%, which was reduced to zero. Water is now added only to fill ponds in the spring and then to replace losses from evaporation and seepage during the growing season. Total water use was reduced from 38 to 1.5 m$^3$/kg of shrimp produced. Implementation of the comprehensive waste-management system reduced total suspended solids discharge from 3.6 to 0.05 kg/kg of shrimp produced. Mass discharge of phosphorus, nitrogen, and 5-day biochemical oxygen demand were reduced by proportionally similar amounts. Implementation of the waste management system did not affect annual shrimp production, which averaged between 3.6 to 5.4 tonnes/ha before and after the system was implemented.

culture ponds. Recirculating and reusing water in this manner reduces the need for water exchange from an outside water source and will dramatically reduce effluent volume and mass discharge of solids, organic matter, and nutrients (Box 7.3). In effect the facility becomes a large, outdoor recirculating aquaculture system wherein culture water is reconditioned in an external treatment unit and water is added only as needed to replace evaporation and seepage losses. In addition to the benefits of reduced water use and reduced discharge volume, reusing water during grow-out reduces risk of introducing infectious disease organisms and predators onto the facility and, concomitantly, reduces the probability of exporting disease organisms or cultured shrimp from the facility to external water bodies. Overall, water recirculation will reduce water use, reduce pollution, and make the facility more biosecure.

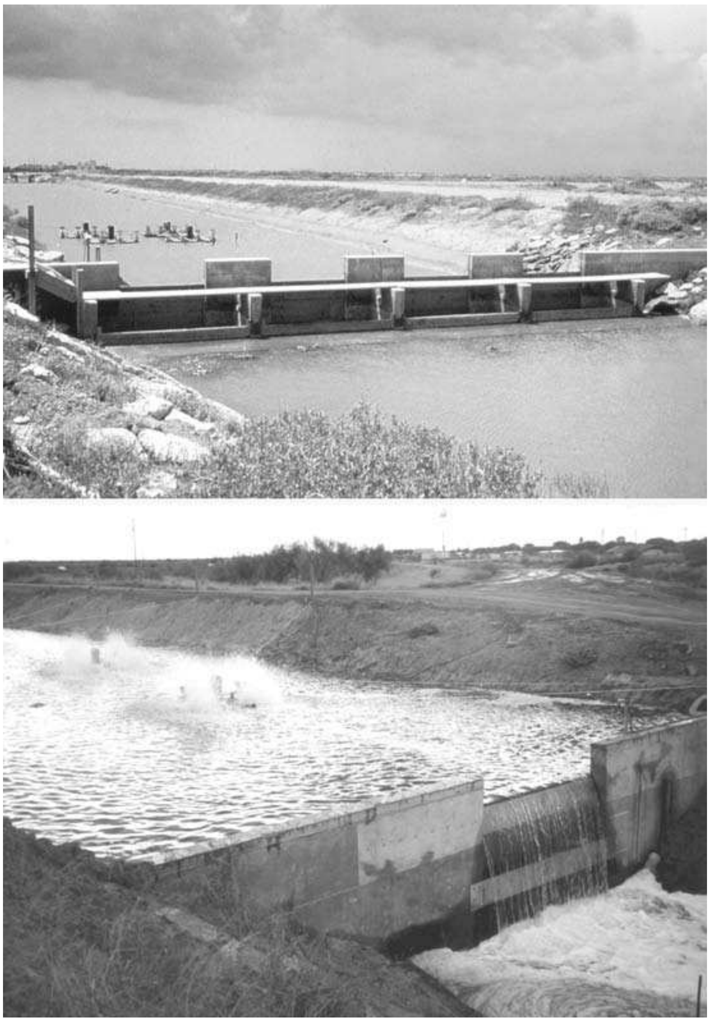

**Fig. 7.3.** Water reuse on this shrimp farm was accomplished by modifying the drainage ditches so that they functioned as waste-treatment units. Ditches were widened and deepened, and weirs were strategically placed to enhance the settling of solids. The top photograph shows the modified ditch before weirs were closed to increase water depth. Aeration enhanced organic matter decomposition and removal of waste nitrogen (bottom photograph). Photographs courtesy of Granvil Treece, Texas Sea Grant Program.

### *Reuse water discharged when ponds are drained*

Shrimp ponds are drained for harvest. However, it is possible to transfer water from the pond being harvested to a reservoir to allow reuse. This technology is widely used to avoid shrimp diseases in small, intensive farms in Thailand. In disease-infected areas, ponds are filled with water, the water is disinfected by chlorination, and after a reconditioning period, specific disease-free shrimp larvae are stocked. Water is not brought in from outside the farm during the crop, which lessens the possibility of introducing disease. Ponds are drained to facilitate harvest. Although implemented as a disease control methodology, adoption of water reuse systems is an excellent means of reducing water pollution and water use.

### *Use settling basins to treat draining effluents*

The suspended solids in effluent released from ponds following heavy rainfall and during water exchange consist of colloidal clay particles and plankton that do not settle quickly, and sedimentation is of little benefit for improving the quality of such effluent (Boyd and Queiroz 2001). When ponds are drained for harvest, sediment is resuspended and particles of mineral soil and organic matter are discharged. These particles are relatively large and can be removed from water by sedimentation for 4 to 8 hours (Boyd 1995a). The final 20 to 25% of pond effluent has a particularly high suspended solids load (Teichert-Coddington et al. 1999), and treatment of this effluent fraction by sedimentation could be especially beneficial (Box 7.4).

### *Use mangrove wetlands to treat effluents*

The waste treatment function of mangroves and other wetland types is well known (Mitsch and Gosselink 2000). Wetlands function as sinks for many chemicals through sedimentation, plant nutrient uptake, microbiological transformations, and adsorption to soil minerals. As with other treatment wetlands, the important factors affecting performance are hydrology (particularly hydraulic loading rate and retention time), soils, and vegetation. The idea of using mangroves to treat effluent from shrimp ponds was suggested by Robertson and Phillips (1995). Unfortunately, few studies have developed specific design criteria for treatment of shrimp pond effluent in mangroves. Hydraulic loading rates of 2.5

## BOX 7.4
## Settling Pond Areas Required for Shrimp Farms

Some shrimp farmers think that settling basins require too much space. However, this view is not necessarily true. Consider a 500-ha shrimp farm with 1-m-deep ponds operated with an average daily water exchange of 2%. The daily water exchange volume would be 100,000 m$^3$, and on a day when 20 ha of ponds are completely drained, the effluent volume would increase to only 300,000 m$^3$ per day. To provide a hydraulic retention time of 8 hours, a 100,000-m$^3$ settling basin would be necessary. This would require a 1-m-deep settling basin of 10 ha or a 1.5-m-deep settling basin of 6.67 ha. These areas would be only 2 and 1.3% of the farm area.

Even if settling basins are constructed in duplicate and with reserve capacity, not more than 4 to 6% of the area of a large farm would be required. Of course, on a small farm, the proportion of farm area devoted to settling would have to be much larger—often 10 to 20% of the farm area. Nevertheless, settling basins seem to be the only practical means of treating effluents from shrimp farms.

to 5 cm/day and hydraulic retention times of 5 to 14 days are recommended for treatment of municipal wastewater by Kadlec and Knight (1996). Although design criteria developed for wetlands designed to treat municipal wastewater are suitable for treatment of shrimp pond effluent, considerably greater hydraulic loading rates and shorter retention times should be sufficient because shrimp pond effluent is considerably more dilute than municipal wastewater (Box 7.5). Shrimp farms that discharge into mangrove areas should install a settling basin to remove coarse solids from shrimp farm discharge to avoid excessive sedimentation in mangrove areas. Removing coarse solids prior to treatment of effluent in mangrove wetlands will reduce the area needed for effective nutrient removal.

### *Monitor off-site water quality*

Some shrimp farms have voluntarily implemented off-site water quality monitoring to ascertain whether water pollution is occurring in receiving water. For example, a large shrimp farm in Madagascar initiated such a program (McNevin 2004). This farm is the major anthropogenic source of nutrients and organic matter to the bay that is the source of water for shrimp culture. The main objective of the study was to determine whether shrimp farm effluents were causing water quality degradation in the bay that might have negative impacts on the ecosystem and adverse effects on shrimp culture. In cases where there are other sources of pollution, it may be impossible to attribute declining water quality solely to shrimp farms. Nevertheless, implementation of off-site water quality

## BOX 7.5
## Treating Shrimp Pond Effluents in Wetlands

A 286-ha shrimp farm in Colombia partially recirculates effluent through a 120-ha mangrove wetland that is about 50-cm deep (Gautier et al. 2001). The hydraulic loading rate is about 29 cm/day and the hydraulic retention time ranges from 2 to 4 days. The wetland removes 95% of total suspended solids and 93% of volatile suspended solids. However, contrary to expectations, inorganic nutrient concentrations increase as water passes through the wetland, a result attributed to nutrient input by a large population of roosting birds.

A 7.7-ha constructed wetland that was 15 to 45 cm deep was used to treat the effluent from 8.1 ha of intensive shrimp ponds in south Texas, USA (Tilley et al. 2002). The hydraulic loading rate was 18 cm/day and the hydraulic retention time was 1 day. The wetland removed 65% of total suspended solids. The suggested ratio of treatment wetland area to pond area was 0.08. This is similar to the calculations of Rivera-Monroy et al. (1999), who estimated that 0.04 to 0.12 ha of mangrove wetland are needed to remove the dissolved inorganic nitrogen from the effluent of 1 ha of semi-intensive shrimp ponds.

These results suggest that the performance of treatment wetlands is variable, but that wetland areas of about 10% of the shrimp pond growing area are generally sufficient to treat effluents.

monitoring is a practice that should be considered by large shrimp farms. Green and Tookwinas (2006) discussed the principles of water quality monitoring. They also outlined programs that could be used to determine whether shrimp farm effluents were affecting coastal water quality. Ward (2006) presented methodology for assessing the carrying capacity of estuaries.

## Salinization

Saline discharge from coastal shrimp culture facilities may sometimes enter freshwater bodies to cause salinization. Inland culture of shrimp also is possible in areas with sources of saline water, and effluents from such facilities can lead to salinization (Boyd et al. 2006).

### *Better Management Practices to Prevent Salinization from Coastal Farms*

#### *Do not contaminate freshwaters with saline effluents*

Effluents from coastal shrimp farms usually are discharged into brackishwater or seawater because they are not located in the freshwater zone, but it may be necessary to route farm effluents away from freshwater bodies in some situations. The author has visited areas in southern Thailand where shrimp farming was extended to the inland side of a coastal highway by placing pipes beneath the highway to convey ocean water to ponds. No provision was made to drain farm effluents back under the highway for discharge into the sea. The highway was a barrier to flow, and nonsaline soils and freshwater canals on the inland side of the highway were severely impacted by saline water from shrimp farms. Today the government in Thailand prohibits the release of saline water onto agricultural land or into freshwater bodies. This practice should be adopted worldwide.

#### *Do not use freshwater from wells to dilute seawater supplies*

Shrimp producers in Asia once thought it necessary to mix seawater and freshwater to provide a salinity of 15 ppt in ponds. Freshwater for this purpose often was obtained from wells. Excessive use of freshwater from wells in Taiwan for shrimp farming and other purposes has caused land shrinkage (subsidence) and seawater intrusion into freshwater aquifers (Liao 1992; Sun 2004). The practice of mixing freshwater from wells with brackishwater or seawater is not necessary for shrimp aquaculture and should be strictly prohibited.

#### *Prevent seepage of saline pond water into groundwaters*

At sandy sites, large amounts of water may seep through the bottoms of ponds to contaminate freshwater aquifers. This problem has been encountered in Thailand (Dierberg and Kiattisimkul 1996), Bangladesh (Mahmood 1986), Indonesia (Cholik and Poernomo 1986), and India and the Philippines (SEAFDEC 1989). Salinization can possibly be controlled by lining ponds with clay blankets or plastic membranes to reduce seepage. The best solution is to avoid such sites for shrimp farming. The ACC certification program requires monitoring of chloride concentration in freshwater aquifers beneath or near shrimp farms. This practice also should be widely adopted.

#### *Do not allow excessive draw down of freshwater aquifers*

Overpumping of freshwater aquifers in coastal areas can lead to saltwater intrusion into them. In addition, land subsidence may result when the water table is drawn down by overpumping (Anonymous 1975).

#### *Do not discharge saline effluents into irrigation canals or onto agricultural land*

The discharge of saline effluent into freshwater areas obviously can cause salinization. It is particularly important not to contaminate irrigation canals with salt (Braaten and Flaherty 2001), and saline water should not be allowed to flow over agricultural land.

### *Better Management Practices to Prevent Salinization from Inland Farms*

In Arizona and Texas, inland shrimp farms are located in arid regions with underground supplies of saline water. There usually are no freshwater streams or shallow freshwater aquifers in such areas, and salinization is not an issue. In other places, inland shrimp farms have been installed in areas with freshwater streams, underground freshwater supplies, or both. Inland shrimp farms have been reported to cause stream salinization in Thailand (Braaten and Flaherty 2001) and in Alabama (Boyd et al. 2006). Nevertheless, if precautions are used, salinization can usually be prevented. It is not unusual to find inland shrimp farms operating with waters of 2 to 5 ppt salinity adjacent to rice farms and fruit orchards in Thailand.

#### *Site, design, and construct farms to prevent salinization of soils and freshwaters*

Inland ponds for culture of shrimp or other marine species should not be constructed in areas with permeable soils or the ponds must be lined to prevent downward infiltration. A ditch should be constructed around the farm area to capture lateral infiltration from ponds. Installation of salt-sensitive plants around the outside of the ditch can serve as sentinel organisms to warn of salt infiltration (Boyd 2001). The species of plants available for this application will vary from place to place. The advice of an agronomist or a horticulturist should be sought in selecting suitable plant species.

#### *Monitor surface and groundwaters for signs of salinization*

Freshwater wells and streams within a 1-km radius of inland shrimp farms should be monitored regularly to determine if salinization is occurring. The Best Aquaculture Practices standards used by the Aquaculture Certification Council outlines a procedure for evaluating an increase in salinization based on chloride concentration (www.aquaculture-certification.org). Boyd et al. (2006) studied the influence of an inland shrimp farm in

Alabama on salt concentrations in groundwater and a nearby stream. This study also can be used as a guideline for monitoring programs.

### *Reuse saline waters rather than discharging*

The most important practice is to operate inland farms as complete water reuse systems (Fig. 7.4) and to maintain essential storage volume to capture rainfall and avoid overflow.

### *Discharge water slowly to prevent excessive increases in receiving stream salinity*

Water must sometimes be discharged from inland shrimp farms. This operation should be done gradually so that the salinity of the receiving stream does not increase greatly. The chloride concentration of receiving streams in Alabama must not exceed 230 mg/L (Boyd et al. 2006). Normal concentrations usually are 10 to 20 mg/L, so a chloride increase of about 200 mg/L is allowable. Inland shrimp ponds in Alabama usually have chloride concentrations of 1,000 to 2,000 mg/L. Thus, effluent volumes equal to about 10% of stream flow are acceptable provided there is adequate mixing to avoid stagnant areas of high chloride concentration around outfalls.

### *Dispose of sediments properly*

Sediment removed from inland farms also could cause salinization if not properly disposed. Water supplies for inland farms normally are low in suspended solids, and sediment in ponds is derived primarily from internal erosion. Thus, sediment removed from pond bottoms should be used to repair areas of erosion on pond embankments.

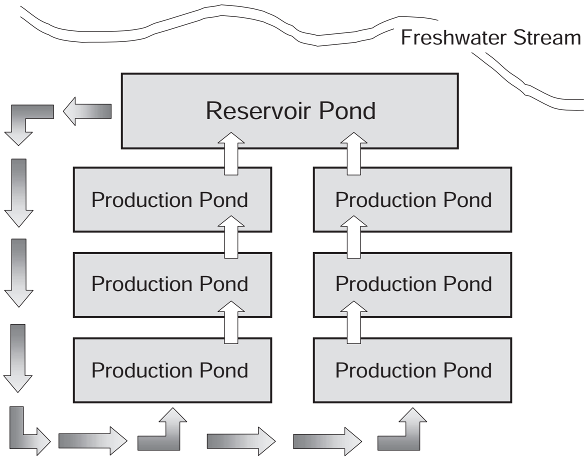

**Fig. 7.4.** An example of a method for storing water for reuse in inland shrimp ponds to prevent discharge of saline water into freshwater streams. Shaded arrows indicate pumped water; white arrows indicate gravity flow. Redrawn from Boyd et al. (2006).

## Pond Dry-Out and Sediment Removal

Pond sediment quality is important in shrimp culture because shrimp spend most of their lives on or burrowed in the sediment. High concentrations of organic matter can lead to anaerobic sediment that can have adverse effects on shrimp growth and survival and on the quality of harvested shrimp. Water quality in ponds with good bottom soil quality tends to be better than in ponds with impaired bottom soils (Boyd 1995a), and maintenance of good soil quality probably improves effluent quality. Moreover disease organisms and their vectors can survive in pond sediment and infect the next crop. Pond dry-out improves conditions for decomposition of organic matter, and disease organisms and their vectors can be killed by a combination of lime treatment to raise pH and dry-out.

Sediment also must be removed occasionally from basins, canals, and ponds on shrimp farms. This sediment has a salt burden and should be disposed in a manner that avoids soil and water salinization or other ecological damage.

### *Better Management Practices for Pond Dry-Out and Sediment Removal*

#### *Dry and lime bottom soils to enhance organic matter decomposition*

Shrimp pond bottom management was discussed by Boyd (2003). The usual procedure is to let pond bottoms dry for 2 to 3 weeks. Drying for a longer period usually is counterproductive because bottoms become too dry for microbial activity and culture time is lost. Acidic pond bottoms should be treated with agricultural limestone to increase sediment pH to 7.5 or 8. Drying allows atmospheric air to enter sediment and improve the availability of oxygen needed for decomposition of organic matter by aerobic bacteria and chemical oxidation of reduced inorganic substances that accumulated during the crop. Tilling of pond bottoms with a disk harrow can improve contact between the sediment mass and air. Tilling usually should be restricted to the upper 10- to 15-cm layer of the bottom, and it is more beneficial in heavy clay soil than in lighter, sandy soil. Pond drains should be closed during the drying period. If rainfall occurs during drying, the accumulated water should be held until solids settle before discharging.

#### *Treat wet soils to destroy vectors of disease and enhance organic matter decomposition*

Pond dry-out usually will eliminate disease organisms and their vectors. Bottoms of ponds often cannot be completely dried during the rainy season. Some ponds receive seepage from adjacent ponds or from a high water table that prevents dry-out. Bottoms of such ponds can be treated with burnt lime (calcium oxide) or hydrated lime (calcium hydroxide) at 1,000 to 1,500 kg/ha to raise the pH of the sediment above 10 to eliminate unwanted organisms. The high pH will decline in 2 or 3 days because carbon dioxide reacts with lime to convert oxides and hydroxides to carbonate. Application of sodium nitrate fertilizer, at 20 to 40 g/m$^2$ over especially wet areas, can help oxidize organic matter between crops (Boyd 1995b).

*Dispose of sediments properly*

Sediment removed from the bottoms of some ponds can be returned to embankments and areas of the pond bottom from which it eroded and compacted. This is the best way to dispose of sediment, because the pond earthwork is repaired and no sediment has to be put outside the pond.

In places where the water supply is highly turbid, a reservoir can be constructed for removal of suspended solids to prevent their sedimentation and accumulation in canals and ponds. However, with or without presedimentation, eventually sediment will have to be removed and disposed of outside farms. Shrimp farm sediment contains a salt burden, and salt will leach from spoil piles during the rainy season (Boyd et al. 1994), and this leachate should be prevented from entering surface or underground bodies of freshwater. This can be done by putting sediment inside a diked area to allow resedimentation of material suspended by rainfall. After sediment has been leached of salt, it can be removed to a vacant area, spread, and covered with grass.

*Treat black water from cleaning pond bottoms by sedimentation*

In Asia, shrimp farmers may use high-pressure water jets to wash sediment of high organic matter content from pond bottoms. Formerly, the water resulting from this operation was discharged directly into canals. The water was black and contained high concentrations of suspended solids. This practice was prohibited in Thailand by a regulation stating that black water cannot be discharged from ponds into public waters (Tookwinas 1996). The practice should be used only where the discharge can be retained in a settling basin for at least 48 hours to allow the suspended particles to settle before final discharge.

## Predator Control

High concentrations of shrimp in ponds provide attractive foraging opportunities for certain species of birds, reptiles, mammals, and fish. Ponds are usually located in rural or isolated areas that already support diverse and abundant wildlife, and many of these animals will be attracted to the large concentration of shrimp in ponds. Ponds constructed in the flyways for migratory birds offer convenient foraging opportunities and, in areas with extensive aquaculture development, the attraction of a year-round food supply may even cause birds to change behavior and migration patterns and linger near farms for longer periods of time (Glahn and King 2004). Predacious fish also can cause serious losses. Mammals (such as otters, mink, and nutria) and reptiles (such as snakes and alligators) may be a nuisance, but rarely cause significant economic losses in shrimp farming.

In addition to direct losses to predation, predators indirectly affect shrimp production by serving as vectors for infectious diseases. Birds and other animals may move infected shrimp from one pond to another or spread pathogens in regurgitated stomach contents or fecal material. Total exclusion of predators is impractical at shrimp farms, and predator control techniques must be employed. Effective control usually relies on a combination of management approaches. Overall, the best approach is integrated pest management where pests are identified, the type and level of damage is assessed through regular monitoring, and control methods are chosen that are appropriate for the predator and level of damage.

### *Better Management Practices for Predator Control*

Wild fish that enter ponds during initial filling or water exchange and birds are the main shrimp predators. Methods of bird control discussed in Chapter 6 also apply to shrimp ponds and will not be repeated here.

The most common method for wild fish control is to completely dry pond bottoms between crops to kill fish and fish eggs remaining in ponds after shrimp harvest. Puddles of water that may remain in pond bottoms may be treated with 10 mg/L rotenone, 100 mg/L chlorine, or 10 to 15 mg/L teaseed cake to kill wild organisms. These procedures should be used with caution in the United States because it is not clear whether they would comply with United States Food and Drug Administration regulations. Inflow to ponds should be passed through filter screens to restrict entry of predators. Screens typically range in opening size from 1.5 to 8.5 mm (Hirono and Leslie 1992). Even finer mesh screens have sometimes been used to prevent entry of disease vectors. These screens must be cleaned almost daily in ponds with water exchange to prevent clogging and restriction of flow.

## Facility Operation and Maintenance

Shrimp producers must store and handle fertilizers, liming materials, feeds, fuels, lubricants, and other chemicals. They also must operate tractors, trucks, aerators, and other equipment. This equipment and the farm infrastructure should be maintained properly. These general operations necessary to support specific pond management tasks should be done safely and in an environmentally responsible manner. Most of the practices discussed in Chapter 6 for freshwater ponds are also applicable to marine shrimp ponds.

The appearance of a shrimp farm is important because a well-organized and properly maintained farm conveys the message that operations are conducted in a responsible manner. The visitor or passerby is much less likely to question the environmental status of a farm with a good appearance than that of one that is not properly maintained. It is especially important to control erosion; provide vegetative cover; and maintain roads, fences, and buildings in good condition. Junk piles and abandoned, worn-out equipment on the grounds are especially detractive (Fig. 7.5).

### *Better Management Practices for Facility Operation and Maintenance*

Pond aquaculture facilities are expensive to build and operate. Protection of the investment by operating farms in a sustainable and economically efficient fashion is in the best interest of both farm owners and environmental protection. Facilities that are well-maintained, managed efficiently, and operated in compliance with all applicable laws and regulations will simultaneously improve long-term economic performance and reduce environmental impacts. As such, all of these management practices are simply part of good farm management.

**Fig. 7.5.** Untidy conditions around a small-scale shrimp farm in Asia.

### *Collect and dispose of solid waste on a regular basis and in a responsible manner according to all applicable state and federal regulations*

Shrimp farms can generate large amounts of waste that include empty bags, food scraps and other solid wastes, paper, used motor oil, scraps from carpentry and mechanical shops, human sewage, and expired feed and agrochemicals. Farms should have procedures for regular and sanitary collection and disposal of wastes.

Containers for collecting garbage and other farm wastes should be located at strategic sites. These containers should be emptied at regular intervals and not allowed to overflow or create other nuisances. The wastes should be burned, put in a landfill, or disposed of by other acceptable methods.

Sanitary facilities for disposal of human wastes using septic tanks or other effective waste treatment systems should be installed. Under no circumstances should human wastes be allowed to contaminate ponds. Sanitation is especially important for small-scale shrimp farms in Asia because permanent or temporary living quarters often are erected beside ponds.

### *Maintain all equipment in good working condition*

Use the best equipment affordable and develop a maintenance program to assure that equipment is always in good repair. Maintain a file on each major piece of equipment that contains maintenance logs, operating manuals, and warranty information. Maintain an on-site inventory of frequently used repair and replacement parts for critical equipment. All personnel should be familiar with equipment operation and the location of back-ups, tools, spare parts, and other materials that may be needed if equipment fails.

### *Use and store petroleum products to prevent contamination of the environment*

Petroleum leaking from storage tanks or farm equipment wastes a valuable resource and can contaminate surface or underground water supplies. Petroleum products also are highly odorous and small amounts in water can cause a disagreeable off-flavor in shrimp. A protective containment berm that retains leakage or tank contents in the event of failure should be constructed around storage tanks. Petroleum storage in above-ground and underground tanks is regulated in the United States by federal and state laws, and information can be obtained from State Departments of Commerce, State Departments of Environmental Quality or Protection, or regional USEPA offices. Aquaculturists should also implement a regular maintenance schedule for tractors, trucks, and other equipment to prevent oil and fuel leaks. Used oil should be disposed of through recycling centers.

### *Use and store chemicals to prevent contamination of the environment*

The most common chemicals used in pond aquaculture are fertilizers, liming materials, and herbicides. These materials will have no adverse effects on the environment when used properly. They should be used only when needed and only for the specific purpose for which they are intended. Herbicide use in the United States is regulated by federal and state laws, and farmers are responsible for using products according to label instructions and disposing of out-of-date chemicals and empty containers according to applicable state and federal regulations. All chemicals should be stored in secure, well-ventilated, watertight buildings.

### *Oxidize sodium metabisulfite solutions completely before discharging them to natural waters*

Many shrimp farms treat shrimp with sodium metabisulfite at harvest to prevent undesirable mottling and blotches on external surfaces. The spent sodium metabisulfite solution sometimes is simply poured into a drainage canal or into the estuary. The solution removes oxygen from water and creates acidity (Boyd and Gautier 2002). Localized fish kills can occur where sodium metabisulfite solutions are discarded. The spent solution should be aerated to completely oxidize sulfite to sulfate and the resulting acidity neutralized with lime. The solution can then be safely discarded into the environment.

### *Develop a response plan for spills of petroleum products, pesticides, and other hazardous materials*

Reporting significant spills of petroleum and pesticides is required by state and federal law in the United States and in some other nations. Shrimp farmers should be aware of all applicable regulations. They also should develop an emergency response plan for all hazardous materials on the farm and all farm employees should be aware of the plan.

### *Develop a record-keeping system*

Good record-keeping is the hallmark of a well-operated aquaculture facility. Records of concerns such as feeding, chemical use, water quality, serious weather conditions, culture operations, and animal inventory facilitate improvements in the efficiency of farm input use. Paper copies of records should be maintained for archival purposes; computerized record-keeping tools can be used for trend analysis and forecasting. Records should be reviewed periodically to determine if they are useful and to provide insight into opportunities for improvement of farm operation.

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## Chapter 8

# Better Management Practices for Net-Pen Aquaculture

*Sebastian M. Belle and Colin E. Nash*

## Introduction

Net pens and cages are submerged, suspended, or floating enclosures used to hold and grow aquatic animals. Net pens and cages may be located along a shore or pier, or anchored and floating offshore, either in freshwater or saltwater (Fig. 8.1) They may be used to culture a variety of shellfish or finfish, but this chapter pertains only to finfish facilities. Cages have rigid frames on all sides and net pens have rigid frames only at the top. These structural differences have little bearing on environmental impacts of culture, so the collective term *net pens* is used throughout this chapter.

Maintenance of good water quality in net pens depends on tides, surface currents, and other natural water movements to provide a continual supply of high-quality water. Unlike flow-through systems, where nutrients discharged from the culture unit are swept away, diluted effluents from net pens in marine systems can return to farm sites by tidal circulation. The health, welfare, and quality of the aquatic animals produced in net pens are directly impacted by the quality of water surrounding and flowing through pens. Importantly, producers using net pens have little ability to protect their animals from degraded water quality and other environmental influences. Thus, any effect that management practices have on water quality or the local environment also directly impacts cultured animal performance and farm economic returns. The intimate linkage between environmental quality, cultured animal performance, and farm profits provides incentives for producers to manage operations in harmony with the local environment. An understanding of local site characteristics is critical to managing farm operations so that the ability of a site to assimilate and process waste solids and nutrients is not exceeded.

Net pens create new underwater structures in local environments. These structures and their associated mooring systems provide three-dimensional habitat similar to engineered artificial reefs. Net-pen facilities can increase the total amount of habitat available and habitat complexity. Structures, such as pens and their associated anchoring systems, preclude access by trawlers to benthic ecosystems under and around the farms. These ecosystems are therefore protected from the physical damage associated with destructive fishing practices. These benefits are, however, dependent on proper site selection and management of the net-pen farm.

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**Fig. 8.1.** An array of net pens used to grow Atlantic salmon in Cobscook Bay, Maine.

## A Place for Net Pens in Global Aquaculture

The development of net pens for fish may have been quite similar to the development of fences and other enclosure methods for terrestrial animals. As with ponds, net-pen enclosures probably evolved from early attempts to enclose and hold wild fish. These early structures were first constructed of stone, brush, and wood. As new materials were developed, these traps came to include the use of natural and synthetic fibers, eventually including the use of netting. Terrestrial and aquatic animal holding systems are based on the concept that enclosing live animals in the present allows food to be stored for future times of scarcity. Today's surplus becomes tomorrow's supply. In terrestrial and aquatic enclosures, the time an animal can be held is, in part, dictated by its physiology and food needs. Extended containment without nourishment will lead to decreased condition, disease, and ultimately death. As aquatic enclosure methods developed, their originators must have faced this challenge and developed methods to feed the enclosed fish. Aquatic fences were the first step and feeding was probably the second.

Early net-pen designs and materials were probably relatively small and simple. Nets were hand-made from natural fibers. This would have limited the size and durability of the net bag. Although net-pen materials and designs evolved rapidly since World War II, locally available and inexpensive materials are still important. As recently as the 1980s, many net pens were constructed of wood sandwiched around some form of flotation material. Bamboo remains a common net-pen material for floating collars in Asia today. After World War II, several technical innovations made larger net pens possible. First, the development of new synthetic fibers such as nylon and large automated looms enabled the fabrication of very large, durable net panels. Second, new materials, such as hot-dip galvanized steel and high-density polyethylene, facilitated the construction of much larger floating collars (Fig. 8.2). More recent innovations include submersible cages designed for deployment in high-energy sites, and the development of knotless mesh, which is stronger and provides less resistance to water flow. Modern net-pen designs vary widely but most consist of several common components, such as a floating collar, a net bag suspended from the collar, and an anchoring system designed to couple the floating collar to

**Fig. 8.2.** New collar materials such as high-density polyethylene have made it possible to construct larger, more durable net-pen facilities.

some fixed point on the bottom or an associated fixed structure such as a dock, house, or offshore platform.

Although net pens, in their present incarnation, are a relatively recent development, they are second only to ponds as the most commonly used fish enclosure in the world (FAO 2006). Beveridge (1987) estimated that approximately 40% of world finfish aquaculture production was cultured in net pens, with the balance of production cultured in ponds. Rapid growth of Asian pond aquaculture has reduced the proportional contribution of net pens, but production from net pens has increased significantly and should continue to grow. Indeed, without the emergence of net-pen technology and the move to marine environments, aquaculture production will always be limited by availability of good-quality freshwater and appropriate land resources. The emergence of reasonably priced and robust net-pen enclosures has opened significant areas of the globe for food production. Until recently, these areas, which represent the vast majority of space and water resources on the planet, were only used in an opportunistic fashion by aquatic hunters.

## Environmental Challenges Associated with Net-Pen Aquaculture

Although concerns about the environmental impacts of aquaculture are not unique to net pens, three factors have heightened concerns about net-pen operations relative to other production methods:

1) Net-pen facilities are an "open" aquaculture system and activities and processes inside the facility directly affect the environment outside the facility, and vice versa;
2) Unlike culture facilities that are operated on private lands, net pens are typically placed in public waters; and
3) Most net pens are operated in coastal marine environments, and the complexity of that ecosystem makes it difficult to accurately assess risks.

These factors, combined with broader social debates about human impacts and global carrying capacity, have caused net-pen operations to be intensively scrutinized by environmental activists. Indeed, with the possible exception of shrimp aquaculture in coastal ponds, no other production method has faced a similar level of scrutiny and criticism.

Net pens—like ponds, tanks, or raceways—are designed to contain fish. But they are distinct from these other culture systems in that water flow is not controlled. Net pens are more like fences than buildings. They are not constructed of earth, concrete, or fiberglass, and they do not include a barrier to contain the water that provides conditions necessary for fish life. Net pens do not require energy to move water. Net pens do not require large-scale structural changes to the ecosystem to contain fish and once net pens are removed, there is little, if any, enduring physical evidence that net pens were present (Johannessen et al. 1994; Yokum 1994; Axler et al. 1998; Brooks and Mahnken 2003; Brooks et al. 2003). As a fish production method, no other enclosure method is as temporary in nature and as closely tied to the aquatic ecosystem that surrounds it. By their very nature, net pens and the animals they contain are immersed in the ecosystem that provides key life-support functions. The only thing between the fish and the ecosystem is the net, making net pens an efficient enclosure method but also presenting serious environmental management challenges.

Like all human activities, aquaculture in net pens has environmental impacts. Environmental concerns about the potential impacts of net-pen operations are numerous, but can be broadly categorized into the following areas: nutrient enrichment and eutrophication, disease transmission between cultured and wild stocks, escapes and their potential impacts on wild stocks, discharges of therapeutants, use of fishmeal and oil in diets of carnivorous species, and the socioeconomic concerns about user conflicts in public waters. Although many of these concerns have focused on salmon farming, the emerging culture of non-salmonid marine finfish and offshore aquaculture are facing many of the same issues. The potential impacts of net-pen operations have been widely discussed, with numerous reviews on the environmental impacts of net-pen operations published (BCEAS 1997; Stickney 2002; Wildish et al. 2004; Islam 2005; Marine Aquaculture Task Force 2007). Three principal variables influence the degree of potential environmental risk from a net-pen operation: production intensity, site characteristics, and characteristics of the cultured species.

### *Production Intensity*

Net-pen operations are generally viewed as high-intensity production systems if intensity is defined on the basis of biomass density (i.e., mass per unit volume of water). This measure of production intensity is appropriate for static culture systems such as ponds, but not with flow-through systems and net pens. The relative culture intensity of these systems is not only defined by the physical volume enclosed by the culture unit, but by the volume of water that moves through the culture unit over time. Thus, in flow-through systems, intensity is more appropriately defined in terms of mass per unit of water flow, not just mass per unit volume of water enclosed. Net pens are essentially flow-through systems that rely on natural water movements instead of pumped water or stream flow. Depending on site characteristics, flow rates can be enormous; for example, in Cobscook Bay, Maine, average current velocities over a full tidal cycle are approximately 0.5 knot

(15.4 m/minute), equivalent to a water flow rate of $2.5 \times 10^6$ L/minute in a typical 15-m net pen. Based on typical maximum densities before harvest (23 kg/m$^3$), this corresponds to a loading rate of 0.024 kg/L per minute. As a point of reference, typical trout raceway loading rates range from 1.5 to 2.0 kg/L per minute (Brannon and Klontz 1989). Thus, compared with typical flow-through systems, net pens would be classified as a low-intensity production system.

Another development that shows the difficulty of generalizing about the intensity of net-pen systems is the use of large, open-ocean net enclosures stocked with large numbers of fish at relatively low densities. For example, huge open-ocean net pens in Japan, the Mediterranean, and Australia are routinely operated at fish biomass densities of less than 2 kg/m$^3$. These densities are much lower than many land-based operations that are classified as semi-intensive. The economics of using such low biomass densities is based on the geometric relationship between the surface area (net area) and the pen volume. As volume increases, the relative amount of surface area (net) required to enclose that volume decreases. Thus, as net pens increase in size, the cost of enclosing water volumes decreases significantly.

Although units of measurement used to quantify intensity and the relative classification of low-, medium-, and high-intensity operations may need some modification as applied to net pens, the concept of production intensity remains useful. This is particularly true when comparing different production levels or farm management methods on the same site. The intensity at which a net-pen facility is operated can directly affect the level of environmental impact or risk associated with the operation. In general, all other factors being equal, higher intensities lead to greater environmental risks. This is based on the direct relationship between waste loading of the surrounding ecosystem and production intensity, and at some point the ability of the ecosystem to cope with that loading is exceeded. In the case of net pens, greater environmental risk also translates into greater business risk because there is a direct linkage between the surrounding environment and the performance of the cultured fish.

The intensity of a net-pen operation can be varied in two ways: 1) by the number of fish in a particular net, farm, impoundment, watershed, or bay; and 2) by the duration that a particular site is occupied and the duration of any fallow period between operational periods. In the extreme, high-intensity operations involve very high fish densities (>45 kg/m$^3$) with no fallowing periods. Low-intensity operations are more difficult to quantify because of the relationship between site characteristics and the ability to process or disperse the metabolic by-products of the fish being cultured. What is high intensity on a "low-energy" site with relatively low water exchange rates and natural biological activity, may be low intensity on a "high-energy" site with high water exchange rates and natural biological activity.

### *Site Characteristics*

Site characteristics can have a dramatic influence on the potential environmental impacts of a net-pen operation. Many documented cases of negative impacts on local ecosystems can be directly attributed to poor site selection. Many early net-pen operations were located in relatively shallow and sheltered coastal bays to reduce the risk of damage to relatively primitive cages with rudimentary anchoring methods. Although these sites allowed relatively large numbers of fish to be grown successfully, the surrounding ecosystem quickly became polluted. These problems were often cited by environmentalists as reasons why net-pen aquaculture should not be allowed. The combination of low-energy sites and the early state of development of net-pen farming methods resulted in many farms failing from self-pollution and poor fish performance.

Net pens are temporary enclosures directly immersed in aquatic ecosystems. Site characteristics that affect the potential impact of net-pen operations on host aquatic ecosystems include water depth; water quality; current speed and flow patterns; storm exposure and maximum sea states; bottom type; background nutrient and light levels; primary productivity; temperature, oxygen, and salinity profiles; natural predator, pest and pathogen distribution and population levels; and any human activities in surrounding areas that may influence site characteristics. Appropriate site selection is one of the most powerful farm management tools available to minimize environmental impacts.

Since about 1995, significant technological improvements in net-pen design and materials have allowed systems to be located in increasingly high-energy, exposed sites. Numerous offshore net-pen designs have been developed and tested in open-ocean conditions (Fig. 8.3). These designs use new technologies and materials to allow the maintenance of structural integrity in extreme conditions, including hurricanes and typhoons. Although new net-pen designs and materials have proven their ability to survive extreme conditions, the economics of open-ocean operations have not yet been demonstrated. However, the benefit of the emergence of these technologies has been realized in near-shore environments, resulting in a general industry-wide trend toward larger facilities in deeper water.

### *Species Cultured*

All net-pen facilities use nets to enclose fish and therefore appear superficially similar. There is, however, a surprisingly diverse and large number of species cultured in net pens worldwide. Most of the public attention on net-pen aquaculture has focused on salmonids, especially Atlantic salmon (*Salmo salar*). Other salmonids cultured in net pens include rainbow (steelhead) trout (*Oncorhynchus mykiss*), sea trout (*Salmon trutta*), coho salmon (*Oncorhynchus kisutch*), and Chinook salmon (*Oncorhynchus tshawytscha*). In addition to the salmonids, several marine finfish species have been commercially produced in net pens (Table 8.1).

The aquaculture of some of these species continues to depend on young fish harvested from the wild. For example, amberjack or yellowtail (*Seriola quinqueradiata*) and Japanese jack mackerel (*Trachurus japonicus*) have been harvested and cultured in net pens in coastal waters of Japan for more than 60 years, and more recently in Korea and Spain; several species of tuna (*Thunnus* spp.) in Australia, Canada, Croatia, Japan, Malta, Mexico, and Spain; and several groupers (*Epinephalus* spp.) in a number of Southeast Asian countries.

The culture of other species in net pens is a genuine farming practice, because young fish are first reared in marine hatcheries and then farmed in nearby coastal enclosures and net pens. These include, for example, Atlantic cod (*Gadus morhua*) in Canada, Norway, and the United States; red sea bream (*Pagrus major*) in Japan; gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) in Mediterranean countries (Fig. 8.4); barramundi (*Lates calcarifer*) in Australia; marine drums (*Sciaenops ocellatus* and

**Fig. 8.3.** Submersible, semirigid net cages for use in deep water. The top photograph is a 3,000-$m^3$ cage deployed 2 km off Ewa Beach, Oahu, used to raised Pacific threadfin (*Polydactylus sexfilis*). Threadfin, locally called moi, are a highly esteemed fish with deep cultural significance in Hawaii. The bottom photograph is a 3,000-$m^3$ submersible cage deployed 1.5 km off the Kona Coast of Hawaii. The cage is used to grow sashimi-grade Hawaiian yellowtail (*Seriola rivoliana*, also called Almaco jack). The cage is normally submerged, as in the top photograph, but it is floated above water for cleaning and maintenance. Photographs courtesy of OceanSpar LLC.

*Pogonias cromis*) in the United States; and several marine flatfish species (Pleuronectidae, Scophthalmidae, and Soleidae) in European countries and Japan. The number of species cultured in net pens for experimental and commercial purposes increased significantly in the last 25 years. In 2002, FAO reported that 178 species of fish were cultured in net pens.

Some of the environmental risks associated with net-pen operations are not associated with the particular species being cultured. For example, issues of nutrient enrichment and pathogen transfer from captive to wild fish are common to nearly all net-pen cultures. There are, however, certain circumstances where the impacts of net-pen aquaculture can

**Table 8.1.** Some of the fish grown in net pens or cages around the world.

| Common Name | Scientific Name | Representative Culture Sites |
|---|---|---|
| Pacific threadfin | *Polydactylus sexfilis* | United States, Taiwan |
| Red drum | *Sciaenops ocellatus* | United States |
| Rockfish | *Sebastes schlegelli* | Korea, Japan |
| Atlantic salmon | *Salmo salar* | Chile, Norway, United Kingdom, Ireland, Faeroe Islands, United States, Canada, Australia, New Zealand |
| Coho salmon | *Oncorhynchus kisutch* | Chile, Canada, Korea, Japan, United States |
| Chinook salmon | *Oncorhynchus tshawytscha* | United States |
| Steelhead trout | *Oncorhynchus mykiss* | Chile, Canada, Korea, United States |
| Barramundi | *Lates calcarifer* | Australia, Thailand, Taiwan, Hong Kong, Singapore, Philippines, Malaysia |
| European seabass | *Dicentrarchus labrax* | Greece, Turkey, Spain, Italy, Spain, Croatia, Egypt, France, Singapore |
| Striped bass and hybrids | *Morone* hybrids | United States, Mexico, Israel |
| Groupers | Family Serranidae | Japan, Taiwan, China, Indonesia, Thailand, Philippines, Korea, Australia, Middle East |
| Black seabream | *Mylio macrocephalus* | Hong Kong, Taiwan, China |
| Gilthead seabream | *Sparus aurata* | Mediterranean countries |
| Crimson seabream | *Evynnis japonica* | Japan |
| Goldline seabream | *Sparus sarba* | Taiwan, Hong Kong, China |
| Red seabream | *Pagrus major* | Japan, Taiwan, China, Korea, Hong Kong |
| White seabream | *Mylio berda* | Hong Kong, Taiwan, China |
| Yellow-finned seabream | *Mylio latus* | Hong Kong, Taiwan, China |
| Mangrove red snapper | *Lutjanus argentimaculatus* | Hong Kong, Taiwan, Singapore, Philippines, Malaysia, China, Thailand |
| Russell's snapper | *Lutjanus russelli* | Hong Kong, Malaysia |
| Golden snapper | *Lutjanus johni* | Singapore |
| Tiger puffer | *Takifugu rubripes* | Japan, Taiwan, Korea |
| Milkfish | *Chanos chanos* | Philippines, Indonesia, and western Pacific countries |
| Mullets | *Mugil cephalus*<br>*Liza* spp. | Mediterranean countries, South America |
| Black drum | *Pogonias cromis* | United States |
| Spotted seatrout | *Cynoscion nebulosus* | United States |
| Japanese flounder | *Paralichthys olivaceus* | Japan |
| Turbot | *Scophthalmus maximus* | Spain, France, Chile, Ireland |
| Common sole | *Solea solea* | United Kingdom, France |
| Atlantic halibut | *Hippoglossus hippoglossus* | Europe, Iceland, United States |
| Rabbitfish | *Siganus* spp. | Philippines, Fiji, Middle East |
| Atlantic cod | *Gadus morhua* | Canada, United States, United Kingdom, Norway, Iceland |
| Cobia | *Rachycentron canadum* | Taiwan, China |
| Japanese jack mackerel | *Trachurus japonicus* | Japan |
| Amberjack/yellowtail | *Seriola* spp. | Mexico, Japan, several Mediterranean countries |
| Tuna | *Thunnus thynnus, Thunnus maccoyii, Thunnus albacares, Thunnus obesus* | Australia, Canada, Croatia, Japan, Malta, Mexico, Spain, Taiwan, Turkey |

**Fig. 8.4.** Net pens in the Frioul Archipelago, near Marseille, France, used to grow European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*). Photograph by John Hargreaves.

be species-specific. For example, species grown in areas where they do not occur naturally present greater risks if they escape than do native species. Although domesticated native species may present genetic risks if they escape, nonnative species have the potential to become invasive and radically change local ecosystems. Nonnative species may also introduce exotic pathogens to local ecosystems. Additionally, net-pen culture of species for which no artificial hatchery methods have been developed rely on the capture of wild juveniles. Fisheries management methods have traditionally focused on managing the harvest of adult fish based on recruitment levels of juveniles. Current fisheries management methods and databases are inadequate to manage fisheries of juvenile fish populations. Unless adequate management programs are in place, net-pen operations that are based on the harvest of wild juveniles may have significant negative impacts on wild stocks. These risks were recently reviewed and summarized in Ottolenghi et al. (2004).

The diversity of species and husbandry practices used in net pens and the widely different aquatic environments used as sites for net-pen facilities mean that environmental hazards and risks vary. It is unrealistic to expect that a standard set of better management practices (BMPs) will adequately address the range of risks encountered in net-pen aquaculture. There are, however, some general approaches that can be applied or adapted to most operations, and it is these that are identified and discussed in the following sections.

## Better Management Practices for Net-Pen Operations

Most of the BMPs for current net-pen technology have been published by national salmon producer associations as codes of practice. Accordingly, most net-pen BMPs come from Australia, Chile, Ireland, Norway, Scotland, and the east and west coasts of Canada and the United States. Belle and Howell (2001) summarized presentations by 15 key industry associations on various Codes of Practice. Many of these codes contain BMPs of varying detail and species specificity. In net-pen aquaculture there is often a close relationship between environmental BMPs and business codes of practice that use BMPs to implement environmental management systems. In Australia, for example, the National Aquaculture Development Committee (NADC 2002) noted that the development and implementation of BMPs by the aquaculture sector, in addition to using resources as efficiently as possible and integrating environmental management into each stage of the operations, was the only way to reap the full benefits of ecologically sustainable development. Therefore, the group proposed that BMPs should be developed and incorporated as part of a code of conduct for the national aquaculture industry.

Norway (Maroni 2000) and Scotland (SEPA 2005) have been among the most active European countries in developing national standards and BMPs because of their long-standing 30-year-old net-pen salmon industries. In these countries, BMPs were developed in close cooperation with producers, but were then embedded in governmental regulations to ensure compliance. Both countries developed and published annual advisory and management documents for monitoring and regulation of marine aquaculture. Sweden has been equally active in monitoring its much smaller industry, but in a more sensitive ecosystem (Ackefors 2000). Consequently, the European Union and its member countries with abundant marine resources, such as Greece, Ireland, and Spain, have simply adapted these BMPs to their own aquaculture sectors.

In the United States and Canada, a number of net-pen BMPs have been developed (MAA 1997, 2002a, b, 2003, 2007). The original impetus for the development of net-pen BMPs in North America was the need to reduce escapes. Consequently most early BMPs focused exclusively on reducing the risk of farm escapes. One difference between Scandinavian and North American BMP programs is that Scandinavian programs tend to be more focused on equipment specifications, while North American programs have focused more on operational protocols. North American programs have been less prescriptive regarding equipment specifications and more focused on equipment testing, preventive maintenance, and monitoring and improvement of standard operating protocols.

Another fundamental difference between North American BMP programs and their European and Scandinavian counterparts is that North American programs have used a combination of regulations, linkages to regulations through permit conditions, and third-party verification as methods to ensure compliance. This approach is seen as supplementing a set of strict environmental regulations that include outcome-oriented metrics and aggressive monitoring programs. European and Scandinavian programs, on the other hand, have tended to be regulatory in nature, with the assumption that, if BMPs are regulatory, compliance with the regulations is all that is required. The challenge net-pen operators face is that compliance with regulations does not appear to be adequate to address concerns of environmental critics. Emergence of third-party certification programs developed by environmental advocacy groups is a clear acknowledgment of this problem. In part, emergence of these programs is recognition that private-sector initiatives can adapt to rapidly changing technologies more quickly than government bureaucracies. Certification programs are also a clear acknowledgment that regulators and resource managers have been relatively ineffective at communicating the efficacy of their regulatory programs to the public and environmental community.

Although a number of BMP programs for net pens have been developed, they have faced criticism from the environmental community—and in some cases, regulators—on two points. First, many BMPs have been developed solely by industry associations with a vested interest in controlling costs of environmental compliance. Second, until recently most BMPs included little or no verification of whether net-pen operators are complying with their recommendations. These two criticisms are not unique to net-pen aquaculture and are discussed in more detail in Chapters 2 and 5.

Two lessons are clear from more recent efforts to develop effective net-pen BMPs (MAA 2003, 2007). First, although producers often have the best understanding of how to modify management practices to reduce environmental risk, industry-developed BMPs will not be embraced unless environmental NGOs are included in the development process. Second, without some form of verification and a robust and meaningful staff training program, BMPs may not be effectively implemented. For example, in a joint report on marine finfish inspections by the Ministries of Agriculture, Fisheries and Food and Water, Land and Air Protection (MAFF/MWLAP 2004) in Canada, it was noted that almost all sites had BMPs in place. However, subsequent deficiencies were generally related to a company's failure to include confirmation that the plan had been reviewed and endorsed by the operator and understood by farm-site staff.

The open nature of net pens and their literal immersion in the surrounding aquatic ecosystem presents significant challenges in managing potential environmental impacts. These challenges are amplified by the fact that net-pen operators, unlike some of their intensive land-based colleagues, have little ability to control the environmental conditions in which animals are cultured. For example, net-pen operators cannot manipulate temperature or control water quality, nor can they shelter their animals from weather or intense sea conditions. Net pens do not contain or channel water flow, and net-pen operators therefore have no ability to process or treat either the water supply or effluent water streams. In these circumstances, where technical interventions to directly control the environment or process water are not feasible, BMPs often represent the only management technique available.

Each of the following sections provides the relevant management options that can improve the environmental performance of net-pen aquaculture facilities. Recommended practices are provided for site selection, feed management, benthic impacts, nutrient release and recovery, biofouling, management of escapes, predator and pest control, and facility operation and maintenance. Net-pens are used to culture a wide array of species of coldwater and warmwater fish in saltwater, freshwater, and brackishwater. The diversity of species, environmental conditions, and culture methods used in net-pen systems make the development of generic environmental management practices challenging. A reasonable practice for one species or facility may be inappropriate for another. Furthermore, practices may be combined in unique ways to achieve the goal of pollution reduction. As such, BMPs should never be developed without consultation with technical experts and all stakeholders (see Chapter 5).

## Site Selection

Appropriate site selection is arguably the most effective management tool to reduce environmental impacts. Appropriate site selection for net pens is critical, not only to minimize potential environmental impacts, but also to optimize fish health and performance, protect worker safety, and minimize production costs. With the exception of site selection, net-pen farm operators have little ability to control the environmental conditions to which their fish are exposed.

Inherent in site selection is the concept of carrying capacity, which is the ability of a site to sustain a particular level of production over time. In aquaculture, the concept of carrying capacity is based on two processes: the biological and chemical responses of the ecosystem to nutrient loading and the impact of those responses on the animals being cultured. Aquatic ecosystems have an inherent capacity to process a waste stream to which they are subjected through a variety of physical, biological, and chemical processes. As waste loading is increased, the structure and function of the ecosystem changes. At some point those changes become so extreme that the ecosystem type shifts. For example, it may shift from an aerobic ecosystem with significant macrofauna and flora to an anaerobic system with predominantly bacterial communities. If loading continues to increase, the ability of the ecosystem to function and provide ecosystem services becomes severely compromised (Pearson and Rosenberg 1978; Midlen and Redding 1998; Pillay 2004).

Beveridge (1984) was the first to apply the concept of carrying capacity to net-pen systems. Although initial efforts were focused on freshwater net pens, more general models were developed and applied to freshwater and marine applications (Beveridge 1987, 2004). Other environmental impact models have complemented this work (Dudley et al. 2000; Carswell and Chandler 2001; Cromey et al. 2002). Although extensive modeling work has been done, it remains clear that prediction of the carrying capacity of a particular site is very difficult. Unpredicted or unknown local site conditions may significantly modify the performance of a site. In Maine, for example, a site with relatively low current speed and tidal exchange was expected to have a low carrying capacity, but empirically showed no signs of negative ecosystem impacts at high fish production levels. Analysis of production data and site characteristics indicated that although tidal currents were normally low, the site was subject to regular storms that periodically generated high rates of water exchange. Overall, the site was actually a high-energy site that could sustain a relatively high level of production.

Site selection has significant potential to determine the risk of environmental impacts associated with net pens. Site selection to minimize environmental impacts may have to balance conflicting goals. For example high-energy, exposed sites tend to reduce impacts associated with benthic deposition of wastes, but because the sites are exposed they may increase the risk of storm damage and fish escapes or compromise worker safety.

Site selection can mitigate local environmental impacts and the cumulative impact of multiple farms in a particular water body. The issue of cumulative impact is common to all forms of aquaculture that rely on flow-through water, or that significantly alter the structure of the ecosystems in which they operate. Cumulative impact is particularly problematic with net pens because they are most often sited and operated in public waters. Although BMPs for specific facilities are relatively well developed, BMPs that address cumulative impacts are new to all forms of aquaculture. For net pens, cumulative impacts are being addressed in a number of jurisdictions through the use of regional, watershed, or embayment agreements. In Maine, for example, salmon farmers who operate in the same bay sign legally binding Bay Management Agreements (MAA 2002a) that limit the fish stocking levels on individual farms and the aggregate stocking levels for all farms in a particular bay. These agreements go further and coordinate biosecurity protocols, year-class rotation, and fallowing cycles. Similar agreements are used in New Brunswick, Canada, and Ireland.

## *Better Management Practices for Site Selection*

### *Conduct baseline environmental site surveys*

Conduct site surveys to characterize the aquatic ecosystem, the habitat that occurs on and around the site, and the prevailing meteorological and hydrographic condition, and confirm that site conditions are appropriate for the cultured species. Site characteristics—especially current patterns—will affect the efficiency of feed utilization (and therefore waste production) and the accumulation or dispersal of wastes.

In the survey, include multiple sampling stations that extend to all areas of the proposed site. Include at least one reference site away from the proposed farm site. Collect an adequate number of replicate samples at each station to provide a statistically valid sample. The number of required sampling stations and replicates will vary depending on the size of the proposed site and degree of variation in conditions over the site. Larger sites with greater variance require more sampling stations. Baseline studies should include an assessment of seasonal variation in site characteristics. Additional guidance on survey design and site criteria can be found in Levings et al. (1995), Hakanson et al. (1988), Findlay and Watling (1997), Wildish et al. (2001), and Brooks et al. (2003).

Document water depths, bottom types, water circulation patterns, and current speeds around the site (Box 8.1). Characterize the species composition, diversity, and abundance of benthic infauna and epibenthic macrofauna and flora at all sampling stations. Site surveys must include a characterization of the predominant seasonal weather patterns and expected associated sea states. Document maximum wind fetch for all compass directions. Calculate maximum wave heights based on fetch, water depth, and a range of expected maximum wind speeds and durations (Beveridge 2004). Examine drogue, current-speed, and weather-pattern data carefully to determine the probability that strong winds and currents may occur in opposing directions. Such opposing patterns can result in wave heights larger than those predicted using the traditional wind-fetch method. Waves generated by opposing wind and current directions also tend to be short periods in nature and very steep. Such waves can have significant destructive power.

At minimum, measure temperature, dissolved oxygen, salinity, and turbidity over the full depth profile at the site. Water quality and currents must be well within the tolerance limits of the species cultured. Inappropriate sites can result in excessive energy use, increased feed conversion and stress, and more waste production.

### *Avoid sites with frequent or extreme weather or sea-state conditions*

Extreme conditions can limit access to the farm site. Fish farmers must be able to routinely observe and access fish and net pens for a number of reasons. Routine observation of farm animal behavior is one of the central principles of animal husbandry and stewardship. Behavioral shifts are often the first indication of fish stress or disease. Remote sensing technologies are improving and are routinely used to monitor feeding responses of fish in net pens (Holland 1987; Bugrov 1996). However, there is no substitute for direct

## BOX 8.1
## Measuring Water Circulation with Drogues

Circulation patterns can be mapped with drogues and a Global Positioning System (GPS) unit mounted on a boat. An inexpensive drogue can be constructed from a 1-$m^2$ piece of light fabric with a piece of 3/4-inch (1.8-cm) diameter galvanized water pipe sewn into sleeves on the top and bottom of the fabric. Drogue flotation is provided by a small surface float connected to the drogue by a length of strong, thin line. Use the smallest float size possible to ensure drogues can be retrieved but are not unduly influenced by surface winds. Depth of drogue deployment can be controlled by the length of the line between the drogue and the float. Drogues should be deployed at multiple locations and depths on the proposed site to characterize overall water circulation patterns. Conduct drogue studies during calm sea states when little wind is present. At a minimum, deploy drogues at a depth equivalent to the mid-depth of the proposed cages and a depth just over the bottom but sufficient to clear minimum depths and any obstructions. At sites with water depth over 30 m, deploy drogues halfway between expected maximum net depth and the bottom. Log drogue position frequently using a GPS unit. Frequency of logging is determined by the speed of drogue movement. The faster the movement the more frequent positions should be recorded. Drogue studies should be conducted over a wide variety of tide stages to characterize accurately site circulation patterns. Use drogue studies to construct circulation maps for the site.

observations to assess fish behavior. In a more holistic fashion, differences in swimming behavior, respiration rates, spatial orientation in the net pen, agonistic behaviors, and whole-school behavior are difficult to observe remotely. Producers must also be able to routinely access fish to sample for growth, feed conversion calculations, and disease monitoring. Producers must be able to access sites regularly to inspect and maintain net pens and mooring equipment.

Extreme conditions can also jeopardize worker safety, product quality, and animal welfare. Net-pen systems are typically floating structures with a suspended net bag. Net pens are moored using a variety of methods. High sea states often result in significant movement of the floating platform and net bag underwater. In the extreme, waves can wash over net pens putting personnel at risk of being swept overboard and possibly sweeping fish out of pens unless they include surface containment nets. Extreme sea states can also place great strain on net-pen structures and the mooring system, leading to equipment failure and increased risk of fish escape and injury to farm personnel. Product quality and animal welfare can be negatively impacted by poor site selection. Fish in net pens at some sites in Scotland subject to heavy swells experienced significant de-scaling and subsequent mortality from abrasions caused by contact with the net bag (Beveridge 2004).

### *Select sites with good water exchange that are not depositional environments*

Adequate water velocities will disperse solid wastes, ensure good water quality, and reduce the probability that the local carrying capacity of the site is exceeded. Whether a site is depositional or erosional depends on current velocity, storm frequency and magnitude, hydrography, and local circulation patterns, among other factors. Bottom type and granulometry can be used to determine whether a site is depositional or erosional. In general, soft mud or clay is indicative of depositional sites. Hard sand, gravel, or cobble generally indicate erosional sites. Sites often consist of a mix of depositional and erosional areas. Map the bottom sediment type to determine deposition and erosion within a proposed site. Select sites that maximize areas of erosion and minimize depositional areas. Current velocities on erosional sites should not cause anchor scouring and increase the risk of mooring failure. Confirm that current velocities on sites of erosion will not significantly exceed typical swimming speeds for the species to be cultured. Consistent currents in excess of species-specific average swimming speeds will cause unnecessary stress and may lead to poor feed conversion. Sites with episodic current events that exceed species-specific average swimming speed may be acceptable provided that events are of short duration and do not exceed species-specific maximum swimming speed or cause animal fatigue or exhaustion. Carroll et al. (2003) classified sites for salmon farming in net pens according to current velocity as very sensitive (<3 cm/second), moderately sensitive (4 to 6 cm/second), slightly sensitive (7 to 10 cm/second), and not sensitive (10 to 25 cm/second). While these classifications are helpful in general terms, sites with relatively low current velocities can still be erosional due to episodic storm events or unique bottom morphologies. An examination of the bottom sediment types is the best way to assess whether a site is depositional or erosional.

### *Select sites with water depths at least twice that of the net pen*

Adequate water depth, combined with good water exchange rates, helps disperse solid wastes and allow good water flow through a net pen. Site depth is usually a trade-off between these advantages and the cost of mooring systems in deep water. Nets close to the sea floor also may have low water flow, be prone to snagging and tearing of the net-pen bottom, and provide greater risk of entanglement of benthic organisms. As water depth increases, maximum wave height and length may increase, requiring substantially heavier mooring systems. Increased depths may also require greater anchor scope to maintain appropriate mooring line and anchor attack angles.

### *Select sites with appropriate bottom type and profile*

Appropriate bottom characteristics allow adequate mooring of the structures proposed for deployment over the expected range of sea states. A wide variety of mooring methods and equipment have been used to anchor net-pen systems (Chapman 1979; Rudi et al. 1988; Riley and Mannuzza 1991; Taylor 1991; Kery 1996; Waldemar Nelson International, Inc. 2001; Beveridge 2004). Although it is important to choose the appropriate anchor design for a particular bottom type there are certain bottom types that are particularly problematic. For example, deep layers (>2 meters) of medium-size cobble are often unstable and it is difficult to achieve effective anchor deployment and high holding power. Bottom profiles are also very important. Anchoring net-pen systems on the edge of steep bottom drop-offs can be difficult. Anchors near or over the drop-off may slide into deeper water, increasing mooring tension and causing mooring failure or pulling the net pen under water, allowing fish to escape.

### *Do not site facilities in areas subject to harmful algal blooms*

Algae—specifically phytoplankton—are of overwhelming importance to the functioning of aquatic and marine ecosystems. However, in some instances algal communities can have significant negative effects. In addition to well-known threats to public health from potent algal toxins that accumulate in shellfish, algae may affect finfish aquaculture by causing dissolved oxygen depletions, physically damaging fish gills, or poisoning fish with toxins. Although problems with harmful algal blooms are primarily an operational problem, loss of fish to harmful algae is wasteful of the resources used to grow fish and, therefore, reduces the environmental efficiency of food production. For example, loss of fish to harmful algae late in the production cycle has a large negative impact on realized feed conversion efficiency because feed used to produce fish up to the point of the fish kill is not converted to useful (marketable) product. Similarly, fish loss reduces the efficiency of resource use for energy, labor, and all other production inputs. Selecting sites with low risk of harmful algal blooms therefore improves production efficiency as well as efficiency of resource use.

Algal blooms can cause dissolved oxygen depletions in two ways. First, dense blooms that suddenly die can impose high oxygen demands as the dead phytoplankton decompose. Sudden algal die-offs can deplete local areas of dissolved oxygen until new water flushes the area. Phytoplankton may also cause low dissolved oxygen concentrations through the normal daily cycle of photosynthesis and respiration. If blooms become excessively dense, daytime oxygen production in algal photosynthesis may not offset total daily community respiration and oxygen may become depleted.

Dense phytoplankton blooms of species with hard external protrusions (called setae, or horns) can cause gill damage when cells become lodged between gill lamellae, leading to clogging of gills and restriction of water flow and oxygen transfer. Sharp setae can also lacerate the gill lamellae, causing bleeding, gill irritation, and excessive mucus secretion. Mucus can become so thick that it inhibits oxygen diffusion across the gills. These phenomena are associated with species of the diatoms *Skeletonema* and *Chaetoceros* and the dinoflagellate *Ceratium*, among others. Phytoplankton blooms can also affect fish through direct toxicity. Net-pen farmed fish are particularly susceptible to ichthyotoxin-producing algal blooms because fish are held captive and cannot escape when winds or currents move blooms into areas around the facility. Ichthyotoxic species causing losses in net-pen aquaculture primarily come from two broad phylogenetic groups: dinoflagellates and phytoflagellates (Box 8.2).

Site selection to avoid harmful algal blooms is difficult because episodes are sporadic and highly unpredictable. Areas with poor water circulation allow blooms to remain in the vicinity of the facility, and yet strong currents may transport harmful blooms into the local area from areas where they initially developed. Criteria for site selection to avoid harmful blooms have been developed by Parker (1987) and summarized by Shumway (1990). In

## BOX 8.2
## Harmful Algae Blooms and Net-Pen Aquaculture

Dinoflagellates are a diverse group of common, mostly marine, biflagellate algae. Many species are covered with armor-like plates of cellulose arranged in patterns that are characteristic for each species. Most dinoflagellate species are benign and an important part of marine and brackishwater food chains. A few species, however, produce potent toxins that cause problems in fisheries throughout the world. Dinoflagellates impact aquaculture most significantly when certain species produce toxins that accumulate in shellfish and find their way through the food chain to humans, where they can cause a variety of dangerous illnesses, including potentially lethal neurological, gastrointestinal, and respiratory disorders. At least one dinoflagellate species, *Karenia mikimotoi* (= *Gyrodinium aureolum*) is also of concern in net-pen aquaculture. This dinoflagellate, apparently widely distributed in temperate coastal waters, produces ichthyotoxins that have killed net-pen farmed salmonids in Norway, Scotland, and Ireland (Smayda 2006).

Phytoflagellates comprise a diverse group of small, flagellated phytoplankton. Representatives of two taxonomic groups—the prymnesiophytes and raphidophytes—cause significant losses of net-pen farmed fish throughout the world. The prymnesiophytes comprise a distinctive group of mostly marine, unicellular algae, and species in two genera, *Prymnesium* and *Chrysochromulina,* produce potent ichthyotoxins. Populations of toxic prymnesiophytes occasionally bloom in coastal waters and brackishwater bays where they kill wild and farmed fish and other gill-breathing animals. Recurrent blooms of toxic *Chrysochromulina* spp. and *Prymnesium* spp. have caused massive losses of net-pen cultured salmonids in European waters (Smayda 2006). Blooms of phytoflagellates in the class Raphidophyceae are responsible for some of the most spectacular algae-related fish kills recorded. Some raphidophytes are found in freshwater environments but the problematic species are brackishwater or marine. Raphidophycean flagellates are found worldwide in temperate oceans, and the species *Chatonella antiqua*, *Chatonella marina*, *Heterosigma akashiwo* (= *Heterosigma carterae*), and *Fibrocapsa japonica* have been implicated in huge losses of cage-grown yellowtail and red sea bream in coastal Japan (Honjo 1994) and caged salmon in coastal British Columbia, Canada (Taylor and Haigh 1993), Chile (Clement and Lembeye 1993) and the United States (Horner et al. 1991). A widespread, 4-month bloom of *Heterosigma akashiwo* in British Columbia in 1997 resulted in the death of pen-reared salmon valued at $20 million (Whyte et al. 1999).

considering whether sites are subject to harmful algal blooms, the following activities should be considered:

- A thorough hydrographic survey including rates of water exchange and presence of offshore frontal or upwelling systems. High rates of exchange reduce the risks of

*in situ* blooms but may allow transport inshore of offshore blooms, and frontal or upwelling systems may be seed areas for offshore blooms. Ideally, site waters will be fully mixed and in contact with fully mixed sea areas.
- An assessment of the nutrient status of the local waters and the accumulation of soft sediments (usually an indication of poor circulation).
- A survey of the phytoplankton community and an investigation of previously recorded species, with special attention to the presence of known noxious species and problems related to harmful blooms.
- A survey for the presence of cysts in local sediments, often an indication that a bloom is possible.

### *Avoid sites where culture activities will negatively impact sensitive populations of fish, birds, or other wildlife*

Examine biological site survey data and any other available historical or survey data to evaluate the presence, distribution, and abundance of threatened or endangered species or critical habitat that may be negatively affected by a net-pen operation. Examples of potential negative impacts include escapes and interbreeding of farm animals with endangered conspecifics, transmission of pathogens to migratory juveniles, and modification of sensitive habitats through localized benthic deposition. Select sites that minimize the potential for these types of impacts. If no such sites are available, develop and implement specific BMPs designed to mitigate those potential negative impacts of the farm. Develop BMPs in cooperation with the appropriate local natural resource management agency.

### *Select sites away from concentrations of predators and pests*

Document and consider the local distribution and prevalence of potential pests and predators for the species to be farmed. Sites located near natural concentrations of predators or pests may result in increased losses of cultured animals and adverse interactions with predator populations. Avoid sites in close proximity to other fish farms or high wild fish concentrations that may harbor or attract predators or pests. Where possible identify any intermediate pest hosts and avoid areas in which these hosts may occur.

## Feeds and Feeding

Fish feed is one of the major inputs of a net-pen operation. Depending on the species cultured, feed can represent 60% or more of the cost of production (Beveridge 2004). Effective feed management is based on two components: reducing waste feed and optimizing feed conversion. Waste feed reduction focuses on ensuring that feed is not lost or discharged prior to consumption by the fish. Optimal conversion focuses on ensuring that all feed offered to fish is consumed and efficiently digested.

Feed management methods have improved significantly over the last 30 years. Early net-pen feeding methods and feeds used “trash fish” either as a direct feed or in wet feeds, consisting of ground-up trash fish with some vitamins and binders added in an on-site manufacturing process. Feeds were either hand-delivered or pumped into net pens using a slurry pump and hose. Feed formulations were primitive, quality was inconsistent, and waste production was high. In many instances, local environmental impacts were severe. Farm-made aquafeeds remain widely used in net-pen culture in many parts of Southeast Asia (Edwards and Allan 2004). Most of the improvements in feed management methods in commercial settings have not been documented in the scientific literature because they have involved applied, on-farm operational modifications. An indirect measure of improvement can be seen in historical trends in feed conversion ratios (FCR; weight of feed offered/weight of fish produced) in Norwegian salmon farming, which have improved from more than 3 in 1980 to 1.2 in 1994 (Asche et al. 1999). Worldwide, salmon farm FCRs have improved from 2.4 in 1972 to 1.15 in 2000 (Sveinson and Engelstad 2001). Currently accepted FCRs for commercially competitive salmon farms are around 1.

Fish nutrition, behavior, and feeding practices are active areas of research, and feeding technology and feed formulations are constantly improving. Much of the feed formulation research for salmonids is conducted by private feed companies and is considered proprietary, although significant nutritional research also occurs within the public sector. Compilations of research in these areas are found in Houlihan et al. (2001) and Webster and Lim (2002). An important research goal is to improve the efficiency of nutrient utilization by fish, thereby enhancing economic returns and reducing waste production. With technology that is rapidly changing, BMPs for feed management should be flexible so that newer and better practices and technologies can be implemented as they become available.

## *Better Management Practices for Feeds and Feeding*

### *Use high-quality diets*

In cooperation with feed manufacturers, seek to minimize nutrient and solids discharges by optimizing feed formulations. Feeds should be formulated for optimum feed conversion ratios and maximum digestibility and retention of protein (nitrogen) and phosphorus for the species cultured. Numerous strategies are available to formulate feeds that reduce environmental impacts while providing the necessary nutrition for fish (Alsted 1988; Gavin et al. 1995; Cho and Bureau 2001; Gatlin and Hardy 2002). Feed formulations should consider pellet stability, sinking rates, palatability, digestibility, energy levels, moisture content, ingredient quality, and the nutritional requirements of the species being grown. Least-cost formulations do not necessarily result in optimal feed conversion ratios, best growth, or minimal environmental impacts. Track individual feed formulations based on these three metrics and compare formulation performance between different production runs of the same species on the same net-pen site.

Feeds should be formulated and manufactured using high-quality ingredients. Feed ingredients should have high dry matter and apparent protein digestibility coefficients. Formulations should be designed to enhance nitrogen and phosphorus retention efficiency, and reduce metabolic waste output (Box 8.3). Feeds should contain sufficient dietary energy to spare dietary protein (amino acids) for tissue synthesis. Feeds should be water stable for sufficient periods such that pellets remain intact until eaten by fish (de la Higuera 2001; Jobling et al. 2001). Questions regarding feed formulations should be referred to a qualified fish nutritionist or feed manufacturer.

## BOX 8.3
## Improved Diets Reduce Waste Loading

Waste generation by net-pen cultured salmonids has decreased significantly with the development and adoption of high-energy diets with increased lipid content, reduced carbohydrates, and improved digestibility (Sugiura and Hardy 2000; Gatlin and Hardy 2002). For example, since the 1980s, the lipid content of salmon feeds has increased from less than 20 to 30% or more. Increasing the energy-density of diets enhances fish growth and spares dietary protein for tissue synthesis rather than energy production, thereby improving protein retention. Protein retention, which was 20 to 25% before the advent of modern, high-energy diets, has increased to more than 40%. Concomitant with increased protein retention, waste nitrogen production has declined by more than 25% (Hardy 1999).

### *Use feeding practices that maximize feed use efficiency*

Efficient feeding methods minimize feed wastage and energy use and maximize feed utilization. The amount of feed offered and the frequency of feeding should optimize the balance between growth and feed conversion. The relationship between growth and feed conversion is complex and influenced by many factors (Brett 1979; Priede and Secombes 1988; Watanabe 1988; Beveridge 2004). In practical terms, feeding only to maximize growth rates can often result in decreased conversion efficiency and increased waste discharge per unit weight of fish produced. The appropriate quantity and type of feed for a given species is influenced by fish size, water temperature, dissolved oxygen levels, health status, reproductive maturity, management goals, and daily and seasonal environmental patterns. Alanärä et al. (2001) and Beveridge (2004) outline how these variables must be considered when managing practical feeding programs.

Feeding efficiency can be influenced by feed particle size, energy content, and feeding frequency. For example, consuming low-energy diets as small pellets fed at a high frequency may result in greater energy expenditures by fish than consuming high-energy diets of a pellet size that is appropriate for a particular fish size fed less frequently. In the first case, increased energy expenditure is caused by fish increasing metabolism more frequently during feeding events that yield less energy than expended. Smaller pellet size also causes the expenditure of more energy than consumed (Cho et al. 1982; Jobling 1994; Smith et al. 1995; Paspatis and Boujard 1996). In general terms, increase pellet size and decrease feeding frequency as fish grow. Feed manufacturers often provide recommendations on pellet size and feeding frequency appropriate for the size and species of fish cultured.

Distribute feed evenly over a sufficiently large area to allow less dominant individuals access to adequate feed rations. McCarthy et al. (1992) showed significant impacts on feed intake in rainbow trout based on social hierarchies. When determining the appropriate feed distribution pattern, do not distribute feed so close to the edge of the net pen that it is swept out of the pen by currents before fish have a chance to consume it. If using automated feeding delivery systems, observe feeding during high current events such as peak tidal flow to ensure that feed is not swept out of pens before consumption. If this appears to be a problem, change the distribution pattern or eliminate feeding during peak current flow.

### *Use efficient feed delivery methods*

Feed can be delivered manually or by demand, automatic, or various mechanical feeders. Manual feeding and air- or water-based transport through pipes or feed guns are the most common feed distribution method used on commercial salmon farms. Cable and disk distribution methods are rarely used in net-pen operations due to their power consumption and the need for stable and rigid pipes to operate properly. Auger distribution methods are used only to move feed short distances from silos to another distribution system. If improperly installed or maintained, augers can result in significant pellet breakage and feed waste.

Manual feeding of fish in large net pens is particularly challenging because it is difficult to adequately distribute feed pellets. Manual feeding is typically used for small net pens or for smaller fish, and can assist in the acclimation of juveniles to the net-pen environment (Fig. 8.5). Manual feeding is used throughout the production cycle in some countries with low wage rates. Manual feeding for long periods can, however, adversely affect worker health through repetitive motion injuries.

Air-based feed distribution systems use either high-pressure, low-volume or high-volume, low-pressure air. Air distribution designs are energy efficient but can move feed only limited distances. Water-based distribution systems require significant energy to pump water but can distribute feed further than most air-based systems. If water-based systems are used, the duration of feed transport should not degrade pellet stability or leach soluble feed nutrients or vitamins. If other performance characteristics of the various distribution methods are acceptable and similar among various designs, choose one that uses less power and delivers the highest quality feed at the point of consumption.

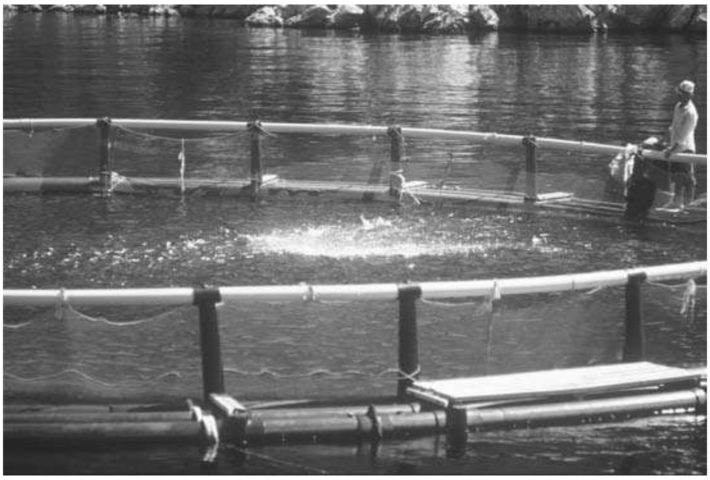

**Fig. 8.5.** Hand-feeding Atlantic salmon in a net pen in Maine.

Improperly adjusted or malfunctioning feeding equipment can over- or underfeed fish, reduce feed efficiency, and increase environmental impacts. Poorly maintained feeding equipment can result in greater feed pellet breakage and increased feed waste. Maintain feeding equipment at or above its operational design specifications with regular preventive maintenance. Regularly calibrate computer-controlled feeding systems to ensure that the amounts of feed distributed correspond accurately to that indicated by automated recording systems.

### *Monitor feed consumption*

Regardless of feed delivery method, use direct or indirect methods to observe fish feeding and monitor feed consumption. Direct monitoring, such as observation of feeding events at individual net pens, should be conducted regularly. Indirect monitoring with video cameras, lift-ups, Doppler, or sonar sensors allow underwater observation of feeding behavior and feed consumption rates when direct observation is not possible.

Indirect monitoring methods are evolving rapidly with the advent of modern sensor and data-transmission technologies. Early systems consisted of home video cameras housed in home-made underwater housings. These systems were moved from pen to pen during feeding and allowed farm operators to observe fish feeding without being physically present in the net pens. Other early systems, such as lift-ups, involved collection funnels sewn into the bottoms of the net pen. The funnels were connected to airlifts that suctioned feed pellets that fell into the collection funnel and delivered them to a screened collection box at the net-pen surface. Farm operators monitored feeding by counting how many feed pellets were not consumed by the fish and were collected by the lift-up system. Although these early systems were an improvement over visual monitoring at the net-pen surface, they were expensive, cumbersome to use, and mechanically unreliable. Over time, indirect monitoring methods evolved and centralized video and Doppler systems with cameras and sensors in each net pen became standard. More recent developments include centralized wireless systems that eliminate the need for expensive and complicated wiring harnesses that were often subject to failure due to chafing and water invasion at connectors.

The most effective method of monitoring feeding and feed consumption is a combination of direct and indirect monitoring. Direct observation allows holistic assessment of fish behavior in situ and maintains a direct connection between the observer and cultured animals. Indirect observation allows underwater assessment that is often difficult unless a worker is diving in a net pen. If automated feeding systems are used, indirect fish monitoring systems can be linked actively to feeding control systems to provide direct control feedback to reduce feed wastage. Even if indirect monitoring systems are employed, direct monitoring can verify that all systems are functioning properly and fish are behaving and feeding normally.

### *Use fish strains with efficient feed conversion*

Variation in feed conversion among families and strains of the same species is significant and heritable (Gjerde and Gjedrem 1984; Hörstgen-Schwark et al. 1986; Gjøen et al. 1993). Direct selection for feed conversion efficiency is difficult, but growth rate can be used as a surrogate for feed conversion because the genetic correlation between those factors is high in terrestrial livestock and fish (Gjedrem 2000). When selecting fish strains, closely examine pedigree lines and historical data available on growth and conversion rates. Purdom (1993), Tave (1993), and Knibb (2000) provide excellent guidance on how to assess and use breeding data.

### *Develop and implement a comprehensive stress-management program*

The goal of this program is to reduce fish stress that may cause poor feed conversion. Although the ability to control environmental conditions is limited in net-pen aquaculture, farm operations can significantly impact fish stress levels. For example, water exchange in net pens may be significantly reduced when nets become fouled. As fouling increases and water flow decreases, the supply of dissolved oxygen may become limiting and fish will be stressed. Stressed fish feed poorly and may die if dissolved oxygen concentrations fall to critically low levels. Changing or cleaning nets will reduce fouling and increase water exchange rates, but physical disturbances associated with changing or cleaning nets may also stress fish. Net changing operations should therefore be conducted in a manner that does not frighten fish and maintains the volume of the net bag during the operation. Nets should be cleaned or changed with sufficient frequency so that water flow through net pens is not significantly reduced, yet not so frequently that fish are stressed unnecessarily and repeatedly.

### *Maintain accurate feeding, fish biomass, and inventory records*

Monitoring long- and short-term changes in feed conversion is one of the most powerful management tools to reduce waste production from individual net pens or whole net-pen sites. Track feed conversion ratios with a record-keeping system for each net pen. Verify that initial stocking inventory records are accurate by spot sampling transport containers and observing fish counting and loading operations at the hatchery. Conduct regular mortality retrieval dives to accurately track fish mortalities and inventories. Increase mortality dive frequency in cages with small fish, during periods of unusually warm water, and during episodes of unusually high fish losses to prevent dead fish from decomposing before retrieval. Track and verify fish growth by sampling regularly to obtain average fish weight and size distributions within individual net pens. The sample size should be sufficient to give an accurate estimate of average fish weight and size distributions in each net pen. Beveridge (2004) provides guidance on the design of a fish sampling program for a net-pen operation. The need for weight samples and mortality retrieval dives should be balanced against the fish stress associated with these activities. Confirm the accuracy of fish size estimates and the efficacy of the sampling plan by comparing estimates to fish size data generated at harvest. Calculate monthly feed conversion ratios based on feeding records and samples. Calculate a final feed conversion ratio using harvest weight data for all fish harvested.

### *Train workers in fish husbandry*

Conduct training in fish biology, fish husbandry, and feeding methods to provide workers with a basic technical understanding that will assist in reducing feed waste and optimizing feed conversion efficiencies. Training should include presentation of easily understood information on fish behavior, the biology of fish growth, nutrition, stress physiology, water quality monitoring, and different feeding strategies and methods. Include training in practical farm management methods that are necessary to track production performance and feed conversion ratios, such as weight sampling and inventory and production tracking methods.

### *Establish an employee incentive program*

Develop and implement an employee incentive program that links some portion of employee compensation to feed conversion ratios and reductions in wastes of all types. If more than one net-pen site is operated by a company, sponsor competitions between different farm sites with performance assessment based on fish yields and feed conversion ratios.

### *Handle and store feeds to maintain quality*

Feed storage, handling, and delivery methods should minimize waste and formation of fine particles of feed. Minimize pellet damage or crushing during feed handling to reduce the creation of fine feed particles (fines) that cannot be consumed by fish. Fines result in higher production costs and a greater discharge of nutrients into the surrounding environment. Relatively low rates of fines can result in significant increases in costs and nutrient discharges. For example, a 1% increase in feed fines on a typical 500-tonne finfish net-pen operation can result in an increase in direct discharges of 5 to 6.5 tonnes of waste feed.

Eliminate sharp edges and corners that will cut or bind pellets if mechanical feeders and feed silos are used. Regularly inspect automated feeders that transport feed using blowers, pellet augers, or water pipes to ensure that pellets are not being damaged during transport to pens. Automated feeders and storage containers should have a fines separator so that fines can be collected and reformed into feed pellets using an on-site pellet press. Use appropriate respiratory protection in confined areas, such as feed storage rooms and silos, because feed fines and dust can present a health hazard to fish farm workers. Fill feed silos with only cup elevators. Do not use blowers to fill silos because they cause more pellet breakage than cup elevators.

Do not stack feed sacks so high that weight loads on the bottom sacks exceed the crush limit of feed pellets. When given a choice between large and small feed sacks choose larger ones if the farm has the capability to handle them without jeopardizing worker safety. Large sacks decrease handling per unit feed weight. Minimize repeated handling of feed sacks (Fig. 8.6).

Maintain feed storage areas that are secure from contamination, vermin, moisture, and excessive heat. Inadequate and long-term storage of feed can affect feed quality. Feed lipid can become rancid and mold can create mycotoxins that cause fish kidney and liver lesions (Black et al. 1988; Ketola et al. 1989). Maintain accurate and current feed inventories to rotate feed, using oldest feed first. Do not store feed beyond the manufacturer's recommended use date. Dispose out-of-date or spoiled feed in a land-based facility, compost it, or use as agricultural fertilizer at levels that are appropriate and do not result in nutrient overloads on application sites. Never dispose of medicated feeds other than by following

**Fig. 8.6.** Off-loading feed from a work boat to a net-pen facility in Maine. Feed transport and handling must be conducted carefully to minimize generating "fines" by abrasion of feed pellets.

the manufacturer's recommendations. Never dispose of any feed by dumping into aquatic ecosystems.

### *Conduct feed trials*

In cooperation with feed manufacturers and qualified fish nutritionists, conduct feed trials with feed formulations designed to reduce the total environmental impact of the feed. Ruohonen et al. (2001) provide guidance on the design and implementation of feeding trials. Experimental formulations that use alternative protein and lipid sources should meet the nutritional needs of the cultured species and maintain apparent digestibility. Include performance metrics that will assess impacts on feed conversion ratios, fish growth, digestibility, and the levels of fecal waste associated with protein sources of plant origin.

When choosing a feed that minimizes environmental impacts ensure that the health and welfare of the fish being fed is protected. Due to concerns about the use of fishmeal and fish oil in all animal feeds (see Chapter 1), make every effort to reduce the proportion of these ingredients in feeds being used. When choosing a feed with reduced fishmeal and fish oil take care to ensure that the total environmental impacts of the feed are not greater than a formulation with higher fishmeal and fish oil content.

## Benthic Impacts

The sensitivity of fish to environmental variables, the "openess" of net pens, and the direct linkages between net pens and the ecosystems in which they are immersed provide strong management feedback loops to net-pen operators. Local environmental degradation as a result of poor farm management directly impacts the performance and health of cultured animals. These relationships have been known for some time. Arizono and Suizu (1977), for example, used an environmental index based on sediment conditions under yellowtail farms to predict disease outbreaks. Braaten et al. (1983) showed a strong relationship between levels of methane and hydrogen sulfide ebullition and fish growth and disease incidence, and Black et al. (1996a, b) clearly demonstrated the connection between fish performance and health and local benthic conditions that were the result of poor farm management or inappropriate site selection.

The interrelationship between management practices and the oceanographic and geophysical characteristics of a site determine the potential for adverse environmental impacts of a net-pen farm. Sites have a variable capacity to assimilate, process, and convert nutrient loads from net-pen farms. If carrying capacity is exceeded, areas under pens may ultimately become overloaded, and benthic invertebrate species diversity may decrease significantly in response to sediment anoxia. Taken to the extreme, the capacity of a site to assimilate, process, and convert nutrients can be reduced.

Waste feed and fish feces constitute most of the solid wastes generated by net-pen operations. Although waste feed will often be consumed by animals attracted to the net-pen site, numerous studies have documented negative environmental impacts of solid waste discharges from net-pen operations (Midlen and Redding 1998; Wildish et al. 2004). On poorly managed net-pen sites, benthic impacts can be significant, with substantial accumulations of organic sediments and the development of anoxic conditions. On well-managed net-pen operations, these conditions are rare (Stickney 2002). On sites that have been negatively impacted, recovery rates depend on local conditions and severity of impact.

Concentration and collection of unconsumed feed and fecal solid wastes is difficult because net pens are often operated in high-energy, open-water environments exposed to currents, waves, and storms. Although it is theoretically possible to install secondary net or deflector systems to collect solid wastes, trials have demonstrated significant operational and economic problems with this approach (Box 8.4). The trend is to select sites with current velocities that minimize accumulation of organic matter and associated benthic impacts rather than attempting to capture wastes. The most effective way to reduce the potential waste impacts from net pens is appropriate site selection, site rotation, polyculture, changing feed formulations, and careful feed management (Stickney 2002; Marine Aquaculture Task Force 2007). Appropriate site selection and feed management are discussed above. Site rotation, fallowing, and polyculture will be discussed here.

Fallowing has been a component of terrestrial integrated pest management and organic farming methods for some time. Fallowing on net-pen farms is a relatively new technique. Management practices that address the linkage between benthic and water-column environments are relatively new, although the way that benthic-pelagic coupling significantly affects water quality and fish performance is well known (Arizono and Suizu 1977; Braaten et al. 1983; Black et al. 1996a, b; Stickney 2002; Brooks et al. 2003). The

## BOX 8.4
## Solids Collection Systems for Net Pens

A number of attempts have been made to collect waste solids from net pens by redesigning the pens to reduce or eliminate the open nature of the culture system. Typically, floating material or plastic bags or raceways have been used to separate and collect solid wastes before effluent discharge into the environment. Wray (1988) and Baklien (1989) experimented with some of the first floating enclosed systems. Further work has occurred on the west and east coasts of Canada with some technical innovations resulting in larger and better-engineered systems (Steven Clark, president Future Seas Inc., personal communication regarding trials of patented floating bag culture system in British Columbia and New Brunswick).

Another approach has been to fit collection units onto the bottoms of pens while keeping the sides open with netting. This method was first attempted by Tucholski et al. (1980), who fitted collector funnels on the bottom of rainbow trout pens in Poland. A more sophisticated computer-controlled system was designed by Enell et al. (1984) in Sweden. This system became the forerunner of a commercial system called the "liftup" system subsequently developed in Norway (Røed 1991; Ervik et al. 1994). This system uses collection funnels on the net-pen bottoms with airlift pumps to lift waste feed and fish feces to surface filters and collection units. Although original trials were promising, they were conducted in a sheltered net-pen site. Subsequent trials in Norway and eastern Canada have demonstrated that the funnel-based systems do not work well in sites with even moderate currents and wave action (Heinig 2004). In higher-energy sites, solids may be swept out of the cage before they are deposited on a collector located on the bottom of the net.

Solids collection systems typically require a power source such as a generator with an associated electrical or air-distribution system. Net-pen systems are moored structures that are moving constantly, and distribution systems that link pens are subject to constant wear and require high maintenance. On net-pen systems that may be intermittently submerged during rough weather, electrical distribution systems can represent a significant worker safety risk.

All of these systems enabled the collection of some solid wastes, but proved to be impractical and very expensive to operate due to the costs of pumping and the labor required to clean and maintain the systems (Dubreuil 2003). Bag- and funnel-based systems are no longer viewed as practical solutions to managing solid waste discharges from net-pen operations (BCEAS 1997; USEPA 2002; Marine Aquaculture Task Force 2007).

sequential changes in benthic ecological communities that occur after cessation of net-pen operations have been documented (Mahnken 1993; Johannessen et al. 1994; McGhie et al. 2000).

A few studies have been conducted of the intentional use of a benthic crop as an environmental management tool to address impacts of net-pen aquaculture on benthic ecosystems. Preliminary work has evaluated benthic grazing species cultured under net pens and initial results appear promising (Tseng 1983; Angel et al. 1992). The development of crops that could be used to generate income and manage net-pen sites during fallowing periods would accelerate the transition to more sustainable farming methods. For example, it may be possible to culture sea cucumbers, sea urchins, or marine annelid worms on a fallowed net-pen site as a means of managing benthic nutrient and organic matter levels. More research on multicrop farm rotation production cycles for net-pen operations is needed.

Because the current state of knowledge on crop rotation is relatively underdeveloped, the only available tools are site rotation and fallowing. Simple fallowing involves the removal of the fish crop from the farm and leaving the net pens empty for some period of time. Site rotation uses fallowing but also includes moving pens to another location and farming in that location while the original location is fallowed. Site rotation and fallowing can be used to control pests or pathogens and to mitigate benthic impacts.

### ***Better Management Practices to Minimize Benthic Impacts***

#### *Site net pens to optimize water circulation*

Give careful consideration to impacts on water circulation patterns when installing net pens and their associated mooring systems (Box 8.5). Gear placement can significantly affect water circulation patterns on a site. Gear deployment should seek to optimize circulation patterns and maximize water exchange through pens, thereby reducing benthic impacts and improving fish health. Net-pen farms in the United States typically operate in public waters leased from the government. Strict siting requirements restrict the number of units at a given site to ensure sufficient flushing to distribute wastes and prevent degradation of the bottom below and near net pens.

#### *Establish a monitoring program to assess benthic impacts*

Baseline environmental studies characterize a site before net-pen operations are established. Then, ongoing monitoring programs examine and document how site ecosystems evolve in response to farm operations. Monitoring programs include methods to distinguish farm impacts from other anthropogenic impacts and from natural background ecological events. Monitoring programs typically include quantitative and qualitative criteria that identify emerging environmental impacts that are of concern and identify what constitutes an unacceptable impact. Monitoring programs provide a mechanism for regular consultation between producers and regulators to facilitate communication, identify potential environmental problems, and provide incentives for the adjustment of farm practices as necessary. Leasing or licensing programs that grant use of or access to public waters typically contain provisions that allow revocation in the event of unacceptable ecological impact.

The sea floor under the farm site should be visually surveyed annually at the same stations established in the baseline site survey. If necessary, adjust the original survey locations to account for changes in facility layout. Sampling stations should be adjusted to remain directly under net-pen positions and referenced in relationship to any previous

## BOX 8.5
## Net-Pen Mooring Systems and Benthic Impacts

Most net pens or net-pen arrays are moored with multiple anchors that allow only limited movement at a particular location. As a result any accumulation of organic sediments is localized beneath net pens at a fixed location. Multiple-anchor arrays are very effective and have significant redundancy that reduces the risks of catastrophic failures due to single mooring failures. Multiple anchor arrays are, however, complicated and expensive to install and maintain. While their inherent redundancy reduces risk of catastrophic failure, their complexity and number of components may increase the risk of individual component failure.

Single-point mooring systems were first developed for the offshore oil industry in the late 1960s. Single-point mooring systems are simpler than multiple-anchor arrays because they use fewer anchors (in some cases only one) to moor a single attachment point on a net-pen system. Single-point mooring significantly reduces mooring costs and allows systems to rotate around the mooring point in response to wind or current forces. Single-point mooring systems may reduce benthic impacts from net-pen arrays because solid wastes will diffuse over a larger area than for systems moored with multiple-anchor arrays. A comparative analysis of mooring a 12-pen array with a multiple-anchor array and a single-point mooring indicated the potential for reduction in benthic accumulation of organic matter of 2 to 70 times with single-point mooring, depending on water currents and the ratio between anchor cable length and water depth (Goudey et al. 2001). Furthermore, the cost of anchoring pens can be reduced by 50% with single-point moorings.

Although single-point mooring systems have great potential, they also have a number of disadvantages. The area occupied by a net-pen array attached to an single-point mooring system is much larger than that occupied by a multiple-anchor array, because the array must be able to rotate freely around the single-point mooring. Single-point mooring systems have little redundancy. If a single component fails the entire array is no longer anchored. As a result, individual components of the single-point mooring system must be able to bear the entire load of the net-pen array and, as such, tend to be much larger and more expensive than multiple-anchor array individual components. Single-point mooring systems have been used in Scotland and the Gulf of Mexico on two pilot projects. The Gulf of Mexico project suffered a mooring failure caused by the failure of a single shackle, resulting in the pen drifting free for 40 days before recovery (Goudey et al. 2003).

positions. Additional sampling stations should be established at predetermined distances away from the current cage positions. Typical distances are 5 and 30 meters up- and downcurrent from net-pen arrays. The survey design should include multiple sampling stations that extend to all areas of the site. Include at least one reference site away from the farm. Collect an adequate number of replicate samples at each station for a statistically valid sample. The number of required sampling stations and replicates will vary depending on the size of the site and amount of variation in conditions over the site. Larger sites with greater ecosystem variation require more sampling stations. See Hakanson et al. (1988), Findlay and Watling (1997), Wildish et al. (2001), and Brooks et al. (2003) for further guidance on survey design.

In particular, the presence of waste feed and how the benthic environment appears to be assimilating the nutrient load should be noted. At minimum, conduct visual bottom surveys that document the proportion of the sea floor covered with *Beggiatoa* mats and the presence and relative abundance of pollution-tolerant benthic infauna. Sampling frequency should be linked to the production cycle of the species cultured. Increase sampling frequency as fish biomass and feeding rate on the site increase toward the end of the production cycle. Include a benthic infauna survey similar to the survey conducted before the site was developed at the end of each production cycle. Characterize species composition, diversity, and abundance of benthic infauna and epibenthic macrofauna and flora at all sampling stations. When bottom surveys are conducted by third parties or regulators, direct and timely communication of survey results to net-pen operators will allow adjustment of management practices if necessary.

### *Fallow sites to allow recovery from benthic impacts and reduce the likelihood of their occurrence*

Fallowing is the interval between operational periods when net pens are empty. Fallowing can be used to allow recovery of the site from benthic impacts, manage disease epizootics, and as an integrated pest management tool. During fallowing, net pens can be left on-site or moved to another location.

Determine the management goals for the fallowing period before initiating the fallowing activity. For example, the intent may be to manage conditions at the net-pen site itself or to coordinate management with other sites in the same hydrologically linked water body in an effort to manage the cumulative effects of multiple farms. These are not mutually exclusive goals and often farmers may seek some combination of goals.

If fallowing is used to reduce or mitigate environmental impact, determine what impacts are specifically being managed and how fallowing will affect those impacts (Box 8.6). If possible, document the specific physical, chemical, or biological processes that should occur during fallowing to mitigate the potential impact. Determine how those processes are affected by temperature, photoperiod, or storm events. Based on this understanding, develop a site-specific fallowing plan designed to achieve the level of environmental impact reduction or mitigation initially established as a goal. Keep accurate records of all fallowing events and any environmental impacts that they are designed to mitigate. Fallowing plans developed to reduce or mitigate environmental impacts should be part of a broader integrated environmental monitoring and management program that uses multiple management methods to reduce and mitigate environmental impacts.

Establish clear, easily measurable metrics that can be used in a monitoring program to define whether fallowing has been successful (Hargrave et al. 2005). Metrics may be absolute values that must be achieved before production is resumed or they may be proportional changes from values that were measured at reference sites. Depending on the specific fallowing goal, site history, and whether there is any research on a particular

## BOX 8.6
## Benthic Impact Remediation

Several studies have documented sequential changes in benthic communities occurring after cessation of net-pen operations on heavily impacted sites (Mahnken 1993; Johannessen et al. 1994; McGhie et al. 2000). Brooks et al. (2003) studied remediation of sediment beneath four commercial salmon farms in Arrow Pass of the Broughton Archipelago of British Columbia. During the 18- to 24-month production cycle, organic carbon accumulated in sediments beneath net pens, reducing oxidation-reduction potential, increasing sediment free-sulfide concentration, and displacing sensitive benthic organisms with tolerant species. This effect extended up to 50 m on the downcurrent side of net pens. Fish biomass and feeding rate increased to a maximum at about 18 months. Fish biomass and feeding rate then gradually decreased during a 9-month harvest period. Chemical remediation of the site began once harvesting commenced and was completed by the end of harvest. An additional 4 to 6 months of fallowing was necessary to achieve biological remediation, defined as development of an invertebrate community structure and abundance similar to a reference station. Chemical and biological remediation of sediment beneath salmon net pens at the Arrow Pass site was rapid (less than 6 months).

In another study, Brooks et al. (2004) assessed the long-term (7-year) remediation of heavily impacted bottom beneath a commercial salmon farm in Carrie Bay of the Broughton Archipelago of British Columbia. In contrast to the Arrow Pass site, sediment organic matter accumulations were greater at Carrie Bay, and extensive mats of *Beggiatoa* were measured to a distance of 145 m from the perimeter of net pens. Sediment remediation at Carrie Bay was much slower than at Arrow Pass. Chemical remediation of sediment at the Carrie Bay site required about 65 months of fallowing. The sediment macrofaunal assemblage at Carrie Bay was markedly different from other salmon farming sites in British Columbia and did not respond to organic loading according to expectations and was therefore considered unusual. After 48 months of fallowing, biological remediation of sediment was nearly complete at distances more than 80 m from the perimeter of net pens.

In general, chemical remediation of sediment beneath net pens occurs quickly compared with biological remediation. The duration of the fallowing needed to achieve chemical and biological remediation is site-specific and depends on the depth of organic matter accumulation, sediment and water physicochemical characteristics, water depth, and current velocity. At most sites, chemical remediation likely occurs within 6 months and biological remediation within 1 year of initial fallowing. Chemical remediation can be best measured by sediment free-sulfide concentration or oxidation-reduction potential along a transect representing the dominant current direction from the net-pen perimeter and compared to a reference site. Biological remediation can be measured by sampling the benthic infauna. A remediated site can be defined as a community structure with all taxa that equal or exceed 1% of the total abundance at a reference site (Brooks et al. 2003).

factor, there are a number of metrics available to assess the degree of chemical or biological remediation (Box 8.6).

Ensure that all production planning and grow-out cycles allow fallowing goals to be achieved. Work closely with sales personnel and customers to ensure that the need for fallowing as part of the overall production plan is understood. Ensure that farm development plans provide an adequate number of sites to ensure that fallowing and production goals can be met, and that production goals do not compromise fallowing goals.

## Nutrient Release and Recovery

Inorganic nutrients are discharged from net pens through direct excretion of soluble nutrients by fish and from decomposition of fecal solids and waste feed that may accumulate on the bottom beneath net pens. The impacts of nutrient release from net pens are very site-specific. Eutrophication occurs in response to elevated nutrient concentration, not nutrient mass loading. The response of the system to nutrient loading depends largely on the flushing time of the site and whether the local ecosystem is nutrient-limited. Well-flushed sites are not likely to experience eutrophication and, in many cases, detecting elevated nutrient levels over background levels has not been possible (Churchill et al. 1994; Heinig 2000; Normandeau and Battelle 2003).

Recovery of dissolved nutrients from any aquaculture production system is challenging. Unlike systems with controlled water flow, the opportunity for nutrient recovery from net pens is limited. Nonetheless, recovery of nutrients from net-pen aquaculture through coculture of macroalgae and bivalve mollusks is an active area of research and development (Box 8.7). Integrated shellfish and finfish net-pen aquaculture is increasingly used as a way to mitigate nutrient and suspended solid discharges from finfish operations. Commercial operations growing mussels and salmon on the same site occur in New Brunswick and Maine. Research projects in Canada and Maine have demonstrated increased growth of shellfish grown in association with salmon farms (Jones and Iwama 1991; Belle 1999; Chopin and Yarish 1999).

### *Better Management Practices for Nutrient Recovery*

#### *Use polyculture to recover nutrients*

If the culture area is potentially sensitive to nutrient addition, consider the practicality of incorporating shellfish or marine plants in polyculture with fish raised in net pens to recover a portion of discharged nutrients and particulate matter (Box 8.7). Where practical, colocate shellfish, marine plant, and finfish farms to maximize production synergies and reduce potential water quality impacts. When considering polyculture, evaluate possible impacts on biosecurity, worker health and safety, public health, and water circulation patterns.

When using polyculture to mitigate nutrient or seston discharges, position shellfish or marine plants to maximize extraction rates. Locations should be selected after careful mapping of site water circulation patterns and distribution patterns of wastes released from pens.

## BOX 8.7
## Co-culture of Salmon, Shellfish, and Seaweeds

Efforts have been made to evaluate the performance of bivalve shellfish, usually blue mussel *Mytilus edulis* and Pacific oyster *Crassostrea gigas*, cultured immediately adjacent to salmon in net pens (Jones and Iwama 1991; Taylor et al. 1992; Stirling and Okumu 1995; Troell and Norberg 1998; Belle 1999). Results are equivocal, with some studies demonstrating beneficial effects on shellfish growth and others demonstrating only a marginal effect of location near salmon farms. Water circulation patterns and the specific location of shellfish relative to fish pens appears to have important effects on the relative benefit. Shellfish locations should be selected after careful mapping of the distribution patterns of wastes from net pens. The most important factor affecting shellfish growth is temperature and background seston concentration. The suspended solids concentration of water moving through net pens is low and only slightly greater than background concentrations, even after feeding. Solids released from net pens are beneficial to shellfish culture only when phytoplankton concentrations are low (Troell and Norberg 1998). In low-energy, poorly flushed sites, dissolved nutrients released from net pens may increase phytoplankton concentration, which can be beneficial for shellfish growth.

Although there is a long history of using seaweeds as biofilters of marine aquaculture, there have been few commercial applications with net pens. Nutrient recovery using seaweeds located near net pens has been evaluated experimentally (Buschmann 1996; Petrell and Alie 1996; Troell et al. 1997; Chopin et al. 1999). The integration of seaweeds into land-based and open-water marine aquaculture systems has been reviewed by Chopin et al. (2001). Growth performance of seaweeds depends on suitable temperature, light, and nutrient concentration. In designing seaweed systems for open-water aquaculture systems, recovery of nutrients will depend on husbandry practices and site conditions, especially nutrient dilution from currents and flushing. The complexity of water movements around net pens suggests that full recovery of nutrients may not be possible unless systems are carefully designed and deployed. For example, large areas (712 to 875 $m^2$) of *Porphyra* (nori) nets would be required to completely recover the nitrogen and phosphorus generated from one tonne of salmon production (Chopin et al. 1999). In trials in Chile, Troell et al. (1997) estimated that 1 ha of suspended *Gracilaria* would be sufficient to remove 6.5% of inorganic nitrogen and 27% of inorganic phosphorus from a 230-tonne salmon farm. However, both systems were two dimensional, in contact with only a small portion of the water column. More efficient systems with seaweed cultured in three dimensions, allowing for contact with most of the water column, have shown greater potential for nutrient recovery and reducing the ecological footprint of net-pen aquaculture (Petrell and Alie 1996; Neori et al. 2004). Inclusion of seaweeds can reduce the ecological footprint of salmon net pens for waste assimilation of nitrogen by 56% and of phosphorus by 94% (Troell et al. 1999).

It is interesting to note that the nutrient, pigment, or phycocolloid content of marine algae cultured near net pens often exceeds that produced conventionally, presumably attributable to the regular supply of nutrients (Troell et al. 1997). Therefore, the economic value of seaweeds raised near net pens would exceed that from seaweed monoculture in a comparable location.

### *Select suitable sites for shellfish polyculture*

Although shellfish may benefit from increased feed sources during finfish production, shellfish and finfish production cycles may not coincide. Natural background levels of phytoplankton and seston must be adequate to maintain shellfish stocks even during finfish harvest and fallowing periods. Assess primary productivity at sites proposed for polyculture of finfish and filter-feeding shellfish to ensure that adequate food sources are available for the shellfish.

### *Ensure that polyculture operations do not compromise product safety*

If the intent is to produce shellfish for human consumption, care must be taken to assure that water quality at the proposed site meets water quality standards set by the Interstate Shellfish Sanitation Conference (ISSC 2005). If therapeutants are used on the finfish site, care should be taken to ensure that any shellfish harvested are free from any residues. Appropriate withdrawal times should be observed for both finfish and shellfish. If therapeutants are being used for the first time, shellfish samples should be tested for residues after the appropriate withdrawal time to confirm that no residues exist.

## Biofouling

Biofouling is the growth and accumulation of aquatic plants and animals on wetted surfaces. It is an increasing problem in most coastal waters and a significant concern in all marine aquaculture (see Chapter 11 for a discussion of biofouling in molluscan shellfish aquaculture). Biofouling at net-pen facilities may occur on any submerged surface, including nets, ropes, cage collars, buoys, boats, and barge bottoms. Fouling decreases the open area of containment nets by increasing the diameter of netting twine. Reduced open area impedes water flow, which increases hydrodynamic forces on the fouled net. Biofouling increases the weight of nets and associated tackle, and it reduces the useful life of nets and ropes from abrasion and chafing by fouling organisms such as shellfish and barnacles. The combined effects of fouling can put severe stress on moorings (Milne 1970) and cause damage to nets (Beveridge 2004). In extreme cases, heavy biofouling loads may increase the risk of fish escape caused by net or cage collar failure. Fouling increases benthic deposition, increases pathogen and pest resident populations, and increases fuel use for work vessels.

Dissolved oxygen to sustain fish in net pens is derived from water flowing through the net. Biofouling reduces water exchange in net pens and therefore reduces dissolved oxygen supplies within the net pen (Beveridge 2004). As fouling increases and water flow decreases, dissolved oxygen concentrations may decline to levels that stress fish. Consequences of fouled nets may include poor feed conversion, increased disease susceptibility, and, in extreme cases, suffocation and death. Changing or cleaning nets will reduce fouling, increase water exchange rates, and increase dissolved oxygen supplies.

Biofouling is primarily an operational issue, but biofouling control has implications for the environmental impacts of net-pen aquaculture. Some biofouling control methods may have adverse environmental impacts. For example, certain chemicals used to reduce fouling rates may adversely impact populations of nontarget organisms in the local ecosystem. Fouling organisms dislodged during cleaning activities may accumulate beneath net-pen facilities, exacerbating the effect of benthic accumulations of organic matter from feeding. The negative impacts of fouling on fish performance also reduces the efficiency of resource use in aquaculture. Accordingly, biofouling control is a significant operational issue with environmental ramifications that should be addressed through careful planning. Air-drying, mechanical removal, and nonchemical procedures to control biofouling are the preferred methods.

### *Better Management Practices to Reduce Biofouling*

#### *Select sites with low biofouling risk*

Appropriate site selection is a cost effective and environmentally sound method of reducing biofouling. When choosing sites, examine local fouling species and fouling rates. Where practical, choose sites with low biofouling rates, slow-growing fouling organisms, or fouling organisms that are easily controlled.

Effective control requires a thorough knowledge of the organisms that are responsible for fouling. Identify the organisms that foul equipment and develop life-cycle charts and short summaries of the ecology of each fouling organism. Identify environmental conditions that trigger reproduction, larval metamorphosis, and settlement. Use this information in an integrated biofouling management plan.

#### *Develop and implement an integrated biofouling management (IBM) plan*

Integrated biofouling management is a comprehensive approach modeled on integrated pest management methods developed in terrestrial agriculture. Integrated biofouling management may involve the use of chemical and nonchemical fouling-control methods. Nonchemical control methods include modifications to farm management practices. The goal of IBM is to effectively control fouling while minimizing the use of chemicals. Effective IBM requires a detailed understanding of the life cycle of fouling organisms so that control methods can be used strategically to break the fouling organism's life cycle and prevent or reduce colonization levels. IBM programs can be complex because biofouling typically involves multiple species that colonize surfaces opportunistically. Although individual growers frequently use multiple techniques to reduce fouling, a comprehensive IBM program is a new concept that has not been applied widely in aquaculture.

Develop a species-specific IBM plan that identifies potential fouling organisms, outlines proposed management strategies, indicates how the strategy relates to the organism's life history and ecology, and explains how any proposed management strategies reduce the risk of fouling. Integrated biofouling management plans should include early prevention and avoidance and regular monitoring for the presence of biofouling organisms. Plans may include maximum density thresholds for biofouling organisms that trigger fouling-control actions. Implement biofouling control actions before fouling impacts fish health or the integrity of the facility. Use multiple fouling-management practices in a manner that reduces the risk that fouling organisms might develop resistance or acclimate to the management practices that are used. Use specialized fouling-control methods in combination with operational practices and production strategies that take into account pest life cycles and ecology to maximize the effectiveness of the fouling control methods. Include BMPs that will reduce the need for use of chemicals while maintaining fouling control. Regularly reevaluate fouling-control methods to determine their efficacy.

Coordinate fouling-control actions with surrounding farmers. Share information with other growers on fouling levels within local bay management areas. Coordinate fouling control actions within local bay management areas to reduce the risk that poorly managed farms are acting as a fouling organism reservoir.

### *Use site fallowing and rotation*

If the specific fouling organism impacting the farm is not widely distributed in the ecosystem, fallowing may be an effective biofouling-control strategy. Identify the fouling organisms of concern and determine their distribution and prevalence in surrounding areas. If the farm appears to be the predominant locus for the organism, it may be possible to reduce levels of infestation by removing the fouled equipment and allowing pest populations to return to baseline levels.

### *Use air drying*

If fouling occurs in only a narrow band corresponding to the upper 1 to 2 meters of the water column, air drying may be an effective, nonchemical fouling-control method. Dessication of nets or equipment hoisted out of the water will kill biofouling organisms but not remove them. Dead fouling organisms will decay and slough off over time if the nets or equipment are reimmersed in water. If air drying is used ensure that fouling levels are not so high that water quality or fish health are affected by this process. Air drying may present an objectionable odor problem to other users of the marine environment.

### *Change and wash nets regularly*

Develop and implement a net cleaning and changing plan that includes a schedule for regular monitoring of fouling levels and a schedule for changing and cleaning nets. Change and clean nets before fouling levels impact fish health and facility integrity. Change nets directly after seasonal fouling organism settlement has occurred to ensure low levels of removed biomass.

As with any farm activity performed in close proximity to fish, disturbances associated with changing or cleaning nets may stress fish. Net-pen farmers have long observed that fish may cease feeding and even die if net changing or cleaning operations are not conducted carefully. Net cleaning or changing must be conducted in a manner that does not frighten fish and maintains the volume of the net bag during the activity. The frequency of net changing and cleaning involves a trade-off of concerns between the benefits of improved water flow and the negative effects of stress caused by the activity.

### *Avoid the discharge of removed fouling organisms to the environment*

Avoid discharging substances associated with in situ cleaning of fouling organisms from nets and cage collars. Pressure washing of nets and cage collars is strongly discouraged unless it is for disinfection and cleaning during site fallowing associated with a disease control program. In these circumstances remove nets and transport them to shore in closed containers for cleaning and disinfection. Do not relocate cage collars before cleaning and disinfection. During normal operations make every effort to use gear and production strategies that minimize or eliminate the need for on-site wash-down and rinsing.

Where practical, wash nets on land away from the net-pen site to reduce discharge of dislodged fouling organisms. When washing nets on land, collect all wastes and dispose properly. In general, move equipment to be cleaned away from the farm so that removed biomass does not adversely affect water quality or become deposited under the farm. In areas with high flushing rates, or depths exceeding three times the maximum net depth, in-place net cleaning may be acceptable. If nets must be cleaned on the net-pen site, ensure that cleaning activities are conducted so that fouling material dislodged from one net pen does not drift through other net pens containing fish.

### *Use approved antifoulant compounds on nets only when necessary*

In areas where high fouling rates require frequent net changes and cleanings, treatment of nets with antifouling compounds permitted by the United States Environmental Protection Agency may represent a lower overall environmental risk than frequent net washing (USEPA 2002). Chemical antifoulants, usually formulated as paints or dips, contain copper compounds that create a toxic layer at the surface as the copper leaches out. Antifoulants should be used according to the manufacturer's label instruction. Workers should be trained on the safe handling and application of antifouling compounds. Appropriate safety equipment should be provided to and used by workers applying antifoulant products. Adequate ventilation and spill containment measures should be in place during the application process. Drying times between compound application and net use must be in compliance with the manufacturer's recommendations. Net application methods should include a means to collect and reuse antifoulant that drips off nets during the application and drying process. Antifoulant products should be handled and stored in sealed and secured containers to prevent spillage.

When using any fouling-control method, comply with all appropriate state and federal regulations and ensure they do not negatively affect farmed fish health. If using antifouling compounds, ensure that there is no possibility of contaminating fish through residue accumulation.

## Fish Escapes

The escape of cultured species (including native species, nonnative species, hybrids, and genetically modified organisms) may pose a variety of potential risks to aquatic ecosystems or unrelated economic activities. Potential risks include pathogen transmission, interbreeding with conspecifics and introgression of alleles, competition for resources, predation, colonization, or disruption and damage to commercial and recreational industries, including aquaculture (Box 8.8). For most of the aquatic species commercially cultured in the United States, these outcomes have neither occurred nor are anticipated to occur because

- Producers have a strong economic incentive to prevent escape of cultured animals and to recover animals that do escape;
- Most pathogens are naturally occurring and ubiquitous;
- Most species are cultured in their native range;
- Successful introduction and spread of a nonnative species often meets strong biological resistance; and
- Federal and state agencies have implemented a variety of invasive-species regulations to prevent, control, manage, or mitigate potential impacts.

Most of the literature on farmed fish escapes has been driven by conservation biologists raising concerns about potential impacts and arguing for aggressively precautionary man-

### BOX 8.8
### Genetic Effects of Escaped Fish on Wild Populations

Numerous publications have discussed the potential impacts of introduced nonnative or domestic fish on native populations (Carlton 1992; Gross 1998; Ritter 1998; Benson 1999; Cross 2000; Pimentel et al. 2000; Myrick 2002; Brooks and Mahnken 2003; Peterson 2004; Naylor et al. 2005; Jonsson and Jonsson 2006). Benson (1999) provides an excellent review of the occurrence and impacts of nonnative introductions, and Jonsson and Jonsson (2006) review the probable impacts of escaped salmonids on wild populations. A preliminary literature search found over 350 papers on introductions and escaped finfish over the last 20 years. Over 83% of these publications were focused on accidental introductions or intentional introductions associated with stock enhancement or restoration programs. Numerous studies have documented impacts associated with large intentional releases from stock restoration and enhancement programs (Bachman 1984; Allendorf and Ryman 1987; Hindar et al. 1991; Waples 1991; Fleming and Gross 1992, 1993; Waples and Do 1994; Busack and Currens 1995; Campton 1995; Roads and Quinn 1999; Cross 2000; Hayes et al. 2004). Of the original 350 publications, approximately 58 were concerned with escaped farmed fish. Most of these focused on escaped salmonids with a few discussing tilapia and aquarium fish. Of all of these studies and reviews, 12 involved empirical field studies: 8 on salmonids, 2 on tilapia, and 2 on aquarium fish. Most empirical studies were field surveys documenting presence or absence of an escaped species. In all but 3 papers (all of which analyzed the same field experiment), no impacts on reproductive success or allele distributions in native populations were quantified. Three studies documented genetic impacts in the same controlled field experiment where domesticated fish were intentionally released and forcibly contained on breeding grounds with wild fish. The genetic profiles of returning progeny were significantly different than the native stocks, indicating hybridization (McGinnity et al. 1997, 2004; Clifford et al. 1998). Allele frequency distributions returned to their original patterns after two generations of spawning without domesticated fish on the spawning grounds.

agement measures (Naylor et al. 2005). Harrell (2002) reviewed and critiqued some of the internal inconsistencies between current conservation theory and existing empirical data and concluded that more field studies are needed. Myrick (2002) suggests that there are a number of methods available to reduce the risk of potential impacts of farm escapes, and that these practices should be considered regardless of whether impacts have been demonstrated. It is not our intent to debate actual and asserted impacts of escaped fish but rather to build on the approach of Myrick (2002) and suggest guidelines to reduce risks of escape and mitigate potential impacts. This approach is consistent with the conclusions of a number of recent international forums and agreements on the management of interactions between escaped farmed fish and wild stocks (NASCO 1994, 1998, 2001, 2006; NASCO Liaison Group 2001; Hansen and Windsor 2006).

## *Alternative Approaches to Preventing Fish Escapes*

Although there is uncertainty surrounding the impacts of escaped fish, there is broad agreement that the elimination of escapes would reduce environmental risk and farm economic losses. Although escapes can theoretically be reduced to zero, significant debate exists regarding how achievable this goal is and what methods are most likely to achieve it. The following sections describe three strategies for eliminating escapes or reducing the impacts of escaped animals. The strategies are not listed as BMPs because the economics of implementation are either unknown or appear to be unfavorable, logistics or other practical consideration presently impede their implementation, or the technologies needed to implement the strategy are not sufficiently developed.

### *Land-based aquaculture*

A number of critics have advocated the elimination of net-pen operations and the movement of all fish culture into land-based facilities as a method of eliminating escapes and reducing other environmental impacts. The assumption behind this suggestion is that land-based facilities, with their solid tank walls and limited number of outlets, will be more effective in preventing escapes. The advantages of this approach seem obvious, but most arguments against land-based systems have centered on cost issues. Some would argue that costs are irrelevant and that increased costs associated with land-based production are simply an accurate accounting of the externalities associated with net-pen operations. To date no systematic comparison of the efficacy of land-based and net-pen culture facilities in reducing escapes has been conducted (Box 8.9), nor has there been a comprehensive comparison of life cycle assessments for land-based and net-pen farms.

### *Double netting*

The installation of secondary containment nets around the outside of the primary nets is another method proposed to eliminate or reduce escapes. The assumption is that the secondary net will contain any potential escaped fish if the primary net fails. Although this approach appears to have some merit, double-net systems have environmental costs, are expensive, significantly increase labor requirements, and may not provide additional protection in the event of catastrophic facility failure. Double-netting systems significantly

## BOX 8.9
## Fish Escapes from Land-Based Facilities

Although a systematic comparison of the levels of escapes from land-based and net-pen operations has not occurred, some investigative work has determined the causes of escapes from land-based facilities (MEASC 2002; NASCO Liaison Group 2007). Electrofishing surveys downstream of land-based facilities and inventory audits indicated that significant numbers of fish have escaped from land-based facilities in Scotland, Norway, and the United States. Carr and Whoriskey (2006) documented levels of escapes from freshwater salmon hatcheries in New Brunswick, Canada and found that 75% of streams with land-based facilities had escaped juvenile salmon. Although numbers varied, in many instances escaped juveniles outnumbered wild salmon. Further work involving audits of Facility Containment Management Systems (MAA 2007) confirmed that land-based facilities can be a source of significant numbers of escaped fish.

reduce water flow rates through net pens. Løland (1991) outlined the mathematics of flow reductions caused by multiple net panels and found that flows can be reduced by as much as 70% depending on mesh size and distance between the net panels. Flow reductions of this magnitude may negatively impact dissolved oxygen in and around net pens, increase sedimentation rates, and alter water circulation patterns on farm sites. The additional stress on fish may predispose fish to diseases and increase feed conversion ratios, resulting in increased waste production per unit fish biomass produced.

The use of double netting doubles the net surface area subject to biofouling. Net fouling may significantly reduce water exchange rates (Beveridge 2004) and negatively impact fish condition and health. Double-net systems will increase the need for net cleaning and disposal of fouling waste or net treatment with antifoulants. This will result in increased labor requirements. Double netting increases loading on net-pen collars and mooring systems, requiring scale-up of net-pen construction materials and structural profiles. These increased equipment requirements, in combination with the additional netting and cleaning, increase the consumption of energy and petroleum products used in the manufacture, maintenance, and operation of the net-pen farm.

Although double-net systems may prevent escapes in the event of a hole in the primary net, there is no evidence that they will provide additional containment in the event of facility structural failure. Structural failures tend to occur during large storm events. Net bags are not designed or constructed to provide the primary structural element that maintains the shape and integrity of a net-pen system. Net bags are designed to be suspended or stretched between steel or high-density polyethylene structural members that provide the strength for net pens. If net-pen elements engineered to withstand large structural stresses fail, it is unlikely that net bags will remain intact. Thus, whether there is one or two net bags, it will not significantly alter the probability of overall containment failure.

### *Biological containment*

There are three principal causes of escapes from net pens: equipment failure, operational errors, and predator attacks. Donaldson (1991) originally outlined two classes of methods used to reduce the risk of escapes and potential impacts. Physical containment focuses on establishing and maintaining physical barriers that prevent escapes but do nothing to mitigate their impacts if they occur. Biological containment focuses on using fish strains that are unlikely to survive in the wild or unable to interbreed with wild fish if they do survive (Box 8.10). Biological containment ultimately may be the most effective method because it will work even if escape occurs. It is important to note, however, that unless the biological containment method reduces survival of an escaped fish, it will not be effective at reducing risks of pathogen transmission, competition for resources, or predation on wild fish by escaped fish.

Ironically, many of the concerns about the impacts of escaped fish are based on the risk that their reduced ability to survive may be transferred to wild populations. On the one hand, reduced fitness is desirable because it will decrease the survival of escaped fish

## BOX 8.10
## Fate of Escaped Fish from Net Pens

Reductions in fitness and decreased survival of escaped fish are well documented (Berejikian 1995; Berejikian et al. 1999; Ford 2002; Hasegawa et al. 2004; Kostow 2004; McGinnity et al. 2004). This reduction in fitness appears to be an artifact of domestication rather than intentional design. Whether these reductions in fitness are sufficient to guarantee a quick death outside the net pen remains open to question. There is certainly considerable anecdotal evidence to suggest that escapees are highly susceptible to predation in the wild. Producers often report rapid predator aggregation and increased predation after significant escape events. A number of studies have documented reduced predator avoidance by farmed fish (Berejekian 1995; Brown and Laland 2001; Johnsson et al. 2001; Sundström et al. 2004).

Several studies have used sonic tracking to follow the fate of fish intentionally released from net pens. Bridger et al. (2001) tracked released steelhead trout and found that they exhibited significant site fidelity to the farm and were targeted by seals. Whoriskey et al. (2006) found that "escaped" Atlantic salmon suffered high mortality rates (56 and 84%), with spring releases surviving better than winter releases. These results are similar to a larger tag-and-recovery study conducted in Norway (Hansen 2006). Although mortality was significant in all of these studies, none approached complete mortality, which would be necessary for effective biological containment. Indeed, in the Whoriskey et al. (2006) and Hansen (2006) studies, individual fish survived for extended periods and moved long distances, thus statistically increasing the likelihood of interactions with wild populations. Successful biological containment must be based on fish that remain reproductively isolated or die quickly outside the net pen.

outside the culture unit and thereby reduce the probability of interacting with wild populations. On the other hand, reduced fitness is undesirable because escaped fish may transfer that reduced fitness to wild populations if escaped fish interbreed with wild fish. This is the conundrum of a species early in the domestication process. A number of groups have advocated using culture stocks that are genetically similar to wild stocks (Naylor et al. 2005; Marine Aquaculture Task Force 2007). Although protective in the short term, that recommendation may be more damaging in the long run because it effectively halts the domestication process. Thus it slows the process whereby (1) farm animals become so different from wild animals that they are no longer able to interact with and impact wild stocks, and (2) farm animals become so dependent on the culture environment of the farm that they are no longer able to survive in the wild. Ultimately, the most effective way to address the issue of impacts of escaped farm fish on wild populations is to accelerate domestication and develop fish strains that flourish in captivity but die in the wild. An interim step would be the development of strains that flourish in captivity, have reduced fitness in the wild, and are unable to breed with wild fish for physical or behavioral reasons. Mandating the use of only wild stocks on farms will inhibit the development of these biological containment methods. The use of stocks not adapted to captive conditions may also reduce animal welfare and increase animal stress and the risk of disease.

Most of the work on biological containment methods has focused on the development of the interim step mentioned above. The production of sterile fish can be achieved using a variety of techniques, including administration of hormones and polyploidy induction. Numerous studies have documented success in the creation of sterile fish groups and reviews of the various sterilization methods are provided by Yamazaki (1983), Thorgaard (1983), Ihssen et al. (1990), Donaldson (1991), Purdom (1993), and Colombo et al. (1998). Cotter et al. (2000) and Benfey (2001) review the potential utility of sterile fish as a biological containment method. Aside from instances of high egg mortality from imperfect polyploid induction, performance at juvenile life-history stages has been comparable to diploid populations. Performance of sterile fish at later life-history stages has been mixed. In some cases fish growth and survival in sterile populations was lower than in diploid populations of the same stocks (Johnstone et al. 1991; Benfey 2001; O'Flynn et al. 1997). In other cases performance of sterile and diploid populations were comparable (Galbreath and Thorgaard 1995; Oppedal et al. 2003). Benfey (1998) suggests that polyploid fish should be viewed as another species, and that culture methods and optimal conditions for their farming may be significantly different than diploid members of the same species. If sterile fish from strains that have been classically selected for good growth and survival as diploids are grown using production strategies and methods more appropriate to their physiology and life histories, maybe they will perform as well as their diploid relatives. Further work needs to be conducted to explore this hypothesis and to continue to refine sterilization methods.

## ***Better Management Practices for Preventing Escapes***

### *Obey relevant regulations*

Follow all local, state, and federal regulations that govern animals (including native species, nonnative species, hybrids, and genetically modified organisms) that may be imported, exported, cultured, or sold live locally or nationally. Contact appropriate state agencies for regulations governing species, facility design and operation, holding and transport, or live sales. Seek the advice from aquaculture extension specialists and appropriate agencies when considering the culture of an unfamiliar species. Contact the United States Fish and Wildlife Service for an import/export license and information about injurious species identified under the Lacey Act. For regulations concerning species and production systems that can be used in marine waters, contact the National Marine Fisheries Service. For health certification of imports and exports, contact the United States Department of Agriculture—Animal and Plant Health Inspection Service (APHIS). For regulatory information concerning genetically modified organisms intended for food or pharmaceutical markets, contact the United States Food and Drug Administration, Center for Veterinary Medicine (CVM) and Center for Food Safety and Applied Nutrition (CFSAN). Currently, there are no transgenic aquatic organisms approved for human consumption in the United States.

### *Consider the effect of site characteristics on the risk of escapes*

Site characteristics that may be relevant include frequency of extreme weather, degree of site exposure, type of bottom, distribution and prevalence of predators, and proximity to high-traffic navigational areas such as shipping lanes, channels, or ports. Select sites that minimize these risks and reduce the probability of net-pen system failures to storm damage, predator attacks, or shipping collisions. These considerations are discussed in the section "Site Selection" above.

### *Minimize the risk of escape during fish transfers*

Conduct all fish transfers—such as stocking, grading, relocation, or harvest—in weather conditions that do not significantly increase the risk of escapes. All fish transfer operations should be under constant visual supervision of at least one person. Use only equipment appropriate for the weather conditions, net-pen designs, and type of fish transfer conducted. Train all personnel in use of fish transfer equipment. Never use makeshift equipment in conditions for which it was not designed. Where necessary or appropriate, use shields or additional nets to prevent fish escaping during transfer. All holding, transportation, and culture systems should be designed, operated, and maintained to prevent escapes.

### *Use strong and durable materials for net-pen construction*

Use cages and nets with design specifications and manufacturing standards that meet generally accepted standards prevalent in the aquaculture industry (Fig. 8.7). Net-pen design, specification, and installation should be commensurate with the prevailing conditions, and capable of withstanding the normal severe weather and maximum sea conditions. Although net-pen designs may involve engineers, certified designs and internationally recognized net-pen standards do not exist. Work is currently underway to develop such standards. In the interim, producers must rely on the reputation of manufacturers and installers and their knowledge of marine operations. Consult extensively with

**Fig. 8.7.** Two styles of modern net pens. In the foreground is a round pen made of high-density polyethylene. In the back are square, steel-collared pens. Choosing the proper pen design for prevailing site conditions can significantly reduce risk of escapes. Barely visible in the photograph is netting over the round pen to prevent access by birds.

other operators who have purchased similar net pens. Do not rely solely on manufacturers' references. Request copies of any engineering studies conducted by manufacturers. Request copies of any warrantees that are offered with net pens. Ask insurance brokers whether they have any experience with the net-pen design and brand proposed for use. Ask brokers whether they have had or have heard of any claims associated with the design and brand. Ask manufacturers for documentation of the qualifications and certifications of the welders who manufacture the net pens.

Develop a site-specific set of net specifications that includes materials specifications and construction details appropriate to the expected site conditions. When developing net specifications confer with other farms in the surrounding areas and on similar sites. Specify net materials profiles and strengths high enough to resist a direct predator attack. These will vary depending on the type and size of anticipated predators. Require that all down-ropes are sufficiently strong to lift the weight of the net panel they are attached to out of the water. Attach down-ropes directly to bottom ropes that join the bottom and side net panels. Specify that net weight attachment points are reinforced and allow for attachment of weights to ropes not netting. Attach one down-rope directly to any weight attachment point and extend the down-rope to the top of the net. Conduct stress tests on all nets with more than 3 years of use in the marine environment when the net is pulled out and cleaned. All nets should be certified as ultraviolet-protected by manufacturers.

### *Properly secure nets to cage collars*

Secure nets directly to the floating cage collar such that the collar, not the handrail, bears the strain of the cage. Install net weights to prevent chafing. Weights should hang below and away from nets. A second layer of net should be added 30 cm (1 foot) above and below wear points. Suspend net weights from independent ropes that are not part of the net bag. Connect net weights to the net bag only at designated and reinforced net attachment locations with rope loops for that purpose.

On sites with current velocities over 1.5 knots (77 cm/second), the use of weight rings is strongly encouraged. Weight rings are solid structures with the same dimensions and form as the perimeter of the bottom of the net bag. Weight rings can be made of steel pipe or high-density polyethylene pipe filled with sand.

### *Install jump nets*

Jump nets can prevent fish from jumping out of the primary containment net. Jump nets should be an integral part of the primary containment net or joined to it in a fashion that prevents fish escape between the primary net and the jump net. Jump nets should be of a height appropriate to the jumping ability and size of fish contained. For example, jump nets should extend at least 91 cm (36 inches) above the waterline of salmon net pens.

In areas with extreme winters, pens may sink slightly due to ice loads from freezing spray. This is a temporary condition that abates as ice melts during submergence. In areas where winter icing occurs regularly, bird nets should be exchanged for winter cover nets. These nets are constructed of netting designed to withstand the rigors of icing and with mesh sizes appropriate to contain the fish being reared if the net pen sinks. On sites that experience winter icing, deploy ice tarps to reduce icing. Ice tarps are made of black heavy-duty tarp material. Tie ice tarps to the outside of the cage collar and stretch them tightly and tie to the top of the hand rail. Deploy ice tarps only on the side of the pen that faces prevailing weather and spray.

### *Use appropriate mooring systems*

Mooring system designs should be appropriate and compatible with the proposed net-pen system (Fig. 8.8). For example, breaking strengths on all mooring connectors should be consistent with or exceed strengths specified by net-pen manufacturers at cage attachment points. Mooring system layouts should consider net-pen design and attach to pens at only locations designated for mooring attachment. Mooring systems should be designed and installed in consultation with the net-pen manufacturer or supplier. The best approach is to require that manufacturers design and install the mooring system because they will have the most experience with their equipment. If this option is not available, ask the manufacturer to approve the mooring installation company that is contracted. Mooring system design, specification, and installation should be commensurate with the prevailing conditions of the site and capable of withstanding the normal maximum conditions likely to occur at a site (Box 8.11).

### *Regularly inspect and adjust mooring systems*

Maintain rigging tensions and component specifications at or above original installation standards. Inspect new components no later than 2 years after deployment. Using a diver or remote video camera, regularly inspect subsurface mooring components. Pay special

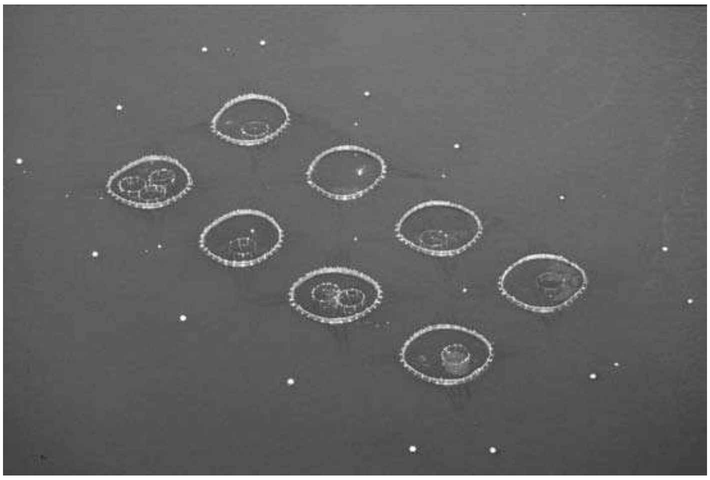

**Fig. 8.8.** High-density polyethylene net pens showing typical farm configuration with multiple-point mooring.

## BOX 8.11
## Mooring System Specifications

Although a number of theoretical studies on mooring design have been conducted (Rudi et al. 1988; Taylor 1991; Riley and Mannuzza 1991; Kery 1996; Waldemar Nelson International, Inc. 2001), internationally recognized mooring system standards do not exist. Chapman (1979) provides some practical guidance on moorings in general. Beveridge (2004) provides practical guidance for mooring methods specific to net-pen farms. The anchor type should be appropriate for the type of bottom. See Chapman (1979), Taylor (1991), and Beveridge (2004) for guidance. All shackles used in mooring systems should be safety shackles, wire-tied, or welded to prevent pin drop-out. All chain used for moorings should be manufactured of at least 32 mm (1.25 inch) stock. All ropes used for mooring lines should be at least 38 mm (1.5 inch) in diameter. All buoys used as hydraulic dampers on mooring lines should have sufficient buoyancy to hold up two times the weight of any mooring lines and chains suspended below it. All mooring components should be at least as strong or stronger than mooring attachment points on the pens. See also Box 8.5 for a discussion of single-point mooring systems.

attention to connectors and rope/chain interfaces. Identify chafe points and subject them to more frequent inspection and removal of marine growth. With the exception of rock-pin anchors, haul out of the water and visually inspect all mooring system components at least once every 6 years. When considering what inspection method to employ, net-pen operators should consider the relative risks and benefits associated with the inspection method. At sites frequently exposed to severe weather or where it is difficult to set anchors, breaking out anchors for visual, above-water inspections may represent greater risks than regular underwater inspections. In these circumstances, increase the frequency of underwater inspections.

### *Clearly mark all net-pen sites*

These markings should be in accordance with the farm's permit for fixed private aids to navigation from the United States Coast Guard and appropriate state authorities. Markings should include lights and radar reflectors to reduce the probability of ship collisions during day or night.

### *Develop Standard Operating Procedures (SOPs) for all routine vessel operations*

Vessel operations around a net-pen site can cause escapes either through propeller net entanglement or collisions with net-pen structures. At minimum, SOPs should cover appropriate operating speeds in good and poor visibility conditions, appropriate methods and locations for bringing vessels alongside pens, and appropriate methods and locations for vessel mooring line attachment. Include SOPs for evacuating site personnel in the event of an emergency or bad weather. Clearly identify the weather and sea-state conditions under which it is not appropriate to bring a vessel alongside pens. The SOPs should require vessel operators to visually assess wind and current direction and whether nets are deflected out from the net pens by currents before approaching the net-pen system. Require vessel operators to normally approach pens from a downcurrent, downwind heading. In the event of opposing currents and winds, vessel operators should determine the dominant influence on the vessel and approach pens in the opposite direction. All vessel operators should receive appropriate training in the operation of vessels. Only qualified and trained vessel operators should operate farm vessels. The SOPs should be designed to minimize the risk of damaging nets and/or mooring system components while preserving farm worker safety.

When mooring feeding barges or work vessels on a permanent or semipermanent basis, consider local current, wind, and wave patterns. Select mooring locations for feeding barges or work vessels that minimize the chance of a vessel impacting a net pen in the event it breaks free of its moorings. Construct and install moorings that are appropriate for the barge or vessel being moored and the expected site conditions. Consult a naval engineer or Chapman (1979) and Taylor (1991) for guidance on appropriate mooring design.

When determining facility layout, restrict direct access to net pens by vessels by some form of removable barrier. Such a barrier has to be removable to allow normal farm operations, such as stocking, net changing, and harvesting. Effective barriers include subsurface cables or ropes and predator netting. The location and type of barrier employed should not be obvious and should be held confidential by all farm employees. Consider having all employees sign a confidentiality agreement.

### *Develop and implement a farm security plan*

Like any aquaculture facility, net pens may be subject to theft, vandalism, or ecoterrorism. Such acts are difficult to predict and protect against. Farm security can be increased through the use of surveillance and proper facility layout. The timing of surveillance and farm operations should be varied to prevent potential perpetrators from planning actions around farm operations. Surveillance methods will be determined by the farm location, site characteristics, and expense of the method. Surveillance methods can include visual observation by land, water, or air. Observation methods may include direct visual observations and remote methods such as video, radar, hydroacoustic, or satellite. Radar and hydroacoustic systems can be linked to automated alarm systems that notify farm personnel of an intrusion when they are not on the farm. Consult with the appropriate law enforcement authorities to determine whether they have any suggestions to improve site security. Familiarize authorities with normal farm operations and site layout. Request that authorities keep the farm on their watch list for patrols. When intrusions are detected, immediately notify appropriate authorities, because individuals involved in theft or vandalism may be dangerous. Include in the security plan a community watch program that involves other user groups that live nearby or are active around the farm site. Meet with these groups and explain normal farm operations and give them contact information for farm managers. Ask for their help in observing any unusual activity on the farm site. The farm security plan should be a confidential document and accessible to only site managers and facility owners.

### *Develop and implement a comprehensive loss-control plan*

At minimum the plan should include the following elements: minimum equipment standards, equipment installation protocols, a preventive maintenance plan, an integrated predator deterrence plan, and a containment management system that includes documentation of management actions and external audits. Plans should allow for continuous improvement and revisions based on innovations in farming methods and technology.

Include minimum equipment and installation standards in the loss-control plan. Where practical, equipment standards should be quantitative and based on manufacturers' specifications. Installation standards should be based on manufacturers' recommendations and consistent with the best professional judgement of qualified equipment installation specialists or an engineer. Where practical, installation standards should include metrics that can be checked over time. For example, materials profile specifications can be used to measure wear on shackles or chains.

Include a preventive maintenance program for cages, mooring systems, and nets in the loss-control plan. The maintenance program should track histories of individual components and include a schedule for regular inspection and maintenance. In the case of cages and mooring systems, the program should document the original purchase date and manufacturer specifications, and the maintenance history of individual cages and mooring system components. The nature of the specific maintenance activities should be identified, the date conducted, any supporting documentation for new materials used, and who conducted the maintenance. In the case of nets, the program should document the original purchase date, manufacturer specifications, and the maintenance history of individual nets. Document the nature of the specific net maintenance activity conducted, the date it was conducted, any supporting documentation for new materials used, and who conducted the maintenance. The net preventive maintenance program should include regular strength testing on nets to detect weaknesses before failures occur. Net testing standards should be developed in cooperation with net manufacturers or an independent testing laboratory, and they should include regular physical strength tests that measure breaking strengths of the net mesh. Increase the frequency of strength testing as nets get older. Retire and properly dispose of nets that fail testing standards.

Include a Containment Management System (CMS) in the farm loss-control plan (Appendix 1). A CMS is a two-part system that includes a Facility Prerequisite Program (FPP) and a Facility Containment Plan (FCP) that is based on Hazard Analysis and Critical Control Point (HACCP) plans. The FPP establishes a series of records and predetermined procedures that will be audited to determine whether the farm is appropriately managing escape risks. The FCP is based on HACCP management methodologies developed by the Codex Alimentarius Commission of the United Nations. The HACCP system was developed for the food industry to manage food-safety risks and has been in place for several decades. The FCP includes a hazard analysis and assigns critical control points only to those steps in the culture process where there is a significant risk for the escape of cultured fish. The FCP includes a process flow chart that depicts all physical activity on the entire farm site from juvenile stocking to the final harvest for transport to a processing facility. The CMS must be in place and available to an independent auditor at all times.

The CMS is intended to reduce the likelihood of cultured fish escape and establish a management climate that seeks constantly to monitor, correct, and improve management actions designed to reduce escapes. The CMS intentionally recognizes that it is unlikely that no escapement will be achieved, but will continue to strive for this goal and record all escapes that may occur to build a database of escapes and their causes. The intent of this database is to be used as a tool to improve operations and identify any underlying causal patterns for escapes. The logging of this information should not be used to penalize site operators by regulatory authorities because it will remove incentives for grower buy-in and investment in the program. Conversely, the deliberate failure to report or log incidents properly as required by the CMS should be viewed as a serious violation by the authorities.

### *Recapture escaped fish*

Where practicable and allowed by law, producers should attempt to recapture fish in the event of a significant escape. Recapture procedures should be based on an escape-response plan developed in consultation with the appropriate resource management agencies responsible for the protection of wild fish and wildlife populations. Use methods that do not violate fish and wildlife regulations. Consult with the appropriate resource management agencies before undertaking recovery actions.

## Predator Control

Any farm that includes aggregations of farm animals within enclosures will attract predators. As with terrestrial farms that use fences, net-pen operations provide ample opportunity for predators to directly view and smell farm animals that may be potential prey. Interactions with predators on net-pen facilities include issues related to impacts of wildlife on farm operations as well as potential impacts of farm operations on wildlife.

**Fig. 8.9.** Lack of effective predator deterrence can result in significant damage and loss.

Predators may consume or harass farmed fish, leading to economic losses. In addition to direct loss of fish to predators, the presence of predators around net-pen facilities can keep fish in a perpetual state of fright, resulting in increased stress and poor feed conversion. Predators may also spread pathogens beyond, within, and among aquaculture facilities, and wounds inflicted by predators may serve as a focus for diseases or reduce the commercial value of the fish (Fig. 8.9). Diseased and stressed fish convert feed poorly with subsequent increased waste production. In rare instances, certain predators may be a danger to farm workers.

Farm equipment such as ropes, twine, or nets provide significant entanglement risks to predators attempting to prey on fish. Loss of wildlife in this manner presents ethical problems and may contribute to a negative public image of net-pen operations. Certain predator control practices may also be viewed as unethical by some people. Predator attacks may compromise the integrity of the enclosure, leading to escape of farmed fish. For example, seals may chew through nets, creating large holes that allow fish to escape.

Although it is highly unlikely that predator control practices in net-pen aquaculture will negatively impact natural populations, many of the animals visiting net-pen sites are classified as threatened or endangered by the United States Fish and Wildlife Service. Aquaculturists must be aware of the legal and ethical limitations on predator control methods for threatened and endangered species.

## *Predators of Fish Cultured in Net Pens*

### *Pinnipeds*

Pinnipeds (fur seals, true seals, sea lions, and walrus) are attracted to locations with concentrated supplies of food, such as fish docks, hatcheries, dams, and fish farms, and places where they can haul out and rest and even give birth. The diet of pinnipeds is predominantly fish, but each species supplements this with a variety of local invertebrates, especially crustaceans and mollusks. Therefore, fish and shellfish enclosures are attractive to pinnipeds.

With the exception of the more remote walrus, pinniped species all over the world have similar behavioral patterns toward human interventions into their habitats. Individual pinnipeds can overintegrate with human activities and become a danger to themselves. Some pinnipeds have become "rogue" animals around human activities, and individuals have been relocated by the authorities to other rookeries or legally destroyed.

Pinnipeds have been an increased nuisance to fish and shellfish producers. For example, seals are known to contribute to the fecal contamination of several shellfish growing areas, and sea lions and seals have been known to eat fish through slack nets, and to bite holes in nets creating avenues of escape. Moreover, their constant close presence is known to stress fish, causing them to lose weight and value.

Drowning after containment in or around a netted structure is the main risk to pinnipeds. Individuals have been entrapped in netting, particularly when it folds in response to current and wave action. But the possibility of a pinniped being entrapped and drowned in the nets of a modern fish farm complex is now remote. Predator nets are now much stronger, and all net-pen walls are kept rigid and taut. Modern net-pen complexes are no longer potential haul-out sites for pinnipeds because the surrounding walkways are well fenced. Advances in the design engineering of net-pen structures, following underwater video research on the behavior of pinnipeds, have greatly reduced the risk around fish farms.

Pinnipeds are protected by the Marine Mammal Protection Act and the Endangered Species Act. Regulations require that the death of any marine mammal around fish farms is reported, and the information is available on public record.

### *Otters*

There are 13 species of otter worldwide. All species appear to be suffering reduction in population size from loss of breeding habitat and disease. Many countries (and states) have listed otter species as threatened or endangered and have successful restocking programs.

Riverine otters have adapted to estuarine and coastal conditions and their diet includes fish, crustaceans, and mollusks found in freshwater and marine habitats. Sea otters remain in their preferred marine habitats and feed entirely on marine organisms. An adult otter consumes about 1 to 1.5 kg of food daily. Their preference for predictable food sources has attracted otters to fish hatcheries, fish farms, and stocked ponds and streams for recreational fishing. Sea otters and river otters are inquisitive mammals, so they are attracted to readily available sources of food, particularly fish and shellfish. Consequently they are attracted to fish and shellfish hatcheries and surface or floating farm structures in search of food, or to haul out to rest and consume their prey. Therefore aquaculture facilities in otter habitats must be maintained vigilantly; the animals can penetrate all but the most secure defenses.

Drowning after containment in or around a netted structure is the main risk to otters. Individuals have been entrapped in netting, particularly when it folds in response to current and wave action. The possibility of an otter being entrapped and drowned in the nets of a modern fish farm complex is now extremely low. Predator nets are now much stronger, and all net-pen walls are kept rigid and taut.

Otters damaging net-pen farms can be removed or deterred by nonlethal preventive measures. Live traps and snares may also be used to catch otters for their removal. In damaging situations involving only one or two otters it may be legal to kill them with a shotgun or small-caliber rifle. Consult with the appropriate natural resource management agency before taking relocation or lethal actions.

### *Sharks*

Although many of the 220 species of sharks occur in brackishwater and freshwater, most are principally marine species. As more marine net-pen operations are developed, problems with sharks attacking fish pens and farm workers may increase. Documented attacks on farms or workers have occurred in the Caribbean, Australia, the Red Sea, the Pacific Coast of Mexico, and off the east coast of the United States. Shark species involved include the great white, bull, Caribbean reef, tiger, and pointer sharks.

### *Reptiles*

Few incidences of attacks by crocodiles and alligators on net-pen operations have been documented. Reptile attacks have been reported from a freshwater tilapia farm in Kenya and a brackishwater barramundi farm in Australia. In the case of the tilapia farm, a worker was killed during the attack.

### *Birds*

Numerous species of birds are found around net pen farms. Net-pen facilities may cause death or injury to birds by trapping them in primary containment nets, surrounding predator-deterrent nets, or horizontal nets stretched over the net pens.

Depending on location and season, several species of birds may be associated with net-pen facilities. The most common birds associated with net pens include

- Gulls and crows may roost briefly on walkways and rails of a farm complex. Gulls may feed on baitfish aggregating around the nets and scavenge on available organic materials, such as exposed biofouling organisms or fish feed. Mortalities of these birds at net-pen farms are extremely rare.
- Surf scoters and other diving birds populate marine bays, inlets, and coastal passages, especially during winter and spring. In addition to feeding on naturally occurring prey, such as clams, they feed actively on biofouling organisms, such as mussels on cage floats and anchor lines. They may also swim through large mesh predator nets to feed on biofouling organisms. Entrapment of these birds is rare because water transparency at commercial net pens is typically good and nets are firmly held in place to deter predators.
- Wading predators, such as herons, may land on net-pen walkways and railings, or sometimes bird covers, to feed or to rest. Fortunately they do not dive into the water and therefore, if protective nets are stretched tightly in place, birds are not trapped or killed. These birds may attempt to capture farmed fish by striking through net meshes.

- Some net-pen complexes serve as seasonal feeding and resting sanctuaries for migrating shore birds. Large numbers of these birds are seasonally common on kelp and algae growing on anchor lines and loose accumulations of eel grass, which provide habitat for prey.
- Raptors, such as eagles, falcons, and hawks rarely interact with net-pen facilities, although they are often seen roosting or nesting in shoreline trees near some net-pen sites. They may feed on wild fish or birds, such as gulls, that are attracted to net-pen farms. Negative interactions, such as entanglement in nets, are very rare.
- Diving predacious birds—such as grebes, loons, and cormorant species—may occur around net-pen farms and may attempt to attack farm fish by striking with their bills through net pens.

The design of net-pen complexes has advanced significantly since 1990 and robust pen-weighting systems are available to prevent deflection or bagging of the nets where birds might once have been trapped. Modern containment nets are about 2.5- to 3.1-cm (1- to 1.25-inch) bar-length knotless nylon for production of subadult fish, and the top edge is held about 1 meter above the water line to prevent side entry. Surrounding predator nets, which are usually installed, are typically constructed of high-denier fiber, and are highly visible in nonturbid waters typical of net-pen sites. Bird covers stretched over the pens prevent diving birds from landing in or entering the pens. Modern, well-managed net-pen facilities that use appropriate equipment and predator deterrence methods should have no negative effects on birds. Net-pen facilities frequently provide habitat and natural food sources for some bird species. Negative interactions with birds at net pens are easily preventable.

### *Integrated Predator Deterrence (IPD)*

Effective predator control relies on a systematic and vigilant management system. One example is Integrated Predator Deterrence (IPD), which is a comprehensive predator-management method that was originally adapted for the deterrence of seal attacks on salmon farms in Maine (Belle 2002). In Maine, IPD has been used on salmon farms since 2002 and is effective when applied systematically. The IPD approach is modeled on Integrated Pest Management principles used in terrestrial agriculture, wherein pests are identified, the type and level of damage is assessed through regular monitoring, and control methods are chosen that are appropriate for the pest and level of damage. The steps of the IPD approach include 1) identification of potential predators; 2) identification of any proposed deterrence strategies; 3) determination of how deterrence strategies relate to the biology, ecology, and behavior of predators; and 4) determination of how the proposed deterrence activity reduces the risk of predator attacks. Effective IPD requires a detailed understanding of the life cycle, ecology, and behavior of a predator so that deterrence methods can be used strategically to prevent acclimation.

Deterrence techniques used may include site selection, modifications to farm animal containment methods and stocking cycles, disruption of predator life cycles, predator harassment, predator relocation, physical barriers, and in unusual cases, lethal predator control. Nonlethal control methods may include modifications to farm management and animal husbandry techniques, the use of behavioral modification techniques, such as visual and sound conditioning signals, and the use of physical barriers. Specialized predator deterrence methods can be used in combination with operational practices and production strategies that consider predator behavior and ecology to maximize the effectiveness of deterrence methods. The goal of IPD is to effectively deter predator attacks while minimizing the need for lethal control methods.

In cases where deterrence has failed and predator attacks occur, all reasonable actions should be taken to try to prevent predators from gaining access to farm animals and to protect worker safety. When predator deterrence has failed, the Integrated Predator Deterrence Plan should be reviewed, and any deficiencies identified and corrected.

### ***Better Management Practices for the Control and Deterrence of Predators***

#### *Consider predator behavior and ecology in site selection*

Select sites away from areas that attract pinniped aggregations, such as haul-out and pumping locations, river mouths, or drop-offs next to deep water. Select sites away from areas that attract reptile aggregations, such as haul-out beaches, nesting sites, and areas where large terrestrial animals come to bathe or water. Avoid the mouths of rivers into which significant marshes or swamps empty. Select sites away from areas that attract otters, such as dens, scent stations, and otter slides. Select sites away from areas that attract shark aggregations, such as spawning grounds, channels emptying sand flats, openings in barrier coral reefs through which tidal lagoons or rivers empty, or drop-offs next to deep water. Select sites away from areas that attract birds. In marine and freshwater environments this may not be possible, but stay away from major migratory flyways, sunning stations, the mouths of rivers and streams, and known areas of high bird densities. Avoid areas with large resident shellfish or baitfish populations that may attract otters and birds.

#### *Collect mortalities regularly*

Ensure that dead and moribund fish are regularly collected and disposed of properly. Proactively cull wounded or sick fish to reduce the attraction of predators. Cull fish quickly to avoid blood loss. Never leave mortalities open to access by predators.

#### *Vary the timing of farm operations*

This can prevent predators from acclimating to human activity patterns. Vary boat routes and approach directions to the farm to ensure that boat noise and activity are not predictable, and cover all areas around the farm.

#### *Comply with all applicable regulations*

When using IPD methods, comply with all applicable federal and state regulations. Lethal predator control is highly regulated by state and federal wildlife and agriculture agencies. Lethal controls should always be employed as a last resort and only after consultation with the appropriate state and federal regulatory agencies. All deterrence methods employed should be humane and should not compromise the health and welfare of farm animals or workers.

### *Use predator nets*

Where practical, use rigid net-pen designs that prevent predator penetration into the net enclosures. If this is not possible, use physical barriers, such as bird and underwater predator nets that are deployed around the outside of the primary fish-containment nets (the photograph in Fig. 8.2 clearly shows bird netting above a net pen). Predator nets for diving birds should be sufficiently deep to exceed maximum bird dive depth or at least extend to the bottom of the primary fish-containment net. Construct predator nets with twines that are the appropriate strength for the expected predator size. Predator mesh size should be large enough to reduce flow restrictions due to fouling but small enough to prevent predator entanglement and access to the primary net. Typical mesh sizes of predator nets are presented in Table 8.2.

Install predator nets an adequate distance from the primary containment nets to prevent predators from pushing the predator net in against the primary net. Correctly weight all predator nets to provide well-tensioned net walls that prevent bowing or folding in currents, or prevent predators from pushing predator nets into the primary containment net or being able to bite loose net folds.

### *Use other physical barriers*

Install strong rigid fences at least 1 meter high to prevent access to net-pen walkways and floating cage collars by pinnipeds and otters for haul-out and sunning. In certain cases battery-operated electric fences may be appropriate. Maintain adequately charged batteries. For reptiles, deploy floating surface net aprons that are at least 10 feet wide around each individual pen. Surface nets should be attached to the outside of the cage collar and stretched out floating horizontally away from the cage at the water's surface to prevent reptiles attacking workers on the cage collar.

Where practical, employ bird cover nets over the tops of pens. Cover nets should be stretched taut and of a high-visibility color. Support cover nets with floating net support rings to prevent birds weighing down the cover net to the water surface. Install roosting prevention devices, such as spikes and tightly strung ridge cables, on all farmhouses and structures.

**Table 8.2.** Typical mesh sizes of predator nets.

| | Bar Length | |
|---|---|---|
| Predator | Centimeters | Inches |
| Birds | 3.8 to 7.6 | 1.5 to 3 |
| Otters | 5 to 7.6 | 2 to 3 |
| Pinnipeds | 10 to 20 | 4 to 8 |
| Sharks | 13 to 20 | 5 to 8 |

### *Use acoustic deterrence devices*

If effective, use acoustic deterrence devices to scare predators away from facilities. Deterrence devices can include tape recordings of alarm cries for the species being deterred, tape recordings of underwater boat noise played through hydrophones, propane cannons, tape recordings of sounds made by animals that prey on the predator species being deterred, radios tuned to talk shows to emulate human presence when farm staff are not on-site, or random underwater noise generators that generate high-decibel noise levels at frequencies that do not affect fish. For seals, use underwater acoustic seal-scarer units that generate random patterns of high-decibel sounds. Always deactivate seal-scarer units before divers enter the water. When acoustic deterrents are used, ensure that power sources cannot be compromised by water and that they are always maintained in a fully charged and functional state.

### *Use visual deterrence devices*

If effective, use visual deterrence devices to scare predators away from facilities. Use human effigies (scarecrows) to imitate the presence of humans when personnel are not on the farm. Move visual deterrences regularly, remove at random times, and place for variable periods of time so that predators do not acclimate to their location and presence. Clothe mannequins in loose garments that flap in the wind. Large inflatable eagle scarecrows that are suspended from poles attached to net pens may be used.

Visual deterrents can include flashing lights or different wavelengths that flash for variable periods at random time intervals. Red lights and red lasers are especially effective. Use Mylar flash tape of the type used in orchards and vineyards to create the appearance of constant motion on the site. Flash tape moves and flashes irregularly and scares predators by creating the impression of movement on the farm.

### *Use dogs as a deterrent*

If appropriate shelter and space are available on the farm site, use dogs as a deterrent. Make sure that facilities are adequate to satisfy the housing and exercise needs of the animal. Never leave the dog on site during dangerous weather or sea conditions.

### *Use olfactory deterrents*

To deter otters, use floating scent stations around the perimeter of the net pen site that contain scent from otter predators, such as coyotes. Ensure that scent stations will not be subject to frequent overwash from waves or rain.

## Facilities Operation and Maintenance

Net-pen farms are expensive to install and operate. Net-pen operators are subject to elevated public scrutiny because they generally operate in public waters. Net-pen farms operate in these public waters under licenses or permits that can be summarily revoked by local, state, or federal authorities. Net-pen operators who do not operate their facilities in a responsible and sustainable fashion risk the revocation of these licenses and permits, and directly jeopardize their own investments.

Net-pen operations may generate solid and liquid wastes. Control, containment and disposal of solid and liquid wastes on a net-pen farm presents unique challenges because of the proximity and intimacy with aquatic ecosystems. As with other water-based farming operations, it may be tempting to view the disposal of wastes directly into that aquatic ecosystem as easy and environmentally benign. “Down the drain” or “overboard” may be viewed as “out of sight, out of mind.” This is, of course, a short-sighted and inappropriate perspective that can result in negative environmental impacts. Net-pen operators must be particularly vigilant in the control and appropriate disposal of solid and liquid wastes during farm operations.

### *Better Management Practices for Facility Operation and Maintenance*

#### *Systematically review farm operations*

Conduct a systematic review of all farm operations and identify any documented environmental impacts. When considering modifications to existing farming methods, include a review of the type and extent of probable environmental impacts that may occur as a result of the new methods. Include in all production planning a systematic review of any probable environmental impacts that would be associated with a particular production plan or method. Use comprehensive stocking and production strategies that optimize production while minimizing environmental impacts. Make diligent and continuous efforts to minimize environmental impacts associated with stocking/seeding, harvesting, feeding, grading, thinning, transfer, cleaning, or gear maintenance. Consider impacts on environmental quality, worker safety, product quality, and animal welfare during the planning and implementation of any operational procedure.

#### *Develop a solid waste management plan*

Forms of solid waste from net pens include biofouling organisms, mortalities, feedbags, packaging materials, scrap rope and netting, and human wastes from workers. To manage, use, and dispose of wastes generated during production activities effectively, conduct a systematic review of farm operations and develop a waste management plan. An effective plan will clearly identify all wastes generated on a site, identify their source and volume, and classify them with respect to any risks associated with their collection and appropriate disposal. Design the waste management plan to minimize the generation of waste while recognizing the practical challenges associated with marine operations. Review all farm operations and consider alternative practices to reduce the use of materials that generate solid waste. The use of packaging and material handling methods that reduce total packaging needs are strongly encouraged. Solid waste management plans should encourage reduction, reuse, and recycling of waste materials. In cases where human or animal health may be compromised by reuse or recycling, use a containment and disposal method that ensures effective disposal and protects human and animal health. At minimum, facility solid waste management plans should address human waste, feed bags, net fouling organisms, scrap rope and netting, fish mortalities, and old feed packaging materials.

### *Collect and return solid wastes to shore for disposal*

Collect all feed bags, packaging materials, waste ropes, and netting, and return to shore for proper disposal using methods and facilities approved by appropriate regulatory authorities. Recycling of these materials is strongly encouraged.

Collect all human waste in sanitary containers and return to the shore for proper disposal. Seal transport containers to prevent spillage and securely tie them down during transport. Farm support vessels of the appropriate size should have approved Marine Sanitation Devices on board. All human wastes should be disposed of according to applicable state and federal regulations.

Collect and return to shore all old feed for proper disposal. Expired or spoiled feed can be composted or used as agricultural fertilizer at levels that are appropriate, and do not result in nutrient overloads on application sites. If feed is to be composted or used as agricultural fertilizer, consult with the appropriate management authorities to ensure environmental regulatory compliance. Never dispose of medicated feeds except by following manufacturer's recommendations. Never dispose of feed by dumping into aquatic ecosystems.

Collect and return to shore all fish mortalities. Proper fish health management is the best method of managing mortalities in net pens (see Chapter 12 for a detailed discussion). Optimizing fish health will reduce the need to deal with dead fish. Even under optimal conditions some mortalities will occur naturally. By design, net pens contain any mortalities that may occur. Monitor mortality rates closely and collect and remove dead fish in a timely fashion. Severe weather may temporarily prevent mortality removal and exposed sites may be more subject to these conditions. Weather permitting, collect mortalities regularly. The frequency of collection will depend on fish size, water temperature, disease status of the site, and mortality rates.

The overall goal of mortality collection is to track accurately mortality rates to assess fish health and maintain accurate farm inventories for feed and business management purposes. The frequency of mortality collection and retrieval operations is determined by balancing the need for accurate inventory and mortality information against any stress or disease risk associated with the retrieval operation. In general, faster decomposition rates of small fish in warm water require more frequent mortality collections than large fish in cold water. Collect mortalities more frequently if mortality rates increase above normal levels. When collecting and removing mortalities, use methods that do not stress remaining animals, compromise biosecurity, or jeopardize worker safety.

Use designated mortality storage and transport containers that are closed containers with tight-fitting lids. Once transported to shore, dispose of mortalities properly using methods and facilities approved by appropriate regulatory authorities. Mortality disposal sites and transport routes should not compromise farm biosecurity. Vermin and birds should never have access to mortalities. The use of composting at remote sites with appropriate environmental controls is strongly encouraged.

### *Conduct harvest activities to minimize environmental impact*

Harvesting and slaughtering operations are significant vectors and risks in the spread of aquatic diseases (Vagsholm et al. 1994; Murray et al. 2002). Water containing blood from diseased fish being slaughtered for disease-control purposes may contain especially high levels of virus (Rolland and Nylund 1998). Even on populations not exhibiting clinical disease, significant levels of the virus could be detected in blood samples collected directly from the fish. Blood-water can stress other animals on the net-pen farm and act as a vector for pathogens and should not be discharged during harvesting operations.

During harvesting, if fish are to be transported alive, move fish directly into transport containers and seal them with adequate life support to maintain animal welfare. Well-boats transporting salmon to slaughter have been implicated in the spread of infectious salmon anemia (ISA) in Norway and Scotland (Vagsholm et al. 1994; Jarp and Karlsen 1997; Murray et al. 2002).

If fish are to be transported dead, conduct stunning, slaughter, and bleeding in a manner that contains bodily fluids, and in particular prevents the spilling of blood or water with blood in it. Design and implement harvest procedures and equipment in a fashion that will reduce any associated discharges. Harvest and postharvest vessel and equipment cleanup procedures should minimize any wastes discharged overboard.

Collect and return to shore for proper disposal any on-site processing wastes, such as fish offal, blood-water, and scales. On-site processing is strongly discouraged as it may compromise biosecurity. If on-site processing must occur, collect and transport all processing wastes to land in containers with tightly sealed watertight lids. Never dispose of processing wastes in aquatic environments.

### *Develop and implement a fuel and oil management and spill-response plan*

Document the locations, types of containment vessels, volumes and types of all petroleum products used during operations. Only allow fuel farm-support vessels at approved fueling stations. Report all fuel or oil spills immediately to the fueling station operator. All onboard spills and leaks should be immediately reported to the captain of the vessel. Appropriate clean-up and repair actions should be initiated as soon as practicably possible. All fuel or oil spills should be reported as required to the appropriate state and federal authorities.

Include communication protocols in the spill-response plan that ensure that appropriate authorities are notified in a timely fashion in the event of a spill. Assemble and preposition spill-response kits adequate to contain the volumes and types of petroleum products identified in the spill-response plan. Train all site personnel as to the type of liquids used on site, and their health, safety, and environmental risk characteristics. Train site personnel in spill response and containment and have preassigned designated roles and responsibilities in spill-response operations. Conduct regular spill-response drills.

### *Do not discharge soaps or disinfectants*

Do not allow the direct discharge of any soaps or disinfectants into the aquatic environment. Follow manufacturers' recommendation for the disposal of all disinfectants.

Use biodegradable soaps and disinfectants. Danner and Merrill (2006) give excellent guidance on the proper use and disposal of disinfectants. Footbaths, equipment dips, or diver dips should be sufficiently large to prevent spillage or splashing during their use. Cover footbaths, equipment dips, and diver dips not in use to prevent overflow from precipitation.

### *Develop a record-keeping system*

Good record keeping is the hallmark of a well-operated aquaculture facility. Records, such as feeding, chemical use, water quality, serious weather conditions, fish culture operations, and inventory facilitate improvements in the efficiency of farm input use. Paper copies of records should be maintained for archival purposes; computerized record-keeping tools can be used for trend analysis and forecasting. Records should be reviewed periodically to determine whether they are useful and to provide insight into opportunities for improvement of farm operations.

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## Chapter 9

# Better Management Practices for Flow-Through Aquaculture Systems

*Gary Fornshell and Jeffrey M. Hinshaw*

## Introduction

Flow-through aquaculture systems depend on water exchange to maintain suitable water quality for fish production and rely on water flow for the collection and removal of metabolic wastes. Water for flow-through facilities is usually diverted from streams, springs, or artesian wells to flow through the farm by gravity. Water pumped from wells or other sources is more expensive and is seldom used except in small hatcheries. Water diverted from springs or surface sources for flow-through aquaculture is regulated by various public agencies, depending on the specific water laws of each state. Diversion of surface water is considered a nonconsumptive use, although pumping groundwater from a well is considered a consumptive use in some states. The discharge of a high-volume, dilute effluent from flow-through aquaculture facilities makes environmental impacts relatively difficult to quantify and greatly limits the treatment from both technological (Summerfelt 1999; Cripps and Bergheim 2000; Bergheim and Brinker 2003) and economic perspectives (Engle et al. 2005).

Production of fish in flow-through culture systems in the United States is usually equated with commercial production of rainbow trout (*Oncorhynchus mykiss*) in concrete raceway systems. Other coldwater fish species produced in flow-through systems include brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*). Additional trout species are produced in these systems by public hatcheries, but the quantity is insignificant compared to commercial rainbow trout production. Flow-through systems are used for production of freshwater stages of salmon, but only 12 commercial salmon facilities were in operation in the United States in 2005 (USDA-NASS 2006a). Thirty-three flow-through facilities for salmon enhancement programs were operated in Alaska by federal, tribal, state, or nonprofit fisheries groups. Flow-through systems are also used on a limited scale for the production of warmwater fish such as catfish (*Ictalurus* spp.) and tilapia (*Oreochromis* spp.). Recently, flow-through systems have been used to produce coolwater species such as yellow perch (*Perca flavescens*), hybrid striped bass (*Morone* hybrids), and several species of sturgeon (*Acipenser* spp.).

Flow-through aquaculture is a mature and relatively stable industry in the United States, particularly with regard to trout production (Fig. 9.1). In 2005, trout farming—the major

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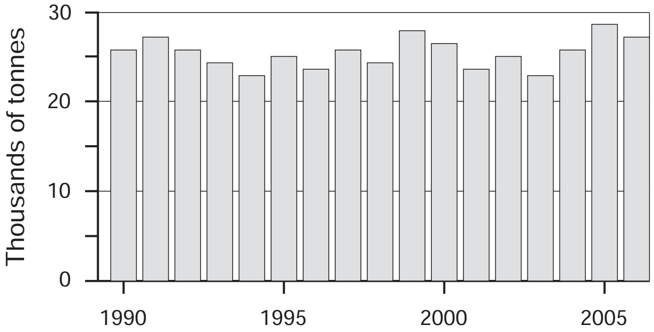

**Fig. 9.1.** United States trout aquaculture production since 1990. *Source:* USDA-NASS (1990–2007); also available at usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1172

commercial flow-through aquaculture industry in the United States—consisted of 410 facilities in 38 states (USDA-NASS 2006a). Major commercial trout production states included Idaho (70 to 75% of domestic production), North Carolina, Washington, California, and Pennsylvania. Federal, state, and other government or noncommercial entities operated an additional 442 flow-through facilities that were primarily or exclusively for trout production. Production of catfish, tilapia, hybrid striped bass, and sturgeon combined produced less than 1% of the biomass of trout produced in flow-through systems. The majority of flow-through fish farms are small, family-operated businesses with average sales per farm of about $130,000 nationally (USDA-NASS 2000). However, the largest 20% of the trout farming operations (108) produce over 85% of the total sales.

## Flow-Through System Hydrology

Flow-through systems are the most commonly used aquaculture production systems for the culture of rainbow trout and other salmonids in the United States (Hardy et al. 2000; Fornshell 2002; Hargreaves et al. 2002; Hinshaw and Fornshell 2002). Flow-through systems include linear earthen and concrete raceways, and tanks constructed from other materials. Concrete raceways are the most common (Hinshaw et al. 2004). Circular rearing tanks are also used in flow-through systems, most commonly for broodstock production.

A raceway is basically a flume for carrying water. The typical raceway production system consists of a tank (rearing unit) or a series of rectangular tanks with water flow along the long axis. In an ideal raceway, water flow will approximate plug flow, with uniform water velocity across the tank cross section. However, friction losses at the tank-water and air-water boundary layers will cause water velocities to vary across the width and depth of the raceway. Greatest water velocities are at mid-depth, with slightly reduced velocities at the air-water interface and greatly reduced velocities along the raceway bottom. A defining characteristic of linear-pass raceways is a water-quality gradient from the inflow to the outflow of the rearing unit during production, with best environmental conditions at the inflow and deteriorating water quality along the length of the raceway as water flows towards the outlet. Circular rearing units are more thoroughly mixed and have relatively uniform environmental conditions throughout the tank.

### *Rearing Unit Configurations*

Rearing units in flow-through systems can be configured in series or parallel (Fig. 9.2). With tanks in series, water flows from one rearing unit to the next one below. Raceways

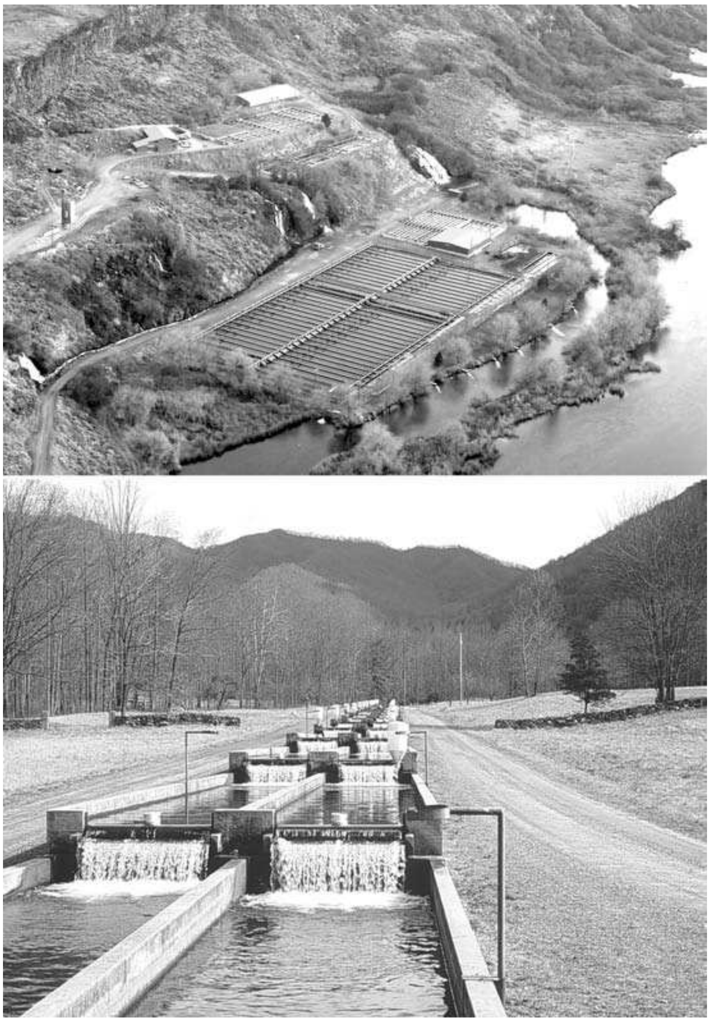

**Fig. 9.2.** Flow-through facilities used to produce rainbow trout in Hagerman Valley, along the Snake River in Idaho (top) and in the Appalachian Mountains of North Carolina (bottom). The Idaho facility has 30 parallel sets of raceways, each set with two raceways in a series. The facility is supplied with artesian springwater emerging from the canyon walls, and at least six springs can be seen in this photograph. The Snake River is at the lower right of the picture. The North Carolina facility has two parallel sets of raceways, each set with 14 raceways in a series. Water is diverted from a small permanent stream hidden in the trees to the left. Top photograph courtesy of University of Idaho Aquaculture Research Institute.

in a parallel system are adjacent to each other and discharge directly into the receiving stream from the settling basin or water treatment system. Constructing raceways in parallel rather than in a series allows more fish to be grown in first-use water, but will reduce the intensity of production per unit of water flow unless oxygenation or aeration is used. In practice most flow-through aquaculture facilities use a combination of tanks arranged in series and parallel raceways. Available water supply and quality, space availability, and topography impact the design of a flow-through aquaculture production facility.

### *Water Sources*

Water sources for flow-through aquaculture include groundwaters and surface waters that are diverted to the farms by gravity. Pumping large volumes of water from wells or surface waters is expensive and is rare except to supply small hatcheries (Hinshaw et al. 2004). Groundwater is used almost exclusively in Idaho, including geothermal artesian wells for warmwater species cultured in raceways. Trout farms in the Appalachian Mountains of the eastern United States rely primarily on water diverted from streams (Fig. 9.3). Trout farms in the northeastern and midwestern regions of the United States rely primarily on spring sources, though streamwaters are also used.

Groundwater is the preferred water source for flow-through aquaculture because it is typically free of suspended solids, pollutants, and pathogens that may be present in surface waters. Also, the chemical composition and temperature of groundwater are stable relative to most surface waters. Favorable attributes of aquifers for flow-through aquaculture use include high-volume artesian flow, abundant alkalinity and hardness, separation from

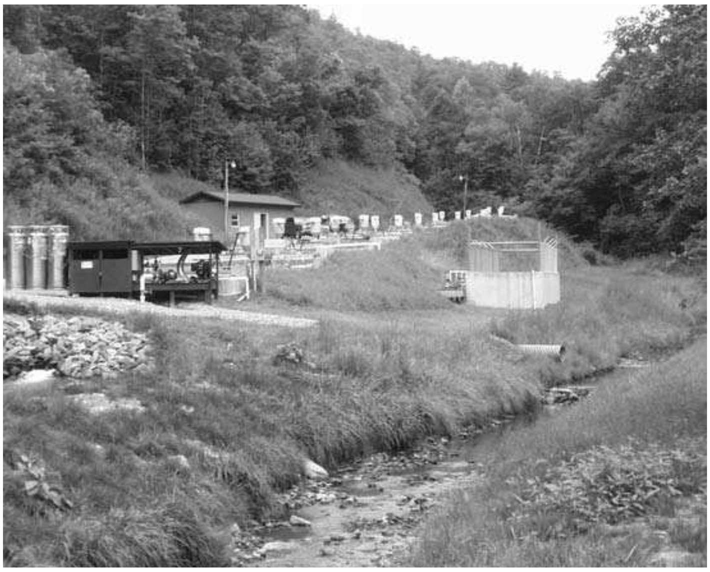

**Fig. 9.3.** A small flow-through facility producing rainbow trout in the Appalachian Mountains of North Carolina. Water from a small stream is diverted into the raceways in the distance and then returned to the stream, after treatment, in the foreground.

potential surface contamination by an impervious layer, and rapid recharge that maintains aquifer volume. The groundwater used for aquaculture in Idaho emerges as springs from the canyon walls of the Hagerman Valley at a constant water temperature of 14.8°C (Brannon and Klontz 1989) (Fig. 9.2, top). The springs arise from the Eastern Snake Plain Aquifer, which is approximately 2.6 million ha in size (Kjelstrom 1995). The Idaho trout industry diverts approximately 62 $m^3$/second of water flow; however, in recent years spring flows have declined as a result of increased groundwater pumping for irrigation, conversion from furrow to sprinkler irrigation, changes in water management, and drought (Fornshell 2002). The Idaho trout industry faces a significant challenge in maintaining current production levels as spring flows continue to decline.

Surface waters are not as desirable for flow-through aquaculture as groundwater because they may contain wild fish populations—a potential source of fish pathogens. In many areas surface waters may contain sediment or could be contaminated by agricultural pesticides and fertilizers. Flows and water temperatures can fluctuate widely throughout the year. For example, in contrast to the stable annual water temperatures of the springs in the Hagerman Valley, daily water temperatures ranged from 2.8 to 19.3°C over 2 years on trout farms in North Carolina using water diverted from surface streams (Tuomikoski and Hinshaw, North Carolina State University, unpublished data). Insufficient water availability resulting from drought and excessive water flows during floods are characteristic of the seasonal and year-to-year variability of surface water supplies. To accommodate periods of high temperatures and low flow rates, many North Carolina trout growers have added oxygenation systems and developed production plans based on seasonal fluctuations. A surface water supply suitable for trout production must have a protected and, preferably, undeveloped watershed.

### *Water Budgets*

In comparison with ponds, water budgets for flow-through aquaculture systems are simple. The budget is controlled by regulated water inflow, and inflow water rate equals outflow rate. Rainfall contributions and evaporation losses are negligible. Flow-through systems use water diversion and control structures that do not allow runoff to directly enter the rearing units in an uncontrolled fashion. Farms that rely on diverted surface waters use waters from protected or undeveloped watersheds. Most raceways are constructed of impermeable materials, so seepage does not occur.

Water flow measurements are taken on a regular basis for production management and because it is often required by law. In the western United States, where water rights are considered property rights, regular reporting of water flow diversions (measurements) is required, along with a description of the flow measurement methodology that must be approved by the agency. The Idaho Department of Water Resources requires an annual report of weekly flow measurements taken from aquaculture facilities in addition to regular inspection and calibration of the flow measuring device. Weirs are one of the oldest, simplest, and most reliable structures that can be used to measure the flow of water in canals and ditches and are commonly used to measure water flowing into flow-through aquaculture facilities.

Water flows per raceway or series of tanks vary in proportion to tank size, fish density, and fish metabolic needs. In practice, water flow rates per raceway are based on desired water exchange rates and, to a lesser extent, water velocity. For example, a 3-m-wide raceway will typically receive 85 to 100 L/second and a 5.5-m-wide raceway will receive approximately 170 L/second.

Flow-through aquaculture systems are a nonconsumptive use of water. Evaporation and other water losses from tanks are minimal, and the only regular removal of water is in the form of fish or fish wastes. Goldburg and Triplett (1997) mischaracterized water use in the Idaho trout industry as consumptive by implying that aquaculture was responsible for declines in groundwater levels in the Eastern Snake Plain Aquifer. Instead, water rights in Idaho are property rights, aquaculture water rights by law are nonconsumptive, and the amount of water that is diverted for use must be returned.

Although water is not consumed during use, flow-through systems use (but do not consume) large volumes of water per unit fish production compared to other aquaculture production systems. Flow-through systems require a continuous flow of high-quality water for fish production and maintenance of water quality within the raceways. Water volume use (based on average annual production of rainbow trout in the United States) is approximately 98 $m^3$/kg, compared to 1.25 to 1.75 $m^3$/kg for channel catfish in undrained levee ponds and 6.5 to 10 $m^3$/kg for channel catfish in watershed ponds (Hargreaves et al. 2002).

The classic concept of water conservation is meaningless in flow-through aquaculture systems because there are no terms in the hydrological mass balance equation that can be manipulated to reduce water use (Hargreaves et al. 2002). However, water use efficiency can be improved by using technologies that increase fish production per unit water flow. Examples of such technologies include rigorous water quality management, high-quality feeds, and using improved fish stocks.

## Site Selection

Location on substandard sites is a frequent cause for failure of aquaculture enterprises. Siting criteria are also important for reducing environmental impacts of flow-through aquaculture. For example, selection of sites with suitable topography—particularly the amount of vertical relief—will allow the use of gravity flow to transport solids to sedimentation basins for collection and removal, thereby eliminating expenses associated with pumping. Suitable slope will also ensure adequate fall between rearing units to reaerate the water (Fig. 9.3, bottom), providing good environmental conditions so that fish efficiently consume and digest feed. Sites with sufficient slope can produce more fish per unit water than sites without sufficient slope. A careful site evaluation should be made prior to investing in the venture. Identification of potential problems before construction and either addressing those problems or locating an alternative site is much less expensive than attempting to solve problems by implementing mitigation measures after construction or, in the extreme, having to abandon the operation. See the North Carolina State University trout production web page (haywood.ces.ncsu.edu/content/TroutInformationandLinks) for details on site selection and other information to consider when starting a trout farm.

## *Better Management Practices for Site Selection*

### *Do not site facility ponds where regulatory or other restrictions apply*

Several state and federal agencies have jurisdiction over flow-through system construction and water use, including discharge into waters of the United States. Contact the local state office of environmental quality or regional Environmental Protection Agency office for guidance. A National Pollutant Discharge Elimination System (NPDES) permit administered under the Federal Clean Water Act may be required (Federal Register 2004). National Pollutant Discharge Elimination System permits protect water quality by regulating the discharge of pollutants from point sources to waters of the United States. An NPDES permit is required for a flow-through aquaculture facility that discharges at least 30 days per year and is a coldwater facility that produces more than 9,070 kg per year and feeds at least 2,268 kg of feed in any calendar month; if it is a warmwater facility it needs an NPDES permit if it produces more than 45,351 kg per year. A facility may be required to have an NPDES permit although it does not meet the above criteria if the permitting authority deems the facility a significant contributor of pollution to waters of the United States. When such a decision is made, the following factors are considered by the permitting authority: location and quality of the receiving stream, quantity and nature of the pollutants discharged, and whether a total maximum daily load (TMDL) is in place within the watershed. Dischargers seeking coverage under an NPDES permit must submit a written Notice of Intent (NOI) to be covered by the permit prior to any construction of the facility.

Section 404 of the Federal Clean Water Act requires a permit issued by the Army Corps of Engineers if an intake and/or diversion structure is constructed to divert surface water from a stream. In addition, if there is a potential that construction of the facility may impact wetlands or discharge dredge or fill material into waters of the United States, a permit may be required by Section 404.

Water use is regulated by various agencies, depending on the specific water laws of each state. Generally, in the western United States a water right is required that specifies the point of diversion, quantity, beneficial use, and priority date. In the eastern United States there are no specific water rights for aquaculture. Surface waters are considered Waters of the State. However, flow-through system operators in North Carolina may divert up to 90% of the stream flow because the diversion of water is for a nonconsumptive use and is returned to the stream.

A propagation permit or commercial fish rearing license is usually required. Depending on the state, Departments of Agriculture, Fish, and Game, or Natural Resources issue the permit that regulates the species of aquatic plants and animals allowed for aquaculture.

At the local level, county planning and zoning departments may require additional permits. Contact the local county planning and zoning department for further information.

### *Avoid contaminated sites*

Most flow-through production sites are located on agricultural land or land that has few alternative uses (USTFA 1994). Land-use history is an important consideration prior to construction. Soils exposed to previous land-use activities such as pesticide storage, pesticide disposal, industrial processes, or urban activities may be contaminated with harmful chemicals. Construction on such sites may cause chemical contamination of surface waters. If earthen raceways are proposed, soil samples should be taken and analyzed for chemical residues. Contaminated soils may impact fish health, product quality, or food safety and should be removed prior to construction.

Operators of proposed flow-through facilities that will divert surface water need to be aware of land-use activities within the watershed. Those activities will impact the quality of the water and possibly cause the water supply to be unsuitable for fish production. Watersheds that are in forests are best, followed by pasture. Avoid watersheds with large urban or industrial sites if possible. If water is diverted from an irrigation canal or lateral, the operator should be aware that canal companies periodically apply herbicides for aquatic vegetation control. Usually these herbicides are not labeled for aquaculture use and may be toxic to fish and other aquatic life. Good communication and coordination with the water master is extremely important to avoid a fish kill on the facility or below in the receiving stream.

Facilities located in agricultural areas may be exposed to contamination from aerial pesticide applications. Local aerial pesticide applicators should be notified of the locations of the flow-through facilities. Good communication, cooperation, and careful coordination with aerial pesticide applicators is important to prevent contamination of the facility (USTFA 1994).

### *Avoid sites that are prone to flooding*

Floods that overflow flow-through aquaculture facilities result in loss of cultured animals, contamination of rearing units with wild fish, and mixing of floodwaters with rearing unit waters. The escape of farmed fish has the potential to impact an ecological community through genetic impacts, disease impacts, competition, predation, habitat alteration, and colonization. Aside from the possible escape of cultured animals, floods are usually catastrophic for the farmer but benign to the environment because rearing unit waters, which generally have better water quality than floodwaters, will be greatly diluted by floodwaters.

Flow-through facilities that divert surface waters from streams are more prone to flooding than those facilities that rely on groundwater. The intake and/or diversion structure should be constructed to divert floodwaters around and away from the flow-through facility. The lower portion of a flow-through facility near a receiving stream may be prone to flooding if the receiving stream floods. In virtually all situations, it is best to avoid constructing any part of a flow-through facility in a 100-year floodplain. The United States Department of Agriculture (USDA) Natural Resources Conservation Service provides information on historic flood levels and recurrence, and guidance on avoiding sites in flood-prone areas. Consult the local county office for information.

### *Avoid sites where discharge may impair protected water resources, at-risk water bodies, and special habitats*

Flow-through systems should not be sited where the discharge may impact sensitive habitats or waters. These areas are generally excluded from coverage under an NPDES permit and typically are sensitive habitats for threatened and endangered species. The United States Fish and Wildlife Service or the National Marine Fisheries Service may designate waters as protected water resources or special habitats. Other sensitive areas include national parks or preserves, national wildlife refuges, national wilderness areas, and rivers designated as wild under the Wild and Scenic Rivers Act. At-risk water bodies may include areas in close proximity to downstream drinking water intakes for municipalities.

### *Select a site with suitable topography*

The slope of a site should be gentle enough to provide ease of access, yet provide a minimum fall of 0.6 to 1 m between raceways for passive aeration. Sufficient drop is necessary prior to discharge into the receiving stream to ensure adequate dissolved oxygen concentrations in the effluent. A 3 to 10% slope is generally suitable for raceway construction (Dunning and Sloan 2001). Selection of a site with suitable topography will also allow the use of gravity flow to remove and transport collected solids from the rearing units to sedimentation basins, thereby avoiding expensive pumping costs.

### *Select a site with sufficient water quantity and quality*

The water quantity and quality from a given source will depend strongly on local climatic and hydrological conditions, and can vary greatly even within a relatively small geographic area. Some groundwaters and surface waters may require pretreatment to remove excess gases and to add dissolved oxygen. Usually cascading incoming water over a fall is sufficient to oxygenate the water and remove excess dissolved gases such as nitrogen and carbon dioxide. In some situations it may be necessary to use a packed column for more efficient aeration and degassing. If the sediment load in the incoming water is high, pretreatment with a sedimentation basin may be warranted to improve water quality.

The quality and quantity of available water will determine the size and type of flow-through system suitable for the proposed site. Flow-through systems require high-quality water and sufficient quantity to sustain productivity and optimal fish health. Water quality should meet the biological needs of the cultured animals. Insufficient water quantity or inadequate water quality will negatively impact fish health and performance, resulting in greater waste production and potential discharge into the environment.

Trout are the most common species cultured in flow-through systems in the United States and they require cold, pure, oxygen-saturated water. Optimum temperatures for rainbow trout production range from 10 to 16°C (Piper et al. 1982). Temperatures should never exceed 24°C and rarely exceed 21°C. If surface water is used for production, stream channels that are shaded by trees are preferred to prevent high water temperatures during the summer. Water supplies should be free of contaminants that may affect product quality or food safety.

Obtaining a reasonable estimate of available water is essential prior to planning and construction of the proposed facility. Water quantity may vary throughout the year and from year to year. This is particularly true for surface waters, but flow from groundwater sources can also fluctuate throughout the year, especially shallow springs that are more easily impacted by climatic conditions and groundwater withdrawals. In the eastern United

States where surface waters are more commonly used, the minimum *7Q10* or 10-year, 7-day average low flow is used to estimate the minimum acceptable flow. In North Carolina, the 7Q10 is approximately 30% of the average stream flow. In general, a minimum flow of 1,900 L/minute is recommended (Dunning and Sloan 2001). However, the minimum flow required for primary income will vary considerably depending on species, market outlets, and profit margins. The United States Geological Survey, state agencies, water districts, and well-drilling companies can provide historical flow information for surface and groundwaters.

## Feeds and Feeding

The most common and visible impact of flow-through aquaculture in the United States is degradation of downstream water quality resulting from failure to control suspended and settleable solids and nutrients discharged from facilities (Hinshaw and Fornshell 2002). For practical purpose, feed is the only source of aquaculture-derived solids and nutrients in flow-through facilities (Cho and Bureau 1997, 2001; Gatlin and Hardy 2002; Tacon and Forster 2003). The short hydraulic residence time in the system and the continuous discharge of water indicates that feed management is critical in controlling the amount of nutrients and solids discharged to receiving waters (Hinshaw and Fornshell 2002).

Optimizing feed utilization by using high-quality feeds and careful feeding practices can significantly reduce the quantity of nutrients and solids generated during culture and released to the environment. Good feed management can also reduce the required capacity of the treatment system, thus reducing capital and operating costs (Cripps and Bergheim 2000). Accordingly, reducing total waste production may also increase the carrying capacity of the production system, thereby enhancing the efficiency of water use. Furthermore, feed is the largest variable cost item, representing 40 to 60% of total variable production costs in North Carolina and Idaho (MacMillan et al. 2003; Engle et al. 2005). Feed must be used efficiently to assure profitability because it accounts for such a large proportion of production costs.

Ingested feed must first be digested before being utilized by the fish. Absorption of the digested protein, lipid, and carbohydrate provides the energy and nutrients for maintenance, growth, and reproduction of the fish. Undigested nutrients are excreted in the feces as solid waste and the by-products of metabolism (nitrogenous waste, phosphorus, carbon dioxide, etc.) are excreted by the gills and kidneys as soluble waste. Feed waste (unconsumed feed) together with fecal material and metabolic wastes make up the total waste associated with feeding and production. The most effective way to reduce environmental impacts from flow-through aquaculture systems is to increase assimilation and retention of nutrients through manipulation of diet formulations and feeding strategies (Gatlin and Hardy 2002; Hinshaw and Fornshell 2002). Wastes are also produced when fish are overfed. The amount of uneaten feed can be reduced by careful feeding, selection of the best feeding method, and monitoring feed consumption.

Better management practices for feeds and feeding fall into two categories: one for feed manufacturers and the other for fish growers (Hardy 2004). Considerations for feed manufacturers include feed formulation, evaluation and selection of feed ingredients, feed production methods, and feed storage and handling. Practices and activities for the grower to consider are feeding practices (amount of feed, feeding frequency, and method of feed delivery), feed pellet size selection, feed storage and handling, feed equipment maintenance, and monitoring fish feeding behavior. The following section will focus on practices of concern to growers.

Fish nutrition and feeding practices are active areas of research, and technology is constantly evolving. An important research goal is to improve the efficiency of nutrient utilization by fish, thereby enhancing economic returns and reducing waste production. Because technology is rapidly changing, practices for feed management should be flexible so that newer and improved technologies can be implemented as they become available. Some of the current and emerging issues in fish nutrition and feed development with relevance to environmental performance include 1) reducing levels of fishmeal and fish oil as primary feed ingredients, 2) increasing feed digestibility, and 3) reducing the cost of feed per unit of fish weight gain (Hardy 2000). Considerable research has been conducted since 1995 to identify alternate protein and lipid sources, reduce pollution through modification of feed formulations, develop feeds for emerging species and broodstock, identify relationships between fish product quality and diets, and increase feed efficiency through the development of nutrient-dense feeds. Unfortunately, most research has focused on nutrient requirements and feed formulation without conducting research on better feeding practices to deliver high-quality, nutrient-dense feeds most efficiently.

### *Better Management Practices for Feeds and Feeding*

#### *Use high-quality feeds*

Use feeds that are formulated to meet the nutritional requirements of the species cultured. High-quality feeds are formulated using ingredients that have high dry matter and protein digestibility. Formulations should be designed to enhance nitrogen and phosphorus retention efficiency and reduce metabolic waste output. Feeds should contain sufficient dietary energy (lipid levels) to spare dietary protein (amino acids) for tissue synthesis. Available phosphorus levels should be slightly in excess of the dietary requirements of the species for each life-history stage, and formulations should be designed to minimize the difference between total feed phosphorus levels and available feed phosphorus levels. Consult a qualified aquatic animal nutritionist or feed manufacturer representative for information regarding feed formulation.

Feeds used in the United States trout industry have changed considerably since 1990. A typical trout production feed in 1990 contained about 38% crude protein and 12% crude lipid on an as-fed basis, whereas the typical trout production feed in 2000 contained 44% crude protein and 22% crude lipid on an as-fed basis (Gatlin and Hardy 2002). In addition to salmonid feeds becoming more nutrient-dense, the level of total phosphorus in the feed has been reduced and the amount of available phosphorus in the feed has been increased to more closely match the metabolic requirements of the fish. Protein retention values have increased during this period through alterations in feed formulations, balancing amino acid levels, and optimization of dietary protein and energy levels resulting in reduced levels of nitrogenous waste. Increased digestibility of feed ingredients has resulted in less solid and nutrient waste excreted by fish (Box 9.1).

## BOX 9.1
## Diet Formulation and Waste Loading

Feeding high-quality, nutrient-dense feeds in flow-through production systems results in significantly greater nutrient retention compared to conventional feeds. For example, in a study that compared the waste output between a nutrient-dense feed and a conventional feed fed to salmonids, the nutrient-dense feed generated 190 kg total solid waste and 3 kg phosphorus per tonne of fish produced compared to 240 kg of solids and 4 kg phosphorus per tonne fish produced with the conventional feed (Cho et al. 1994). In another study, feeding Atlantic salmon nutrient-dense diets reduced the total nitrogen load to the environment by approximately 35% and that of phosphorus by about 20% (Johnsen and Wandsvik 1991). The nutrient-dense feeds also reduced solid waste output significantly due to increased digestibility of feed ingredients and improved feed conversion ratio.

The increased lipid level (energy density) of nutrient-dense feeds has been shown to spare dietary protein and limit ammonia production of fish (Gatlin and Hardy 2002). As a result of altering diet formulations over the years through selection of better quality feed ingredients, balancing dietary amino acids, and optimizing dietary protein and energy levels, protein retention has doubled in farmed Atlantic salmon from about 22 to 45%. Similarly, protein retention improved in rainbow trout from about 30 to 40% from 1990 to 2000 primarily by altering diet formulations (Gatlin and Hardy 2002).

Modern nutrient-dense feeds would not be possible without the adoption of extrusion and expanded feed manufacturing technology by feed manufacturers. These processes allow the production of feeds with greater dietary lipid levels relative to feeds produced by the traditional steam pelleting process. During extrusion the feed mixture is exposed to higher temperatures and pressure for a longer period than steam-pelleted or expanded feeds. More than 80% of the starch is gelatinized during extrusion, compared to less than 40% for steam pelleting and 65 to 70% for expanded feeds (Barrows and Hardy 2001). Maximum lipid levels are 18% for steam-pelleted feeds, 25% for expanded feeds, and 38% for extruded feeds (Barrows and Hardy 2001). Extruded feeds can be manufactured to float, sink slowly, or sink, whereas all steam-pelleted and expanded feeds sink. Extruded and expanded feeds have low levels of fines and good pellet durability, whereas steam-pelleted feeds tend to be fragile.

Extruded feeds are expensive to manufacture because of the large amounts of energy expended during feed manufacture. Steam pelleting is the least expensive method of the three manufacturing technologies. Purchasing the least expensive feed is not necessarily the most profitable option for a fish grower or most beneficial for the environment. The cost of feed is not as important as the cost of feed per unit of fish weight gain. A more expensive high-quality feed can be more profitable than less expensive feed by providing better feed conversion efficiency (Barrows and Hardy 2001). Using high-quality, nutrient-dense feeds and best feeding practices, feed conversion ratios of less than 1.0 can be achieved with salmonids (Cho et al. 1991; Johnsen and Wandsvik 1991; Hardy 2004). A yield verification study of 12 commercial trout farms in four states over 2 years beginning in 2004 quantified average feed conversion ratios of 1.16 (Tuomikoski and Hinshaw, North Carolina State University, unpublished data).

### *Use efficient feeding practices*

Feed can be delivered by hand, demand feeders, or mechanical (automatic) feeders. Regardless of the delivery method or system, the amount of feed offered should optimize feeding level and maximum growth. This entails feeding at a level that supports near optimum feed conversion ratios and avoids feed waste (Hardy 2004). Feeding methods can affect the proportion of feed that is wasted, although there is limited documentation of this relationship for farms using high-quality, nutrient-dense feeds (Hinshaw and Fornshell 2002). As much as 50% of feed dispensed at a Canadian trout farm was wasted during periods of very high and low water temperatures due to misjudgment of the point at which satiation was reached during feeding and incorrect calculations of fish growth (Cho 2006). It is generally easy to observe wasted feed in flow-through production systems without the aid of a feed waste-detection device. In addition, avoid feeding too close to the tailscreen where feed may be discharged before fish are able to consume it. When using nutrient-dense feeds and better feeding practices for flow-through systems, only 5% or less of feed is wasted (Hinshaw and Fornshell 2002).

Observe fish feeding behavior every day to prevent feeding to excess, which is an economic loss and leads to greater waste output. Fish should be fed to near satiation and closely monitored or fed a daily feed ration based on a feeding guide that incorporates energy and nutrient requirements (Cho and Bureau 1997). Fish should not be fed less than near satiation, or growth and facility productivity will be reduced. In general, fish require a greater amount of a less nutrient-dense feed than of a more nutrient-dense feed, assuming the feeds have a similar protein and energy balance (Cho and Bureau 2001; Bureau et al. 2006). A feeding guide provides only a suggested ration because no single feeding guide can apply to the diversity of species, genetic strains, fish size, feed composition, water temperature, water quality, and other factors encountered in aquaculture production. Arbitrary use of feeding guides or poor feeding practices will result in feed wastage, greater waste output, and economic losses (Cho and Bureau 2001). Feed waste is mainly a result of poor feeding practices rather than a shortcoming of the feed itself.

### *Feed to near satiation when feeding by hand*

To strike a balance between maximum growth, optimum feed conversion ratio, and minimization of feed waste, fish fed by hand should be fed near satiation. Feeding by hand allows regular observation of fish feeding behavior and external appearance, and subjective adjustment of feed ration based on feeding response and environmental conditions (Fig. 9.4). Determining the correct amount to feed fish is difficult because feed intake can vary from meal to meal, and from day to day due to environmental conditions and other factors. Feeding by hand, as such, is more skill than science and requires paying close attention to the feeding activity of the fish to determine when to cease feeding.

**Fig. 9.4.** Feeding rainbow trout by hand in a North Carolina raceway.

Daily feed ration can be calculated using fish size and biomass, expected feed consumption, and water temperature or subjective evaluation of fish feeding response. To ensure that all fish have access to the feed and to avoid feed waste, distribute twice as many feed pellets as fish in the rearing unit in a 5- to 10-minute period. Repeat this process at 10-minute intervals until the entire ration for that feeding is fed or until feeding activity declines (Hinshaw 1999). Healthy, actively feeding fish are usually satiated within 20 to 30 minutes of feeding and feeding more than the fish can consume within that period is wasteful and results in poor feed conversion.

Hand feeding is the best method to administer medicated feed and to train fish to use demand feeders. However, hand feeding is labor intensive and it is very difficult to determine the point at which fish are fed to near satiation.

### *Ensure properly adjusted and sufficient number of demand feeders per rearing unit*

Demand feeders allow fish to feed themselves by activating a rod or trigger that releases feed from a hopper suspended over the tank. Demand feeders are probably the most common method of feeding fish in flow-through production systems.

Locate demand feeders at intervals of 7 to 9 m along rearing unit walls. Klontz (1991) recommended six demand feeders (three per side) in rearing units 3 m wide × 30 m long to minimize size variation among fish. Size variation among fish in a rearing unit results in decreased feed efficiency, more fed waste, and poor growth among the smaller fish as the larger fish outcompete them for feed. Feeding activity of rainbow trout is usually spread throughout the day when demand feeders are used because individual fish choose to eat at different times, possibly reflecting their relative social dominance (Barrows and Hardy 2001). Spreading feed throughout the day with demand feeders ensures that all fish have equal access to feed, which may reduce size variation among fish compared to that obtained when other feeding methods are used. Furthermore, the use of demand feeders does not lead to sudden declines in dissolved oxygen concentration that may occur with hand or mechanical feeding, because feeding activity and the associated postprandial oxygen demand are spread throughout the day.

Demand feeders are typically loaded with a sufficient supply of feed for 3 to 4 days. If this ration of feed is consumed within 2 to 3 days, additional feed should not be provided until the feeding period has ended. Adjust the feeder so that the feed is removed over the entire period for which the feeder is loaded. Due to increased lipid levels in newer nutrient-dense feeds, demand feeders may clog and not release feed. Demand feeders require regular attention to ensure proper adjustment so that a relatively small amount of feed is dispensed with each trigger event to minimize feed wastage. Best performance (i.e., least waste produced) is achieved by using a feeding guide adjusted for specific conditions found on the farm.

Demand feeders are sensitive to motion caused by waves and wind, and if not protected from such motion, feed can be inadvertently released and discharged into receiving waters. Wind shields constructed from PVC pipe can reduce the risk of inadvertent feed spillage. Demand feeders are also easily emptied quickly by waterfowl and occasionally by other animals, such as horses and bears, resulting in the potential discharge of large amounts of feed. To prevent access by animals to the demand feeders use exclusion structures or barriers.

### *Observe feeding activity when using mechanical (automatic) feeders*

Mechanical feeding involves the use of machines to deliver feed, including electric, water-powered, and solar-powered feeders with variable timers. There are feeders that use compressed air to deliver feed at preset intervals, and truck- or trailer-mounted units that are hydraulically operated blower feeders. Clear Springs Foods, a large flow-through trout facility in Idaho, developed a mechanical, computer-controlled feed system that delivers frequent small meals, which maximizes fish health and performance while maintaining minimum dissolved oxygen levels in the water (MacMillan et al. 2003). The use of blowers or air-driven mechanical feeders to deliver feed to large or numerous raceways and ponds minimizes labor costs and permits the frequent delivery of feed. The disadvantage is that fish are fed regardless of appetite. Thus, it can be relatively easy to feed fish to excess with mechanical feeders. Therefore, to avoid feed waste and water quality degradation, fish feeding activity must be observed daily and feeding rate adjusted as necessary.

### *Feed the daily predicted gain in fish growth*

Fish grow rapidly and the daily increase in growth should be determined and feeding rate adjusted accordingly to avoid feed waste. Therefore, it is important to determine the rate of fish growth to ensure the fish are fed the appropriate amount. Overfeeding is wasteful and adds to effluent pollution. Apart from feed quantity and quality, water temperature is the single most important factor affecting fish growth (Barrows and Hardy 2001). The minimum temperature at which rainbow trout will grow is 3°C. At this temperature appetite is suppressed, the digestive system operates very slowly, and rainbow trout require only a maintenance diet (0.5 to 1.8% body weight/day, depending on fish size) (Hinshaw

1999). Feeding more than this wastes feed. At temperatures above 20°C, a trout's digestive system does not utilize nutrients well and most of the consumed feed is only partially digested before being excreted. The optimum range of water temperature for growing rainbow trout is 13 to 18°C. It is critical to adjust feeding rates (energy intake) because water temperature varies to ensure appropriate energy intake for the metabolic needs of the fish, optimize fish growth, and avoid feed waste.

A formula for growth prediction that accounts for water temperature is the thermal-unit growth coefficient, TGC (Box 9.2). According to Cho (1992) the TGC equation has been shown experimentally to follow closely the actual growth curves of rainbow trout, lake trout (*Salvelinus namaycush*), brown trout, Chinook salmon (*Oncorhynchus tshawytscha*), and Atlantic salmon (*Salmo salar*). However, since TGC values and growth rate are dependent on species, stock, nutrition, husbandry, and other factors, it is necessary to determine the specific TGC value for a given production system using past growth records. The TGC value is calculated as

$$\mathrm{TGC} = \frac{\left(W_{\mathrm{F}}^{1/3}\right) - \left(W_{\mathrm{I}}^{1/3}\right)}{\sum[(T)(\mathrm{days})]} \tag{9.1}$$

where $W_{\mathrm{F}}$ and $W_{\mathrm{I}}$ are the final and initial fish weights (g), respectively; $T$ is the water temperature in degrees Celsius; and *days* represents the number of days in the interval. Once the TGC value is determined, growth can be predicted by the following:

$$W_{\mathrm{F}} = \left\{W_{\mathrm{I}}^{1/3} + \sum[(\mathrm{TGC})(T)(\mathrm{days})]\right\} \tag{9.2}$$

*Maintain production and feed records to evaluate feed management efficiency*

Several factors can affect the performance of fish fed a particular feed, and the exact outcome due to these factors is difficult to predict. It is prudent to keep careful records of fish performance to be able to evaluate the feed and feed management program.

## BOX 9.2
## Temperature-Based Trout Growth Prediction

For example, assume that a group of rainbow trout is monitored for growth over a 16-week period. The beginning weight is 1 g and the final weight is 59 g. Water temperature is 15°C. TGC = (59 $g^{1/3}$ – 1 $g^{1/3}$) ÷ Σ [(15°C)(112 days)] = 0.00172. To predict growth based on the TGC, assume another group of rainbow trout from the same facility at a beginning weight of 10 g and grown for a period of 4 weeks. Estimated final body weight = $W_F$ = [10 $g^{1/3}$ + Σ [(0.00172)(15°C)(28 days)]$^3$ = 24 g. From this information the estimated daily gain [(24 g – 10 g) ÷ 28 days] is calculated and used to compute the amount of feed required using rearing unit inventory information and a feeding chart adjusted to local conditions.

To deliver an appropriate ration and avoid feed waste, production and feed records must be maintained. Production records provide important inventory information—such as average fish weight, number of fish, and total biomass within a rearing unit from which the daily ration is calculated—and often provide the first clue that the fish are not performing as expected. At water temperatures above 13°C, fish populations should be sampled at least monthly and feed amounts adjusted accordingly, whereas in cooler waters a sample frequency of every 1 to 2 months is adequate (Hinshaw 1999).

Feed and fish growth records allow assessment of feed efficiency. The most common measure of feed efficiency on fish farms is the feed conversion ratio. Feed conversion ratio is the ratio of the amount of feed fed to a group of fish over time divided by the total weight gain of the fish over the same time period (kg fed/kg gain). Lower feed conversion ratios indicate efficient feeding relative to higher values. For example, with salmonids a feed conversion ratio of 1.0 is often obtained when feeding high-quality feeds, whereas a feed conversion ratio of 2.0 indicates a possible problem with feed, feeding program, water quality, or fish. The feed efficiency ratio, which is the inverse of the feed conversion ratio, increases as efficiency increases.

### *Use the appropriate feed particle size based on fish size*

Feeding the appropriate feed particle size is a critical part of preventing feed waste. If the feed particles are too large, the fish cannot ingest the feed until the particles disintegrate, resulting in considerable feed wastage. If the feed particles are too small, the fish may not be able to consume all the feed before it either sinks to the bottom or is flushed from the rearing unit. Once a sinking feed reaches the bottom of a rearing unit, many fish species will ignore it. Fish size determines the appropriate feed particle size: Smaller fish require smaller feed particles than larger fish (Table 9.1). A rule of thumb is to select a feed pellet size that is one size smaller than what the average size fish in the rearing unit can consume. When switching up to the next sized particle, especially for small fish, the change should be gradual. The change can be made by mixing the two sizes together and feeding the

**Table 9.1.** Recommended sizes of steam pelleted and extruded feeds for rainbow trout.

| | Feed Size | |
|---|---|---|
| Fish Size (g) | Steam Pelleted | Extruded |
| 0.13 to 0.40 | Starter | |
| 0.23 to 1.13 | Number 1 granule | |
| 0.60 to 2.30 | Number 2 granule | 1.0 mm |
| 1.8 to 4.5 | Number 3 granule | 1.5 mm |
| 4.5 to 15 | Number 4 granule | 2.0 mm |
| 11 to 30 | 2.4 mm | 2.5 mm |
| 23 to 57 | 3.2 mm | 2.5 to 3.5 mm |
| 50 to 151 | 4.0 mm | 3.5 to 4.5 mm |
| 91 to 454 | 4.8 mm | 4.5 to 5.0 mm |
| 227 to 907 | 6.4 mm | 6.5 to 8.0 mm |
| >1375 | 9.5 mm | 9.5 mm |

**Table 9.2.** Recommended number of daily feedings for rainbow trout.

| Fish Size (g) | Feedings/Day | Fish Size (g) | Feedings/Day |
|---|---|---|---|
| 0.18 to 0.23 | 8 to 10 | 15 to 30 | 3 |
| 0.23 to 0.60 | 8 | 30 to 50 | 2 to 3 |
| 0.60 to 1.8 | 6 | 50 to 150 | 1 to 2 |
| 1.8 to 4.5 | 4 | 150 to 454 | 1 |
| 4.5 to 15 | 3 | >454 | 1 |

mixture for several days. Following this practice will help minimize size variation among the fish.

### *Base feed frequency on fish size when hand feeding or using mechanical feeders*

Feed frequency is based on fish size and how quickly fish consume feed. When small fish are started on feed they should be fed small amounts at frequent intervals. Sinking feeds should be fed slowly and more frequently than floating feeds to avoid feed waste and potential water quality deterioration. Fingerlings utilize feed more efficiently when fed more frequently. Infrequent feeding of large amounts is the principal factor causing inefficient utilization of feed with subsequent accumulation of waste feed in the rearing unit (Barrows and Hardy 2001). Salmonid fry and fingerlings can consume more than 1% of their body weight at a single feeding. A general rule of thumb is to feed 1% of body weight per feeding and to adjust the feed frequency to obtain the desired feeding percentage to ensure that all fish have access to feed. Thus if fish are being fed 5% of body weight per day they should be fed five feedings per day. See Table 9.2 for recommended feedings per day for rainbow trout.

### *Manage within the system carrying capacity*

The carrying capacity of a flow-through aquaculture system is the fish biomass the production system can support while maintaining an environment conducive to healthy, fast-growing fish. Fish compensate for suboptimal environmental conditions and challenges in culture systems through the expenditure of energy (Barton and Iwama 1991), but this may come at the expense of food conversion and nutrient retention efficiencies. When food conversion and nutrient retention efficiencies decline, greater negative impacts on water quality can result in proportion to the amount of feed applied and fish produced. Fish loading and feeding rates based on profit maximization rather than yield maximization (Losinger et al. 2000) can also reduce mass discharge of nutrients and solids.

Carrying capacity is usually expressed as allowable biomass per unit flow (*loading*) or allowable biomass per unit volume (*density*) (Piper et al. 1982; Hinshaw 2000; Westers 2001). Several methods have been developed to calculate carrying capacity based on oxygen consumption, fish growth rate, feeding rates, water temperature, water flow rates, and other factors. Provided that the appropriate limiting factors are monitored, the approach to determining carrying capacity (i.e., managing loading or density) is a matter of operator preference (Hinshaw 2000). True et al. (2004a) reported raceway densities at five Idaho trout farms ranging from 27 to 51 $kg/m^3$ and Hinshaw et al. (2004) reported typical carrying capacity between 20 to 80 $kg/m^3$, with water exchange rates per rearing unit of 3 to 6 times per hour. Tuomikoski and Hinshaw (North Carolina State University, unpublished data) developed an inventory-management protocol for a trout yield-verification study that required growers using systems without supplemental oxygen to split the fish biomass in the rearing unit when densities reached 80 $kg/m^3$ and for growers with systems with supplemental oxygen to split the fish when densities reached 160 $kg/m^3$. In terms of loading rates, Brannon and Klontz (1989) reported an average rearing unit carrying capacity of 1.8 kg/L per minute, and with serial water reuse, up to 9.6 kg/L per minute. Operating flow-through aquaculture systems for coldwater species within these ranges, the United States trout industry has routinely attained feed conversion ratios approaching 1.0 over the last decade.

Normally, dissolved oxygen is the first and most critical limiting factor. In the eastern United States, typical surface waters used for trout culture are poorly buffered and slightly acidic. The first limiting factor for such waters is dissolved oxygen. In poorly buffered systems where pure oxygen is not added and carbon dioxide is removed, the next limiting factors are solids and nitrogenous wastes excreted by the fish. Depending on the flow-through system design, these factors will become limiting after approximately ten serial reuses of the water. More uses are feasible if solid wastes are efficiently removed. In systems that add pure oxygen, the next limiting factor is accumulation of dissolved carbon dioxide (Colt and Orwicz 1991; Hinshaw 2000). Where water supplies have a pH greater than 7.5 and total alkalinity greater than 60 mg/L as $CaCO_3$, such as in Idaho, dissolved oxygen is normally the critical limiting factor for the first three to six reuses of the water (Hinshaw 2000; Fornshell 2002). After that, un-ionized ammonia levels become limiting. Colt and Orwicz (1991) provided mathematical models for determining carrying capacities based on ratios of various chemical parameters such as pH, un-ionized ammonia, and carbon dioxide, with cumulative oxygen consumption by the fish.

In general, fish biomass in flow-through systems for coldwater species should be decreased when dissolved oxygen levels fall below 6 mg/L at the outflow of the rearing unit. Typically, trout growers establish a predetermined level of dissolved oxygen flowing out of one rearing unit and into the next. For example, incoming water at first use is at 100% oxygen saturation, and the predetermined limit of outgoing water is set at 70% of saturation. Available oxygen is calculated based on water flow and incoming concentration of dissolved oxygen. Allowable biomass is calculated by dividing available oxygen by the metabolic oxygen consumption of the fish. Oxygen consumption rates vary by species, water temperature, fish size, and feeding rate. On-farm consumption rates can be determined by monitoring influent and effluent dissolved oxygen concentration for a known biomass of fish, feed fed, and water flow rate over a defined period, or values can be located in the literature for species of interest.

Piper et al. (1982) recommended using flow and density indexes to calculate carrying capacity. The loading rate is calculated as $F = W/(L \times I)$, where $F$ = flow index (weight of fish per unit fish size and water), $W$ = known permissible weight of fish, $L$ = length of fish in inches, and $I$ = water flow in gallons per minute. Standard flow index tables are available. Rearranging the formula to $W = F \times L \times I$, the permissible weight can be calculated. The density index is calculated as $W = D \times V \times L$, where $W$ = permissible weight of fish, $D$ = density index, $V$ = raceway volume in cubic feet, and $L$ = fish length in inches.

Recommended flow and density indexes are from 0.5 to 1.0 when pure oxygen is not used.

Westers (2001) used a series of formulas that consider the relationship between loading rate (kg/L per minute), density (kg/$m^3$), and water exchange rate per hour ($R$) as the basis for rational design and operational values for intensive, flow-through production systems: loading rate (Ld) = $(D \times 0.06)/R$; density ($D$) = (Ld × $R$)/0.06; water exchange rate ($R$) = ($D$ × 0.06)/Ld.

The flow and density indexes discussed above were developed by public hatcheries where production goals differ from those at commercial facilities. The indexes therefore tend to be conservative relative to potential carrying capacity. In general, loading rate becomes limiting before density. A common misperception is that poor fish performance (reduced growth, poor feed efficiency, disease problems) is caused by high densities, when in fact, poor fish performance is usually related to insufficient flow to sustain the metabolic needs of the fish biomass (Fornshell 2002). Most trout growers base their carrying capacity on empirical observations relative to the primary limiting factors of dissolved oxygen and un-ionized ammonia. This approach was initially formalized by Smith and Piper (1975) and Westers and Pratt (1977), who presented a synthesis of design criteria for flow-through systems based on metabolic characteristics of trout, using tolerance limits of 5 mg/L minimum dissolved oxygen and 0.0125 mg/L maximum un-ionized ammonia-nitrogen. Those criteria remain in use within the United States trout industry.

### *Handle and store feeds to maintain feed quality*

Damaged feed due to improper storage can result in water quality deterioration indirectly through decreased feed efficiency and directly through the addition of fines to the rearing unit. Feed should be protected from contamination, vermin, moisture, and excessive heat. Proper feed storage is critical for preserving nutrient quality and preventing the production of toxins by microorganisms (USTFA 1994). Dry pellets contain less than 10% moisture and should be kept dry and cool. Never store dry feeds in a freezer (Barrows and Hardy 2001). Although the rate of lipid oxidation slows down when the feed is in the freezer, freezing can enhance lipid oxidation by making it easier for air to penetrate feed pellets. When feed is placed in a freezer the process of slowly freezing concentrates pro-oxidant minerals, such as iron and copper, within water pockets in pellets (Barrows and Hardy 2001). In addition, temperatures increase during the defrost cycle, so that over time oxidation proceeds although the feed is in the freezer. Feeds with higher moisture levels and not protected by preservatives should be stored frozen and fed immediately after thawing. Humidity and heat must be minimized for any feed type during storage. Humidity promotes the growth of molds, yeast, and bacteria, which can produce toxins. Never feed fish moldy feed. Heat accelerates the oxidation of lipids and vitamins. Rancid lipids are toxic and produce off-flavors that reduce feed palatability. Feeding rancid feeds to fish can also produce off-flavors in the final product meant for human consumption.

Feed should not be used past the manufacturer's recommended use date, which generally is 90 days. Manage feed purchases, usage, and storage to keep feed fresh. Feed should be rotated such that the oldest feed is fed first. Handle bag and bulk feed gently to minimize pellet disintegration and the creation of fines. Fish feeds are fragile in comparison to other animal feeds, and up to 3% fines by weight can be expected from normal handling

(Barrows and Hardy 2001). Install screens or other devices on feed equipment to collect small particles if fines are a problem. Physically damaged feeds contribute to water quality deterioration, lower feed efficiency, and potential fish health problems caused by gill irritation from feed fines.

### *Regularly inspect feeding equipment to ensure efficient operation*

Improperly adjusted or malfunctioning feeding equipment will impact feed efficiency, waste generation, and profitability. In situations where the malfunctioning equipment results in feeding to excess, water quality will deteriorate and more waste will be produced. Malfunctioning equipment can also lead to feeding less than near-satiation, resulting in economic loss.

## Solids Management

Fish fecal matter and uneaten feed are the major constituents of solids produced in flow-through aquaculture. Accumulation of solids in the rearing units can degrade environmental conditions within the culture unit and stress fish (Cripps and Bergheim 2000). Solids can irritate and partially cover gills, provide habitat for pathogenic organisms, and consume dissolved oxygen as they decompose.

Solids and associated nutrients in facility effluents can also adversely impact environmental conditions in the receiving water body. Phosphorus is a nutrient of particular environmental concern in freshwater as excessive discharge of phosphorus to receiving waters may cause water quality degradation through eutrophication. Particulate phosphorus comprises a considerable portion of total phosphorus discharged from flow-through aquaculture systems. True et al. (2004a) reported mean particulate phosphorus discharge representing 40% of total phosphorus discharge. Solids capture and removal are important factors affecting phosphorus discharge. To a limited extent solids capture and removal can reduce nitrogen discharge. About 9% of the nitrogenous waste produced by salmonids is in particulate form (Foy and Rosell 1991).

Effluent from flow-through aquaculture systems is characterized by large discharge volumes with low solids concentrations (Boardman et al. 1998; Cripps and Bergheim 2000; Fornshell 2000; Hinshaw and Fornshell 2002; True et al. 2004a). Effluents with these characteristics are not easy to treat and implementing practical, cost-effective treatment is a difficult economic and engineering challenge. Treatment technologies for the removal of solids from flow-through systems include microscreens (Cripps and Bergheim 2000; Hinshaw and Fornshell 2002), dual-drain tanks (Lekang et al. 2000), swirl separators (Cripps and Bergheim 2000), the “appurtenance for settleable solids in-raceway separation” (ASSIST, a modified swirl separator) (Wong and Piedrahita 2003), plate separators, baffles, media filters, air flotation, foam fractionation, chemical flocculation, and constructed wetlands (Boerson and Westers 1986; Boardman et al. 1998; Summerfelt 1999; Cripps and Bergheim 2000; True et al. 2004b, c; Stewart et al. 2006a). However, the majority of these treatment options are not applicable for commercial aquaculture because they are impractical, costly, or both (Boardman et al. 1998; Hinshaw and Fornshell 2002). Sedimentation, or settling, is the most widely applicable and cost-effective technology for removing solids produced in flow-through aquaculture systems (Stechey and Trudell 1990; Boardman et al. 1998; True et al. 2004a). Solids produced in flow-through aquaculture can be settled and collected in quiescent zones coupled with offline or full-flow settling basins, or by full-flow settling basins without quiescent zones (Fig. 9.5).

*Quiescent zones* are screened-off areas below the rearing area at the downstream end of raceways or culture tanks (Fig. 9.6). The screen, typically constructed with PVC or aluminum pipe mounted on a wood frame, prohibits fish from entering the quiescent zone, allowing solids to settle undisturbed. Ideally, quiescent zones should be installed in every rearing unit, but it is essential that last-use rearing units have quiescent zones to settle solids prior to effluent discharge into receiving waters. Stechey and Trudell (1990) recommend a number of small treatment units designed to a treat a portion of the total facility flow, as opposed to one large treatment unit designed to treat the entire facility flow. Retrofitting quiescent zones into an existing facility is generally easy and relatively inexpensive. Keyways can be bolted directly to concrete raceway walls to hold screens in place to separate quiescent zones from rearing areas. Metal pilasters can be attached to the raceway floor in a similar manner as keyways in raceways that are too wide to break up

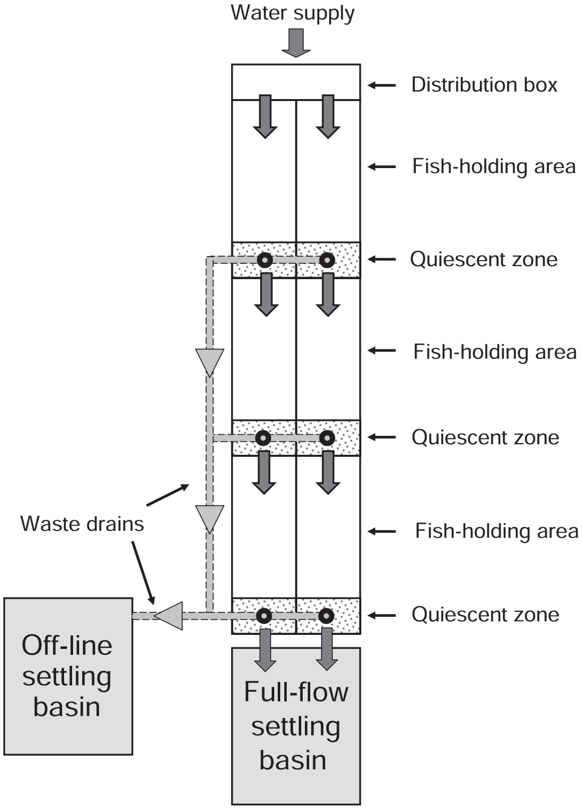

**Fig. 9.5.** Overhead schematic of water and waste flow in two parallel sets of raceways, each set having three raceways in a series. Solids produced during culture can be settled and collected in quiescent zones at the end of each raceway coupled with offline or full-flow settling basins, or by full-flow settling basins without quiescent zones.

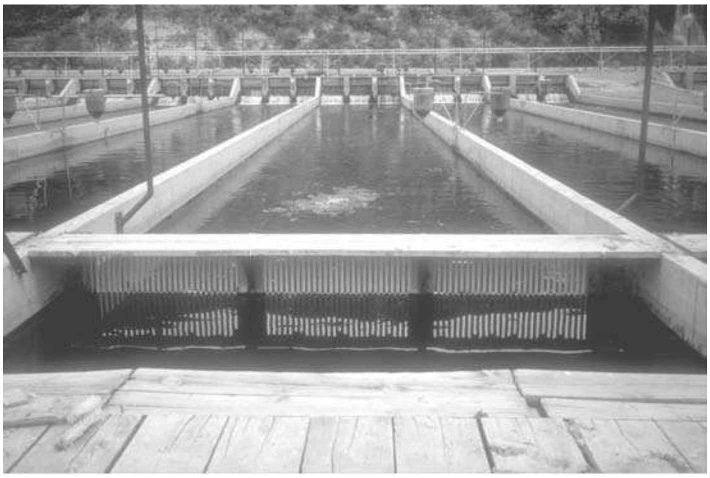

**Fig. 9.6.** The quiescent zone of this raceway is in the foreground, separated from the fish-holding area by a barred screen. The screen prevents fish from entering the quiescent zone, allowing solids to settle undisturbed.

the width of the raceway. These structures can be used to support catwalks to allow personnel access to screens for cleaning, repair, mortality removal, and other activities.

Offline settling basins receive the concentrated solid waste stream from quiescent zones, but not the entire facility flow. Average flow to an offline settling basin is usually less than 1% of total facility flow over a 24-hour period and 1.5% of total facility flow during working hours. The combination of quiescent zones and offline settling basins is the most commonly used system of solids capture and removal in concrete flow-through production systems. Each facility should have at least two offline settling basins. This allows the settling of solids in one basin while conducting solids removal and clean-out operations in the other basin.

Full-flow settling basins treat the entire flow of a facility and may be used with or without quiescent zones. Full-flow settling basins are most common on smaller aquaculture facilities with low flow volumes, typically less than 0.28 $m^3$/second, and where sufficient level land exists for basin construction. A full-flow treatment system should include two settling basins to allow one basin in operation as the other one is cleaned.

### *Better Management Practices for Solids Management*

#### *Match raceway dimensions and water flow rate to maximize self-cleaning*

Linear rearing units designed to promote plug flow and sufficient water velocity to prevent settling of solids within rearing units allow efficient capture of solids using quiescent zones or other settling basins. Shallow rearing units, generally less than 75-cm water depth, provide good horizontal flow and promote self-cleaning (Stechey and Trudell 1990). Westers (1991) recommends a water velocity of 3 cm/second as a good compromise between allowing heavy solids to rapidly settle and sufficient velocity to create good hydraulics. True et al. (2004a) observed solids settling in raceways from insufficient water velocities at all five commercial facilities studied. Solids that settle within rearing units are difficult to remove, degrade water quality, increase solubilization of nutrients, and may irritate fish gills, leading to disease. Once solids settle in the rearing units, considerable labor is required for removal (MacMillan et al. 2003). Prior to fish handling or harvest, solids should be removed from the rearing area by sweeping them down to the quiescent zone, otherwise resuspension of solids may exceed the total suspended solids effluent compliance limit.

Dimensions of raceways vary greatly throughout the country, and several factors other than solids management are considered in raceway design, including space availability, site slope, personal preference, and cost. A common design for raceways is a length:width: depth ratio of 30 : 3 : 1. Raceways constructed in Idaho since the mid-1990s are not as long (20 to 24 m) as raceways constructed with the 30 : 3 : 1 ratio (45 m). Design of shorter raceways is based on maintaining adequate water velocities to prevent settling of solids. Also, construction of shorter raceways was based on the observation that fish were not using the entire length of longer raceways. Shorter raceways also allow more frequent water exchange and decreased constructions costs. New raceways are also narrower, thus requiring less labor for grading and harvesting. Raceway dimensions based on various water flow rates and a design criteria of 3 cm/second raceway water velocity are provided in Table 9.3.

Increasing the width or depth of raceways while maintaining a constant flow rate increases the raceway cross-sectional area, which reduces water velocity. If water velocity is reduced below the critical minimum, more solids settle within the rearing unit. Stechey and Trudell (1990) observed that several trout production facilities in Ontario, Canada, could improve solids removal from rearing units by simply reducing water depth within rearing units. Flow of water through a raceway is much more important in determining production than raceway volume, and as such, reducing raceway water depth to enhance solids removal will have little, if any, impact on production.

Another option to consider if the rearing unit is oversized for the amount of water flow available is to install baffles. State of Michigan salmonid hatcheries use baffles in raceways to obtain water velocities from 10 to 40 cm/second beneath the baffles, thereby preventing waste solids from settling in the rearing units (Boersen and Westers 1986). Baffles are useful in fry and fingerling rearing units because the fish are too small to move solids downstream with their swimming activity. However, baffles can be troublesome because they must be moved whenever the fish are worked, and algae and other detritus attach to the baffles, increasing their weight considerably.

**Table 9.3.** Water flow rates for raceways of various dimensions needed to achieve a water velocity of 0.03 m/second.

| Raceway Width (m) | Water Depth (m) | Water Velocity (m/second) | Water Flow Rate ($m^3$/second) |
|---|---|---|---|
| 1.8 | 0.76 | 0.03 | 0.041 |
| 3.0 | 0.76 | 0.03 | 0.068 |
| 3.7 | 0.76 | 0.03 | 0.084 |
| 5.5 | 0.76 | 0.03 | 0.125 |
| 5.5 | 0.91 | 0.03 | 0.150 |

### *Design, construct, and manage circular rearing units to be self-cleaning*

Circular tanks with properly designed inlets and drains can be very efficient at removing solids from the rearing unit. Recommended diameter:depth ratios for circular tanks range from 5 : 1 to 10 : 1; however, many tanks have ratios of 3 : 1 and circular silo tanks have ratios of 1 : 3 (Timmons et al. 1998). Several factors influence the selection of a tank diameter:depth ratio. These include space availability and cost, water head, fish species, fish loading rates, feeding rates and methods, and ease of worker access to the fish within the tank.

Properly designed, constructed, and managed circular tanks promote a primary rotating flow that creates a secondary radial flow that carries settleable solids to the bottom center of the tank, making the tank self-cleaning. Because aquaculture solids have specific gravities that are relatively near that of water, sloping the tank floor toward the center drain does not improve the self-cleaning efficiency of the circular tank. A sloped floor is useful only for draining the tank for maintenance (Timmons et al. 1998).

Rotational velocity should be as uniform as possible from the tank wall to the center of the tank and from surface to bottom, and great enough to make the tank self-cleaning but not great enough to fatigue the fish. Water velocities of 0.5 to 2.0 times fish body length per second are considered optimal for fish health, muscle tone, and respiration. Water velocities of 15 to 30 cm/second are necessary to move settleable solids to the center of the circular tank. The upper water velocity for tilapia is 20 to 30 cm/second, and for salmonids the following equation (Timmons et al. 1998) can be used to calculate nonfatiguing water velocities: $V_{\text{safe}} < 5.25/L^{0.37}$, where $V_{\text{safe}}$ is the maximum design velocity in fish body lengths per second and L is fish body length in cm.

Tank hydraulic problems can be minimized through proper design of the influent flow mechanism. When water enters the tank tangentially to the tank wall at the tank outer radius, it spins around the tank creating a primary rotating flow. The primary flow creates a secondary flow in relation to the tank bottom and tank side that causes an inward radial flow at the tank bottom and an outward radial flow at the tank surface. It is the inward radial flow at the tank bottom that moves the settleable solids toward the center of the tank. However, depending on the manner in which water is introduced into the tank, the tank diameter:depth ratio, and the overall rate of flow leaving the center bottom drain, an irrotational zone can develop around the center drain that reduces the effective settling area through decreased water velocities and poor mixing.

Timmons et al. (1998) compared four methods of introducing flow into circular tanks: 1) a traditional open-ended pipe; 2) a short, horizontal, submerged, distribution pipe with its axis oriented toward the tank center and with evenly spaced openings along its length; 3) a vertical submerged distribution pipe with evenly spaced openings along its length; and 4) an inlet flow distribution pipe that combines both vertical and horizontal branches. The traditional open-ended pipe created the worst tank hydraulics resulting in nonuniform velocity profiles in the tank, poor mixing in the irrotational zone that resulted in short-circuiting of the flow, resuspension of solids at all tank depths, and poor flushing of solids from the bottom. Water exchange and water mixing were improved throughout the tank with the horizontal submerged pipe, but bottom tank velocity was weaker and insufficient for effective solids removal. The vertical submerged inlet pipe provided better self-cleaning than either the open-ended pipe or horizontal submerged pipe, but the stronger bottom current resulted in poor mixing in the irrotational zone and short-circuiting and, therefore, less efficient use of flow exchange. Combined vertical and horizontal inlet structures provided the best tank hydraulics, especially when placed away from the tank wall, allowing the fish to swim between the pipe and wall. This design resulted in uniform mixing, prevention of short-circuiting flow, uniform velocities along the tank depth and radius, and effectively transported solids to the tank bottom and out the center drain. As with raceways, having larger fish and greater biomass within the circular tank enhances solids removal through swimming activity.

Proper tank hydraulic design is more important with larger tanks than with smaller tanks (<1 $m^3$) because the overall rate of water exchange is greater with smaller tanks. Rapid water exchange rates result in good water quality as more oxygen quickly enters the tank and the wastes are rapidly flushed away. For tanks greater than 6 m in diameter, placing multiple flow distribution pipes at different tank locations can improve tank hydraulics with subsequent solids removal efficiency, velocity uniformity, and through water mixing. However, multiple distribution pipes interfere with fish handling.

The bottom drain should be located in the center of the tank because circular tank hydraulics concentrate waste solids at the bottom and center of the tank. The drain should be designed to continuously remove solids. The bottom center drain structure also controls water depth within the tank with either an internal or external standpipe. The use of an internal standpipe requires a larger-diameter pipe sleeve placed over and outside the internal standpipe. The internal standpipe controls the water depth of the tank and perforated slots at the base of the outside pipe or a gap at the base of the outside pipe forces water to flow up between the two pipes carrying the waste solids out through the inner pipe. A perforated plate or screen can be used to cover the drain when an external standpipe is used to control tank water depth. Materials such as aluminum, stainless steel, fiberglass, or plastic can be used to cover the drain. Piper et al. (1982) recommend oblong slots rather than round holes because the slots are easier to clean, provide more open area, and do not clog as easily as round holes.

Circular culture tanks can be converted into swirl separators through the use of a second elevated drain to discharge the majority of flow relatively free from solids (Davidson and Summerfelt 2004). The Cornell-type dual-drain tank has a center drain on the bottom and an elevated drain partway up the tank sidewall. Such a design allows a relatively easy retrofit with existing circular culture tanks. The low-flow, high-solids effluent from the bottom drain is between 1 to 20% of the flow, and the high-flow, low-solids effluent from the elevated drain is between 80 to 99% of the flow. About 78% of total suspended solids produced daily can be removed from the bottom drain with 12 to 15% of total system flow (Summerfelt et al. 2000). The solids concentration from the bottom drain effluent is ten times greater than the solids concentration of the effluent passing through the elevated drain. In the right situation the use of dual-drain circular tanks can confer an economic advantage by reducing capital costs, space requirements, and head loss of downstream settling basins.

### *Base settling basin area on overflow rate*

Overflow rate ($V_o$) is an empirical parameter describing the settling characteristics of solids in a specific wastewater. Overflow rate is defined as the volume of water flow per unit time divided by the surface area of the settling basin ($m^3$/day per $m^2$), but it is usually expressed in the equivalent mathematically reduced form as velocity (m/day, or more conveniently, cm/second). Solids with a critical settling velocity ($V_{sc}$) greater than or equal to the overflow rate will settle from suspension in the settling basin or, expressed another way, the overflow rate is mathematically equal to the critical settling velocity ($V_{sc}$), which is the settling velocity of the slowest-settling (i.e., smallest) particle that is to be removed by sedimentation.

The concept of sedimentation and overflow rate can be explained in the context of an "ideal settling basin" with the following assumptions (Stechey and Trudell 1990): 1) the direction of the water flow is horizontal and water velocity is constant at all points in the settling area, 2) there are no interactions between particles (that is, settling is considered discrete), 3) the concentration of suspended particles of each size is evenly distributed across the vertical cross-section of the inlet area, and 4) once a particle settles to the sludge area it is permanently removed. In this ideal settling basin, the settling paths of all discrete particles are straight lines and all particles with the same settling velocity move in parallel paths. As the water flow pushes particles forward across the settling basin, the particles move downward from gravity. As a result of these two forces the particles move both forward and downward in a trajectory (Fig. 9.7). A particle that enters the inlet area of an ideal settling basin at the top and settles at the bottom of the basin at the junction of the outlet area during its theoretical detention period represents the overflow rate. Other particles that have settling velocities less than the overflow rate will settle in the ratio $V_{sc}/V_o$ depending upon their vertical position in the settling basin at the inlet area. The removal of suspended solids by sedimentation in an ideal settling basin is a function of the settling basin surface area and is independent of settling basin depth. This is important because the required surface area is easily calculated from overflow rate and water flow rate into the basin. Furthermore, removal efficiency for suspended solids is a function only of overflow rate and flow rate, and is independent of retention time (Stechey and Trudell 1990).

Overflow rate is determined by conducting a laboratory test to determine the settling characteristics of effluent solids (Wong and Piedrahita 2000). The test generates a relation-

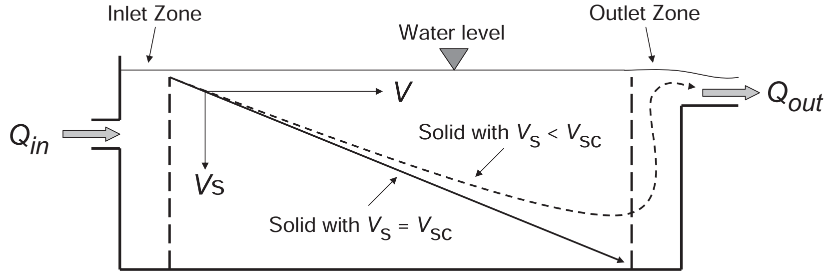

**Fig. 9.7.** Cross section of an idealized settling basin. The particle trajectory as it travels down the basin is described by a vector with a horizontal component equal to water velocity ($V$) and a vertical component representing settling velocity ($V_s$). If the particle settles at the critical settling velocity ($V_s = V_{sc}$), it settles to the bottom before reaching the outlet zone (solid line) and can be collected as sludge. If the particle settles slowly ($V_s < V_{sc}$), the particle reaches the outlet zone before it settles to the bottom (dotted line) and is swept out of the basin.

ship, called the *settling curve,* describing the distribution of settling velocities for solids in the wastewater. From the settling curve, an *overflow rate* (i.e., a minimum settling velocity) can be selected that will result in removal of a certain proportion of the solids. Settling velocity curves allow for rational settling basin design because basin surface area is calculated directly from the desired overflow rate and the water flow rate into the settling basin (Box 9.3). As such, trade-offs between the overflow rate and particle removal

## BOX 9.3
## Design Procedure for Settling Basins

Settling basin surface area (A) is calculated by dividing the water flow to the settling basin ($Q$) by the overflow rate ($V_o$), which is equal to the settling velocity of the slowest settling (i.e., smallest) solid particle that the basin will remove (the critical settling velocity, or $V_{sc}$). For example, suppose that a settling basin is designed to remove 90% of the solids in a raceway effluent and, from a laboratory-derived settling curve, it was determined that 90% of the solids in that effluent had a settling velocity ($V_s$) of 0.94 cm/second or greater. The desired basin overflow rate ($V_o$) is equal to the critical settling velocity ($V_{sc}$), which is equal to the settling velocity of the slowest settling particles to be removed ($V_o = V_{sc} = 0.94$ cm/second = 0.0094 m/second).

Assume the water flow rate into a quiescent zone settling basin is 0.071 $m^3$/second. Using the formula

$$A = Q/V_{sc},$$

the settling basin surface area in this example is

$$A = (0.071\ m^3/second) / (0.0094\ m/second) = 7.6\ m^2$$

If the raceway is 3 m wide, the required length (L) of the quiescent zone is

$$L = 7.6\ m^2 \div 3\ m = 2.5\ m$$

So, for this flow rate, 90% of the solids entering a quiescent zone 2.5 m long by 3 m wide would settle to the bottom where they can be collected and removed.

The Idaho Waste Management Guidelines for Aquaculture Operations (IDEQ, undated) recommends doubling the calculated settling area to compensate for less than ideal conditions. This seems more than adequate given that compliance for solids and total phosphorus with the 1999 Idaho general aquaculture permit has been generally very good (USEPA 2006a). Effluent limits have been achieved 100% of the time by about 90% of approximately 100 facilities. Between 2000 and 2002, only 2% of trout facilities in Idaho exceeded standards for the average monthly concentration of total suspended solids for raceway effluent (a net increase of 5 mg/L) and offline setting basin effluent (a net increase of 67 mg/L).

efficiency can be evaluated from the laboratory-derived data, rather than through costly trial and error.

There is no single overflow rate appropriate for all settling basins. The appropriate overflow rate for a settling basin depends on settling basin type, end-of-pipe compliance limits, and local water quality standards. Several factors, including flow surges, wind sheer, scour, short-circuiting, and turbulence ensure that ideal conditions for settling do not prevail in settling basins, thereby reducing the solids removal efficiency of the basin. Solids settling velocities also vary considerably depending on fish species, life stage, water temperature, feed composition, and fish culture practices (Table 9.4).

Certain practices can have a dramatic effect on settling efficiency by causing solids to fragment, resulting in smaller particles with slower settling velocities. The net result is that larger settling basins are required to achieve the same level of solids removal. Particles that pass through vacuum heads, pumps, and pipes become smaller. Fish grading, harvesting, and other activities within raceways or ponds should be conducted to minimize particle fragmentation and the disturbance and possible discharge of accumulated solids.

The Idaho Waste Management Guidelines for Aquaculture Operations (IDEQ, undated) recommends overflow rates for quiescent zones, full-flow settling basins, and offline settling basins for trout flow-through production systems based on Stechey and Trudell (1990). These recommendations are based on a general reduction in particle size as solids move through a facility and the type of settling basin used to capture solids. In general quiescent zones capture relatively larger and more intact particles at the end of raceways compared to offline settling basins where particles are typically smaller and more fragmented. Therefore, recommended overflow rates for quiescent zones (0.94 cm/second) are less than those for offline settling basins (0.046 cm/second). Recommended overflow rates for full-flow settling basins (0.40 cm/second) are intermediate between quiescent zone and

**Table 9.4.** Some observed settling velocities of trout-derived solids.

| Reference | Settling Velocity (cm/second) | Particle Size (μm) | Conditions |
|---|---|---|---|
| Viadero et al. (2006) | 0.40 | 392 ± 122 | Quiescent-zone sludge, calculated, Ziegler-brand feed |
| Viadero et al. (2006) | 0.50 | 490 ± 90 | Quiescent zone sludge, calculated, Freedom brand feed |
| True et al. (2004a) | 0.16 | <814 | Average measured velocity taken from effluent below quiescent zone |
| True et al. (2004a) | 2.31 | >814 | Average measured velocity taken from effluent below quiescent zone |
| Wong and Piedrahita (2000) | 1.7 | | Measured median value from quiescent zone effluent |
| Wong and Piedrahita (2000) | 0.7 | | Measured median value of trout feces manually stripped |
| Warrer-Hansen (1982) | 2 to 5 | | Fecal casts |
| Stechey and Trudell (1990) | 0.046 to 0.09 | | Finer, lighter particles |

offline settling basin overflow rates. In addition, if the flow rate of water entering a settling basin varies, the design should be based on the greatest rate.

### *Design, construct, and manage settling basins to minimize turbulence and short-circuiting*

Continuous-flow settling basins have four functional areas. The inlet area functions to evenly distribute the flow over the cross-section of the basin. Sedimentation takes place in the settling area and solids accumulate in the sludge area. Clarified water is discharged from the outlet area.

Flow surges, scour, wind shear, short-circuiting, and excessive turbulence decrease settling basin efficiency and increase the amount of solids discharged in the effluent. In an ideal basin the flow of water approximates plug flow, where a cross-section of water entering the settling zone from the inlet zone moves as a solid body with uniform velocity throughout the settling basin. However, short-circuiting and turbulence are inherent in all settling basins. Currents of varying velocities, nonuniform heating of the water by the sun in large basins, or wind shear results in a portion of the flow discharging sooner than the theoretical retention time. A wind speed of only 6.5 km/hour can cause surface currents with a velocity of about 3.6 cm/second, which is greater than desired raceway water velocities and overflow rates in settling basins.

Inlet and outlet structures must be properly designed to minimize short-circuiting and maintain settling basin efficiency. Inlet design should be based on 1) even introduction of the influent across the entire cross-section of the settling zone, 2) sufficient reduction of the influent velocity to the settling zone to prevent excessive turbulence and mixing, and 3) establishing flow through the settling zone in even horizontal paths. A submerged weir extending across the width of the settling basin with a height that is approximately 85% of the water depth and 30 to 60 cm wide with chamfered edges will effectively distribute flow across the width of the settling basin in an even, horizontal path at a velocity that minimizes turbulence.

One of the easiest and most common designs uses pipes to introduce and discharge water to and from settling basins. Pipes produce poor flow characteristics for sedimentation, causing short-circuiting at the inlet and upwelling and scouring at the outlet. Examples of inlet structures that produce poor flow characteristics in settling basins include straight pipes, downward elbows, straight pipes with target baffles, reversing-flow, multiple channels with target baffles, and free-fall weirs. Screens that separate the rearing area from the quiescent zone will cause turbulence as water passes through the screen. Screens should restrict fish from the quiescent zone and minimize turbulence caused by the cross or vertical support members of the screen. Screens should be cleaned regularly because algae, debris, and mortalities cause additional turbulence.

The outlet should consist of a weir across the entire width of the settling basin. The weir, including dam boards used in quiescent zones, should be level to ensure uniform discharge across the entire weir length. *Weir rate,* the water flow rate divided by weir length, determines the length of the outlet weir. A maximum weir rate of 372 $m^3$/day per m of weir is recommended for flow-through aquacultural operations (Stechey and Trudell 1990). Excessive weir rates will increase the velocity of discharged water, causing scouring and updraft. This is readily observed where water is discharged through a standpipe or where a settling basin has a constricted weir. Weir length should be maximized if possible.

Settling basins should be rectangular, because irregular-shaped basins cause poor flow characteristics and short-circuiting. Additional freeboard height or shrub or tree windbreaks will provide protection from wind.

### *Remove solids from settling basins in a timely fashion*

Solids should be removed from quiescent zones with a frequency sufficient to prevent cohesion of solids and minimize nutrient leaching (Box 9.4). Accumulated solids become sticky and viscous over time, making removal difficult. Solids accumulation can cause water quality deterioration, adversely impacting fish health and production in downstream rearing units. Nutrient leaching occurs rapidly from rainbow trout sludge, with the majority of nutrients released within the first 24 hours (Garcia-Ruiz and Hall 1996; Stewart et al. 2006b).

Feeding rate, settling basin efficiency, sludge storage capacity, labor availability, and compliance limits all influence cleaning frequency. Typically fish at or near market size are in the lower portion of a facility and comprise the largest portion of the swimming inventory. As such they receive the largest portion of the daily feed allotment and produce the majority of the waste. Lower-portion and last-use quiescent zones should be cleaned more frequently compared to other quiescent zones on the facility to protect receiving water quality. The Idaho Waste Management Guidelines for Aquaculture Operations (IDEQ, undated) recommends cleaning quiescent zones a minimum of twice per month on lower raceway sets and once per month on upper raceway sets. Daily solids removal will reduce nutrient leaching (Stewart et al. 2006b), although the practicality and affordability of such a rigorous cleaning schedule remains to be demonstrated (MacMillan et al. 2003). Approximately 1-week intervals represent an optimal balance between labor requirements and effluent compliance (MacMillan et al. 2003). Provided effluent compliance limits are met, quiescent zone cleaning frequency can be variable within and between facilities.

## BOX 9.4
## Quiescent Zone Cleaning Frequency and Waste Loading

Quiescent zone cleaning frequency determines solid waste residence time within the quiescent zone, which in turn affects phosphorus dissolution kinetics. The longer the residence time the greater the loss of solid phosphorus to the dissolved form, which is directly discharged into the aquatic environment. Phosphorus effluent characteristics were measured at two trout farms with different quiescent zone cleaning frequencies. The farm with a greater quiescent zone cleaning frequency (once/week) had 49% dissolved phosphorus in the effluent compared to 67.5% for the farm that cleaned quiescent zones once every 2 weeks (True et al. 2004a).

The most common method of solids removal from quiescent zones is by suction through a vacuum head. Usually a standpipe in each quiescent zone connects to a common pipe that carries slurry to an offline settling basin. A flexible hose and swivel joint connect the vacuum head to the standpipe so the vacuum can be manipulated to clean the quiescent zone. Floats, empty milk jugs, or plastic soda bottles are attached to the flexible hose to prevent resuspension of the solids while cleaning. Suction is provided by head pressure from raceway water depth and gravity, or where insufficient elevation exists by pumps. Vacuum heads may be commercially available but most are manufactured on the farm. Designs include slotted pipes, triangular heads, open hoses, and rectangular vacuum heads mounted on wheels. Proper sizing of pipes and pumps is necessary to ensure adequate suction at the vacuum head. Insufficient suction results in resuspension of the solids before they can be vacuumed and increases cleaning time. The Idaho Waste Management Guidelines for Aquaculture Operations (IDEQ, undated) recommends 379 L/minute flow to operate a vacuum head 30- to 46-cm wide. Pump and pipe manufacturers can provide assistance in sizing pipes and pumping equipment.

In small rearing units such as hatchery troughs and fingerling ponds with small quiescent zones it is more efficient to simply remove the standpipe and push the solids with a broom or squeegee device to the suction port. The cleaning process is critical and care must be taken not to resuspend solids regardless of cleaning method. Occasionally fish will enter the quiescent zone from the rearing area, so it is prudent to remove those fish as soon as practical because fish can resuspend solids within the quiescent zone.

Offline and full-flow settling basins are excavated in soil or constructed of concrete. Earthen settling basins are less expensive to construct, but solids removal is much more difficult compared to concrete settling basins. Typical depths range from 1 to 2 m; however, 1.2 m provides adequate solids storage, provided basins are cleaned monthly. Usually the flow to one settling basin is diverted to another settling basin a few days before the first basin is ready to be cleaned. This allows complete settling of solids before decanting the clean supernatant to another settling basin. Avoid decanting the supernatant into the receiving stream, because the last portion of the supernatant may exceed total suspended solids and other water quality parameter compliance limits. When the basin is cleaned using a backhoe or front-end loader the material must be sufficiently dry to handle (Fig. 9.8). Depending on geographic location and season, the material is allowed to dry for several days or more to a consistency of about 25 to 35% solids by dry weight. A ramp at the shallow end of the basin is necessary for equipment access.

Odor will be a problem during drying of the material and solids removal from the basin. Locating the basin as far away as possible from neighbors is prudent, and placing windbreaks around the basin will minimize odor problems.

Another option is to pump the material directly out of the basin and into a tank truck or livestock manure spreader. When a slurry pump is used to remove solids from a basin the material is initially too viscous and must be mixed prior to pumping. The bulk of solids settle at the inlet end of the basin, so placing the inflow at the deepest end of the basin can facilitate solids collection and removal, as well as minimize viscosity and mixing problems. To facilitate mixing, the basin should be equipped with 10- to 15-cm-diameter pipes to convey material from the sump to the other end of the basin. Slurry pumps are typically hydraulically powered and limited in their capacity to handle high concentrations of solids. Slurry pump manufacturers should be able to provide power unit and hydraulic

**Fig. 9.8.** The water in this concrete settling basin has been decanted to allow removal of the accumulated solids.

pump specification for individual applications. A pump with sufficient capacity and power can load a 15,000-L tank truck within 15 minutes with slurry containing about 12% solids.

Cleaning a settling basin requires 1 to 3 days, depending on the amount and consistency of solids and the hauling distance for disposal. Frequent cleaning will facilitate solids removal efficiency. At minimum settling, basins should be cleaned every 6 months. For situations where there is only one offline or full-flow settling basin, solids can be removed with a pump without diverting water flow to the basin, similar to cleaning a quiescent zone. For situations where a facility does not have equipment to remove and transport solids, a licensed contract hauler can be hired.

## Solids Disposal

Good management of wastes produced in flow-through aquaculture extends beyond proper solids management, effluent nutrient reduction, and compliance with effluent standards. Management must also include proper solids handling, drying, storage, and disposal.

Components of solids disposal require consideration of odor control, safe and clean solids transport, storage lagoon site selection and design, land application techniques, site selection, crop compatibility, hydrogeology, and soil type and depth. The most important objective of solids disposal is to ensure that constituents harmful to water quality do not leach into groundwater or flow into surface waters.

Aquaculture solids contain plant nutrients and can be used as a soil amendment. The nutrient composition of solids varies with feed type, feeding rate, management practices, and age of solids (Axler et al. 1997; Naylor et al. 1999; Yeo et al. 2004). Organic matter in aquaculture solids can also improve soil tilth, which improves soil moisture retention (Yeo et al. 2004). However, the nitrogen in waste solids is not as available to plants as inorganic, soluble nitrogen, and solids may not contain the proper balance of nutrients for optimum plant growth. As such, additional nutrients may be required when waste solids are used as a plant fertilizer (Westerman et al. 1993; Yeo et al. 2004). Characteristics of waste solids from trout farming and their fertilization properties are presented in Table 9.5 (Smith 1985; Willett and Jakobsen 1986; Olson 1992; Westerman et al. 1993; Axler et al. 1997; Naylor et al. 1999). Solids from trout farming are more similar to other animal manures than to municipal or domestic sewage (Yeo et al. 2004) and, as with other animal manures (Table 9.6), are less likely to have significant levels of toxic contaminants than fertilizers derived from municipal wastewater or sludge (Krieger et al. 1987; Yeo et al. 2004).

Although aquaculture solids and sludge contain beneficial plant nutrients, the relatively low percentage of solids (8 to 12%) in fish manure slurry presents logistical, regulatory, and cost challenges for disposal. First, the rather dilute nutrient content results in a relatively low fertilizer value. For example, the 83,000 $m^3$ of aquaculture waste solids that is produced annually in south-central Idaho is sufficient to fertilize only a few hundred hectares of cropland (Breckenridge et al. 1990). Transport of fish manure is cost prohibitive beyond several kilometers from a trout production facility, although methods that reduce the water content of the sludge would make disposal more efficient. Crop farmers are

**Table 9.5.** Percentage (dry weight basis) of nitrogen (N), phosphorus (P), and potassium (K) in trout manure.

| Percent of Dry Weight | | | |
|---|---|---|---|
| N | P | K | Reference |
| 2.83 ± 0.66 | 2.54 ± 1.20 | 0.10 ± 0.05 | Naylor et al. 1999[a] |
| 3.30 | 1.03 | 0.03 | Willett and Jakobsen 1986[b] |
| 3.15–5.49 | 1.34–3.51 | 0.29–0.43 | Olson 1992[c] |
| 2.95–16.11 | 0.88–6.60 | 0.05–0.96 | Westerman et al. 1993[d] |
| 1.78–15.31 | 0.35–1.85 | 0.29–0.88 | Westerman et al. 1993[e] |
| 2.44–3.60 | 0.94–3.80 | | Axler et al. 1997[f] |

[a] Settleable solids collected from settling units at 12 commercial trout farms.
[b] Concrete-lined ponds, age of solids unknown.
[c] From three fish farms using concrete settling basins, age of solids unknown.
[d] Samples from raceway settling sections, less than 2 weeks old.
[e] Samples from settling basins, 1–9 months old.
[f] Samples from raceways, less than 2 weeks old.

**Table 9.6.** Levels of nine potentially toxic metals in municipal sewage sludge, fish waste solids, and cattle manure compared with the EPA ceiling concentrations for land application.

| | Concentration (mg/kg) | | | |
|---|---|---|---|---|
| Metal | EPA Upper Limit[a] | Fish Waste Solids[b] | Municipal Sewage Sludge[c] | Cattle Manure[c] |
| Arsenic | 75 | 0.3–0.8 | 0.03–53 | 6.1 |
| Cadmium | 85 | <2.5–5.0 | 3.3–203 | 2.5 |
| Cobalt | | 3.1–10 | 2.4–30.1 | 6.1 |
| Chromium | 3,000 | 18–41 | 50.5–13,349 | 180 |
| Copper | 4,300 | 11–32 | 126–7,729 | 55 |
| Mercury | 57 | 0.03–0.11 | 1.6–20.7 | 0.1 |
| Nickel | 420 | 8–22 | 29–800 | 28 |
| Lead | 840 | 4.2–11.2 | 80–676 | 17.5 |
| Zinc | 7,500 | 117–545 | 475–10,900 | 298 |

[a] 40 CFR § 503 (Inorganic Pollutants in Sewage Sludge; USEPA 1994).
[b] Krieger et al. (1987).
[c] Mumma et al. (1984).

hesitant to apply aquaculture solids without guidance on application rates, effects on crop production, and impact on soil crusting. Odor can also be a limitation for farmer acceptance of fish manure as a fertilizer. Meeting local and state regulatory requirements also may present a challenge that impacts the cost-effectiveness of disposal options. Classification of aquaculture solids varies among local and state regulatory agencies. Aquaculture solids may be classified as agricultural, industrial, or municipal waste depending on local regulations, and the designation will impact disposal options. Disposal of solids should comply with all applicable local and state regulations and be conducted to prevent the material from entering surface or groundwater. Disposal options are site-specific practices that require compliance with local regulations and consideration of local conditions such as soil types, topography, land availability, climate, and crop.

## *Better Management Practices for Solids Disposal*

### *Apply solids to land*

Land application of aquaculture solids is the most common disposal method and, when done properly, provides a safe disposal method that also benefits crops and soil. Site conditions, timing of application, application rates, crop type, crop nutrient uptake capacity, crop rotation, and land availability should be considered prior to land application.

Fallow fields are best suited for land application of aquaculture solids because crops can be smothered by the solids or damaged by the vehicle and equipment that is applying it. Once at a site, the outlet valve (15-cm minimum diameter) on the tank is opened. A spreader bar or splash plate located below the valve will ensure distribution of solids across the width of the truck (see Fig. 10.14 in the next chapter). Application rate is determined by the speed of the truck as it is driven over the field. As the tank empties, the speed of the truck is reduced to maintain a constant application rate. The quantity of solids removed from even very large trout operations is small and, given the dilute nature of the solids, it is almost impossible to apply too much of the material unless multiple applications are made over the same ground. As a precaution, one can wait to apply a second application until a crop has been grown and harvested.

Relatively little land area is required to make use of solids produced in flow-through aquaculture. The solids produced annually from a facility with an inventory of 454,000 kg of trout fed 6,800 kg of feed per day are sufficient to fertilize approximately 40 ha of cropland (IDEQ, undated). Although relatively little land is actually needed for solids application, a much larger potential land area is needed to ensure availability throughout the year because it may be difficult to locate fallow fields during the growing season or accessible fields during winter or periods of poor weather.

Avoid applying aquaculture solids on land near surface waters or on steep slopes where solids could enter surface waters with runoff. Areas with exposed bedrock or insufficient soil depth to allow plowing should be avoided to prevent leaching of nutrients into groundwater. Avoid applying solids in areas with shallow water tables or fields with natural springs. Application onto frozen ground increases the potential for runoff and should be avoided.

Consider prevailing winds and the proximity of neighbors because of the intense odor during and immediately after land application. Once applied, aquaculture solids will form a crust unless plowed or disked into the soil, which will minimize odors.

For smaller flow-through production systems, such as those typical in the eastern United States, it is usually not practical to develop a land application plan for cropland unless the owner of the trout farm also owns cropland. In such instances, other alternatives should be considered, such as small-scale horticultural, landscape, or garden applications.

Transport of aquaculture solids to the site of application using tank trucks is preferable to dump trucks or conventional livestock manure spreaders. Tank trucks are easier to seal; this prevents spillage of solids onto public highways, which is a safety and environmental hazard. Transport vehicles should be maintained in excellent working condition and driven by qualified personnel.

Under certain conditions it may be possible to pump the solids from a settling basin directly into a sprinkler irrigation system. If farmland is adjacent to the aquaculture facility, the capital and operating costs of the sprinkler system may be cost-effective relative to the cost of pumps, transport trucks, labor, and alternate irrigation systems. Direct use in sprinkler irrigation eliminates the discharge of effluent from settling basins to receiving waters during the irrigation season. Nozzles on sprinklers should be sufficiently large to minimize clogging by debris and to handle relatively high flow rates. Timers can be installed to control the frequency and duration of irrigation to prevent runoff. Solids concentration from direct sprinkler application is much more dilute compared to the solids concentration from land application of sludge. The average concentration of total suspended solids from a sprinkler application in Idaho was 2,300 mg/L, or about 0.2% solids, compared to 8 to 12% for solids slurries applied to land (IDEQ, undated). One drawback to direct application through sprinklers is that a relatively large settling basin is needed to store material during the nonirrigation season.

### *Extend treatment of solids in storage lagoons or evaporation ponds*

Storage lagoons or evaporation ponds may be used to further thicken and stabilize solids or store them when land application is impossible. Storage lagoons are usually shallow, bermed earthen ponds. A large surface area to volume ratio will enhance solids drying. Storage lagoons tend to be self-sealing, but should not be constructed in areas with exposed bedrock, thin or sandy soil, or shallow water tables where contamination of groundwater may occur from seepage. A minimum of 60 cm of undisturbed native soil should lie above any fractured bedrock or rock outcropping. Idaho regulations require a liner to control seepage in storage lagoons. The maximum allowable seepage rate in Idaho for wastewater storage lagoons, including those at aquaculture facilities, is 0.32 cm/day. Clay, cement, or polyethylene liners may be used. If clay is used the following specifications must be met:

1) A minimum of 60 cm of soil with a clay content of 5 to 15% placed in 15-cm lifts and properly compacted; or
2) A minimum of 30 cm soil with a clay content ±15% placed in 15-cm lifts and properly compacted; and
3) The clay liner must also be placed on side slopes of the lagoon.

Care must be taken to avoid breaching the clay liner when solids are removed from earthen storage lagoons. Storage lagoons should not be located in areas prone to flooding or near neighbors who may find the odor offensive. Lagoons should be located no closer than 30 m from surface waters, 60 to 90 m downslope and 90 to 150 m upslope from private water supplies, 90 to 150 m from any residence, and 300 m from a public well (IDEQ, undated). Earth embankment design also should include (IDEQ, undated)

1) Minimum inside slopes of 2 : 1;
2) Minimum outside slopes of 3 : 1;
3) 5% increase in design height to allow for settling;
4) Vegetation on outside slopes to prevent erosion;
5) Use of practices to reduce rodent habitat; and
6) Accessibility for weed control, dike maintenance, and harvesting equipment.

Storage lagoons may present a safety hazard for children and/or animals. Fencing and warning signs may be necessary, depending on site location and local requirements.

Dried solids are relatively easy to store and transport. They will have an earthy odor and can be readily applied to newly seeded grass, gardens, flower beds, or farmland. Some nutrients are volatilized during drying, but dried material is an excellent soil amendment that adds some nutrients and humus, and enhances soil moisture retention. Storage lagoons are particularly effective for drying aquaculture solids in the hot arid climate of the American west.

### *Compost solids*

Thickened and dewatered waste solids may be composted, which stabilizes solids, produces a valuable soil amendment, and offers an alternative to direct land application. Composting also provides flexibility with regard to timing of land application because compost stores well without generating odors or attracting flies and, therefore, can be applied as convenient.

Composting is the aerobic decomposition of organic materials by microorganisms under controlled conditions. Composting occurs over a wide range of conditions (Table 9.7) although the speed of the process and the quality of the finished product are mostly determined by the selection and mixing of raw materials. Composting generates heat and releases carbon dioxide and water vapor. The amount of water lost can be substantial, so composting reduces the initial volume of the raw material. Costs associated with composting include additional handling, labor, and raw materials. However, composting can be cost-effective if suitable cropland is not available for direct land application, transport distances are great, or a market exists for the finished compost product. Other organic by-products of aquaculture production, including dead fish, spoiled feed, and fish processing waste, can also be composted.

Solids from a settling basin are dense, wet, and nitrogen-rich. Composting requires mixing waste solids with one or more suitable materials that will absorb moisture, add carbon, and provide porosity. Suitable amendments include straw, cornstalks, wood chips, sawdust, and yard trimmings. Two to three volumes of amendments per volume of waste solids are needed, depending on the amendments used and the initial moisture and consistency of the settling pond waste. Composting characteristics of trout waste solids vary with source and handling. Waste solids that are collected earlier in the handling process, such as those collected from raceway quiescent zones, contain more organic matter and nutrients, which will invigorate the composting process and enrich the compost. However, the greater moisture levels of those solids will require additional volumes of amendment (Buyuksonmez et al. 2005).

Windrows or aerated piles can be used to compost fish manure. A *windrow* is a long narrow pile of organic material that is regularly turned to provide aeration. The windrow can be passively aerated by supplying air to the pile with perforated pipes embedded in the pile. A blower supplies air to actively aerated piles, allowing greater control of the composting process. The composting process is accelerated considerably if the compost pile is properly constructed and airflow is sufficient and uniformly distributed.

A relatively large trout flow-through production facility in Idaho has been composting fish manure since the University of Idaho initiated a fish manure and fish mortality compost research and extension project in the early 1990s. The facility is located adjacent to the Snake River near Hagerman, Idaho and produces between 900 to 1,400 tonnes of trout

**Table 9.7.** Recommended conditions for composting.

| Condition or Variable | Reasonable Range[a] | Preferred Range |
|---|---|---|
| Carbon to nitrogen ratio (C : N) | 20:1 to 40:1 | 25:1 to 30:1 |
| Moisture content | 40–60% | 50–60% |
| Oxygen concentration | >5% | >10% |
| Particle size (diameter, cm) | 0.3 to 1.25 | Varies[b] |
| pH | 5.5–9.0 | 6.5–8.0 |
| Temperature (°C) | 43–65 | 55–60 |

*Source:* Modified from Rynk et al. (1992).

[a] Recommended conditions are for rapid composting; conditions outside these ranges can also produce successful results.

[b] Depends on specific materials used, pile size, and weather conditions.

annually with a water supply of 3.4 $m^3$/second. The offline settling basin consists of three separate cells, each of which is cleaned approximately every 2 months. The cells are cleaned the same way as a typical settling basin except that straw is added to the solids to absorb additional moisture during the drying process. Once the material is sufficiently dry to allow handling, a front-end loader removes the material from the offline settling basin and places it in a windrow. Additional straw is added as the windrow is formed until the ratio of straw : aquaculture solids is about 3 : 1 by volume. Initially the material is too moist to form a windrow of any height. The material is dry enough to form a windrow 2 to 3 m high after about 1 week. New material is simply added onto the end of the windrow as other settling basin cells are cleaned. The windrow is turned and aerated about every 3 to 4 weeks with a front-end loader. The relatively small amount of organic matter in aquaculture solids causes the material to decompose quickly (within a few weeks) and at lower temperatures compared to other organic materials. It is rare for temperatures within the windrow to exceed 37°C, whereas temperatures generally surpass 60°C in compost piles of dead fish, even during the winter. The compost process is complete after several months when the straw has decomposed.

Suitable farmland for direct application of solids generated by this particular facility was a great distance away, representing a considerable expense for waste disposal. Composting fish manure is less expensive and the process integrates well with farm operations. Straw is available year-round at low cost and is easily transported to the trout farm and stored until needed. Although this facility is one of the larger trout-farming operations in Idaho, the amount of compost produced is surprisingly small. Composting can reduce the volume of raw materials by 50% or more. The area used for composting is only about 550 $m^2$. Through word of mouth, local residents become aware of availability and pick up all the compost they want for free. From the farm's perspective, it is easier to make the finished compost available to the public for free than to develop a market for the material.

### *Treat solids in constructed wetlands*

Constructed wetlands have been used to treat a variety of wastewaters, including those from domestic septic systems, small municipalities, and agricultural activities (Yeo et al. 2004). Nutrient removal rates in constructed wetlands are determined by hydraulic retention time, type of vegetation, solar radiation, microbial activity, and temperature. Common plants used in constructed wetlands include cattails, bulrushes, rushes, and sedges. Constructed wetlands require little to no energy to operate and attract wildlife, and can be aesthetically pleasing. Much has been written about the use of constructed wetlands as a treatment technology for various effluents. Sources of additional information include Kadlec and Knight (1996) and the USDA Water Quality Center of the National Agricultural Library (www.nal.usda.gov/wqic/wetl.shtml).

The lengthy hydraulic residence time (4 to 10 days) required to treat effluents in constructed wetlands precludes their use to treat primary flows from flow-through aquaculture. A facility in Idaho with an average flow of 1.07 $m^3$/second would require constructed wetlands with a volume of 37 to 93 ha-m to achieve a 4- to 10-day hydraulic residence time. Miller and Semmens (2002) estimated wetland construction costs of \$37/$m^2$ (\$370,000/ha) and estimated a wetland to function for 5 to 10 years without major maintenance or renovation. A constructed wetland may be suitable to treat the secondary flow from an offline settling basin for a small flow-through facility. Assuming a 5-year life-span for secondary treatment and fish production of 9,072 kg/year, a constructed wetland of 150 $m^2$ would increase the cost of production by \$0.13/kg (Miller and Semmens 2002).

### *Use solids collected from earthen flow-through systems to repair embankments*

In-pond settling of solids occurs in earthen flow-through "ponds." Earthen flow-through ponds are almost always small sites with low flow and a hydraulic retention time of 1 hour or more. Fish are harvested at the upstream end of the pond to reduce the amount of solids discharged during harvest. Earthen flow-through production systems should be designed to allow diversion of water around any pond while maintaining water flow to other ponds. A full-flow settling pond below rearing ponds can ensure adequate treatment of the effluent to minimize solids discharge to the receiving stream. After fish are harvested, water is diverted away from the earthen pond to allow the bottom to dry. When solids are sufficiently dry to permit handling they can be removed with a drag line or backhoe. These solids differ considerably from those in settling ponds for concrete raceways and consist mainly of silt and clay enriched with fish fecal solids. The material has little crop value as a soil amendment, but can be used to repair pond embankments, which erode over time, or renovate other areas of the pond. Other potential disposal methods include land application and use as fill material.

## Fish Escape

If allowed to escape, farmed fish from flow-through or other aquaculture systems may potentially impact the surrounding ecosystem directly or indirectly through genetic impacts, disease impacts, competition, predation, habitat alteration, and colonization. The probability of significant ecological impact increases as the number of escaped individuals increases (Myrick 2002). In the case of rainbow trout from commercial flow-through aquaculture facilities, there is no evidence that fish escape often or in great numbers. The potential impacts of escaped rainbow trout from commercial aquaculture facilities must be put into context: Rainbow trout grown for food represent only a fraction of the rainbow trout grown in flow-through systems in the United States. Most rainbow trout (more than 150 million) are grown for intentional release to enhance natural populations for recreational angling. This is more than double the 65 million trout grown for other purposes (USDA-NASS 2006a).

Although much attention is focused on the potential impacts of nonnative fish that may escape from culture facilities, most states closely regulate species allowed for production in flow-through aquaculture systems. Species allowed in flow-through or other "open" culture systems are often restricted to those that are native, naturalized, or determined by regulatory authorities to have a low risk of successful colonization of surrounding habitats. Although documented impacts of escaped fish from flow-through aquaculture are lacking, there is an abundance of research documenting impacts from intentional release of native or nonnative species that may be cultured in flow-through systems (e.g., salmonids and tilapia). Thus there are strong incentives to prevent escape of fish from flow-through aquaculture systems by following recommended practices.

By design, flow-through aquaculture systems are hydrologically linked with receiving waters, most often discharging to a natural watercourse from a waste-treatment facility on the farm, such as a settling pond or quiescent zone. Flow-through systems will also be linked with the water supply, although the supply may be a groundwater source that does not contain fish and has a flow-control apparatus. Some flow-through systems, particularly those located in the eastern United States, divert water from a natural watercourse, providing a route for possible fish escape through both the inflow and outflow. Prevention of escape can be easily incorporated into system design and operation because flow-through systems require methods and structures to control water flow. Properly designed, constructed, and managed facilities offer a very low risk of escapes.

### *Better Management Practices for Preventing Escapes*

#### *Consider the risk of flooding in site selection*

Flooding can put a farm at risk for fish escape by removing fish barriers or through physically washing fish from the tanks. The farm should be constructed so that the elevation of the lowest raceway, tank, basin, or pond in the system is above the 100-year floodplain as defined by the USDA Natural Resources Conservation Service, the United States Geological Survey, or equivalent natural resource agency. To ensure adequate outflow from the lowest tank in the system, the elevation should be sufficient to allow water to continue to discharge even during periods of high water in the receiving stream. In regions with relatively steep terrain, barriers or ditching may be required to divert overland flow from impacting raceways during periods of excessive precipitation.

#### *Use effective fish barriers and screening*

Most species of fish have a natural tendency to swim upstream or downstream depending on their life stage, variations in water quality or chemistry, food supply, or the level of fish density in the system. Both water inflow and discharge points require fish barriers with screening or slotted bars with sufficiently small openings to retain the smallest fish in adjoining tanks. Intake structures should be screened with slotted or perforated metal, wood, or plastic material to prevent passage of debris or fish into the facility and to prevent the smallest fish from upstream movement. The most commonly used material for intake screening is perforated aluminum, although large flows may require more sophisticated traveling screens if plant growth could occlude the screening. Screens should be checked at least daily to prevent clogging and ensure their structural integrity. A fish barrier screen of mesh or bars should also be used at the upstream end or head of the first tank in the system. Barriers made of vertical bars (Fig. 9.9) are less prone to failure from clogging, and can be constructed from wood, metal, or plastic. The bar spacing for fish retention varies with fish size (Table 9.8). For fish smaller than 20 g, plastic mesh or perforated metal screens may be preferred. A horizontally mounted screen can be added above the water inflow area in each tank as needed to prevent small fish from jumping over the barrier (Fig. 9.10).

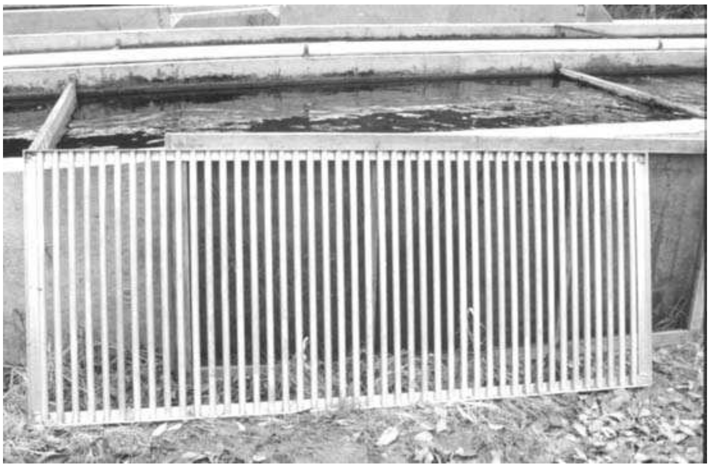

**Fig. 9.9.** A fish barrier screen of vertical metal bars.

**Table 9.8.** Bar grader spacing to exclude rainbow trout of various sizes.

| Bar Spacing | Fish Weight | | Fish Length (mm) | |
|---|---|---|---|---|
| (mm) | (g/fish) | (fish/kg) | K = 1.10[a] | K = 1.25[a] |
| 5 | 1.5 | 666.7 | 51 | 48 |
| 6 | 2.8 | 357.1 | 64 | 61 |
| 10 | 4.9 | 204.1 | 76 | 74 |
| 13 | 28.4 | 35.2 | 137 | 132 |
| 14 | 42.6 | 23.5 | 157 | 150 |
| 16 | 56.4 | 17.6 | 173 | 165 |
| 19 | 113.5 | 8.8 | 216 | 208 |
| 22 | 227.0 | 4.4 | 274 | 264 |
| 25 | 283.8 | 3.5 | 295 | 284 |
| 27 | 340.5 | 2.9 | 312 | 302 |
| 28 | 368.9 | 2.7 | 323 | 310 |
| 29 | 397.3 | 2.5 | 330 | 318 |
| 30 | 454.0 | 2.2 | 345 | 330 |
| 32 | 510.8 | 2.0 | 358 | 345 |
| 35 | 681.0 | 1.5 | 394 | 378 |
| 37 | 794.5 | 1.3 | 417 | 399 |

*Source:* Modified from Hinshaw (2000).

[a] The condition factor is a measure of the relative "plumpness" of fish and varies with feeding rate, fish strain, and relative fish health. The factor, K, is calculated as (100 × fish weight in g) ÷ (length in cm)$^3$.

Fish exclusion screens are also used in flow-through systems to prevent fish from entering quiescent zones or moving from tank to tank within the facility allowing for better stock management. The last tank in the system should have a screen at the beginning of the quiescent zone capable of retaining the smallest fish in the adjacent upstream tank. A screen of similar spacing may be placed in the outflow from the quiescent zone if redun-

**Fig. 9.10.** Netting hung horizontally above the water inflow area prevents small fish from jumping into the upstream raceway.

dant containment is needed to prevent fish from moving into the facility from receiving waters. The discharge flume, pipe, or canal should be screened between the receiving waters and the settling ponds or last quiescent zone in the system, depending on system configuration. Screening for the discharge should be sufficiently large to ensure adequate open area for maximum discharge flows, with openings sufficiently small to prevent fish escape, and constructed of a material that will prevent predators or other wildlife from gaining entry to the system. Discharge areas are often a primary route of entry for predators such as otter or mink, and also may be attractive to beaver.

For culture of potentially invasive nonnative species, screen redundancy can be used to reduce the risk of fish escape. Production of sterile or monosex fish will also reduce the risk of impact from these fish if escapes were to occur.

## Predator Control

The extremely high standing crops of fish and their vulnerability in shallow raceways and tanks with clear water makes flow-though facilities extremely attractive to fish-eating predators. Predators can cause severe losses in flow-through aquaculture. Several states with flow-through aquaculture of trout report predators as the primary cause of fish loss. In 2005, Massachusetts, Wisconsin, Utah, and Virginia reported losses from predation at 70%, 67%, 64% and 61% of total losses, respectively (USDA-NASS 2006b). Glahn et al. (1999) surveyed 24 trout facilities in the northeastern United States and reported that 5 facilities sustained bird predation losses exceeding $10,000. The Pennsylvania Fish and Boat Commission estimated losses to bird predation at state trout hatcheries exceeding $500,000 annually prior to initiating a bird control program (Falker and Brittingham 1998). Annual fish losses at trout facilities in Pennsylvania averaged $725 per raceway through mallard depredation and $969 per raceway through depredation by common grackles

(USDA-APHIS 1997). Among four trout facilities in Pennsylvania, annual losses from great blue herons ranged from $422 to $28,784 (Glahn et al. 1999).

Predator management control practices should minimize the interaction between wildlife and cultured animals to protect wildlife, minimize production losses, and prevent increased aquaculture waste production. Predators may spread pathogens beyond, within, and among aquaculture facilities, and wounds inflicted by predators may serve as a focus for diseases or reduce the commercial value of the fish. The mere presence of predators, especially birds, around aquaculture facilities can keep fish in a perpetual state of fright, resulting in increased physiological stress and poor feed conversion. Diseased and stressed fish convert feed poorly, with subsequent increased waste production. Predators also serve as vectors of infectious diseases, which may negatively impact wild fish. Whirling disease for example, caused by *Myxobolus cerebralis*, can be spread by fish-eating birds. Limiting access of predators to moribund and dead fish minimizes the potential spread of pathogens into wild populations.

Depredation losses are caused primarily by birds, but mammals such as mink and otter also prey on fish. During 1993 and 1994, Pitt and Conover (1996) observed predators and surveyed managers at fish facilities in the intermountain western United States to determine the species responsible for depredation losses. Great blue heron, black-crowned night heron, osprey, and California gull were the most important predators. Feral cat, raccoon, and striped skunk fed mostly on moribund or dead fish and had little impact upon production. At two closely monitored facilities, losses to bird depredation were 7% and 0.6% of annual production. In the northeastern United States, great blue heron, common grackle, and mallard appear to be the most problematic species (Glahn et al. 1999). Black-crowned night heron can also cause significant losses, although this species was precluded from the study by sampling procedures. Herons consume all sizes of fish whereas common grackles and mallards eat mostly smaller fish (Glahn et al. 1999). Ospreys may appear for brief periods at aquaculture facilities during spring and fall migration, but their impact can be significant because ospreys consume large fish.

Fortunately flow-through aquaculture facilities are usually smaller than pond facilities, which provide opportunities for effective predator control that are economically or logistically impractical for ponds. Factors that should be considered before deciding on predator control measures include the species of predators causing the damage, the extent of the damage, estimated cost and effectiveness of control measures, type and size of facility to be protected, species and size of fish grown, impact of control measures on facility management, and cost-benefit ratio (Curtis et al. 1996).

## *Better Management Practices for Predator Control*

### *Assess predator impact, identify the predator responsible for losses, and check with appropriate regulatory agencies*

An important aspect of Integrated Pest Management is to thoroughly assess the status of depredations before choosing control measures. Initial assessment activities and regulatory considerations are fundamentally similar for all land-based aquaculture facilities and are discussed in the "Predator Control" section of Chapter 6. Lethal control measures should be considered only as a last resort after a thorough assessment of the situation and determination of the ineffectiveness of nonlethal control measures, and that lethal control is legal. See Boggess (1994a, b) and Hill (1994) for additional information in the prevention and control of wildlife damage.

### *Use enclosures to totally exclude predators from the facility*

Total exclusion is obviously the most effective means of preventing predators, especially birds, from entering aquaculture facilities, but exclusion structures also have the greatest capital costs compared with other predator-control methods (Box 9.5). However, total exclusion systems are also most protective of wildlife. Exclusion systems vary from temporary netting or screens placed over individual raceways to complete enclosure of the entire facility (Fig. 9.11). Polypropylene netting, plastic netting, and chicken wire with mesh sizes of 2.54 cm to 5.1 cm are suitable materials for total exclusion. Light-gauge, galvanized wire fencing with hexagonal mesh (chicken wire) is preferred by trout growers in Idaho for its durability.

Exclusion structures must be sufficiently strong to prevent netting from sagging within a bird's striking distance when birds land on the structure. Herons have been observed walking on unsupported netting and spearing fish through holes torn into the netting. The enclosure structure should not interfere with normal operations and allow for facility maintenance and feeding, grading, and harvesting of fish. The height of the structure that completely encloses a facility must be sufficiently high to allow normal operations,

## BOX 9.5
## Physical Barriers for Predator Exclusion on Trout Farms

Beginning in the late 1980s and continuing through the 1990s, nearly all flow-through aquaculture facilities in Idaho installed complete predator-exclusion structures. The impact can be seen by comparing predator losses across years. In 1989 Idaho trout growers estimated predator-related losses at 23% of total losses (USDA-NASS 1989). During 2004, predator-related losses were reported as 5% of total losses (USDA-NASS 2006b). Losses from predators in Idaho were not reported for 2005 to avoid disclosure of individual operations.

To provide some idea of the costs involved in total predator exclusion, a 2-ha facility in Idaho was completely enclosed at an estimated cost of $92,000 (Bill Jones, Jones Trout Farm, personal communication). The cost of enclosing a 0.63-ha trout-rearing facility in Pennsylvania with a chain-link fence and overhead wire system was $42,040 (Glahn et al. 1999). Two California state trout hatcheries experienced bird depredation problems estimated at $50,000 to $60,000 annually in 1979. The facilities were completely enclosed and production increased 25 to 30% at both facilities. Although the cost of exclusion was high, the return on investment was realized within 3 to 4 years (Gorenzel et al. 1994).

including the entry and exit of fish transport and feed delivery trucks. In areas that experience severe weather conditions, the support structure must be sufficiently sturdy to prevent collapse when exposed to high winds or covered with ice or snow. It may be necessary to design the enclosure to allow removal of netting or panels before impending storms.

### *Use barriers or impediments to partially exclude predators from the facility*

Partial exclusion systems employ overhead wires, lines, netting, screens, perimeter fencing, and other devices to discourage birds from feeding or perching at aquaculture facilities. They do not prevent predator access to the facility. Partial exclusion systems are less effective than total exclusion, but they are less expensive to construct.

Arrays of overhead wires are effective at discouraging birds such as gulls and ospreys, but are relatively ineffective against wading birds and mammals. Overhead wire systems consist of heavy-gauge monofilament lines or high-tensile galvanized or stainless steel wires suspended horizontally in a grid pattern or in parallel over the water surface. Wires or lines with spacings of 25 cm appear to be adequate to deter most aerial predators. Lines should be visible to birds to be most effective. Adding streamers or other objects at intervals will increase effectiveness and also minimize bird injury or death. Fencing or netting of the sides and ends of the facility can be added to prevent wading birds and other predators from entering the area. Overhead wire systems usually require little maintenance.

Wires or perimeter fencing around ponds or raceways can deter herons or other wading birds but birds may eventually learn to avoid these obstacles. Aerial predators are not deterred by these systems. Fencing should be at least 1 m high (Gorenzel et al. 1994). Most wading birds prefer to land on the ground and then wade to a pond; thus construction

**Fig. 9.11.** The Norfolk National Fish Hatchery in Arkansas is completely covered with netting to discourage bird depredations. Photograph courtesy of Jimmy Avery.

of inward angled or vertical barriers around ponds or raceways may discourage wading birds from foraging around the edges and from entering the area (Curtis et al. 1996). Electric wires and fencing have had varying success at deterring wading birds. Maintenance problems and frequent grounding of the system by blowing debris limit their usefulness. A nonlethal electric current is necessary to protect humans and birds.

Strips of spikes or spines can be used to deter perching or roosting birds. Metal or plastic spike barrier strips are commercially available, but can also be constructed by hammering nails through wood lath and placing the lath at the appropriate location.

Frightening devices and techniques are used to modify predator behavior and to discourage feeding, roosting, or gathering at aquaculture facilities. They do not work against mammalian predators and are of limited value against birds. To be effective a frightening program should be established prior to birds establishing regular feeding habits at the facility. Frightening programs are only effective for short periods because the birds soon lose their fear and some will continue to feed and attract other birds to the site. The effectiveness of a frightening program can be enhanced by the use of rifles or shotguns (with an appropriate permit). Frightening devices and techniques include noise (distress calls, pyrotechnic devices, automatic exploders, and electronic noisemakers), visual scare devices (lights, scarecrows, effigies, predator models, mirrors, reflectors, streamers, and vehicles), radio-controlled airplanes and boats, water spray devices, patrols and visitation, and dogs.

### *Modify the habitat on or near facilities to discourage predators*

Relatively minor changes in habitat on or near farms can help reduce losses or make other management efforts more effective. Keeping the facility free of debris, trash, excessive vegetation, and food (spilled fish feed and open bags of feed) will make the site less attractive to predators. Changes in fish culture practices may also make the facility less prone to losses. Small fish are more susceptible to predation than large fish, so raceways or tanks with small fish should be located near buildings or close to areas with more human activity. Delayed stocking of small fish in the spring may be an option if the predation problem involves seasonal birds such as common grackles.

## Mortality Removal and Disposal

Mortality of cultured species in aquaculture is unpredictable and highly variable among rearing units and facilities. A facility may experience chronic mortality of a few fish per day or a catastrophic loss caused by infectious disease, acute environmental stress, or structural failure. Depending on water temperature and species, dead fish either float or sink, with warmwater fish typically floating and coldwater fish sinking. In flow-through production systems mortalities tend to accumulate on the screens at the end of the rearing units.

Dead fish cause several problems in flow-through aquaculture. Dead fish may serve as a source of infectious agents that may spread to other culture units or into effluent-receiving waters. Decomposition of dead fish degrades water quality inside culture units and in effluents. Dead fish may also restrict water flow and cause overflow of the culture unit or failure of tank or raceway structural components. Dead fish must be disposed of using an environmentally sensitive approach.

### Better Management Practices for Mortality Removal and Disposal

#### *Follow recommended aquatic animal health management practices*

Prevention and minimization of mortalities through proper fish health surveillance and management are the best methods for managing mortalities. Reducing losses to infectious or environmental diseases will reduce the need to remove and dispose of dead fish. Fish health management includes timely removal of dead and moribund fish, which can be a potential source of pathogens. Analyzing mortality rates and trends for each rearing unit may identify developing fish health problems before they become severe and may provide diagnostic information that may help identify the cause. Most states offer diagnostic services and treatment recommendations for disease problems. General guidance on aquatic animal health management is presented in Chapter 12.

#### *Regularly remove dead fish from rearing units*

Dead fish that accumulate on a screen impede the free flow of water from one rearing unit to the next, and the increased water pressure may cause the screen to fail, resulting in fish escape or diversion of flow away from downstream rearing units. On facilities with quiescent zones at the end of raceways, dead fish will accumulate on the screen that separates the rearing area from the quiescent zone, which may decrease the solids settling efficiency in the quiescent zone.

Dead fish should be removed daily as part of routine operations. Screens should be checked for debris and dead fish and cleaned at the beginning of each work day. Depending on rates of fish loss, screens should be rechecked throughout the day. Dead and moribund fish are commonly removed with a long-handle dip net from raceways and placed into a bucket or barrel. The head of the dip net is rectangular and the net is shallow relative to those normally used to catch fish. This design of the mort net allows rapid removal of dead and moribund fish. The dip net should be disinfected between uses among rearing units to minimize spread of pathogens by dipping into a bleach or iodine solution. Nets and other equipment used to handle dead fish should be separated from other equipment and thoroughly disinfected after all dead fish are collected for the day. Mortalities from each rearing unit should be recorded by weight, number, or both. Mortalities can then be subtracted from estimated population totals to maintain an inventory for each rearing unit and the facility.

#### *Prevent the discharge of dead fish into receiving waters*

National Pollutant Discharge Elimination System permits include prohibited discharges such as “any floating, suspended or submerged matter, including dead fish, in amounts causing nuisance or objectionable condition or that may impair designated beneficial uses in the receiving water” or “the discharge of fish mortalities, kill spawning, processing wastes, and leachate from these materials to waters of the United States is prohibited.”

(USEPA 2006a, b). In the event of a structural failure or other catastrophe that results in the unauthorized discharge of mortalities to a receiving water the permittee must notify the permitting agency by telephone within 24 hours from the time the permittee became aware of the circumstances.

Appropriate screens between each rearing unit and on the outlet to the receiving water will prevent the discharge of mortalities. There are, however, restoration and stock-enhancement activities where spawned carcasses of salmonids are returned to waters for nutrient replacement. State, federal, or tribal hatcheries usually conduct these activities.

### *Use approved methods for mortality disposal*

Disposal methods are site-specific and usually governed by state or local regulations. In Idaho, the State Department of Agriculture regulates dead animal movement and disposal. The regulations specifically include commercial fish under the definition for dead animals. Approved methods of disposal under the Idaho Code include rendering, burial, disposal in an approved sanitary landfill, composting, digestion, incineration, burning (as authorized by the Administrator), and decomposition under specific conditions. Mortalities may be used as fertilizer in some localities. Check the appropriate state agency for approved mortality disposal methods.

Burial may be the most common method of fish mortality disposal. Under the Idaho Administrative Code (IDAPA 02.04.17), dead animals must be buried to such a depth that every part of the dead animal is covered with at least 92 cm (36 inches) of earth. The location of the burial site must be

1) At least 92 m from any wells, surface water intake structures, and public or private drinking water supply lakes or springs;
2) At least 92 m from any existing residences;
3) At least 15 m from property lines;
4) At least 30 m from public roadways;
5) At least 61.5 m from any body of surface water such as a river, stream, lake, pond, intermittent stream, or sinkhole; and
6) Burial sites shall not be located in low-lying areas subject to flooding, or in areas with a high water table where the seasonal high water level may contact the burial pit.

Situations occur where the number of dead fish is large enough to require extraordinary disposal measures. When such a situation occurs in the state of Idaho, the Administrator for the Department of Agriculture may take exceptional or extraordinary methods as necessary to protect the health and welfare of human and animal populations. One such method is mass burial.

Rendering can be a desirable disposal method if a rendering plant is relatively nearby and if dead fish are acceptable at the plant. In Idaho a rendering plant must be licensed and approved by the State Department of Agriculture. In some instances the rendering plant will pick up the dead animals, but usually farm personnel will transport fish to the plant. In either situation, the Idaho code prohibits any liquid or fluid from the dead animals to drip or seep from the vehicle during transport. In addition dead animals must be concealed from public view during transport and the vehicle hauling the dead animals must proceed directly to the destination. Dead fish mortalities are usually transported in leak-proof barrels in the back of pickup trucks.

Composting of dead animals in Idaho must be done with methods approved by the Administrator of the Department of Agriculture Environmental Quality. Composting may offer an alternative that uses less labor and reduces environmental risk compared with burial. Composting has been widely used on poultry farms to manage mortalities and the techniques used on poultry farms have been adapted to fish farms (Fornshell et al. 1998) (Box 9.6).

## Facility Operation and Maintenance

Flow-through aquaculture systems are among the most expensive to build and require substantial investment to operate. They require constant management of water supply and flow-control structures, oxygenation equipment (if present), tank structures, and waste management systems. Because of the high biomass of fish held in flow-through rearing units, fish loss will occur within minutes of water flow cessation or problems with oxygen delivery. Discharges may also exceed permitted limits if waste management structures and operations are not maintained. Flow-through aquaculture facilities subject to the federal Aquaculture Effluent Limitation Guidelines (Federal Register 2004) are required to include

### BOX 9.6
### Composting Dead Fish

Dead fish can be composted in structures adapted from poultry farms. A series of three square wooden bins, approximately 1.2 m on a side, are constructed with each board attached to the frame to provide a 2.5-cm slot between boards. The slot facilitates passive aeration of the compost pile. The front of each bin has a series of removable boards, similar to dam boards in a raceway, for access. Wire mesh is placed around the bottom of each bin and on the lid of each bin to keep animals out. A base layer of straw about 30 cm thick is added to the first bin. Dead fish are placed in the center of the bin and covered with about 15 cm of straw. Each day additional fish and straw are added until the bin is full. Once the first bin is full the material is “flipped” into the adjacent bin and the process begins again with the first bin. When the first bin is filled again, the material from the second bin is flipped into the third bin and the material in the first bin is flipped into the second bin. On a test facility with an estimated annual production of 35,000 to 45,000 kg of trout, the first bin was filled in about 3 weeks based on a daily average of 5 kg of dead fish. Fish compost temperatures usually surpass 60°C, even in winter. By the time the third bin is emptied there is little or no evidence of fish remaining, but the material is not yet true compost because it contains partially decomposed straw. The material can be recycled back into the first bin as an amendment or left as a freestanding compost pile that will continue to decompose.

specific management practices and record-keeping activities as part of a management plan included with their National Pollutant Discharge Elimination System (NPDES) permits (USEPA 2006c). Facilities that are managed efficiently and operated in compliance with all applicable laws and regulations will simultaneously improve long-term economic performance and reduce environmental impacts.

## ***Better Management Practices for Facility Operation and Maintenance***

### *Maintain the facility in good condition*

A log or other written record should be used to schedule and record facility maintenance activities. A written record will provide documentation of maintenance for regulatory and management purposes, but also can help identify aspects of the farm where management approaches may be changed to reduce maintenance and costs, and improve efficiency. The frequency of maintenance activities may vary depending on the location, facility age, and mode of operation. Some recommended maintenance schedules are listed below.

### *Daily maintenance*

Visually inspect water-flow control structures to ensure proper function, and make adjustments as needed to maintain suitable flow or bypass. Examine dam boards, weirs, or other flow control structures for leaks and structural integrity, and repair or replace as necessary. Water flows to the different segments of the farm should be adjusted as fish loading and management goals dictate.

Inspect and clean debris screens and fish-exclusion screens daily. Any leaks from pipes or flumes should be scheduled for repair. Examine discharge screens for clogging and damage from predators, and make any necessary repairs to screens as soon as possible.

### *Monthly maintenance*

Hatchery buildings, raceways, and settling basins should be inspected at least monthly to ensure employee safety, fish holding capability, and system performance. Visually examine raceway walls for cracks and repair immediately to prevent deterioration. Roads, bridges, and other infrastructure should be inspected regularly and scheduled for repair as needed.

Visually inspect chemical and feed storage areas for signs of leakage into or from the facilities and for rodent or other pest infestation. Fuel or other petroleum product storage containers or tanks should be inspected for leakage and response taken quickly if leaks are detected.

### *Maintain all equipment in good working condition*

Use the best equipment affordable and develop a maintenance program to assure that equipment is always in good repair. Maintain a file on each major piece of equipment that contains maintenance logs, operating manuals, and warranty information. Maintain an on-site inventory of frequently used repair and replacement parts for critical equipment. All personnel should be trained to properly use equipment and should know the location of back-up equipment, tools, spare parts, and other materials that may be needed if equipment fails.

### *Use and store petroleum products to prevent contamination of the environment*

Petroleum leaking from storage tanks or farm equipment wastes a valuable resource and can contaminate surface or underground water supplies. Petroleum storage in aboveground and underground tanks is regulated by federal and state laws, and information can be obtained from state departments of commerce, state departments of environmental quality or protection, or from regional USEPA offices. A protective containment berm that retains leakage or tank contents in the event of failure can be constructed around storage tanks, and secondary containment tanks or liners may be required in some areas. Fuel storage tanks should be located at least 50 m and downslope from groundwater wells and surface waters. A regular maintenance schedule should be implemented for tractors, trucks, and other equipment to prevent oil and fuel leaks. Store used oil in a designated waste oil container until recycled. State and federal law requires reporting of significant spills of petroleum products on fish culture facilities.

### *Use and store chemicals to prevent contamination of the environment*

When used according to label directions, chemicals can be used in flow-through culture systems with little or no adverse affect on the environment. The most commonly used chemicals in flow-through systems are water treatments such as salt, parasiticides such as formalin, and disinfectants. Use chemicals only when needed and only for the specific use indicated on the label. Chemical use in flow-through systems is tightly regulated and individuals are responsible for using these products according to label directions and disposing of containers and unused chemicals according to applicable federal and state regulations. Chemicals should be stored in a secure area, away from fish culture areas, feeds, and water sources, in locations that are dry, void of drains, well-ventilated, and not subject to extreme temperatures. Emergency response, spill prevention, and containment planning are a critical part of chemical management on flow-through facilities. Develop an emergency response plan and keep it at a readily accessible location. The plan should specify response procedures and telephone numbers for key staff and emergency and regulatory authorities. All facility employees should be familiar with the plan and its contents. State and federal law requires reporting of significant spills of chemical products on fish culture facilities.

### *Collect and dispose of solid waste on a regular basis and in a responsible manner according to all applicable state and federal regulations*

Solid waste containers should be installed in convenient locations on the farm. Containers should be emptied regularly and the waste disposed of in a permitted landfill or other approved facility.

### *Develop a production planning and record-keeping system*

Proper planning in management of a flow-through aquaculture system helps ensure that water quality, fish health, production, and economic goals are met and environmental impacts are minimized. The key to successful planning in flow-through aquaculture is an effective system of record keeping. Records of water flow, water quality, fish inventory, feeding, waste treatment, fish mortality and health, chemical use, and equipment maintenance are all critically important in sustaining an economically viable and environmentally friendly fish facility. Water flow rate and water quality records will provide a basis for determining carrying capacity for the system, and will assist in determining the basis for changes in fish performance.

Records of activities such as feeding, chemical use, or waste management may be required by state or federal regulations. Although fish inventory, water quality, and feed records are of obvious benefit in management and environmental protection, keeping logs of inspections, maintenance and repairs, employee training, and waste management efforts are also valuable and should be kept as good business practice.

Paper copies of records should be maintained for archival purposes; computerized record-keeping tools can be used for trend analyses and forecasting. Records should be reviewed periodically to determine whether they are useful and to provide insight into opportunities for improvement of farm operation.

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## Chapter 10

# Better Management Practices for Recirculating Aquaculture Systems

*Steven T. Summerfelt and Brian J. Vinci*

## Introduction

Recirculating aquaculture systems use flowing water to intensively culture fish and, by definition, treat and reuse a large proportion of the water to maintain adequate environmental conditions in fish culture units. Recirculating systems use unit treatment processes designed to remediate the effects of fish metabolism on water quality. Processes are incorporated to add dissolved oxygen and to remove solids, dissolved nitrogen compounds (ammonia and nitrite), and dissolved carbon dioxide (Summerfelt et al. 2001). In recirculating systems, fish are confined in tanks, particulate solids are removed by clarifiers or filters, dissolved wastes are reduced by biological filters, gases are added (oxygen) or removed (carbon dioxide) by strippers/aerators, and oxygenation units are used to increase oxygen concentrations above saturation (Table 10.1). Processes to provide advanced oxidation and pH or alkalinity control may also be required.

Recirculating aquaculture systems allow greater control of the rearing environment, especially water temperature, than is possible in flow-through, pond, or net-pen culture systems. Recirculating aquaculture systems minimize water use, allowing fish production in regions where water is scarce. However, minimizing water use also puts wastes into a concentrated and relatively small volume effluent (Chen et al. 1997). The concentrated effluent reduces the volume of wastewater to be treated and, thus, the size and cost of wastewater treatment. The concentrating effect from recycling water also can in some instances make it practical for recirculating aquaculture systems to discharge directly to publicly owned treatment works (POTWs). The increased waste capture efficiency significantly reduces the waste load discharged in facility effluent (Chen et al. 2002), sometimes allowing recirculating aquaculture systems to produce fish in locations that must contend with strict environmental regulations. In addition, recirculating aquaculture systems are more amenable to implementation of biosecurity measures than outdoor systems because of a smaller facility footprint, reduced water use, and a more intensive level of management (Summerfelt et al. 2001). Recirculating aquaculture systems also allow fish farms to locate near markets that provide a better price for locally produced or fresh fish.

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**Table 10.1.** Unit processes used in recirculating aquaculture systems to control water quality.

| Component | Purpose | Example Types |
|---|---|---|
| Culture unit | Contain fish during growout, allow fish to feed, and flush feces | Circular or octagonal tanks<br>Linear-flow raceways<br>Mixed-cell raceways |
| Solids removal | Remove solids via settling, sieving, flotation, or filtration | Microscreen filters<br>Settling basins<br>Tube/plate settlers<br>Roughing filters (packed with random rock or plastic, or with structured plastic)<br>Swirl separators<br>Pressurized filters (sand, activated carbon, and plastic bead)<br>Gravity filters (high rate sand and slow sand)<br>Flotation/foam fractionation |
| Biofiltration | Provide surface area where microorganisms can establish; when the reused flow passes across these surfaces, the microbes remove a portion of the dissolved wastes | Fluidized media reactors<br>Rotating biological contactors<br>Trickling filters<br>Submerged large media filters<br>Pressurized bead filters |
| Stripping/aeration | Contact water with air at near atmospheric pressures | Mechanical-surface mixers<br>Diffusers<br>Columns (open to atmosphere or enclosed with forced ventilation)<br>a. Packed or tray<br>b. Spray<br>Shallow airlifts<br>Corrugated inclined plane<br>Stair-type drops |
| Oxygenation | Contact water with purified oxygen at pressures greater than atmospheric. | U-tubes<br>Columns (atmospheric pressure and pressurized)<br>a. Multistage[a]<br>b. Packed or tray<br>c. Spray<br>Oxygenation cones<br>Oxygen aspirators<br>Diffusers<br>Enclosed mechanical-surface mixers |
| Ozonation | Oxidize constituents in the water | Same types of equipment described above for “Oxygenation” |

[a] Low-head oxygenators.

Costs of constructing and operating recirculating systems can increase the cost of producing fish in to the point that they cannot compete economically against less costly technologies. For example, recirculating systems are not typically used to produce channel catfish (*Ictalurus punctatus*), which are most cost-effectively produced in ponds. Likewise, the production of food-size rainbow trout (*Oncorhynchus mykiss*) or salmon in commercial recirculating systems is still minor compared to the biomass commercially cultured in flow-through systems and net-pen systems, respectively. Commercial recirculating aquaculture systems are being used to produce relatively higher-value fish or fish that can be effectively niche-marketed for a higher price, such as salmon smolts, certain ornamental and tropical fish, tilapia (*Oreochromis* spp.), hybrid striped bass (*Morone* hybrids), sturgeon (Acipenseridae), yellow perch (*Perca flavescens*), rainbow trout, walleye (*Sander vitreus*), arctic char (*Salvelinus alpinus*), and halibut (*Hippoglossus* spp.) in North America and eel (*Anguilla anguilla*), sea bass (*Dicentrarchus labrax*), turbot (*Scophthalmus maximus*), and African catfish (*Clarias gariepinus*) in Europe (Summerfelt et al. 2001). Additionally, recirculating aquaculture systems in North America are being used at public hatcheries to produce trout, char, and salmon for recreational stock enhancement or restoration of threatened and endangered aquatic species (Brazil et al. 2004; Summerfelt et al. 2004a).

Under the 2004 federal aquaculture effluent limitation guidelines (Federal Register 2004), recirculating aquaculture systems with an annual production exceeding 45,454 kg (100,000 pounds) are classified as concentrated aquatic animal production (CAAP) facilities and are required to obtain a National Pollutant Discharge Elimination System (NPDES) permit before discharging wastes into waters of the United States. The NPDES permit is contingent upon development of a facility-specific best management practices (BMP) plan that specifies how the permittee will reduce discharge of potential pollutants (see Chapter 4 for details of the requirements). Discharges into sewers flowing into POTWs are not covered under the 2004 aquaculture effluent limitation guidelines.

Although there are a number of diverse recirculating aquaculture systems, only a few recirculating aquaculture systems discharging wastewater directly to a receiving water body (and not to a POTW) have an annual production exceeding 45,454 kg. In the case of tilapia for example, according to the American Tilapia Association, recirculating systems accounted for more than 75% of the more than 8,000 tonnes of annual tilapia production in the United States by the end of the 1990s. Presently, several of the largest tilapia producers in the United States have no discharge to receiving waters because they discharge to POTWs. Some of the larger commercial recirculating aquaculture systems that produce tilapia also agronomically apply their concentrated wastes on fields or treat these wastes within constructed wetlands before discharge.

There is great heterogeneity among recirculating systems, in part due to the wide variety of species being cultured and the broad range of conditions under which the fish must be grown. Differences exist even among systems used to culture the same species, especially in different regions of the continent. Continuing with the tilapia example, some recirculating tilapia production systems rely completely on traditional physical/chemical and fixed-film biological treatment processes (Liao and Mayo 1974; Timmons and Losordo 1994; Summerfelt 1996; Timmons et al. 2002) while others use a green water (Drapcho and Brune 2000; Brune et al. 2003) or other suspended-growth treatment process (Serfling 2000, 2006). Others include an aquaponic component (Rakocy et al. 1992; Rakocy 1997) to treat the water using plants that are also marketed as produce. Total suspended solids (TSS) concentration in these different systems can range from less than 10 mg/L to greater than 150 mg/L. Thus, various recirculating systems can have distinctly different water quality and volumes of water discharged (Twarowska et al. 1997; Chen et al. 2002). Therefore, the design of waste management systems must consider the specifics of each recirculating aquaculture system to successfully achieve waste collection, transfer, storage, treatment, and utilization. A waste management system that works specifically with a particular facility cannot be assumed appropriate for another facility.

Another important example of the heterogeneity among recirculating systems is the application of semirecirculating or partial-reuse systems that use large volumes of make-up water, similar to some flow-through facilities, yet employ internal water treatment technologies to allow for multiple water uses that increase fish production and waste capture efficiencies (Wheaton 1991; Summerfelt et al. 2004b; Vinci et al. 2004). Partial-reuse and semirecirculating systems are used in coldwater, coolwater, and warmwater fish culture applications, but the water temperature in this type of system is largely dependent on the make-up water temperature, unless the recirculating water is passively or actively heated or cooled. One large semirecirculating system (Massingill et al. 1998) is located in an area of the southwest United States where large volumes of surface and groundwaters are used for irrigation, and in this type of situation the fish farm discharge can be directed into canals for use irrigating vegetables or other crops. In these relatively unique situations, semirecirculating systems and integrated aquaculture-agricultural practices can lower production costs for both products, conserve water (i.e., water is not consumed), and eliminate environmental effects from discharge, because much of the waste load is consumed on-farm.

Although most larger recirculating aquaculture systems require a continuous but relatively small flow of make-up water, recirculating systems are clearly distinguishable from flow-through systems because recirculating systems require biological treatment within the system to prevent ammonia from accumulating to harmful levels and they have a distinctly different hydraulic residence time (Liao and Mayo 1974; Chen et al. 2002). Flow-through systems will typically operate with an overall hydraulic residence time less than 1 to 3 hours (IDEQ, undated). However, a recirculating system with a hydraulic residence time of at least 12 hours would be considered an open system, yet this system would likely capture and remove >90% of the particulate solids produced while controlling culture tank water quality. A longer hydraulic residence time is indicative of a higher degree of water reuse, and particulate waste capture efficiencies will approach 100% as recirculating system hydraulic residence time approaches or exceeds 10 days. Therefore, to maintain suitable water quality, recirculating systems must assume the treatment burden for 90 to 100% of the ammonia and particulate waste produced. This is similar to the waste treatment burden carried in static-water pond aquaculture, and both systems carry a much higher waste treatment burden than flow-through or net-pen systems.

## Recirculating Aquaculture Systems and the Environment

Recirculating aquaculture systems are unique among the other production systems described in this book and, as such, they have a unique set of potential environmental impacts. For many recirculating aquaculture systems, the lack of direct hydraulic connectivity with the environment means that environmental issues that are critical in other systems—such as fish escapes and disease transfer to wild stocks—are easily controlled. In addition, recirculating aquaculture systems are most often enclosed in a building to control water temperatures, and they use only small amounts of makeup water. These features make the facility more amenable to biosecurity measures. Either by design or through implementation of biosecurity practices, it is easy to exclude predators and to prevent exchange of fish pathogens between an indoor facility and outside waters (Summerfelt et al. 2001).

The major facility-level environmental issues when using recirculating systems are the point-source waste streams generated during culture. This is therefore the focus of this chapter. Two distinct waste streams may be produced: small but concentrated slurries of captured biosolids and, in some cases, more dilute but relatively larger volume system overflows. The volume of system overflow from recirculating systems is much smaller than that discharged from a typical flow-through fish culture system (Figs. 10.1 and 10.2).

Concentrated slurries of captured biosolids are created by the backwash of the solids capture unit, such as a microscreen filter or settling unit. The slurry of captured biosolids will typically contain most of the suspended solids, biochemical oxygen demand, and total phosphorus produced in the recirculating system (Heinen et al. 1996; Davidson and Summerfelt 2005). However, if present, the larger volume system overflow—created when system volume is displaced by the addition of new water—will often contain most of the total nitrogen produced in the system. The overflow will likely have concentrations of dissolved organic nitrogen and suspended solids that are comparable to, or less than, that found in the fish culture tanks (Davidson and Summerfelt 2005). The largest fraction (75 to 80%) of total nitrogen contained in the system overflow is in the form of dissolved inorganic nitrogen (Braaten 1991; Heinen et al. 1996), most likely split between total ammonia (un-ionized ammonia and ammonium) and nitrate. The ratio of total ammonia to nitrate depends on the degree of nitrification that occurs in the system relative to denitrification. Filterable or settleable solids within the unit contain relatively little (about 15%) of total effluent nitrogen but most (50 to 85%) of the effluent phosphorus (Braaten 1991; Heinen et al. 1996). The large variability in the phosphorus fractionation between dissolved and particulate matter is principally caused by the duration of biosolids storage in the recirculating system (or its downstream treatment processes) and the type and level of phosphorus in the fish feed.

Dealing with these point sources of waste requires capturing, transferring, storing, treating, or utilizing the concentrated waste biosolids and—sometimes—the comparatively

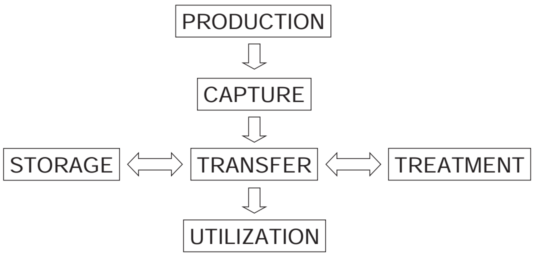

**Fig. 10.1.** Waste management requires that wastes that are produced are captured first and then transferred to units for storage, treatment, or some form of utilization.

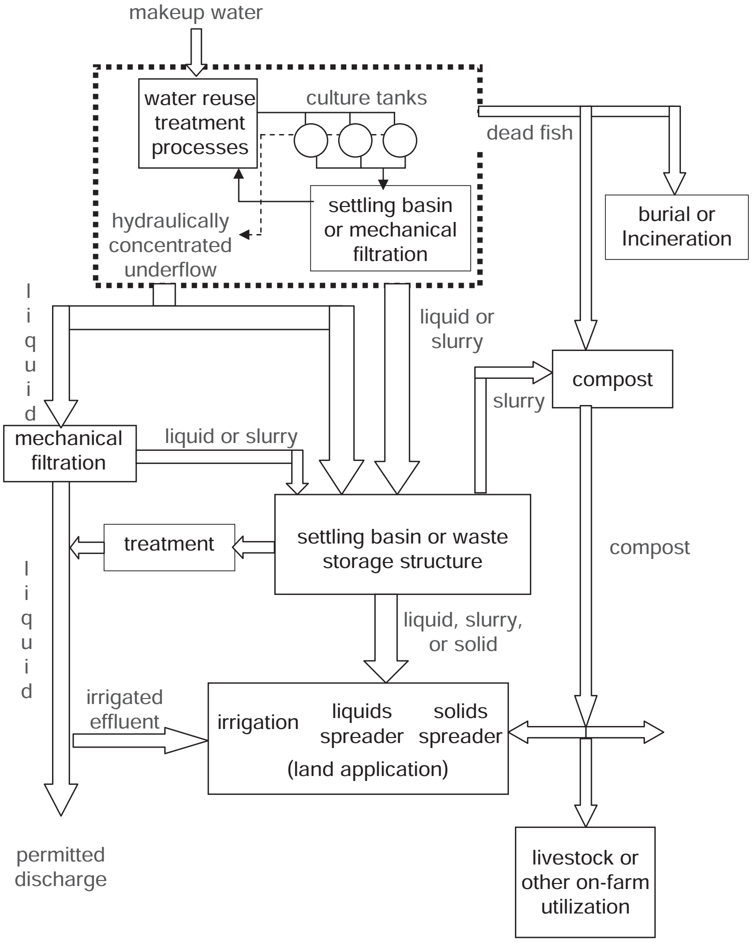

**Fig. 10.2.** Possible waste management routes to first capture or treat the wastes and then transfer wastes to storage, treatment, or some form of utilization.

concentrated recirculating system overflow. Removing waste biosolids from all water flows as rapidly as possible is probably the best approach to minimizing release of phosphorus and organic matter to the environment, because these constituents leach rapidly from captured or thickening biosolids (Brazil and Summerfelt 2006; Ebeling et al. 2006). The comparatively small overflow from recirculating systems may contain concentrated dissolved wastes that must also be treated before the effluent can legally be discharged. Fortunately, concentrating the dissolved wastes into a comparatively small production-system overflow reduces the volume of wastewater to be treated and provides increased waste treatment efficiency. This significantly reduces the size and cost of on-site wastewater treatment (Summerfelt 1999; Chen et al. 2002). In fact, the waste-concentrating effect that is inherent in the design of recirculating systems can, in some instances, make it practical to discharge wastes directly to POTWs.

## Site Selection

Location on substandard sites is a frequent cause of failure of aquaculture projects. Most of the siting criteria important in reducing environmental impacts of recirculating aquaculture systems are also critical in assuring profitability of the venture. For example, facilities should not be built in areas prone to flooding to avoid contaminating the system with surface water or even losing fish and equipment to floods. Site selection also requires identification of a reliable make-up water supply for the system that is clean, uncontaminated, and of sufficient volume to meet system requirements. As such, a careful site evaluation should be made prior to construction regardless of the legal requirements. Identification of potential problems before construction and either addressing those problems or locating an alternative site is much less expensive and more environmentally benign than solving problems by implementing mitigation measures after construction or, in the extreme, having to close the farm and abandon the site. Because of the relatively small facility footprints and water requirements, siting of recirculating aquaculture systems is commonly less of a problem than for other production systems.

### *Better Management Practices for Site Selection*

#### *Do not site facilities where regulatory restrictions apply*

A site must be considered carefully before construction to identify all restrictions and regulations that may apply to the use of the land and water for aquaculture. City and county zoning and building restrictions differ widely among locations and can affect construction requirements and costs. Local, state, or federal agencies may have authority over land use, water use (including discharge into waters of the United States), and building construction. For guidance, contact the local state office of environmental quality and the local state office of the United States Department of Agriculture Natural Resources Conservation Service (NRCS). A National Pollutant Discharge Elimination System (NPDES) permit administered under the federal Clean Water Act may be required. Additional site review may be required by the United States Army Corps of Engineers, which administers and enforces provisions of Section 404 of the Clean Water Act. Section 404 regulates, among other activities, conversion of wetlands to farming, including aquaculture facilities. Local and state coastal zone agencies can restrict development in the coastal zone and may require extensive design review of architectural design and layout features.

Recirculating aquaculture systems should not be sited where the discharge may impair protected water resources, at-risk water bodies, and special habitats. These areas are generally excluded from coverage under an NPDES permit and typically are sensitive habitats for threatened and endangered species. At-risk water bodies may include downstream drinking water intakes for municipalities.

#### *Site facilities only in areas with suitable topography and hydrology*

When selecting a site to build a recirculating system, avoid flood-prone areas. Floods can contaminate the system with surface water, damage equipment, or cause catastrophic loss of fish. Site topography should allow for discharge into receiving waters at an elevation above flood level. Site topography should also allow construction of sump pumps, culture tanks, and any required treatment vessels in a manner that considers water table depth to avoid floating an empty vessel if the ground becomes saturated with water.

Construction of facilities and access roads should not alter natural water flows needed to sustain surrounding habitats. Unit processes used for wastewater treatment (such as tanks, ponds, or wetlands) should not be located where containment failure could result in loss of life or damage to residences, industrial buildings, highways, public utilities, or environmentally sensitive areas.

## Feeds and Feeding

Feed is the major input of nitrogen, phosphorus, organic matter, and solids in recirculating aquaculture systems (Liao and Mayo 1974; Chen et al. 2002). The water treatment processes in a recirculating system remove or transform a portion of feed-derived wastes in the recirculating water. Therefore, the concentration of wastes within the fish culture water are much lower than expected based on waste loading from feed (Liao and Mayo 1974; Summerfelt and Vinci 2004b). Operating recirculating systems at a feed loading within the assimilative capacity of the water treatment processes is important to maintain water quality inside the culture tank and provide a better environment for fish growth (Colt et al. 1991; Colt 2006). For recirculating aquaculture systems, the loading of potential pollutants to a receiving body of water is not entirely related to feed input, but is dependent on the effectiveness of waste capture and treatment processes within the recirculating system and on any additional effluent treatment processes used to clean the water before discharge (Losordo et al. 1994; Summerfelt 1999; Chen et al. 2002; Davidson and Summerfelt 2005). Feed management is therefore only one factor among many in the control of potential pollution from recirculating aquaculture systems. Feed management does, however, provide benefits other than environmental protection. Feed represents the largest single variable cost of fish production, and feeding methods that minimize waste feed and maximize productivity will improve production efficiency and farm profitability. Minimizing waste feed will minimize the wastes that must be treated in the recirculating system and ultimately the amount of waste released to the environment. Feed management is therefore one of the most important aspects of recirculating aquaculture systems.

Fish nutrition and feeding practices are active areas of research, and technology is constantly evolving. An important research goal is to improve the efficiency of nutrient utilization by fish, thereby enhancing economic returns and reducing waste production. Because technology is rapidly changing, feed management should be flexible so that newer and better practices can be implemented as they become available.

### *Better Management Practices for Feeds and Feeding*

#### *Use high-quality feeds*

Feeds should be formulated to meet the nutritional requirements of the cultured fish and to optimize digestibility, improve efficiency, and reduce waste output (Gatlin and Hardy

2002). For feeds used in recirculating systems, minimizing metabolic excretion of nitrogen from amino acids catabolized to provide metabolic energy and minimizing nitrogen excretion in feces from indigestible protein are important in feed formulation. Therefore high-quality feeds for recirculating systems are 1) those with amino acid profiles that meet but do not substantially exceed dietary requirements for individual essential amino acids and 2) those containing sufficient dietary energy from carbohydrates and lipids to spare dietary protein for tissue synthesis. Further, available phosphorus in feeds should slightly exceed the dietary requirements of the fish, taking into consideration the species and life history stage. Efforts should be made in feed formulation to keep total phosphorus levels as low as possible while maintaining appropriate available phosphorus levels. Finally, feeds should be formulated using highly digestible feed ingredients, especially those having high apparent digestibility coefficients for dry matter and protein. Feed pellets should be water stable and should be shipped and handled at the farm to minimize pellet breakage and production of fine particles. Stored feed should be secure from contamination, vermin, moisture, and excessive heat. Long-term storage of feed can affect feed quality. Feed should be rotated (use oldest feed first) and not stored beyond the manufacturer's recommended length of time.

### *Use efficient feeding practices*

The feed ration for a given species is influenced by feed formulation, water temperature, fish size, dissolved oxygen and carbon dioxide concentrations, fish health, and management goals (Goddard 1995). Feed size should be appropriate for the size of fish in each rearing unit. Feed ration should optimize the balance between maximum growth and maximum feed efficiency. Feed can be delivered by hand, by demand feeders, or by mechanical and automatic feeders. Whenever possible, feed utilization should be monitored by observing feeding behavior or by looking for trends in waste feed that collects within the culture unit or waste feed exiting the culture unit (Goddard 1995; Summerfelt et al. 1995). Multiple feedings distributed over a 24-hour period will provide more uniform water quality within a recirculating system than a feeding schedule offering feed only once or twice daily.

Feeding equipment improperly adjusted or malfunctioning can over- or underfeed a population of cultured species, which can diminish feed and production efficiency. Therefore, feeding equipment should be checked periodically to ensure efficient operation.

### *Feed within the carrying capacity of the system*

Unlike open systems, such as flow-through raceways, the loading of potential pollutants to a receiving body of water from a recirculating system is primarily dependent on waste capture and treatment processes within the system rather than on feed input (Liao and Mayo 1974; Summerfelt and Vinci 2004b). Loading from recirculating systems also depends on any additional effluent treatment processes used to clean the water before discharge (Chen et al. 1997, 2002). However, increased waste production and waste discharge can be a direct consequence of operating at feed levels in excess of the recirculating system's carrying capacity.

Water quality criteria required to maintain healthy and fast-growing fish are the basis for designing water-reuse processes. The parameters of primary concern are dissolved ammonia, nitrite, oxygen, carbon dioxide, nitrogen, and solids (Noble and Summerfelt 1996; Summerfelt et al. 2001; Colt 2006) because those variables can affect fish growth and health. Certain fish, such as salmonids, require excellent water quality for health and fast growth. Maintaining high water quality standards within recirculating systems requires effective treatment of all waste metabolites that could compromise fish health, The following should be considered during system design (Summerfelt et al. 2001; Summerfelt and Vinci 2004a, b):

1) Selection of unit processes that achieve high removal efficiencies;
2) Specification of culture tank exchange rates that are rapid enough to adequately supply dissolved oxygen and also prevent the waste produced during one pass through the culture system from degrading water quality; and
3) A system design that allows for relatively simple cleaning routines to remove sediment and biological growth from all pipes, sumps, channels, and unit processes within the recirculating system.

Fish respiration (consumption of dissolved oxygen and production of carbon dioxide) and the production of waste metabolites are proportional to feeding levels (Beveridge et al. 1991; Colt et al. 1991). Therefore, to maintain adequate water quality, recirculating aquaculture systems should be operated at feeding levels that are within the assimilative capacity of the system's water treatment processes and water flows (Summerfelt et al. 2001; Summerfelt and Vinci 2004a, b). Dissolved oxygen is usually the first environmental variable to limit culture tank carrying capacity (Colt and Watten 1988; Colt and Orwicz 1991; Colt et al. 1991) which, in simplistic terms, is the maximum fish biomass that can be supported at a selected feeding rate. In most tank-based recirculating aquaculture systems, carrying capacity is not determined by the volume of water in the system's culture units but rather by in-tank aeration, oxygen supplementation, and water flow (Colt and Orwicz 1991; Colt et al. 1991; Colt and Watten 1988).

Flowing water carries dissolved oxygen to the culture unit, receives the waste produced in the culture unit, and carries the wastes away from the culture unit to treatment units before they accumulate to harmful levels. Water flow requirements through culture units within the system can be much greater than make-up water flow requirements that flush the system, because recirculating systems will, by definition, treat and reuse large portions of the system make-up water flow. Of primary importance is the removal of waste metabolites—ammonia, carbon dioxide, and TSS—whose production is directly proportional to feed load. Biofilters, aeration columns, and filters/clarifiers are unit processes used to control ammonia, carbon dioxide, and TSS accumulation within recirculating systems. Aquacultural engineering texts and many other publications provide the methodology to design biofilters, aeration columns, and filters/clarifiers to treat a given flow or the waste metabolites produced by a given feeding rate (Timmons and Losordo 1994; Summerfelt 1996; Summerfelt et al. 2001; Timmons et al. 2002).

Liao and Mayo (1972) used a steady-state mass balance to predict the expected water quality exiting a culture tank ($C_{out}$) within a recirculating system based on the mean rate that waste metabolites are produced, $P_{\text{waste}}$ (kg waste/day), the efficiency that water treatment processes remove the waste (i.e., the waste fraction removed, $f_{\text{rem}}$), the recycle water flow rate, $Q$ (L/minute), and the fraction of water flow that is reused, $R = [(Q - Q_{\text{new}})/Q]$. Summerfelt et al. (2001) and Summerfelt and Vinci (2004b) modified this mass balance to account for concentration of waste, $C_{\text{new}}$ (mg/L) in the make-up flow ($Q_{\text{new}}$) as shown in the following equation:

$$\mathrm{C}_{\text{out}} = \left\{ \left( \frac{1}{1 - R + (R \cdot f_{\text{rem}})} \right) \left( \frac{P_{\text{waste}}}{Q} \right) \left( \frac{10^6\,\text{mg}}{\text{kg}} \right) \left( \frac{\text{day}}{1{,}440\,\text{min}} \right) \right\} + \{(1 - R)(C_{\text{new}})\} \tag{10.1}$$

For practical purposes, $P_{\text{waste}}$ can be estimated from the mean feed-specific waste production constant, $a_{\text{waste}}$ (kg waste/kg feed), the feeding rate, $r_{\text{feed}}$ (kg feed/day per kg fish), the culture tank volume, $V_{\text{tank}}$ (m$^3$), and fish density, $\rho_{\text{fish}}$ (kg fish/m$^3$ culture volume), as shown in the following equation:

$$P_{waste} = (V_{tank})(\rho_{fish})(r_{feed})(a_{waste}) \tag{10.2}$$

Most warmwater recirculating systems operating in temperate climates reuse nearly all of the recirculating flow to conserve heated water, generally operating with $R > 0.99$ where $R = [(Q - Q_{\text{new}})/Q]$ as defined above. However, these warmwater recirculating systems will usually replace less than 40% of the total water volume of the reuse system on a daily basis (Summerfelt and Vinci 2004b). In these warmwater recirculating systems, waste accumulation depends mostly on the ratio of $P_{\text{waste}}$ to $Q$ (which is the mean concentration of waste that would be produced in a single pass through the tank) and the $f_{\text{rem}}$ across the water treatment units (Fig. 10.3). Even in recirculating systems that use significantly more make-up water ($R$ = 0.90 to 0.99) to maintain cool or coldwater temperatures, the accumulation of wastes in recirculating systems is largely controlled by $P_{\text{waste}}/Q$ and the $f_{\text{rem}}$ across the water treatment units; $C_{\text{waste}}$ is little influenced by $R$ until $f_{\text{rem}}$ is less than approximately 0.5 (Fig. 10.3). Thus, selection of biofilters, carbon dioxide stripping units, and solids capture equipment that provide a $f_{\text{rem}}$ of greater than approximately 0.6 will help control, respectively, total ammonia nitrogen, carbon dioxide, and TSS at concentrations that are not much greater than what would be encountered in a single pass through the fish culture tank. Proper use of this mass balance relationship helps to ensure that the design will provide safe water quality for the fish when they are reared at maximum carrying capacity (Summerfelt and Vinci 2004b).

## Solids Management

Particulate wastes include uneaten feed, dissolved metabolites, and fish feces (Beveridge et al. 1991; Chen et al. 1997). Waste feed and fish fecal matter are waterborne and require separation for efficient management of water quality within the recirculating system. In fact, waste biosolid management (Fig. 10.1) is arguably the most critical process in recirculating aquaculture systems. Solids decomposition can degrade system and effluent water

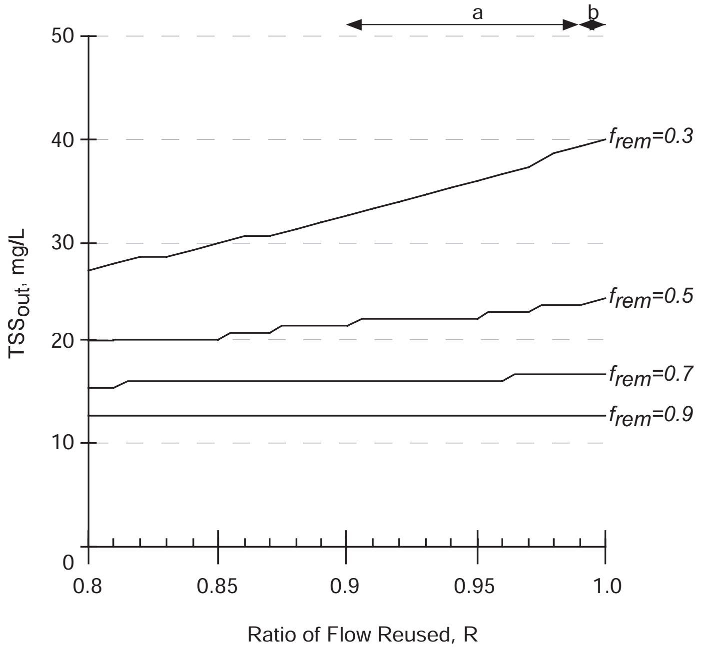

**Fig. 10.3.** The mean waste concentration of effluent from a single-drain fish culture tank (e.g., $TSS_{out}$ in this example) in a water reuse system at steady state is primarily dependent on the concentration of waste generated in a single pass through the tank ($P_{waste}/Q = 10$ mg/L in this example) and the fraction of waste removed ($f_{rem}$) across the waste treatment unit. The concentration of culture tank effluent becomes more dependent on the ratio of flow reused ($R$) when treatment efficiency declines to less than 50%. Letters indicate the typical fraction of flow reused for (a) coldwater and (b) warmwater recirculating systems.

quality and thus directly and indirectly affect fish health, the performance of other unit processes within recirculating systems, and the quality and treatability of the water discharged from the system (Summerfelt 1999; Summerfelt et al. 2001; Chen et al. 2002). Approximately 22% of the feed fed (wet weight) can be removed from a recycle system as TSS on a dry weight basis (Davidson and Summerfelt 2005), but this can range from 10 to 30% depending on system design, fish species, and feed formulation (Chen et al. 1997).

Solids removal is also the primary objective of aquaculture effluent treatment because solids can impact the aquatic environment and should be intercepted and removed as thoroughly as possible prior to discharge (Chen et al. 1997, 2002; Bergheim et al. 1998; Cripps and Kelly 1996; Summerfelt 1999; Cripps and Bergheim 2000). Many recirculating aquaculture systems ultimately must use on-site treatment or disposal to be rid of the relatively small but concentrated slurry of captured biosolids backwashed from the recirculating system because it cannot be discharged to a receiving water (Chen et al. 1994, 1997, 2002; Twarowska et al. 1997; Summerfelt et al. 1999; Adler and Sikora 2005; Brazil and Summerfelt 2006; Ebeling et al. 2006; Summerfelt and Penne 2007; Sharrer et al. 2007). In some cases, it may also be necessary to treat the more dilute but relatively larger volume system overflow before it is discharged (Heinen et al. 1996; Davidson and

Summerfelt, 2005). However, as an alternate to on-site treatment, either of these waste flows could be discharged to a POTW.

Once they are treated, even though the waste concentrations may be relatively high, the cumulative waste load discharged to receiving watersheds from recirculating systems are generally much lower in TSS, biochemical oxygen demand (BOD), total ammonia-nitrogen, and total phosphorus than would be discharged from a similar-sized single-pass or serial-reuse flow-through production facility (Chen et al. 2002).

## *Better Management Practices for Solids*

### *Track water and waste flows using a process-flow drawing*

A simple diagram can be prepared that locates treatment processes and identifies water and waste flow rates in a recirculating aquaculture system and its effluent treatment system. The process-flow drawing will create a simple visual representation of the physical waste production, treatment, transfer, and storage processes. The process-flow drawing must identify each culture tank or system, all relevant treatment processes in each recirculating or effluent treatment system, and waste storage or utilization options, in conjunction with the location and volume of recirculating, makeup, and discharge flow rates. Figure 10.2 can serve as a generic starting point when developing a process-flow drawing for waste management at a specific production facility.

### *Use circular tank designs*

Circular tanks can rapidly concentrate and remove settleable solids. Circular tanks are designed to promote a primary rotating flow that creates a secondary radial flow that carries settleable solids to the bottom center of the tank, making the tank self-cleaning (Timmons et al. 1998; Davidson and Summerfelt 2004). The self-cleaning attribute of the circular tank depends on the overall rate of flow leaving the bottom-center drain, the strength of the bottom radial flow toward the center drain, and the swimming motion of fish resuspending the settled materials. The factors that affect self-cleaning within circular tanks are also influenced by the water inlet and outlet design, tank diameter-to-depth ratio, water rotational period, size and density of fish, size and specific gravity of fish feed and fecal material, water exchange rate through the culture tank, and surface loading rate of water flow through the center of the tank (Timmons et al. 1998; Davidson and Summerfelt 2004). However, in a well-designed circular tank, only about 5 to 20% of the total flow passed through a circular tank may be all that is required to concentrate settleable solids at their bottom and center, which in some instances allows circular culture tanks to be managed as swirl settlers. Solids are often flushed from circular tanks in less than 1 to 4 minutes (Davidson and Summerfelt 2004), which minimizes opportunity for breakdown and dissolution of the particulate matter into smaller particles that are more difficult to remove and that readily leach dissolved organic matter and nutrients. In addition, concentrating solids into a relatively small bottom-drain flow will increase the solids removal efficiency at the downstream solids removal process (Fig. 10.4) in comparison to those removed from an unconcentrated flow (Twarowska et al. 1997; Davidson and Summerfelt 2005; Veerapen et al. 2005).

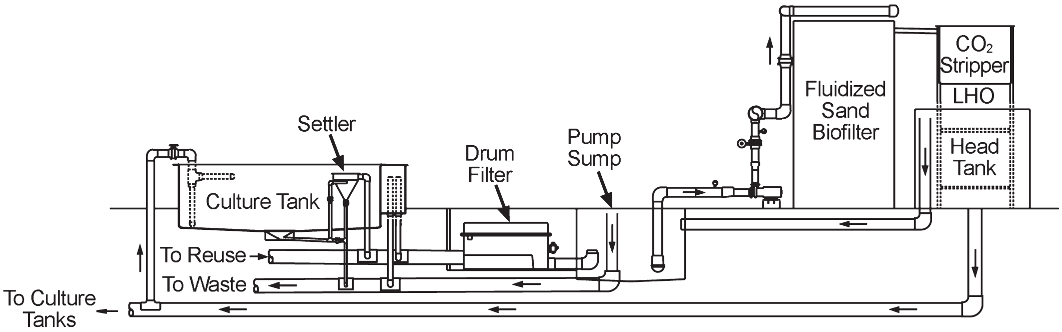

**Fig. 10.4.** Profile view shows the path water takes through the major components within one type of recirculating aquaculture system that is operated with dual-drain culture tanks (from Summerfelt et al. 2001). Make-up water is added in the sump pump through a float valve (not shown), and excess water overflows the system from the bottom discharge of each settler and/or from the sump pump. Courtesy of PR Aqua, Nanaimo, British Columbia, Canada.

### *Design rectilinear culture tanks to prevent solids from settling*

If used, rectilinear raceway tanks should be designed to prevent the settling of solids within the rearing unit. Recirculating systems that use raceway tanks can use baffles (Westers 1991; True et al. 2004) or provide extremely rapid hydraulic exchange rates to create water velocities that approach 15 cm/second to move solids more rapidly out of the tanks. Solids flushed from the fish culture areas of raceways can be captured in quiescent zones, other settling basins, or mechanical filters (Chesness et al. 1975; Henderson and Bromage 1988; Westers 1991; IDEQ undated). Solids that settle and decompose in rearing units can leach oxygen-consuming organic matter, nutrients, and fine particulate matter that degrade water quality and may irritate fish gills and lead to fish disease.

### *Remove solids rapidly and gently*

Rapid, effective, and gentle removal of waste solids within a solids treatment unit is the best approach to maintaining good water quality within a recirculating system. The longer the waste feed and fish fecal solids—which are fragile and labile organic particles—are held within the recirculating water flow, the greater opportunity that dissolution forces such as hydraulic shear and microorganisms will have to disintegrate larger particles into finer particles. Nutrients and soluble organic matter (BOD) are readily leached from fine particles, and these components are more difficult to remove from water than are intact fecal pellets or uneaten feed pellets. If unit processes are not installed to remove fresh and intact solids rapidly, decomposition of solids within the system can degrade water quality and affect fish health and the performance of other unit processes. Also, products of solid decomposition are more difficult to remove from aquacultural effluents.

Waste solids leaving the rearing tank can be removed from the bulk flow using settling basins or microscreen filters (Davidson and Summerfelt 2005). In addition, ozone and foam fractionation can be used to remove extremely fine organic particulates, so they complement solids removal via settling or filtration (Summerfelt et al. 2001). Conventional sedimentation and microscreen filtration processes are often used to remove solids larger than 40 to 100 μm. However, few processes used in aquaculture can remove dissolved solids or fine solids smaller than 20 to 30 μm.

Microscreen filters are the most widely applied technology for capturing and removing solids within recirculating systems. Microscreen filters sieve and strain solids from the recirculating water as it passes through a screen with small openings (Fig. 10.5). Solids larger than the screen openings are retained on the screen until they are cleaned off and removed by water backwash, which may occur continuously, periodically, or on demand (Summerfelt 1999). Microscreen filter performance depends on the screen opening size and influent TSS concentration. Treatment efficiency tends to increase with increasing influent TSS concentration (Summerfelt et al. 2001). Although a variety of different screen size openings are used in aquaculture, Kelly et al. (1997) recommend 60- to 100-μm openings and Summerfelt et al. (2001) recommend 80- to 110-μm openings for removing salmonid wastes. Use of finer screen openings will reduce the hydraulic capacity (i.e., flow rate) of the filter and require more frequent backwash cycles and more backwash flow than larger screen openings for the same total filter area. Typical microscreen filters used in aquaculture are the drum filter, disk filter, and inclined belt filter.

The best solids removal processes remove solids from the system as soon as possible and expose solids to the least turbulence, mechanical shear, or microbiological degradation. Pumping water containing fresh fecal matter is to be avoided. Note that microscreen filters and swirl separators (with a continuous underflow) do not store solids for an

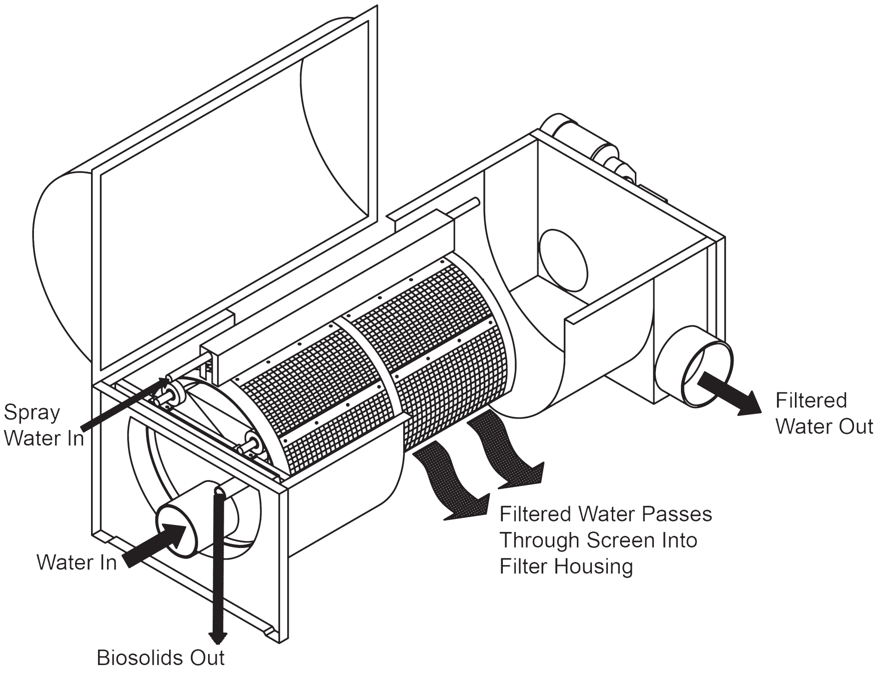

**Fig. 10.5.** A process flow diagram for a microscreen drum filter. Courtesy of PR Aqua, Nanaimo, British Columbia, Canada.

appreciable period. Significant degradation or resuspension/flotation of the solids matter should be avoided, but can occur in treatment units such as settling basins and granular media filters because of their relatively infrequent backwash (Chen et al. 1993a).

Not all recirculating aquaculture systems maintain low levels of suspended solids, as is typically the goal in a recirculating systems used for sensitive species such as trout and salmon. Other species may tolerate elevated levels of suspended solids and may actually consume the algae or microorganisms found in these solids. Examples include some recirculating systems used for tilapia, shrimp, catfish, and certain other species. Some of these systems rely on photosynthetic organisms, heterotrophic bacteria, or a combination of the two to control dissolved wastes (Serfling 2000, 2006; McIntosh 2001; Brune et al. 2003). These treatment systems use what may be generically referred to as suspended-growth processes. In these instances, the rapid removal of waste solids is not a goal because the suspended growth is used for heterotrophic treatment of organic carbon and autotrophic nitrification of ammonia. Total suspended solids concentration in suspended-growth systems can exceed 150 mg/L. Eventually, solids are flushed from the system. Thus, waste management must consider the specifics of each recirculating aquaculture system to successfully achieve waste collection, transfer, storage, treatment, and utilization.

### *Remove solids from concentrated backwash flows before they are discharged*

Solids backwashed from solids removal units tend to be dilute, with 0.1 to 2% total solids content. These solids must be further concentrated and thickened, which typically occurs in settling basins, resulting in concentrations of up to 5 to 10% total solids content. Other sludge thickening methods include sand beds (Palacios and Timmons 2001), created wetland drying beds (Reed et al. 1995; Summerfelt et al. 1999), wedgewire sieves, inclined belt filters (Ebeling et al. 2006), bag filters (M. Sharrer and K. Rischel, The Conservation Fund Freshwater Institute, unpublished data), membrane biological filters (Sharrer et al. 2007), filter presses, centrifuges, and vacuum filters. All of these techniques have specific advantages and disadvantages (USEPA 1987; Black and Veatch Inc. 1995). Solids dewatering within a gravity thickening tank is the most frequently applied technology, probably due to its simplicity (Chen et al. 1997; Brazil and Summerfelt 2006). Septic tanks and leach fields (Fig. 10.6) are another relatively simple option for treating backwash flows from recirculating systems at smaller fish farms (Summerfelt and Penne 2007).

Gravity thickening basins operate according to discrete particle settling principles. However, because gravity thickening basins usually receive water with elevated solids content, which are further concentrated in the basin, the solids are also subject to compression settling within the layer of captured solids at the bottom of the basin. The particles in this region begin to form a structure of particle-particle contact and the slurry is concentrated further. When used to treat backwash flows, gravity thickening tanks are referred to as offline settling units and are loaded intermittently (but sometimes continuously) and provide for the collection and storage of biosolids. The appropriate design criterion for estimating the area needed for settling is the surface loading rate, which is defined as the volume of water flow per unit time per square unit of settling area, and is commonly expressed as cubic feet per second of flow per square foot of settling area. In general, the surface loading rate for gravity thickening basins used to treat intermittent backwash flows should be approximately 0.0009 to 0.0015 foot$^3$/second per foot$^2$ of settling area (0.28 to

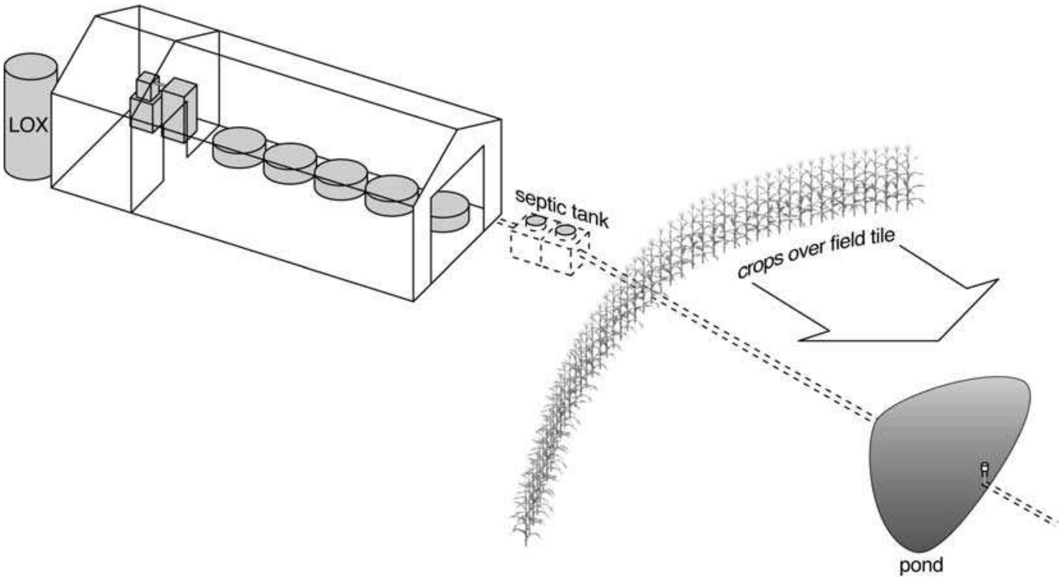

**Fig. 10.6.** Schematic drawing of a septic tank and leach field for treating concentrated fish production waste from a relatively small recirculating aquaculture production system (from Summerfelt and Penne 2007). Note that, in this example, excess effluent that is not removed in the field tile is directed to a settling pond at the end of the tile line.

0.46 L/second per m$^2$) (Mudrak 1981; Bergheim et al. 1993, 1998; IDEQ undated). Gravity thickening tanks use hydraulic retention times of between 20 to 100 minutes (Liao and Mayo 1974; Henderson and Bromage 1988; Bergheim et al. 1993, 1998).

A gravity thickening tank used to treat backwash flows from a recirculating system will be relatively small compared to the settling basins used in flow-through systems because the backwash flows from recirculating systems are relatively small and concentrated. For example, the backwash flow from a microscreen filter is only 0.1 to 0.3% of the bulk flow being treated if the filter is intermittently flushed or approximately 1% of bulk flow if the filter is continuously flushed (Summerfelt et al. 2001). Thus, achieving a conservative hydraulic loading rate does not necessarily require a large gravity thickening tank.

Gravity thickening tanks should be operated to provide nonturbulent conditions. Tanks can be rectangular to produce linear flow or they can be circular to produce a radial flow. In a rectangular vessel, water flows from one end, down the long axis of the vessel, to the opposite end in a linear manner. In a circular vessel, such as a radial-flow settling tank (Fig. 10.7), water is gently introduced within the center of the circular vessel and it then flows radially to a collection launder located around the perimeter of the vessel (Davidson and Summerfelt 2005). Radial-flow settling can also be built in a square vessel that incorporates a center feed and an outlet collection launder about the tank perimeter (Fig. 10.8).

Inlet and outlet designs for a gravity thickening tank must minimize turbulence and short-circuiting to maximize solids capture. Designs must evenly introduce the flow into the settling basin and decrease the influent water velocity and turbulence. Settling efficiency can also be improved by collecting water exiting the vessel across a weir that

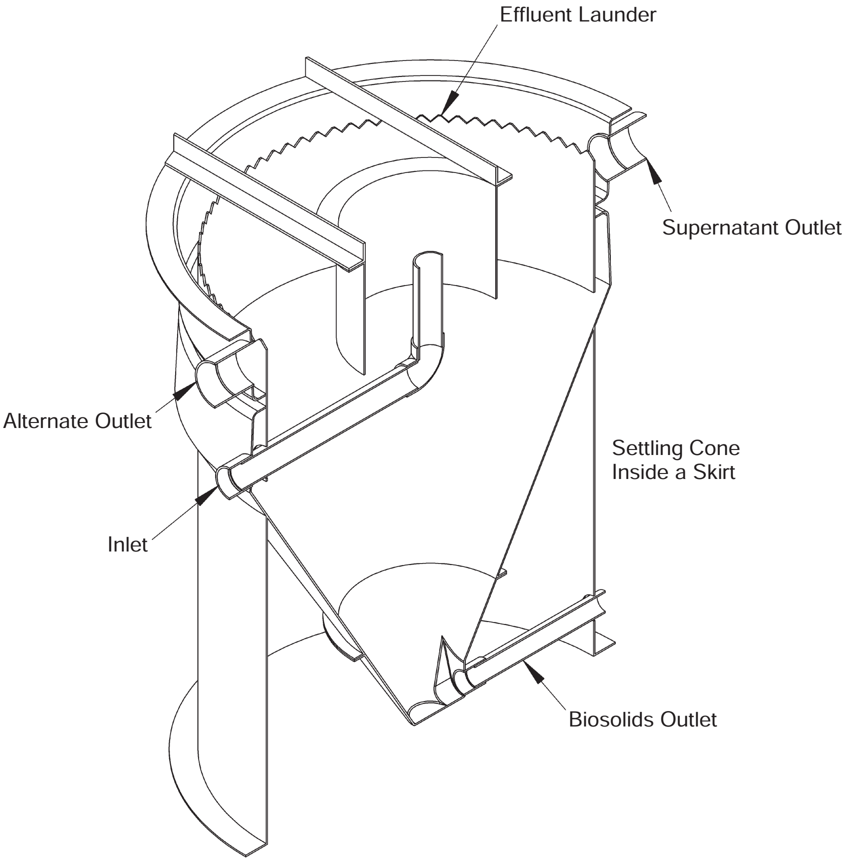

**Fig. 10.7.** Cross-sectional view of a radial-flow settler—that is, a circular center-fed gravity thickening basin (from Davidson and Summerfelt 2005).

minimizes scour and upwelling (IDEQ undated). For example, turbulence produced by the inlet flowing into the center of a radial-flow settler is diminished inside a turbulence-dampening cylinder (Fig. 10.7 and 10.8); the water injected into the center of the tank then flows down (below the turbulence-dampening cylinder) and then up, in the radial and outward direction, until it reaches the overflow collection launder that surrounds the perimeter of the settler (Davidson and Summerfelt 2005). Turbulence is reduced at the outlet of a radial flow settler due to the steadily decreasing water velocity along the settling path and a sizeable outlet weir length, which provides a relatively low weir-loading rate (Davidson and Summerfelt 2005).

Flow surges, scour, wind shear, short-circuiting, and excessive turbulence can decrease capture efficiency and can contribute to increased solids in the effluent of settling tanks (Henderson and Bromage 1988). If the thickening unit stores the captured solids in the flow being treated for more than a few hours, this will promote leaching of soluble organic matter, nutrients, and fine particulate matter that degrade water quality. In addition, algae growth and microbial production of gases such as nitrogen and methane can float and

**Fig. 10.8.** A center-fed radial-flow settler (without water) at the Maine Department of Inland Fisheries and Wildlife's Enfield Fish Hatchery contained in a rectangular concrete vessel. Note the turbulence dampening cylinder for the inlet flow (located at the center of the vessel) and the effluent collection launder (located about the perimeter of the vessel).

**Fig. 10.9.** Some floated solids are captured by a scum baffle in the radial-flow, offline settling tank at the Pennsylvania Fish and Boat Commission's Big Spring Fish Culture Station, Newville, Pennsylvania.

resuspend settled solids (Fig. 10.9). For these reasons, biosolids must be removed from thickening units as frequently as practical. Biosolids left too long in settling basins may also become sticky and viscous, making removal difficult. A procedure or mechanism to remove the dewatered manure from the thickening device must be incorporated.

Solids thickening tanks will often discharge a supernatant (overflow), which will be a relatively small-volume discharge that contains the highest concentration of wastes, leaving

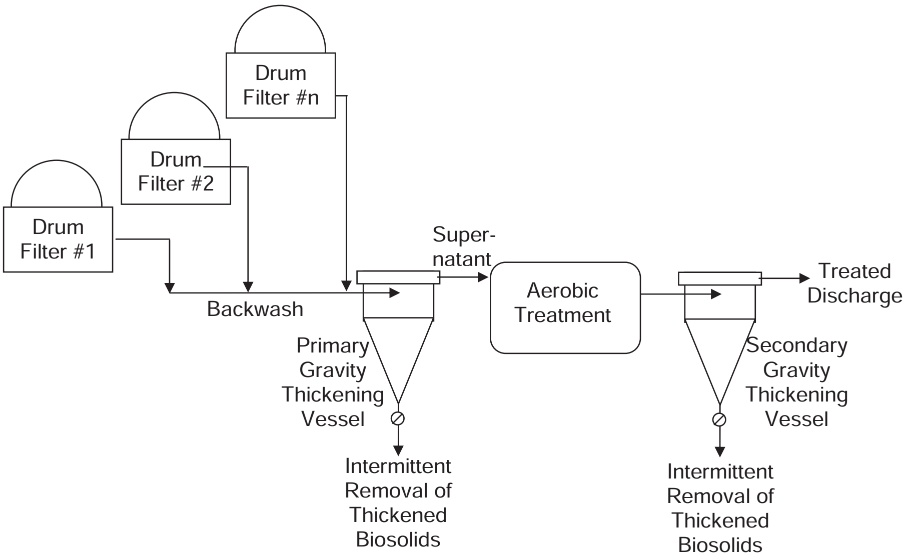

**Fig. 10.10.** Gravity thickening tank overflow can contain high levels of carbonaceous biochemical oxygen demand, total phosphorus, and total nitrogen (primarily ammonia nitrogen) that will require treatment in an aerated basin (shown above), aerobic lagoons, created wetlands, or other suitable technologies (from Brazil and Summerfelt 2006).

a recirculating system (Brazil and Summerfelt 2006). Therefore, treating thickening tank overflow before discharge can reduce the mass load of wastes discharged from the recirculating system. Treatment can be relatively simple and inexpensive—at least compared to recirculating system processes—due to the extremely low volumes that must be treated (Brazil and Summerfelt 2006). Removal of organic matter, phosphorus, and nitrogen (often fractionated largely into ammonia) may be required, and can be accomplished with properly designed aerated basins, aerobic lagoons, created wetlands, anaerobic filters, or other suitable technologies (Fig. 10.10). Alternatively, the thickening tank overflow may be reused beneficially for irrigation or hydroponics.

Inclined belt filters (Fig. 10.11) are a more complicated but more efficient treatment option than gravity thickening tanks. Inclined belt filters do not store biosolids in the flow that they treat, but, rather, captured biosolids are rapidly scraped from the rotating belt into a collection hopper (Fig. 10.11) that is not in the flow path (Ebeling et al. 2006). Rapid biosolids removal minimizes the leaching of nutrients and organic matter into the process flow that is discharged or treated further. When the optimum doses of alum and polymer are applied in combination, an inclined belt filter increases the dry matter content of the sludge to approximately 10% solids and reduces suspended solids and soluble phosphorus concentration of the effluent by 95% and 80%, respectively (Ebeling et al. 2006). By eliminating the need for settling tanks or ponds, the leaching of phosphorus and nitrogen is minimized and the dewatered sludge is in a form that can be readily transported, stored, or disposed. Inclined belt filters have been installed to improve waste capture, dewatering, and disposal at private and public intensive aquaculture facilities (Fig. 10.11).

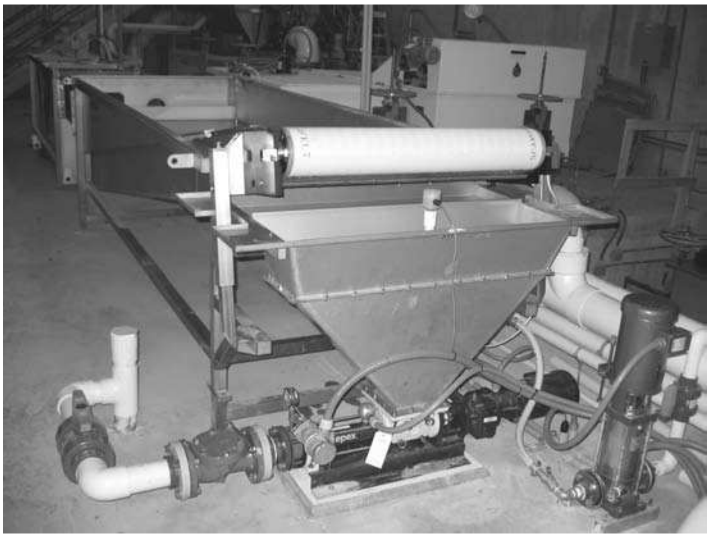

**Fig. 10.11.** A belt filter will scrape thickened biosolids into a collection hopper (shown centered on the drawing). The scraped biosolids are then directed to a progressive cavity pump (shown below the collection hopper) that will move the scraped biosolids to a nearby storage tank (not shown), as installed at the United States Department of Agriculture, Agricultural Research Service, National Cold Water Marine Aquaculture Center in Franklin, Maine.

### *Remove solids from system overflow before discharge*

Depending on requirements for new water, some recirculating systems will have an overflow in addition to a concentrated backwash flow. The concentration of solids in the overflow is typically similar to that found in the fish culture tanks (Davidson and Summerfelt 2005). Suspended solids contained in the overflow may require further treatment. Waste solids can be removed from the overflow before it is discharged using a treatment unit such as a settling basin (e.g., full-flow settlers, inclined tube or plate settlers, radial-flow settlers, or swirl separators), microscreen filters (drum, disk, or belt filters), granular media filters (e.g., bead or sand filters), or dissolved air flotation systems. For example, microscreen drum filters (Fig. 10.5) are sometimes used to treat the overflow discharged from salmonid-producing recirculating systems.

## Solids Storage

Concentrated aquaculture solids can be temporarily stored in thickening basins that have been designed to accommodate the accumulation of solids. However, solid-liquid separation becomes less effective as sludge accumulates within these basins. Increasing sludge depths can compromise settling basin hydraulics and the stored solids can ferment, leading to solids flotation and dissolution of nutrients and organic matter. In many cases sludge from thickening units (e.g., gravity settlers or microscreen belt filters) is transferred to larger sludge storage structures capable of holding solids accumulated over months of operation (Figs. 10.12 and 10.13). Ideally, these offline storage structures will have no

**Fig. 10.12.** A biosolids storage tank, such as this one at the United States Department of Agriculture, Agricultural Research Service, National Cold Water Marine Aquaculture Center in Franklin, Maine, is designed to hold months of captured and thickened biosolids with no discharge until the stored biosolids can be hauled to a final disposal site.

**Fig. 10.13.** A large, impermeable plastic storage bag with gas vents through the top of the bag offers a lower initial fixed cost option to fish manure storage.

overflow, because they store the entire manure slurry contents until it can be removed for disposal. Biosolids storage structures include earthen ponds, above-ground tanks, and below-ground tanks (USDA-NRCS 1996). Design of all structures, earthen or manufactured, should include considerations for internal and external hydrostatic pressure, flotation and drainage, live loads from equipment, and dead loads from covers and supports (USDA-NRCS 1996).

### *Better Management Practices for Solids Storage*

#### *Properly design earthen ponds used for biosolids storage*

Earthen ponds are generally rectangular basins with inside slopes (horizontal : vertical) of 1.5 : 1 to 3 : 1. Depending on site geology and hydrology, earthen ponds can have liners of concrete, geomembrane, or clay. Because they are uncovered, earthen pond design must include consideration of the capacity to store rainwater and effective solids removal. If removed with pumps, solids must be agitated to provide a uniform consistency. Ponds can be agitated with hitch-type propeller agitators that are powered by tractors or by agitation pumps. Propeller agitators work well for large ponds, while chopper-agitator pumps work well for smaller ponds. Solids can be removed with heavy equipment, in which case pond design should include ramp access (maximum slope of 8 : 1) and suitable load capacity in the unloading work area (USDA-NRCS 1996; Wright et al. 1999).

#### *Use tanks for biosolids storage*

Biosolids may also be stored in tank structures above or below ground. Storage tanks are primarily constructed of reinforced concrete, metal, and wood. Reinforced concrete tanks may be cast-in-place walls, foundation, and floor slab, or they may be constructed of precast wall panels, bolted together, and set on a cast-in-place foundation and floor slab. Metal tanks are also widely used, with the majority being constructed of glass-fused steel panels that are bolted together (Fig. 10.12). There are many manufactured, modular tanks commercially available in reinforced concrete, metal, and wood (USDA-NRCS 1996). Large, impermeable, plastic storage bags with gas vents through the top of the bag (Fig. 10.13) offers a storage solution with a lower initial fixed cost.

#### *Be aware of precautions required due to gas and odor generation during solids storage*

Solids degradation during storage can produce dangerous levels of hydrogen sulfide, methane, and hydrogen gases. In tanks with little air exchange the atmosphere may contain these gases and also be depleted of oxygen. Use Occupational Safety and Health Association confined-space guidelines when considering all aspects of the human interface with a solids storage structure and take every practical precaution to prevent harm to those working around these structures. State and local regulations regarding odors from the manure storage vessels must be followed.

## Solids Treatment and Disposal

Fish fecal solids contain nitrogen and phosphorus and can be used as a soil amendment. The composition of solids removed from an aquaculture system will vary according to feed formulation fed to the fish, biosolids age, and treatment of solids inside and outside of the system (Chen et al. 1993b, 1997, 2002; Westerman et al. 1993). Except for zinc, waste biosolids removed from fish culture systems contain lower (typically much lower) concentrations of contaminants such as cadmium, arsenic, chromium, copper, nickel, and lead than cow manure or POTW sludge (Mudrak 1981; Olson 1991; Ewart et al. 1995). According to Olson (1991), the concentration of zinc in fish manure (450 mg/kg) is slightly greater than that reported in cow manure (298 mg/kg), but is much less than reported in municipal POTW sludge (1,460 mg/kg). Zinc may be elevated because fish feeds are usually supplemented with zinc and other trace minerals. Although levels are usually low, the salts and heavy metal content of recovered solids must be taken into account when considering long-term application on agricultural crops.

Fish fecal solids should be defined as an agricultural waste, although certain state or local government authorities may consider solids recovered from recirculating systems an industrial or municipal waste simply because it is captured in an effluent treatment process (Ewart et al. 1995). This designation by local or state authorities can limit waste disposal options. Transport of waste biosolids from the facility to another point of disposal or reuse is a major factor in the costs of sludge management, because thickened sludge still contains at least 90% water (Black and Veatch 1995; Reed et al. 1995).

Disposal of solids should comply with all applicable local regulations. Solids disposal should be conducted in a manner that prevents the material from entering surface or groundwaters. This will be a site-specific practice according to local regulations, soil type, topography, land availability, climate, crops grown, and other factors. Disposal options include land application on agricultural lands, long-term storage lagoons, composting, and reed drying beds. Disposal options and practices for solids generated in recirculating aquaculture systems do not differ greatly from those generated in flow-through aquaculture. Additional details on solids disposal are presented in Chapter 9.

### ***Better Management Practices for Solids Treatment and Disposal***

#### *Land application*

Land application is the most common method of aquacultural waste solids disposal. Proper application of aquaculture biosolids provides a safe method for waste utilization while fertilizing crops and amending the soil (Mudrak 1981; MacMillan 1992; Pardue et al. 1994; Cripps and Kelly 1996). Application rates of animal manure is governed in most states by guidelines or regulations that limit nutrient loading and the concentration of pathogens, salts, heavy metals, and other contaminants to protect the crops and prevent runoff or groundwater contamination (Mudrak 1981; Olson 1991; Outwater 1994; Ewart et al. 1995; Chen et al. 1997; IDEQ undated). Odor problems can limit application of waste biosolids. To reduce odor problems during land application and storage, waste biosolids can be aerobically stabilized or pasteurized with lime at a sustained pH of 12 (Bergheim et al. 1998).

Fish manure in liquid form may be sprayed directly onto agricultural land. In slurry form, fish waste may be pumped into a tank truck with a liquid spreader and then land-applied (Fig. 10.14). Finished compost generated from aquacultural waste solids may also be applied onto agricultural land at agronomic rates. In some instances, supernatant or leachate from slurry treatment processes with high nutrient concentrations can be irrigated at agronomic rates.

### *Lagoons*

Manure slurries from aquaculture operations may be treated in waste-treatment lagoons that thicken and stabilize the manure (Chen et al. 1997). Anaerobic lagoons will digest solids and reduce their volume by 50 to 75%, but have also been reported to create severe odor problems (Chen et al. 1997, 2002). Aerobic lagoons are aerated (or loaded lightly in comparison with anaerobic lagoons), which increases their operating cost (Chen et al. 1997). State and local regulations regarding odors from the lagoons must be followed.

### *Composting*

Thickened and dewatered manure may be composted, especially if environmental factors or transportation costs can make sludge disposal on cropland impractical or uneconomical. Composting stabilizes the waste solids and produces a valuable soil amendment (Chen et al. 1994, 2002). Aerobic static piles and windrows are the most common methods for composting manure on farms (Adler and Sikora 2005). Any excess supernatant, leachate, or filtrate leftover from slurry treatment processes may contain elevated solids, organic

**Fig. 10.14.** In some locations, fish manure can be spray-irrigated directly onto agricultural land, as shown applied to pasture at the Conservation Fund Freshwater Institute in Shepherdstown, West Virginia.

matter, and nutrient concentrations that will require a suitable disposal plan. State and local regulations regarding composting should be considered.

### *Reed drying beds*

Depending on location and local regulations, an aquaculture facility may have only limited and costly options available for disposal of thickened manure, especially if transportation costs make sludge hauling for disposal on cropland uneconomical. Disposing sludge on-site within created wetlands may be an attractive alternative. A constructed reed drying bed can provide on-site treatment of a concentrated solids discharge with an uncomplicated, low-maintenance, plant-based system. Reed drying beds are vertical-flow wetland systems (Fig. 10.15) that have been used to treat thickened sludge (1 to 7% solids) produced in the clarifier underflow at wastewater treatment plants (Nielsen 1990; Outwater 1994; Reed et al. 1995) and have also been used to treat manure from commercial recirculating systems (Summerfelt et al. 1999). Thickened biosolids are loaded in sequential batches onto the reed drying bed every 7 to 21 days. Only 7 to 10 cm of thickened biosolids is applied during a given application. The 1- to 3-week intervals between biosolids applications allow for dewatering and drying, which is facilitated by the vegetation growing on the sand bed. Reed beds have a useful lifetime of up to 10 years.

## Nitrogen and Phosphorus Treatment

Discharge of ammonia may or may not be regulated, depending on regulations that can differ from state to state, but nearly all recirculating systems use biological nitrification

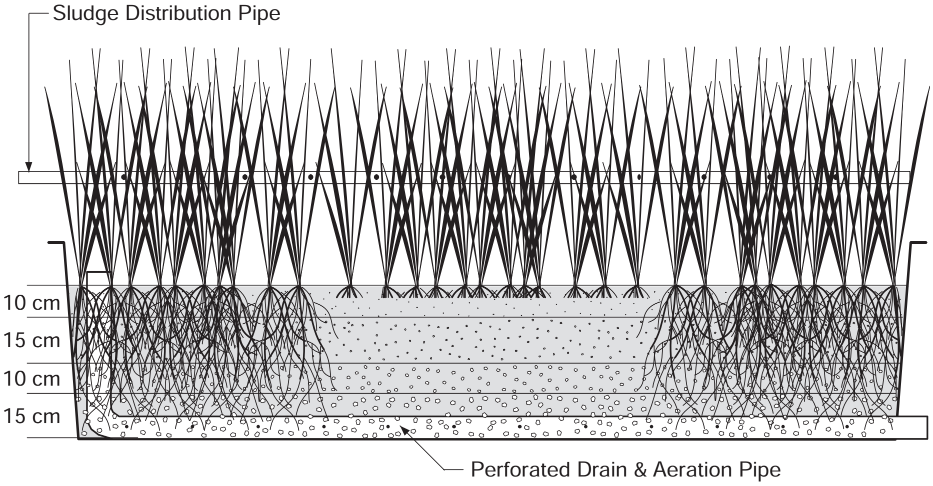

**Fig. 10.15.** Schematic of a reed drying bed (a vertical-flow wetland system) for long-term disposal of thickened biosolids (from Summerfelt et al. 1999). The composition of each vertical layer of aggregate shown: sand (top layer), 6-mm washed pea gravel, 12-mm round washed pea gravel, and 5-cm round washed pea gravel to cover the perforated drainpipe (bottom layer).

to convert ammonia to nitrate because the un-ionized form of ammonia is toxic to fish whereas nitrate is relatively nontoxic. Accordingly, total ammonia concentrations will be relatively low and nitrate will make up the largest fraction of dissolved nitrogen discharged from a recirculating aquaculture system that includes a nitrification process. When required, nitrate can be removed by biological denitrification (van Rijn et al. 2006). Nitrate removal with denitrification is, however, more complex and costly than solids control and is infrequently used to treat aquaculture effluents.

Because phosphorus is primarily associated with solids, rapid solids removal from the system is the best way to remove phosphorus from recirculating system effluents. Removal of dissolved phosphorus is more complex and expensive, especially if the regulatory limit for phosphorus is low. When required, dissolved phosphorus removal can be accomplished by granular or mechanical filtration (Ebeling et al. 2006; Sharrer et al. 2007), biological treatment (Brazil and Summerfelt 2006; Sharrer et al. 2007), or chemical precipitation (Ebeling et al. 2003, 2004; Rishel and Ebeling 2006). These advanced waste treatment options may be necessary for treating the relatively small but concentrated slurry of captured biosolids backwashed from the recirculating system. However, with regard to large overflows, there are few economically viable phosphorus removal options beyond the adoption of good solids capture and disposal technologies.

## Water Conservation

The volume of water required to produce a unit of fish in recirculating systems is less than for single-pass, serial-reuse, and net-pen culture systems (Chen et al. 2002). Recirculating systems conserve water resources because they do not require much water to achieve a given level of production. However, they still require a reliable water supply of a minimum flow rate, even if they can be operated without new water for short periods (days or weeks, depending on the system). Eventually, all recirculating systems require new water to replace water lost to evaporation or from flushing concentrated biosolids. New water requirements may be especially low in recirculating aquaculture systems that are operated at high salinities to culture marine species because these systems are often operated to recover saltwater contained in backwash effluent to allow its reuse within the system and to reduce salt discharge to the environment. Partial water reuse systems, on the other hand, require much higher volumes of new water (to flush ammonia) compared with more traditional recirculating aquaculture systems that use biofiltration for ammonia control.

Practices for water conservation are not listed here because water conservation is inherent in the design principals for recirculating aquaculture systems. However, facility managers should strive to conserve water at every opportunity by minimizing water use in and around the aquaculture facility.

## Predator Control

Recirculating aquaculture systems are usually enclosed in buildings to minimize the energy input required to maintain optimum aquaculture water temperatures. The building excludes predators from the culture unit. As such, predator control is not an issue for indoor recirculating aquaculture systems. Predators may be important in outdoor recirculating systems (for example, partial reuse systems) and the predator-control measures outlined in Chapter 9 for flow-through systems can be used to reduce predator impacts.

## Fish Escape

Escape of cultured species (including native species, nonnative species, hybrids, and genetically modified organisms) may pose a variety of potential risks to aquatic ecosystems or unrelated economic activities. Potential risks include pathogen transmission, interbreeding with conspecifics and introgression of genetic material, competition for resources, predation, colonization, or disruption and damage to commercial and recreational industries including aquaculture.

Although effluent volume from recirculating aquaculture systems is typically very small compared with other culture systems, most systems discharge some water to receiving waters. Thus, fish can escape from recirculating systems if the facility is improperly sited and if adequate physical barriers are not provided between the culture vessels and the point of discharge.

### *Better Management Practices for Preventing Escapes*

#### *Be aware of all regulations affecting transport and culture of aquatic animals*

Before importing or transporting an aquatic species (including native species, nonnative species, hybrids, and genetically modified organisms), follow all local, state, and federal regulations that govern type of species allowed for aquaculture, importation, holding, and transport. Contact appropriate state and federal agencies for regulations governing aquaculture, importation, holding, and transport, because most states tightly regulate the species allowed for aquaculture. Seek the advice from aquaculture Extension specialists and appropriate agencies when considering the culture of an unfamiliar species. Contact the United States Fish and Wildlife Service for an import/export license and information about injurious species identified under the Lacey Act. For regulations concerning species and production systems that can be used in marine waters, contact the National Marine Fisheries Service. For health certification of imports and exports, contact the USDA Animal Plant Health Inspection Service. For regulatory information concerning genetically modified organisms intended for food or pharmaceutical markets, contact the United States Food and Drug Administration, Center for Veterinary Medicine and Center for Food Safety and Applied Nutrition.

#### *Design the facility to minimize opportunities for escape*

Design the facility to provide secure containment of cultured animals. To prevent escape or loss of cultured animals, barriers of appropriate size and strength should be installed on the facility discharge and on the new water entry into the facility. In some instances, three distinct barriers are required between the culture unit and the discharge: 1) an exclusion screen on the tank drain, 2) a microscreen filter in the effluent treatment process, and

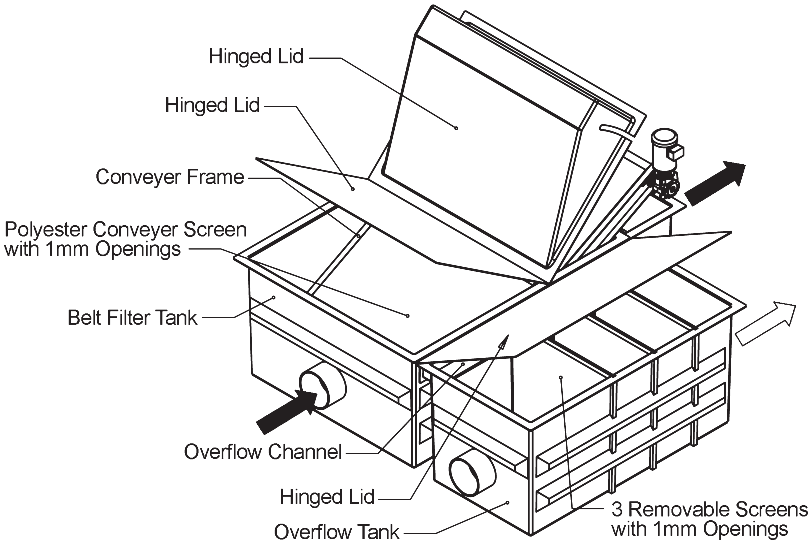

**Fig. 10.16.** An inclined belt filter system is used to exclude Atlantic salmon from discharge at the United States Department of Agriculture, Agricultural Research Service, National Cold Water Marine Aquaculture Center in Franklin, Maine. Figure courtesy of PR Aqua, Nanaimo, British Columbia, Canada.

3) a fish-exclusion screen just before discharge. Multiple exclusion devices are needed because water may overflow and bypass microscreen drum filters caused by failure of the backwash or drive mechanism or when filters are hydraulically overloaded. A procedure or mechanism should also be incorporated to prevent debris from plugging the barriers, thus preventing water from overflowing or bypassing the screens. An inclined belt filter installed with 1-mm belt openings (sized for Atlantic salmon, *Salmo salar*) can provide for automated cleaning of the fish exclusion screens and a reliable dedicated fish exclusion technology (Fig. 10.16).

### *Do not locate facilities in areas prone to flooding*

One of the benefits of using recirculating system technology is flexibility in siting the facility at favored locations. One aspect of siting is to avoid areas prone to flooding. This siting criterion not only protects the considerable infrastructure investment, but also reduces the risk of animals escaping when floodwaters overtop culture units.

## Mortality Removal and Disposal

Fish mortalities in aquaculture are unpredictable and highly variable among facilities, rearing units within a facility, the species cultured, and the specific disease. A facility may experience chronic losses of a few fish dying per day for long periods or a catastrophic loss caused by infectious disease or acute environmental stress. Depending on water temperature and species, dead fish either float or sink after dying, with fish in warm water typically floating and fish in cold water typically sinking. Dead or moribund fish are transported by flowing water to a tank drain, where they can accumulate against screens and restrict water flow from the culture unit. In recirculating systems, dead fish that sink tend to accumulate on the exclusion screen on the bottom center drain of circular tanks or on the outlet screen of linear raceways. Floating fish will accumulate on the surface of circular tanks, where they are relatively easy to see. A simple, fast, and reliable method to remove fish mortalities from culture vessels, whether large or small, is required to decrease labor costs, reduce the spread of fish disease within the facility and to outside waters, and prevent the dead fish from restricting water flow and cause overflow of the culture unit. Dead fish must be disposed of using an environmentally sensitive approach.

### Better Management Practices for Mortality Removal and Disposal

#### Reduce mortalities by using good fish husbandry and fish-health management practices

Fish health is largely dependent on the quality of the environment and the presence and virulence of pathogens. The first aspect of fish-health management is to monitor and control water quality within the facility. Water quality can deteriorate if a treatment process in the recirculating systems is not operating properly, so develop a water quality monitoring plan to identify and correct problems with the water treatment processes before fish health is seriously compromised. A biosecurity plan should be developed to prevent introduction and dissemination of pathogens throughout the fish culture systems. Ideally, introduce only eggs that have been certified free from specific pathogens. If fish must be introduced from a facility that has not been certified free from pathogens, quarantine the fish in a separate culture area and monitor for pathogens or diseases during a quarantine period. If diseased fish or pathogens are inadvertently introduced to the facility, the problem must be addressed through mitigation and disinfection techniques that are costly, time consuming, and do not necessarily lead to the elimination of the pathogen once introduced.

Develop a fish health monitoring plan appropriate for the facility. To the extent possible, prevent disease outbreaks and the spread of disease by following recommended aquatic animal health management practices. See Chapter 12 for general guidance on aquatic animal health management.

#### Remove dead fish in a timely manner

Dead fish should be removed from culture units as soon as possible—at least once daily—to reduce the spread of fish disease, maintain unrestricted water flow, and reduce water quality deterioration resulting from the decay of dead fish within the system. Dead fish that sink may be difficult to detect at the bottom center of large circular culture tanks that are deep or contain turbid water. A procedure or mechanisms should be identified and incorporated for detecting and removing dead fish from the bottom-center drain of deep culture tanks.

Dead fish removed from each culture unit should be counted and weighed as needed to adjust inventory. Provide separate nets for each culture unit or, alternatively, disinfect nets and or other equipment before using them in other culture units. All nets and equipment that have been used to move or inventory dead fish should be disinfected before the end of the work day to prepare them for use the next day.

#### *Prevent the discharge of dead fish into receiving waters*

Do not discharge dead animals into receiving waters. Appropriate barriers (such as those discussed above for preventing fish escape) will prevent discharge of dead fish into receiving waters. Use only approved methods of mortality disposal. Disposal methods may be site-specific and usually governed by state or local regulations. Disposal options include composting, rendering, use as a soil amendment, incineration, or landfill. Notify the appropriate regulatory agency by telephone within 24 hours whenever structural failure or other catastrophe causes the unauthorized discharge of mortalities to a receiving water.

#### *Use approved methods for mortality disposal*

Disposal methods are site-specific and are usually governed by state or local regulations. Disposal options include composting, rendering, use as a soil amendment, incineration, or landfill. Refer to Chapter 9 for details of these disposal options.

## Facility Operation and Maintenance

Recirculating aquaculture systems are expensive to build and operate. Operating recirculating aquaculture systems in a sustainable fashion can protect the environment and protect the farm investment. Long-term economic performance is enhanced and environmental impacts are reduced when recirculating aquaculture facilities are well-maintained, managed efficiently, and operated in compliance with all applicable laws and regulations. Without proper operation and maintenance, water treatment equipment can fail and degrade water quality to the point that fish growth and survival are compromised. Waste discharge violations can also occur if water treatment equipment is not properly maintained within the recirculating system or its effluent treatment processes.

### ***Better Management Practices for Facility Operation and Maintenance***

#### *Maintain the facility in good condition*

Water pumps, water treatment equipment, back-up generator systems, liquid oxygen tank systems, dissolved oxygen probes, and other monitoring or alarm systems provide vital life-support in recirculating aquaculture facilities. Preventative maintenance can reduce potential catastrophe from equipment failure and a maintenance plan should be developed to ensure that the critical equipment is maintained in good operating condition. Critical equipment should be checked at least weekly or daily if possible. Equipment operating manuals, warranty information, and records of cleaning and other preventative maintenance procedures should be kept in a convenient location, such as the facility manager's office. In addition, an inventory of frequently used repair and replacement equipment or parts should be maintained at a convenient location. Personnel familiar with equipment operation, replacement, and repair must be available to respond immediately if equipment fails.

Pumps are especially important because they recirculate water through the fish culture tanks and water treatment units. Pumps should be checked frequently to determine whether they are operating at an unusual temperature or amperage or whether they are producing an unusual noise or vibration. If a problem is identified, the pumps or their motors should be replaced with a spare before they fail. The suspect pump can then be inspected and serviced before it fails.

Backup electric generators and liquid oxygen tank systems are also critical life-support equipment. Backup electric generators should be exercised weekly to test for automatic startup and operation and tested at full-load approximately twice annually. Fuel levels for the backup generators should be checked and maintained above predetermined levels. Liquid oxygen tank systems should be checked daily for stored liquid oxygen levels and for leaks at fittings and valves.

Water treatment equipment, especially equipment with moving parts, can fail and should be monitored and proactively maintained. For example, cleaning and preventative maintenance procedures are crucial to maintaining efficient microscreen drum filter operation. The following routine maintenance can be performed on a microscreen drum filter approximately weekly (while power to the unit is off to prevent injury): 1) pressure-wash filter screen panels to remove organic debris; 2) use a pressure washer to clean the interior and exterior drum filter wall surfaces, spray nozzles, backwash tray, lid, wheels, and drum filter walls; and 3) use a water hose to spray around the water-level float switch body and chamber to remove any debris accumulation that could cause the switch not to activate the backwashing process. At 2-month intervals check lubrication and oil levels in the drive unit and check the condition of filter screen panels for organic and mineral accumulation; increased backwashing frequency is a good indication that screens should be soaked in calcium remover. At 6-month intervals (or as needed) remove filter screen panels and soak each in calcium- or mineral-remover solution to thoroughly clean filter screens.

Probes and meters for monitoring dissolved oxygen and other environmental conditions should be calibrated based on manufacturer's recommendation. Note that conditions within the recirculating system may require more frequent cleaning and recalibration than the manufacturer's recommendations. Process control and alarm equipment should also be checked for proper operation.

### *Use and store petroleum products to prevent contamination of the environment*

Store and use petroleum products in a manner that prevents them from contaminating the fish culture systems or the environment. Information on petroleum storage regulations can be obtained from state departments of commerce, state departments of environmental quality or protection, or from regional EPA offices. Implement a regular maintenance schedule for tractors, trucks, and other equipment to prevent oil and fuel leaks. Used oil should be disposed of according to state or federal regulations.

### *Use and store chemicals to prevent contamination of the environment*

Store and use chemicals in a manner that prevents them from contaminating the environment. Water treatments and disinfectants are the most common chemicals used in recirculating aquaculture. Chemical use is regulated by federal and state agencies, and individuals are responsible for using products according to label instructions and disposing of containers and unused chemicals according to applicable state and federal regulations. Chemicals should be used only when needed and only for the specific use indicated on the label. All chemicals should be stored in secure, well-ventilated, watertight buildings.

Develop a response plan for spills of petroleum products, pesticides, and other hazardous materials. State and federal law requires reporting significant spills of petroleum and pesticides. The plan should be developed specifying response procedures, key staff, and regulatory authority phone numbers, and all facility employees should be aware of the plan.

### *Collect and dispose of solid waste*

Provide suitable containers to confine and collect solid wastes at convenient locations. Dispose of solid waste on a regular basis and in a responsible manner according to all applicable state and federal regulations.

### *Develop a production planning and record-keeping system*

Good record keeping can facilitate improvements in the efficiency of farm input use. Records, such as feeding, chemical use, water quality, serious weather conditions, fish culture operations, and fish inventory facilitate improvements in the efficiency of farm input use. Paper copies of records should be maintained for archival purposes; computerized record-keeping tools can be used for trend analysis and forecasting. Records should be reviewed periodically to determine whether they are useful and to provide insight into opportunities for improvement of farm operations.

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## Chapter 11

# Better Management Practices for Bivalve Molluscan Aquaculture

*R. LeRoy Creswell and Aaron A. McNevin*

## Introduction

Molluscan shellfish account for nearly a quarter of total global aquaculture production (FAO 2005). In 1984, production of molluscan shellfish (2.1 million tonnes) was similar to the capture fishery for mollusks (2.2 million tonnes). However, from 1984 to 2004 mollusk aquaculture increased nearly fivefold, with a total global aquaculture production of 11.7 million tonnes. Meanwhile the capture fishery for mollusks decreased slightly to 2.0 million tonnes (FAO 2005). China is the leading producer, accounting for 85% of the global share of cultured shellfish. The other top mollusk-producing countries in decreasing order of importance are Japan, Thailand, Korea, Spain, and the United States.

In the United States, cultured shellfish remains one of the most successful and stable forms of aquaculture (Table 11.1). Bivalve mollusk aquaculture production in the United States exceeds 220,000 tonnes (FAO 2005). Oysters are the most common bivalve mollusk cultured in the United States, accounting for approximately 61% of cultured shellfish. Clams account for 31% of shellfish aquaculture production, and the remaining 8% is divided among mussel, geoduck, and scallop culture. Production of bivalves in the United States is concentrated in three main areas: the Gulf of Mexico, the mid- to north-Atlantic seaboard, and the Pacific Northwest. Washington State accounts for the greatest production, followed by Virginia, Louisiana, California, and Oregon (USDA-NASS 2006). Although many species of bivalve mollusks are under various stages of aquaculture development in the United States, only about 20 species (Table 11.1) currently are in commercial production using methods described in this chapter. Because gastropods such as abalone (*Haliotus* spp.) account for less than 4% of total mollusk aquaculture in the United States, this chapter will focus on environmental best management practices for bivalve species.

Bivalves obtain nutrition by *filter feeding,* a mode of food acquisition in which the gills have assumed the function of trapping food as well as serving as a respiratory surface. In the process of filter feeding, cilia on the gills induce water currents that move through the mantle. Suspended particles are removed as the current passes through the gills where they are sieved and entangled in mucus. Particles retained during filter feeding range from a few

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**Table 11.1.** Bivalve mollusks commercially cultured in the United States.

| Common Name | Species | Culture Locations | Culture Methods |
|---|---|---|---|
| Eastern oyster | *Crassostrea virginica* | Atlantic, Pacific, Gulf | Intertidal, on-bottom bags, suspended longlines, floating trays (nursery) |
| Pacific oyster | *Crassostrea gigas* | Pacific | Intertidal, rack and bag, floating bags, suspended longlines |
| Kumamoto oyster | *Crassostrea sikamea* | Pacific | Rack and bag |
| European flat oyster | *Ostrea edulis* | Pacific, Atlantic | Lantern nets, stacked trays, floating trays |
| Olympia oyster | *Ostrea conchaphila* | Pacific | Bottom |
| Quahog or hard clam | *Mercenaria mercenaria* | Atlantic, Gulf | In-bottom, bottom bags |
| Softshell clam | *Mya arenara* | Atlantic | Intertidal, on-bottom, floating trays (nursery) |
| Littleneck clam | *Protothaca staminea* | Pacific (Alaska) | Bottom |
| Butter clam | *Saxidomus gigantea* | Pacific | Bottom |
| Manila clam or Japanese carpet shell | *Venerupis philippinarum* | Pacific | Bottom |
| Razor clam | *Siliqua patula* | Pacific | Bottom |
| Atlantic mussel | *Mytilus edulis* | Atlantic, Gulf | On-bottom, suspended rope, raft |
| Blue mussel | *Mytilus galloprovincialis* | Pacific | Raft, longline |
| Bay mussel | *Mytilus trossulus* | Pacific | Raft, longline |
| Geoduck | *Panopea abrupta* | Pacific (Washington) | Bottom |
| Sea scallop | *Placopecten magellanicus* | Atlantic | Lantern nets, ear-hanging |
| Bay scallop | *Aequipecten irradians* | Atlantic, Pacific, Gulf | Lantern nets, ear-hanging, bottom |

to several hundred micrometers in diameter, and include phytoplankton, detritus, small zooplankton, bacteria, and soil particles. The particle-laden mucus is then moved to the mouth where the particles are sorted by size. Small particles are retained for digestion, and larger particles are rejected as mucus-bound “pseudofeces.” A fraction of the ingested particles are digested and assimilated, and the remainder is excreted as fecal pellets. The filter-feeding mechanism, which is unique among the major cultured aquatic species, is a major determinant of the interactions and impacts of bivalve mollusks on the environment.

Larvae and juvenile mollusks produced in hatcheries are fed phytoplankton from prepared cultures, but this represents a very small biomass of shellfish and reflects high production costs. Once hatchery-reared animals reach sufficient size, they are transferred to an environment where they are completely dependent on naturally occurring organic materials for nutrition. As such, they are net consumers of particulates and nutrients, rather than net producers of potential pollution, as are nearly all other forms of aquaculture (Folke and Kautsky 1989; Shpigel et al. 1993). Overall, the presence of filter-feeding shellfish communities enhances water quality and establishes a link between water column and benthic food webs.

The quantity of nutrients removed by shellfish harvest can be quite large. For example, mussels contain about 1.4% nitrogen and 0.14% phosphorus (Shumway et al. 2003). Harvest of 1 tonne of mussels therefore contains 14 kg nitrogen and 1.4 kg phosphorus. Annual yields of mussels range from as little as 7 tonnes/ha in Australia to as much as 1,500 tonnes/ha in Spain (McKinnon et al. 2003). Thus, mussel harvest from a 1-ha production area could remove from 98 to 21,000 kg nitrogen and 9.8 to 2,100 kg phosphorus from the water. The ability of shellfish to remove nutrients from water can effectively mitigate anthropogenic activities associated with forms of coastal development that promote excessive nutrient enrichment. Shellfish aquaculture may provide the most economical and environmentally suitable means for offsetting the adverse effects of coastal development that contributes to degradation of the coastal marine environment (Newell et al. 1999).

Bivalves are also important in transferring organic matter from water to sediments. Deposition of pseudofeces and feces by shellfish in culture areas may alter the organic profile of sediments and thus impact the diversity and abundance of benthic invertebrates. However, these alterations are temporary, and benthic communities are quickly restored after the cultured shellfish are harvested and the grounds are allowed to lie fallow (Olin 2002).

Shellfish aquaculture provides a complex three-dimensional structure that serves as habitat for a diverse array of fish and invertebrate fauna. These "artificial reefs" provide habitat for marine plants and animals that transfer energy and nutrients through aquatic food webs to fish, shorebirds, and mammals. Shellfish aquaculture also provides benefits by reducing bottom disturbances from the harvest of wild stocks. Shellfish farms concentrate and focus harvesting activities that otherwise would take place over a much wider area.

Despite obvious environmental benefits, there has been some criticism of shellfish aquaculture. Negative public perceptions related to the environmental impact of mollusk culture include displacement of benthic aquatic vegetation; discarded nets and equipment; displeasing aesthetics associated with plot markers, working vessels, and platforms; and increased turbidity and disruption of sediments during harvesting.

At a workshop in Charleston, South Carolina, in January 2000 supported by the Cooperative Research and Information Institute, over 50 prominent molluscan shellfish scientists, industry representatives, and policy makers in the United States convened to develop a national shellfish plan that would chart the course for the future in shellfish research and management. The following recommendation was made with regard to interactions between shellfish aquaculture and the environment (Shumway and Kraeuter 2000):

| | |
|---|---|
| Objective: | Develop, adopt, and promote best management practices (environmental code of practices) for the shellfish aquaculture industry and wild fisheries. |
| Rationale: | The shellfish industry is under increasing regulatory and public scrutiny as a result of the Endangered Species Act, the Sustainable Fisheries Act, and associated identification and protection of essential fish habitat. The animals that are cultured by the shellfish industry are an integral part of the marine ecosystem, and commercial shellfish growers are clearly dependent upon a healthy ecosystem. Best management practices (BMPs) and environmental |

codes of practices (ECOPs) will foster environmental stewardship. Adopting BMPs or ECOPs will be crucial to the survival and continued prosperity of the shellfish industry.

## Shellfish Cultivation Practices

Environmental impacts of bivalve culture are closely linked to culture methods. Culture practices that may affect environmental performance include methods of broodstock collection, seed production (hatcheries or wild spat collection), grow-out (on-bottom or off-bottom), and harvest. These practices vary widely depending upon species and the geographical area in which the animals are cultured.

Shellfish culture consists of spat (seed) production and grow-out of spat to marketable size. Spat may be dredged, handpicked, captured on spat collectors, or reared in hatcheries by spawning adult broodstock. There are two fundamental types of grow-out: bottom culture and off-bottom culture. The type of culture system employed reflects the biology of the species. A variety of clam species cultured in the United States (hard clams, Manila and littleneck clams, and geoducks) must burrow into the substrate. Other bivalves, such as scallops, oysters, and mussels, are epibenthic and attach to surfaces on or above the bottom.

### *Clam Culture*

The major clam species farmed along the Atlantic and Gulf Coasts are the hard clam (*Mercenaria mercenaria*) and the soft-shell clam (*Mya arenaria*). Along the Pacific coast, the primary farmed species are the Manila clam (*Venerupis philippinarum*), the littleneck clam (*Protothaca staminea*), and the butter clam (*Saxidomus gigantea*).

Clam aquaculture begins with the acquisition of mature clams, or broodstock, which are spawned under hatchery conditions. Fertilized eggs develop for approximately 5 to 12 hours into a multicellular trochophore stage before transforming into shelled straight-hinged veliger larvae at around 24 hours postfertilization. Larvae spend approximately 1 week in larviculture tanks and then are transferred to nursery tanks for growth during their early juvenile stage (Castagna and Kraeuter 1981). Juveniles are then transferred to a grow-out location in open waters. Grow-out of juvenile clams to harvest takes place intertidally or subtidally, depending upon location. Spawning, larviculture, nursery, and grow-out methods for clam production are similar regardless of species cultured.

#### *Seed production*

Clam aquaculture in Asia typically relies on the collection of juveniles from the wild by sieving them from sediments with hand tools or with mechanical, hydraulic devices in areas of heavy settlement (Spencer 2002). However, throughout other regions of the world, clam seed are produced in hatcheries.

Hatcheries typically are located near the shore of a bay or estuary where sufficient quantities of good-quality water can be pumped into the facility. In some instances, water for hatcheries is pumped from a greater distance offshore to avoid pollution and to ensure adequate water quality. Other hatcheries use shallow seawater wells to provide predator-free seawater and to mitigate salinity fluctuations during excessive rain events. However, well water may require pretreatment to reduce ammonia, nitrate, or sulfide levels. Continuously flowing seawater is not necessary in a hatchery because shellfish larvae and algal food are cultured under static-water conditions (Castagna and Manzi 1989). Broodstock are usually maintained in temperature-controlled, recirculating systems or flow-through tanks that require low water exchange.

Food (phytoplankton) production is a critical component of a successful commercial shellfish hatchery, and facility design usually is dictated by the method of algal culture. Early hatcheries employed the Wells-Glancy method for algal production, a technique that utilized natural light and naturally occurring phytoplankton species that were pumped from local waters into culture tanks (Glancy 1965). Although inexpensive, the Wells-Glancy method produced cultures with unreliable species composition, standing stock, and nutritional quality. Most current hatcheries culture several monospecific cultures of phytoplankton in sterile plastic bags or translucent fiberglass tubes. Environmental conditions are closely controlled with artificial light sources, insulation, and heat exchangers for water temperature regulation, and well-defined algal nutrient media (e.g., Guillard's f/2; Guillard 1958). In newer hatcheries, pipes and tanks are constructed almost solely from polyvinyl chloride (PVC) plastic and fiberglass, respectively. These structures allow flexibility of hatchery design, and typically they are cheaper than concrete tanks and metal pipes. The constant challenge of reducing fouling in pipes and tanks requires rearing units and plumbing that can be rapidly disassembled for cleaning and easily reassembled. Antifoulant chemicals are not used in hatcheries because larval tolerance to such chemicals is typically low (Castagna and Manzi 1989).

Clam broodstock usually are selected from wild stocks for optimal color and morphological traits, as well as rapid growth, high fecundity, and good survival. Because most modern clam hatcheries can control the rearing environment, spawning can take place at any time of the year. Broodstock between 35 to 80 mm in shell length are optimal size for spawning (Spencer 2002). After an adequate broodstock population is established, it can be used for gamete production for several years. Broodstock collected from the wild quickly are transferred to the hatchery where they are cleaned and placed in holding tanks where final selection can be made.

Brood clams chosen to spawn are taken from conditioning tanks and transferred to spawning troughs. Some hatcheries use serotonin to stimulate spawning (Gibbons and Castagna 1984), but this practice is not common and normally is used only for reluctant spawners. Temperature cycling is the most common method to induce spawning (Loosanoff and Davis 1963; Spencer 2002). The trough is partially filled with cool water to stimulate the extension of the clam's siphon. After 15 to 30 minutes, the water is drained and replaced with warmer water. This process is repeated for 1 to 6 hours. If spawning is not initiated by thermal induction, a male clam may be sacrificed so that sperm can be harvested and introduced to the females to induce spawning.

Fertilization of Manila clam eggs occurs within 60 to 90 minutes in waters at 25ºC at a salinity greater than 28 ppt (Spencer 2002). Egg incubation requires the highest-quality water, so water should be sterilized with ultraviolet radiation to remove fungi and bacteria. Within several hours, eggs develop into D-larvae (the D is used in reference to the shape of the larvae). Mass-cultured unicellular algae are added as food at the D-larval

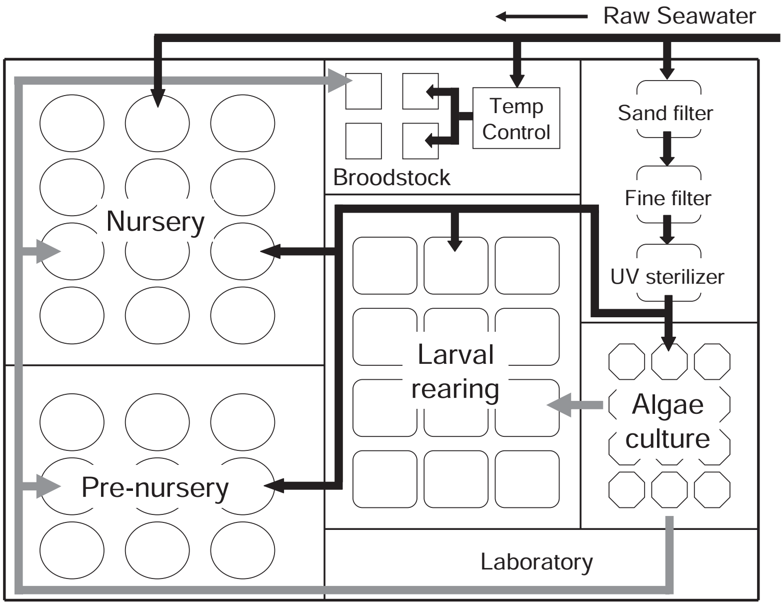

**Fig. 11.1.** Plan view of a generalized bivalve mollusk hatchery showing water flow, water treatment processes, and distribution of food (cultured algae).

stage. Water is exchanged several times per week, if not daily, when temperatures are warm in the larval rearing tanks. During tank cleaning, organisms are graded and deformed larvae discarded. Because clam larvae are planktonic during the first 10 days of development, feeding is increased, but as the larvae reach the pediveliger stage, the feeding rate and larval density are reduced to ensure adequate growth.

Pediveligers are transferred to downwelling systems—cylinders with a screen bottom of appropriate mesh size and provided a downward current to facilitate settlement. Once metamorphosis has taken place, clams can no longer swim, and the seed clams are transferred to a nursery system. A well-designed bivalve hatchery will separate each production area (e.g., algae culture, larviculture, broodstock, and nursery) to avoid cross-contamination (Fig. 11.1).

There are three common types of nursery systems. The upflow method suspends the spat on mesh screens in the water column while water is forced up from the bottom of the rearing unit. This method allows for constant water flow to bring food organisms to the juvenile clams while facilitating cleaning (Manzi and Whetstone 1981; Spencer 2002). Upwelling systems may be land-based, often using cultured algae, or field-based floating rafts or barges equipped with electrical pumps or supplied by tidal currents—termed *FLUPSYs* or *Floating Upwelling Systems* (Hadley et al. 1994; Flimlin 2000) (Fig. 11.2). A less common land-based nursery system uses wooden trays lined with plastic and with a thin layer of sand on the bottom. Spat are placed in the trays which are then placed in fiberglass raceways. Field-based systems are the third type of nursery. In field-based systems, clams are placed on the substrate in shallow subtidal or low intertidal areas utilizing aggregate cover, baffles and pens, or plastic mesh tenting (Castagna and Kraeuter

**Fig. 11.2.** Floating Upwelling System, or FLUPSYS. Photograph courtesy of John Scarpa.

1977, 1981). In Asia, where there is sufficient natural spatfall year around, clam nurseries usually involve creating an intertidal pond where spat can be placed in trays with sand and placed in the pond. The ponds are filled with seawater, and the clams feed on natural organisms. Algal cultures are not added to these ponds, but organic fertilizers such as barnyard manure are added to stimulate algal blooms.

### *Grow-out*

After reaching appropriate size, clams are transferred to grow-out plots in the intertidal zone of bays and estuaries (Loosanoff and Davis 1963). The grow-out activity is simple but requires constant monitoring to ensure adequate production. Siting of grow-out plots is critical because excessive siltation, or excessive periods of air exposure between tides, can impede growth and survival (Spencer 2002).

The most common methods of grow-out are ground plots, tray culture, and soft bags. Ground plots can be prepared by removing large stones and debris to smooth the bottom in the culture area. Mesh screens can be installed to prevent overburrowing and suffocation of clams in soft substrate. Where substrate is more densely packed, there is no need for a mesh barrier and clams can be set directly on the bottom. At locations where the substrate is too compact for burrowing, trays can be used. Trays vary in size depending upon equipment available at harvest. Typical trays have a fine mesh bottom that allows water to pass but excludes soil and reduces the weight of trays at harvest. A firm sand or soft mud is desirable for tray culture, although gravel can be used. Trays are popular only where sediment is not of good quality, because clam production is highest in the natural sea bottom (Spencer 2002). A common method for grow-out used by clam farmers in Florida is called *soft bag culture*. Soft bags are pillows of nylon mesh that completely enclose the clams. The soft bags are staked to the substrate (Philippakos et al. 2001; Adams et al. 1991).

Manila clams typically are seeded at 500 to 1,000 spat/$m^2$. A plastic mesh, usually with 5-mm openings, is placed on top of clam beds to protect against predation by fish and crabs (Spencer 2002). The mesh also prevents loss of clams from plots, and is particularly important where nonnative species are cultured. Trays also are covered with netting and placed in culture plots. Regardless of which method is used, the principle is the same—clams must be provided a sediment substrate in which they can burrow. Nets at clam grow-out plots must be cleaned and repaired frequently to allow adequate water exchange, food availability, and protection from predators. Cleaning is performed with brushes or brooms, but in areas of France where the substrate is sandy, tractors can be equipped with roller brushes to clean the clams.

Grow-out periods for the hard shell clam depend on temperature and food availability, but typically range from 18 to 36 months (Kraeuter and Castagna 2001). In Europe, Manila clam plots usually are harvested after 24 to 36 months (Gosling 2003). The Taiwanese can achieve marketable size clams in 18 months by using intertidal ponds (Chen 1990).

Clams are commonly harvested from ground plots by hand in the United States and Canada, yet there are some producers who use dredging devices to harvest clams. In many states mechanical harvesting of shellfish is prohibited, and the farmer should contact the appropriate agency for current regulations. In Taiwan, rakes with nylon bags attached are used to disrupt the soil and remove the clams. Another mechanical aid to harvesting is a plow-type collector that is pulled behind a tractor. Boats equipped with hydraulic suction devices can be used to suck clams into mesh bags. As the water, clams, and sediment are pumped into the bag, water pressure cleans the shells. Trays are manually harvested using a variety of vessels, often catamaran-style pontoon boats or single-hulled boats with a boom. The trays often are placed on a tractor-drawn platform. Shells can become discolored in grow-out plots if hydrogen sulfide is present. Because discoloration will reduce market value, some farmers wash shells with bleach (Chen 1990). At typical stocking densities, 3-year-old plots of Manila clams could yield between 10 and 15 kg of meat/$m^2$. Manila clams in Europe can yield up to 20 kg meat/$m^2$ (Spencer 2002).

Where coastal waters are polluted, clams bioaccumulate metals, potentially toxic substances, viruses, and bacteria. Depuration of these contaminants takes place after removing clams from final grow-out. Clams can be reset in natural areas that are less productive, and yet the water is of better quality, or clams can be transferred to an enclosed system using purified water. Water in enclosed systems is purified by chlorination, ozone treatment, or ultraviolet irradiation (Blogoslawski 1989). Although depuration is a beneficial practice, cracked and chipped shells resulting from handling and transporting of clams during depuration can be a serious problem.

## *Oyster Culture*

The following discussion on oyster culture will emphasize culture of the Pacific oyster (*Crassostrea gigas*), the most widely cultivated oyster in the world.

### *Spat production*

Oyster aquaculture in France, China, and Japan relies heavily on natural spatfall for seedstock (Spencer 2002; Gosling 2003). Various spat collectors are used, depending on tradition and practical experience. In France and Japan, spat collectors often are made from the shells of scallops, oysters, or other bivalves, a material called *cultch*. Cultch can be laid out in trays, but a more common method is to drill holes in pieces of cultch and suspend them from ropes or wires. This allows three-dimensional use of the water column for collection of spat, thus increasing efficiency. It also is common to use plastic tubes or trays that have been presoaked and sun-dried to remove any hazardous chemicals that reduce success of spat settlement (Gosling 2003). The plastic device is suspended in the water column and spat settle on it. After collection, spat are transferred on the plastic to a grow-out facility.

Hatcheries are an important source of spat in many other countries. For example, according to Ward et al. (2000), the Pacific oyster industry in Australia was derived from importation of this species from Japan to Tasmania in the 1940s and 1950s and is almost entirely hatchery-based. Hatchery techniques for culturing the Pacific oyster in the Pacific Northwest have been described by Breese and Malouf (1975). Hatcheries typically are located near the shore of a bay or estuary where sufficient quantities of good-quality water can be pumped into the facility. Temperature and salinity play an important role in spawning and larval development; thus, hatcheries typically are situated where these two variables remain within an acceptable range for the cultured species so expensive modifications to temperature and salinity are not necessary. Broodstock and larvae are fed algal cultures and care must be exercised to avoid water quality deterioration in culture vessels as a result of feeding. Continuously flowing seawater is not necessary in a bivalve hatchery because both larval and algal food are cultured in standing water (Castagna and Manzi 1989; Castagna et al. 1996), but broodstock culture requires some water exchange.

Hatchery design depends on the method of algal culture. The Glancy method was an early, low-technology method utilizing local phytoplankton species; ambient nutrients and sunlight for algal production; and, consequently, solaria and greenhouse-type structures (Glancy 1965). Most hatcheries now use a more controlled hatchery environment, similar to that used for clams.

Broodstock usually are selected from wild stocks for optimal color and morphological traits as well as rapid growth rates, high fecundity, and good survival. In the United States and Europe, domesticated strains of oysters have been developed and used as broodstock. The characteristics of broodstock vary depending on the market for oysters. For example, in France, shell morphology is an important characteristic because much of the market is for oysters served in the shell.

Oysters chosen for broodstock can be harvested from existing farm stocks and transferred to hatcheries or they can be held and reared in hatcheries. Broodstock are transferred to conditioning tanks that receive unfiltered water supplemented with cultured algae.

Pacific oyster broodstock require a salinity greater than 25 ppt and temperature of 20 to 24°C (Spencer 2002). Broodstock feeding relies on plankton in incoming seawater or algae from laboratory cultures (Matthiesson 2001). Use of algal cultures for food avoids introduction of disease and fouling organisms common in natural waters. Algae typically are cultured from commercially available, pure strains. Feed is provided conservatively to encourage efficient removal by oysters and minimize discharge of algae during water exchange (Spencer 2002).

Two spawning techniques are used in the production of Pacific oyster seed: thermal cycling and surgical removal of gametes. In thermal cycling, two separate water supplies, one of 18 to 20°C and the other 28 to 30°C, are used alternatively (Spencer 2002). Broodstock are transferred to spawning troughs typically made of fiberglass. Troughs are filled partially with cooler water to stimulate the extension of the oyster's siphon. After 15 to 30 minutes, water is drained and replaced with warmer water. This process is repeated for 1 to 6 hours. Eggs and sperm may be collected and quantitatively allotted to containers, or both sexes may be left to mass fertilize. The other method of obtaining gametes is to sacrifice the oyster and surgically remove the gametes from the adults, which is termed *strip spawning* (Helm and Millican 1977). This method allows for closer examination of egg quality. Pipettes can be inserted into the gonads and gametes siphoned out. Eggs and sperm are transferred to separate containers of sterile water. Fertilization takes place under controlled conditions in containers where eggs and sperm are added proportionally.

After fertilization, egg chromosome numbers can be manipulated to produce triploid oysters. Triploid organisms, which are sterile, have three sets of chromosomes and grow faster than normal oysters because they do not spend energy on reproduction. Chew (1994) reported that triploid Pacific oyster culture in the United States accounts for one-third to one-half of total production.

Triploid oysters are produced by blocking the release of the second polar body in newly fertilized eggs. There are several chemicals that induce triploidy, but the most successful one is cytochalasin B (Scarpa et al. 1994). This compound has been approved for use in oyster hatcheries in the United States by the Food and Drug Administration. Other chemicals studied to induce triploid production include caffeine and 6-dimethylaminopurine (Nell et al. 1996), but these chemicals, which are not approved for use on oysters in the United States, are not as effective as cytochalasin B. Triploids can be produced when tetraploid oysters (which are fertile) are mated with normal diploid oysters (Que et al. 2003). The development of tetraploid oysters has revolutionized triploid production for the oyster culture industry because no chemicals are used on edible oysters. Guo and Allen (1994) developed and patented the tetraploid procedure for Pacific oysters, which involves blocking the first polar body in eggs from triploids fertilized with sperm from diploids (although triploids are sterile, there are rare instances when triploids can produce eggs).

In larval culture, the density of organisms from fertilization tanks is managed to ensure adequate growth of straight-hinge or D-stage larval oysters. Aeration is used to maintain larvae in suspension (Helm and Spencer 1972) and feeding with culture algae is initiated. Water is exchanged 3 or 4 times per week in the larval rearing tanks. After about 10 days, larvae reach the pediveliger stage, and the feeding rate is lowered. When pediveligers reach the eyed-stage, usually between 10 to 12 days, settlement substrate is added. This may be cultch, either whole shell or ground to the approximate size of a sand grain (200 µm), plastic sheeting, or other hard surfaces. Once 70 to 80% of the pediveligers have reached the eyed stage, the tank is illuminated; pediveligers swim away from the light, and settle quickly (Spencer 2002). After metamorphosis, oysters can no longer swim and they attach to the settlement substrate. Onset of metamorphosis can be accelerated by the addition of L-DOPA (L-3,4-dihydroxyphenylalanine) and/or epinephrine (Coon et al. 1985).

Oyster spat are removed from settlement substrate by scraping with a sharp straightedge or, in the case of ground shell (termed *microcultch*), separated by sieving on the appropriate sized mesh. Spat are then transferred to the nursery system. There are two common types of nursery systems for Pacific oysters. The upflow method suspends spat on mesh screens in the water column while water is forced up from the bottom of the rearing unit. This method allows constant water flow to bring food organisms to juvenile oysters. Weekly water exchange used in nursery units flushes wastes to the environment and allows spat to be cleaned. A less common nursery system uses wooden trays lined with plastic and with a thin layer of sand on the bottom. Spat are placed in trays that are then transferred to a fiberglass raceway. Flow rates and densities are similar to those of the upflow method. Spat are kept in the nursery until large enough for transfer to the grow-out system.

### *Grow-out*

Spat of about 20 mm in length, either collected from the wild or raised in hatcheries, are transferred to grow-out sites. Two culture techniques are employed: bottom culture and off-bottom culture. The two methods are practiced widely, and in the United States a combination of bottom and off-bottom culture is used. In China, where spatfalls are regular, oysters have been collected traditionally on artificial rock piles. Rocks are typically natural marble or flagstone and are sometimes cleaned with a liming material and set out to dry before being placed in areas with natural spatfalls (Spencer 2002). After spatfall, rocks are moved to more productive and protected locations to grow to market size. The production process in China takes approximately 4 years, and meat yields can be up to 15 tonnes/ha (Cai and Li 1990).

Another method of bottom culture used in France relies on mesh screens placed over spat laid on sediment in the intertidal zone. Alternatively, spat may be combined in mesh socks, which are laid on the bottom. The oysters are allowed to grow for 12 to 24 months, removed, graded, and relaid for an additional 12 to 24 months. Densities are usually 5 to 7 kg/m$^2$ during the early stage of growth, and 0.7 to 0.9 kg/m$^2$ for the final stage of grow-out (Gosling 2003). In all bottom-culture techniques, there is a need for predator protection. To keep crabs from entering culture areas, fences about 40-cm high often are built of plastic mesh or other readily available material (Gosling 2003).

Off-bottom culture of oysters is more common than bottom culture in some Asian countries and uses various structures for oyster attachment. The benefits of off-bottom culture are avoidance of benthic predators, site selection that is independent of sediment type, and three-dimensional use of the water column (Brett et al. 1972). Raft culture typically requires a site with deeper water to prevent the trays or lines from "bottoming out" during low tide. A common grow-out method is the culture of oysters on seabeds. In this discussion, *oyster ranching* refers to the collection of oysters from the wild, replanting in another ocean region, and dredging at harvest. Oyster ranching is practiced in numerous countries, including the United States, the United Kingdom, Mexico, France, Germany. This typically entails distributing oysters on cultch or spat directly into the sea and harvest by dredging or manually with tongs. This culture method is inexpensive but less controllable and could be more destructive to the seabed.

In the United States, production techniques vary by location. In the Pacific Northwest and northern California, most farmed oysters are produced by on-bottom techniques (Mathiessen 2001). The main species produced is *C. gigas*; however, there is some culture of the native oyster, *Ostrea conchaphila*. The seedstock can be obtained from hatcheries or from the wild. However, hatchery techniques to produce triploid oysters make wild-capture of spat relatively inefficient for producers. Seed, whether collected from the wild or produced in the hatchery, settle on oyster cultch and are laid in protective bays and inlets. In areas where the seabed is not suitable for grow-out, suspended oyster culture can be practiced or oyster shells or gravel can be applied to the seabed to produce a more rigid surface (Matthiessen 2001). Most grow-out is practiced in the intertidal region, and oysters are harvested manually or by dredging (Matthiessen 2001).

In the Gulf of Mexico, producers typically culture *C. virginica* by extensive bottom-culture techniques, and oysters are harvested by dredging from boats. Dredges are metal baskets with a row of spikes on the lower side. When dragged over oyster beds, dredges uproot the oysters from the bed and force loose oysters into the basket. Suction dredges are also used and are efficient in clearing bottoms of 10,000 bushels per day. Some oyster producers on the east coast and in the Gulf of Mexico use racks or sacks suspended on stakes as a grow-out method.

In Louisiana coastal waters, the Delaware River, and the Chesapeake Bay, respective state agencies spread cultch in the coastal waters, and private growers harvest cultch with attached seed (*C. virginica*) that is transferred to private culture plots. The culture technique typically is bottom culture. Dredging and manual harvest are common in these regions.

In the Chesapeake Bay, there is a concerted effort to replenish the declining oyster populations with the nonnative Suminoe oyster (*C. ariakensis*). As of 2007, there are production trials underway in the bay with triploid Suminoe oysters.

### *Mussel Culture*

Unlike production of other shellfish, mussel producers typically rely on capture of wild seed for transplantation to grow-out sites because hatchery-produced spat are too expensive (Spencer 2002). Mussels are grown on rafts, stakes (the *bouchot* system used in France), longlines and suspended socks (mesh tubes), or laid directly onto the seabed (Bardach et al. 1972; Korringa 1976; Lutz 1974, 1979, 1980; Hurlburt and Hurlburt 1980).

#### *Spat collection*

When bottom culture is used for mussel grow-out, spat are usually collected by dredging. Dredging disrupts the seabed and dislodges substrate and mussels that are caught in a basket. Boats for dredging spat usually are equipped with multiple dredges. Dredging operations usually take place in waters that are 1 to 20 m deep. In Holland, a typical dredging boat is 30 m long and has four dredges (Chalfant et al. 1980). Mussels are mixed with substrate particles and commercially unimportant bivalves. A washer-grader system on the dredging boat cleans and selects the mussels. Unwanted substrate and bivalves are separated and returned to the water. Mussels ranging from 8 to 13 mm are most desirable for replanting in culture plots (Hurlburt and Hurlburt 1980). Juvenile mussels should be transported as quickly as possible (usually 1 day) to grow-out culture systems to prevent excessive mortalities (Korringa 1976).

Mussels release large numbers of propagules into water by natural reproduction, and the larvae settle on suitable substrate. The most common method for collecting mussel spat is to suspend artificial substrates in water to encourage spat settlement. Spat collectors are especially convenient for capturing spat for off-bottom culture, and this culture method represents about 85% of mussel culture.

Seed collection with spat collectors is simple and requires little technical proficiency. Nevertheless, the best sites for spat collection often are overlooked. The presence of adult mussel beds often is perceived as a prerequisite for spat collection sites. Incze and Lutz (1980) described sites without adult mussel beds in the immediate vicinity that yielded large spatfalls on artificial collectors. Stability of water quality and moderate to strong currents are better site selection criteria for spat collectors because spat may be transported many kilometers from mussel beds by currents. Sites with good water quality and water flow sometimes are superior to sites near mussel beds. Up-river estuary environments that are prone to excessive wave action and high salinity and temperature fluctuations seldom are good locations for spat collection (Incze and Lutz 1980).

Materials for construction of spat collectors vary widely and depend on local availability, durability, and cost (Spencer 2002). Historically, wooden poles have been used in France (the bouchot method), but ropes suspended in the water column now are the most common method. Ropes used in spat collection are similar to those used to suspend mussels for grow-out culture. Many ropes are suspended to increase surface area and promote higher rates of settlement (Spencer 2002). Dare (1980) found that split-film polypropylene suspended off-bottom was an efficient spat collector.

### *Grow-out*

On-bottom grow-out systems are an extensive and traditional form of mussel culture. Mussels are dredged from natural beds and transferred to culture plots where water depths range from 3 to 6 m. Culture plots typically are leased from the government. Mussel growth varies with food supply and temperature, and many farmers leave mussels in beds for 18 to 24 months or longer (Spencer 2002; Dijkema and van Stralen 1989). Bottom culture of blue mussels (*Mytilus edulis*) can yield 100 to 125 tonnes/ha of shell-on mussels. With a 30% meat yield (Hurlburt and Hurlburt 1980), the harvest equates to 33 to 41 tonnes/ha of mussel meat.

Mussels cultured on-bottom are harvested by dredging. Sediment collected with mussels is removed by flushing with seawater on harvest boats or by confining harvested mussels in a porous container that is dragged behind the boat. Mussels also may be relaid on sandy substrate for several weeks until contaminating sediment is purged naturally.

Off-bottom mussel culture using suspension techniques has become more common than on-bottom culture because it is widely adaptable. Spat are transferred from artificial spat collectors to the culture substrate by hand. Numerous types of suspension structures are used in off-bottom grow-out of mussels (Jenkins 1985; Jamieson 1989; Yakily 1989). The suspension structure employed varies greatly by country, often related to traditional use.

In raft culture, spat from artificial collectors are attached to raft lines that hang in the water column. Alternatively, seed may be collected from exposed, rocky mussel beds and transplanted to mesh socks that are hung from rafts (Hickman 1992). Mussels on seeded lines or in socks are reared for 5 to 6 months until the weight of mussels is approximately 100 to 200 kg. Mussels are then thinned by removing enough from each rope or sock to fill three or four more ropes or bags. They are then replaced on rafts and cultured for an additional 12 to 18 months. Mussels are harvested using cranes to lift mussel colonies from the water. Yields are typically 10 kg/m of rope.

Longlines can be suspended by plastic floats on the water surface or they can be weighted below the surface. Vertical lines containing the mussels attached to longlines are typically 4 to 6 m long (Spencer 2002). Culture periods can range from 12 to 24 months, and upon harvest, the weight of mussels is 7 to 14 kg/m of rope (Hickman 1992).

Bouchots or pole culture used in France is one of the original culture techniques for culturing blue mussels. Spat are collected on wooden or aluminum poles during May and June. Juveniles are then transferred to mesh socks that are wound around poles for grow-out (Spencer 2002). In the French bouchot system, three to five socks wrapped around each pole yield 25 to 60 kg of mussels.

### *Scallop Culture*

As with other bivalve culture, scallop culture can be divided into spat production and grow-out of spat to market size. Wild spat can be collected in areas of natural spatfalls, but where spatfalls are absent or unreliable, scallop spat can be produced in hatcheries. Grow-out uses on-bottom or off-bottom techniques in open coastal systems (Hardy 2006).

#### *Spat production*

Collection of wild spat takes place in areas where natural spatfalls are dependable. Ito (1986) and Ito et al. (1988) describe procedures for procuring spat. Spat collector design varies according to tradition and materials available for construction. The most common type of spat collector is a mesh sack stuffed with substrate to increase surface area for settlement. Sacks are suspended from rafts or, more commonly, longlines during spatfall. Scallops fall through mesh openings of the sack and settle on internal substrate. Certain species of scallops will detach from initial settlement after they reach 10 mm; therefore, spat collectors should have mesh with 6-mm openings (Hardy 2006). Ito (1991) also described spat collectors made from kelp (Laminariaceae) suspended from longlines. Unlike other bivalve species, scallop spat are sensitive to handling and must be rapidly transferred to grow-out systems (Hardy 2006).

Seedstock production in hatcheries depends on the environmental tolerance of individual scallop species. Temperature and salinity play important roles in scallop spawning and larval development. Ideally, hatcheries should be located near the shore of a bay or estuary where water is naturally suitable for direct use so that expensive temperature and salinity alterations are not needed. As in clam hatcheries, continuously flowing seawater is not necessary because scallop larvae and algal food are cultured in standing water (Castagna and Manzi 1989), and broodstock management requires only limited water exchange. The design of scallop hatcheries is similar to those for other bivalve species and locations (see Fig. 11.1).

Broodstock usually are selected from wild stocks for optimal color, desirable morphological traits, rapid growth, fecundity, and good survival. Broodstock are transferred to conditioning tanks that receive unfiltered water supplemented with cultured algae. Spawning is induced by cycling water temperature, as described above for clams. Sperm are released before eggs; thus, once spawning starts, each scallop is placed into an individual container. Eggs are transferred to containers of sterile water and combined with sperm. Alternatively, scallops that have been thermally cycled and spawned can be allowed to mass fertilize in spawning troughs.

Fertilized eggs are collected and gently separated by washing through mesh screens. Egg incubation requires high-quality water to avoid fungal and bacterial infection of eggs. Water may be filtered, but many modern facilities use ultraviolet irradiation to sterilize water. In China, antibiotics such as terramycin, chloromycetin, and penicillin are often used to eliminate infections in larval culture tanks (FAO 1991). Ethylenediaminetetraacetic acid (EDTA) may be added to water in incubation containers at 1 mg/L to prevent heavy-metal toxicity (Utting and Helm 1985). This is also a common practice in China (FAO 1991).

Within 96 hours, eggs develop into D-larvae and densities in incubation containers are reduced to ensure good growth. At this stage, mass-cultured unicellular algae are added as food. Water is exchanged 2 or 3 times per week in larval rearing tanks (Hardy 2006; Spencer 2002). To reduce water use, minimize disease risks, and efficiently utilize algae, recirculating systems often are used at this stage. Metamorphosis is reached within 3 to 4 weeks after fertilization (Hardy 2006). Metamorphosis occurs over a 2-day period, and at completion of metamorphosis, scallop larvae are ready for transfer to the nursery.

There are several nursery methods for rearing scallop spat. Most involve flow-through systems, but water-recirculating systems also are used. In flow-through systems, seawater passing through a 45-µm filter is supplemented with algae (Spencer 2002). As spat reach suitable size for survival in open waters they are transferred to the grow-out site.

Attempts to induce triploidy by treatment of scallops with caffeine and 6-dimethylaminopurine have not been successful (Nell et al. 1996). Yang et al. (2000) produced triploid scallops by treatment with cytochalasin B, but efficiency of triploid production and triploid survival were low. Chromosome modification for polyploidy is not yet a common practice in commercial scallop culture.

### *Grow-out*

Scallop spat can be grown to market size with either on- or off-bottom culture techniques. Although suspended scallop culture allows more efficient use of the water column, certain conditions favor the production of scallops on the sea floor. For example, strong storms can dislodge rafts and longlines, and bottom culture of scallops is more practical in areas with heavy seas or where storm surges are frequent and intense.

Equipment needed for seabed scallop culture is less expensive and easier to maintain than that needed for off-bottom culture, but growth is often slower because scallops reared on the seabed do not have access to the greater abundance of plankton in the midlevel water column (Hardy 2006). Bottom culture of scallops is most prevalent in Japan and is known as *sowing culture*. Before grow-out begins, the seabed is dredged to remove predators such as starfish and sea urchins (Gosling 2003). Scallop spat are placed on the sea floor at 5 to 6 individuals/m$^2$ (Ito 1991). Some small-scale scallop farmers construct barriers of netting or stone around culture plots to deter predators (Hardy 2006). This procedure is feasible only when scallops are harvested by divers because dredging destroys the barriers. In some instances, particularly larger-scale culture, barriers are not used, and thus dredging is employed for harvest. About 80% of scallops are recovered when harvested by dredging (Spencer 2002).

Off-bottom culture of scallops is the primary method for culturing scallops. In China, the common off-bottom method uses *lantern nets* to confine scallops during grow-out. Lantern nets (Fig. 11.3) are elongated cylindrical nets with regular horizontal partitions. The open cylindrical shape is maintained by galvanized steel rings that also separate each layer of the multitiered net. The lantern net, stocked with juveniles, is suspended in the water column using ropes attached to longlines or rafts. Harvest timing at the grow-out stage is dependent on species, but can range from 6 to 18 months. Survival is usually about 85% under optimal conditions.

Pyramidal *pearl nets* are also used for scallop culture. The base area of pearl nets is typically between 0.75 to 1.0 m$^2$, and nets are spaced vertically about 0.5 m apart. Strings of 7 to 10 pearl nets are hung on rafts or longlines with approximately 4 m between strings (Spencer 2002).

Ear-hanging is a traditional Japanese method wherein a hole of 1.3 to 1.5 mm diameter is drilled in the left or right anterior "ear" of the shell hinge (Ito 1991). A nylon thread or stainless-steel hook is passed through the hole and the threaded scallop is attached to a branch line at approximately 15-cm intervals. Each branch line (6 to 10 m long) may hold up to 130 scallops. Branch lines are then suspended from rafts or longlines. Ear-hanging is less expensive than using lantern nets but is unsuitable for areas with strong wave action.

## Regulatory Requirements for Shellfish Aquaculture Operations

The molluscan aquaculture industry is subject to a host of local, state, federal, and—where applicable—international laws that regulate the use of marine waters for farming and quality assurance of seafood products. Molluscan aquaculture in coastal waters in the United States is usually conducted on public property through shellfish leases managed by state natural resource agencies. The terms and conditions of these leases vary from state to state, but generally require growers to obtain regulatory permits from state and federal environmental protection agencies, the United States Army Corp of Engineers, and public health agencies. The situation in Washington State differs in that growers can hold private title to shellfish grounds in the intertidal zone (Olin 2002). The regulatory environ-

**Fig. 11.3.** A lantern net used for off-bottom culture of scallops and oysters. Photograph courtesy of Norman Blake.

ment can be confusing and frustrating, with overlapping or vague boundaries of jurisdiction among regulatory agencies, complicated permitting pathways, or regulators with limited specific knowledge about shellfish aquaculture. Nonetheless, for the shellfish aquaculture industry to prosper, it is incumbent upon growers to be knowledgeable and to comply with all pertinent regulations and permitting processes (i.e., municipal, county, state and regional, federal, and international).

A Section 10 permit, issued pursuant to the Rivers and Harbors Act of 1899, is required for activities in or affecting the navigable waters of the United States. The regulations are located at 33 CFR §320.1–320.4. The discharge of dredged or fill material in waters of the United States is permitted by the United States Army Corps of Engineers under Section 404 of the Clean Water Act (33 USC §1344). The corresponding regulations are located at 33 CFR §323.1–323.6.

Constructed works also must be installed, marked, and maintained in accordance with guidelines of the Ports and Water Safety Act administered by the United States Coast Guard. Before placing a structure in navigable waters, the owner or operator must apply for Coast Guard authorization to mark the structure in compliance with 33 CFR §66.01–66.05. Depending on the circumstances, aquaculture operators may be required to mark the site or obstacle during the day and by adequate light at night. The regulations explain the lighting requirements for structures.

The Clean Water Act prohibits the discharge of pollutants from a point source into waters of the United States, except as authorized by a National Pollutant Discharge Elimination System (NPDES) permit. Regulations for aquaculture operation discharges can be found at 44 CFR §125.10–125.11. In addition, on 30 June 2004, the United States Environmental Protection Agency (USEPA) issued its final rule (Federal Register 2004) setting forth standards for concentrated aquatic animal production (CAAP) facilities (fish farms, hatcheries, reserves, and other aquaculture). Concentrated aquatic animal production facilities are point sources subject to the NPDES permit program (40 CFR §122.24). The USEPA regulations establishing the effluent limitation guidelines and new source performance standards for CAAP facilities are available at 40 CFR §451.1–451.24.

If gear is to be deployed in an area frequented by marine mammals or endangered species (sea turtles, for instance), the operator may need permits from the National Marine Fisheries Services under the Marine Mammal Protection Act and/or the Endangered Species Act. The relevant regulations are located at 50 CFR §216.1–229.34. Critical habitat as defined by the Endangered Species Act is 1) an area occupied by a species listed as threatened or endangered within which are found physical or geographical features essential to the conservation of the species, or 2) an area not currently occupied by the species which is itself essential to the conservation of the species. Federal agencies are required to consult with the United States Fish and Wildlife Service about the effect of actions they authorize, fund, or carry out on designated critical habitat.

Compliance with applicable regulations is a basic requirement for sustainable and responsible shellfish aquaculture. Obeying the law is not a better management practice, but rather a fundamental obligation. Shellfish farmers should become knowledgeable and involved in the legislative process, particularly as it relates to protecting the marine environment and the grower’s livelihood. It is implicit in any Best Management Practice that all participants in the industry will take responsibility to determine what requirements apply and to comply with those requirements. This is the basic underpinning of responsible aquaculture (MAA, undated).

In 2002, the Pacific Coast Shellfish Growers Association drafted Environmental Codes of Practice for the Pacific Coast Shellfish Industry (PCSGA 2002) that establish the following general objectives and suggested strategies for Pacific Coast shellfish aquaculture businesses:

Objective: Ensure operations meet or exceed regulatory and environmental standards.
Suggested Strategies:

1) Become knowledgeable about and keep current on all rules, regulations, certification, and permit requirements governing shellfish aquaculture operations.
2) Compare all statutes and agency rules against shellfish activities to ensure compliance.

Objective: Promote sound environmental policies and innovative practices and techniques that help protect and restore the environment.
Suggested Strategies:

1) Identify opportunities for conserving and protecting natural areas and for enhancing functions and values of growing areas and beaches.
2) Continue to experiment with and develop more efficient cultivation methods that also provide benefits or protections for the environment.

3) Incorporate environmental policies into employee training and orientation.
4) Become involved in local watershed and water quality improvement activities and support legislation and regulatory policies that promote environmental protection, especially water quality.

## Site Selection, Access, and Maintenance

Site selection is a critical component for operational success because molluscan aquaculture is conducted almost exclusively in situ. The obvious consideration in evaluating potential sites is the performance of the target species at that location (e.g., growth rate and survival). Water chemistry (especially salinity and temperature), phytoplankton standing crops, and taxonomic composition, sediment type, presence of disease organisms or harmful algae, and anthropogenic influences on water quality play important roles in promoting good survival and rapid growth of shellfish throughout the production cycle. Water depth, ease of access, protection from severe weather events, and security are important practical considerations for operating a shellfish aquaculture operation.

In addition to the ecological considerations associated with site selection, sociopolitical issues can influence the suitability of a particular location for an aquaculture enterprise. It is important to identify other stakeholders adjacent to the farming operation, including surrounding property owners and local residents, and potential sources of sewage, pollutants, or other contaminants detrimental to the well-being of shellfish, or other potential conflicts. User conflicts—such as access, water quality impacts, aesthetics, boating, and navigation—can be minimized if attention and forethought are used at the onset of a culture activity and during site selection.

### *Better Management Practices for Site Selection*

Because shellfish culture relies on natural processes to supply food to cultured species, appropriate attributes of sites will affect not only the waste processing from the culture activity, but also the growth rate and success of the husbandry effort. Thus, sites are integrated into culture processes to a greater degree than many other forms of aquaculture.

Consideration of the carrying capacity of estuarine ecosystems where sites are chosen for shellfish culture can be incorporated into site selection, but currently there is no technically feasible or financially viable method to determine this. There have been attempts and models can be applied, but typically the water body must be closely monitored to provide data applicable to a carrying capacity model. Thus, shellfish farmers are more likely to monitor changes in the ecosystem that affect growth and survival of cultured stock, and adjust practices accordingly, rather than attempt to quantify or develop a carrying capacity index. Further, BMPs for carrying capacity should be considered as a suite of practices that are presented in this chapter; there are no direct, specific “carrying capacity BMPs.” The intention of this section is to highlight the major components of site selection and the associated BMPs that improve environmental performance.

### *Select sites of appropriate depth, salinity, substrate, oxygen, and water flow characteristics*

Sites with appropriate environmental conditions will promote good shellfish growth and survival. Water exchange and tidal currents should ensure a good supply of food for shellfish crops and promote a healthy benthic environment by enhancing the dispersion of solid wastes. Operators should evaluate historical, current, and potential near-term changes in water quality.

Climatic and meteorological considerations that may affect sites at different times of the year should be taken into account when selecting a site (for example, El Niño/La Niña years may have dramatic effects on water quality). Depth of the water column under suspended culture gear, rafts, or float-homes should be sufficient to avoid groundings and facilitate dispersion of wastes from biofouling control or shellfish processing operations (Box 11.1).

### *Maintain benthic biodiversity*

Clams, oysters, mussels, geoducks, and scallops are cultivated within the substrate, directly on the seabed, or above the seabed for the duration of the culture period. There may be changes in the sediment condition and a reduction in the biodiversity of benthic organisms directly beneath and around the edges of shellfish farms. Through the processes of filtration of phytoplankton and other organic material and the deposition of feces and pseu-

## BOX 11.1

## Ecosystem Productivity and Oyster Aquaculture

A study of the Thau Lagoon of the Mediterranean Sea along the coast of France (Chapelle et al. 2000) demonstrated potential effects of oyster culture on the pelagic environment. Oyster plots occupied about 10% of the lagoon area and yielded about 30,000 tonnes/year of Pacific oysters. Oysters had a major influence on the ecology of the lagoon. Nutrient input from the watershed of the lagoon coincided with rainfall. During dry periods nitrogen was recycled through the activity of oysters, and the system remained highly productive even though there was no input of nitrogen from the watershed. Oysters also had important impacts through filtration of plankton and other particulate matter, and biodeposition. Filtration reduced plankton abundance and suspended solids concentration, and biodeposition caused enrichment of sediment with organic matter in culture areas. Local water-column hypoxia resulted from oyster respiration and other benthic respiration in the oyster-farming areas. Oxygen consumption rates in these areas were increased by about 300 times, in contrast to areas of the lagoon without oyster farming. Oyster beds increased respiration rates and caused local hypoxia even though plankton abundance was diminished through filtration by oysters.

## BOX 11.2
## Benthic Impacts of Shellfish Aquaculture

In France, oyster culture gear was associated with a three- to fourfold increase in meiofaunal abundance, concomitant with a 42% reduction in benthic macrofauna (Castel et al. 1989). Changes in benthic species diversity and abundance were caused by increased predation on macrofauna and reduced dissolved oxygen associated with localized nutrient loading.

Extensive bacterial mats have been observed under shellfish longlines (Dahlbäck and Gunnarsson 1981), and changes in benthic community composition in an area of intensive oyster culture were observed in Spain (Tenore et al. 1982). Small increases in organic matter concentrations in sediment have been observed in mussel culture (Tenore et al. 1982). Hayakawa et al. (2001) studied seasonal variation in biosedimentation by Pacific oysters (*Crassostrea gigas*) in the Ofunato estuary in Japan.

The magnitude of benthic impacts is site-specific. Crawford et al. (2003) observed that the farming of oysters and mussels in Tasmania had little effect on benthic communities compared with effects of salmon aquaculture cages (Crawford et al. 2001, 2002). There were no extensive mats of *Beggiatoa* bacteria, no spontaneous outgassing from sediment, no major shifts in benthic infauna to species tolerant of high organic loading, no redox potential values of 0 millivolts or less (indicating anaerobic conditions), and no elevated concentrations of sulfide as is often observed beneath salmon net pens. Thorne (1998) made similar observations of shellfish culture in Tasmania. As a result, Crawford et al. (2002) did not recommend monitoring of shellfish areas in Tasmania other than annual video records.

dofeces, bivalve mollusks transfer nutrients from the water column to the underlying sediments, resulting in elevated nutrient loading, increased biochemical oxygen demand, and in extreme cases, anoxic conditions (Olin 2002).

Monitoring benthic biodiversity is expensive and time consuming. Thus, every effort should be made to avoid alteration of the environment to avoid monitoring costs. If biodiversity indexes are developed, producers can obtain assistance from local extension agents. If deterioration or major changes in benthic biodiversity occur (either macro- or microfauna), attempts should be made to identify the practices leading to the problem and then to improve or eliminate those practices. Should biodiversity continue to decline, fallowing sites may allow for original organisms to reestablish. Biodiversity should be maintained, and if culture conditions do not allow for coexistence with the natural fauna, the selected site may be inappropriate (Box 11.2).

### *Avoid sites with submerged aquatic vegetation*

Submerged aquatic vegetation, primarily marine angiosperms collectively known as *seagrasses,* provide habitat for many finfish and invertebrate species of commercial, recreational, or ecological importance. In many cases the habitat requirements for submerged aquatic vegetation and shellfish are similar and they could spatially overlap, each affecting the other. Placement of nets and equipment, vessel traffic, and some harvesting methods conducted on or near seagrass habitat can have deleterious effects.

The effects of shellfish aquaculture on submerged aquatic vegetation depends on the shellfish being cultured, the method of culture, and the specific location. For example, the substrate of Manila clam grounds is often modified by the addition of gravel or crushed oyster shell to improve settlement success and growth. This could bury aquatic vegetation if sites are not adequately assessed prior to initiation of the activity (Toba et al. 1992, 1993). Stake methods used to culture oysters in Oregon adversely impact eelgrass beds through increased sedimentation and physical disturbance during planting and harvesting, while eelgrass declines associated with rack culture systems can be attributed to erosion and shading (Everett et al. 1995). In contrast, the mussel *Modiolus americanus* has a positive effect on nearby seagrass *Thalassia testudinum* beds by increasing sediment nutrient levels, resulting in enhanced seagrass growth, and by increasing the density of epiphytic grazers, resulting in reduced epiphytic fouling on seagrass blades (Peterson and Heck 2001a, b).

Despite equivocal environmental impacts, areas with submerged aquatic vegetation should be avoided. Furthermore, shellfish aquaculture activities over existing submerged aquatic vegetation beds are prohibited in many states, and new leases are not issued in well-vegetated areas.

Potential deleterious impacts on submerged aquatic vegetation from intertidal shellfish aquaculture also arise when workers walk or drag beach skiffs through seagrass beds during low tides. Designate access routes and landing and staging zones to avoid areas that support seagrass beds.

### *Minimize risks to navigation when selecting sites*

Shellfish aquaculture is conducted in the intertidal and immediate subtidal area of navigable waters. Navigable waters are defined as bodies of water over which a vessel of virtually any description can operate. Any containment structure or equipment that impedes or restricts navigation or poses a risk to navigational safety must be in compliance with existing regulations. As such, almost all shellfish aquaculture operations that occur in navigable waters will require permits. Approval from the United States Army Corps of Engineers is required prior to the construction of any works located below the high-water mark in any navigable waters. A work is defined as any structure, device, or materials on, in, or under the water that may impact navigation. An operator seeking to deploy shellfish gear in navigable waters will need to obtain a Section 10 permit from the Corps of Engineers. A Section 10 permit, issued pursuant to the Rivers and Harbors Act of 1899, is required for activities in or affecting the navigable waters of the United States. Regulations are located at 33 CFR §320.1–320.4.

### *Locate Floating Upwelling Systems (FLUPSYs) to comply with navigational requirements and to minimize impacts on the benthic environment*

Nursery operators should avoid placing FLUPSYs in areas that will shade submerged aquatic vegetation or impede navigation. FLUPSYs attached to existing docks are unlikely to impact submerged aquatic vegetation because the docks will have already been subject to such regulations. While moored, FLUPSYs should comply with navigational regulations and be anchored and marked sufficiently. In the case of tidal flow FLUPSYs, a properly sized single-point mooring should be sufficient to prevent drag during storm events.

### *Select sites that do not impede public access*

Early in the site selection process, establish the availability of access to the facility for motorized transport of equipment and harvesting. Determine practical access routes to the site prior to submission of any permit applications or development of the site. Whenever feasible, limit access to the site to foot or boat traffic. In many cases, state jurisdiction over the availability and location of submerged land leases may limit options for practical access routes. For example, if access to the leased site is through a wetland buffer zone, access may require special permitting.

Use public access points wherever possible to minimize traversing private property. If the only practical access to the site is through private lands, secure written permission or a contractual agreement from the landowner whose property is being traversed. Take careful measures to include the extent of activities (e.g., time of day, weekends) and the type and amount of equipment and materials that will be transported.

### *Select sites for hatcheries and land-based nurseries with a sufficient supply of high-quality water*

Hatchery success depends on the availability of a sufficient supply of good-quality water. Temperature and salinity play an important role in spawning and larval development. Therefore, to reduce costs of adjusting temperature and salinity, hatcheries should be located where water quality is nearly optimal. Hatcheries typically are located near the shore of a bay or estuary where sufficient quantities of water can be pumped into the facility. In some instances, water for hatcheries is pumped from a greater distance offshore to avoid pollution and ensure adequate water quality. Continuously flowing seawater is not necessary in a hatchery because both larvae and algal food are cultured in standing water (Castagna and Manzi 1989). It should be noted that broodstock management requires small amounts of water exchange.

Many of the BMPs addressed to ensure proper management of grow-out sites can be applied to the construction and siting of hatcheries and land-based nurseries.

### *Site land-based facilities in locations that minimize environmental impacts and public health concerns and that are aesthetically consistent with adjacent properties*

The beginning of any "good neighbor policy" for aquaculture operations is siting a land-based facility in a compatible neighborhood and designing the facility to blend well with existing structures. Architectural design and plot layout, adequate space for storage of supplies and equipment, strategically placed and well-maintained landscape plants, and paved drives and parking areas will contribute to the facility's acceptance by neighbors and the local community.

## Facility Construction

The molluscan shellfish aquaculture industry continues to develop innovative equipment, farming techniques, and construction standards that facilitate increased productivity and efficiency. Facilities located on lands that are not zoned for agriculture must be in compliance with local construction and zoning regulations and consistent with submitted development plans. All necessary zoning and construction permits should be secured before site clearing and construction commences.

### ***Better Management Practices for Facility Construction***

#### *Minimize erosion during construction of land-based facilities*

Carefully examine drainage patterns of sites prior to facility construction because they may impact the culture of shellfish and environmental quality. High sediment loads can cause sediment accumulation, leading to blockage of waterways, suffocation of native vegetation, elevation of turbidity, and reduction of dissolved oxygen levels. Stormwater runoff is often associated with high nutrient loads or the release of unwanted chemicals into aquatic environments.

Natural drainage patterns should be incorporated into facility design. Any modification of these patterns should use swales and/or berms to direct surface water flow that is consistent with natural hydrology. During construction, stabilize exposed soils to prevent erosion and use silt barriers to prevent turbidity of surrounding surface waters or the inadvertent sedimentation of adjacent ecosystems.

#### *Properly mark site boundaries, structures, and equipment*

Most states require that a shellfish lease be clearly demarcated by stakes or buoys at the corners of the lease, usually designating a minimum distance between intervening boundary markers. The site should be clearly marked to show lease boundaries and any impediments to navigation. This practice is important for boater safety and provides some protection to shellfish growing areas. Well-maintained equipment and clearly marked aquaculture sites will reduce the potential for commercial or recreational marine traffic to approach or enter the site in an unsafe manner (Fig. 11.4).

Some growers will use additional markers to delineate the perimeter of a lease or specific subsections within its boundaries. However, placing markers in close proximity or using fencing materials that restrict access to a lease is prohibited in most states; therefore, physical exclusion should be avoided. An overabundance of unnecessary and highly visible stakes (usually white PVC), or poor maintenance of stakes or markers, can lead to complaints from other users or upland property owners related to unwanted visual impacts. Thus, the number of stakes or other markers should be used effectively and efficiently to make the site aesthetically acceptable. Stakes or markers that are damaged, heavily fouled, or unnecessary should be removed.

Ensure that aquaculture structures are properly (and legally) marked to assure safe navigation near the farming site. Floating and/or elevated structures should be marked in conformance with United States Coast Guard guidelines (33 CFR §64) and properly permitted. Ensure all lights are installed in compliance with United States Coast Guard

**Fig. 11.4.** Posted shellfish lease with appropriate signage and boundary markers. Photograph courtesy of the Florida Department of Agriculture and Consumer Services.

requirements. Report any hazards or obstructions to safe navigation to the appropriate authorities. Mark all anchor lines and cables or submerge them sufficiently to prevent obstruction.

### *Secure shellfish culture structures properly*

All structures and equipment should remain within the designated boundaries of the aquaculture site. To prevent dragging and drifting of equipment beyond lease boundaries, properly size and set all anchors used to secure rafts, vessels, floating structures, and equipment. Securely fasten and regularly monitor and maintain all floating and fixed equipment.

### *Place nets and equipment in suitable areas*

Consider access patterns and normal operating procedures when laying out growing areas in order to provide sufficient space to facilitate daily activities and minimize impacts to the environment and users in adjacent waters. Place shellfish containment systems and other culture gear to permit efficient operations and maintenance on-site without interfering with adjacent areas and users. Containment systems may include racks, cages, mesh bags, hanging lines from flotation devices, or bottom netting used to prevent predation.

The spatial distribution of such equipment will influence operational efficiency, natural functions of the habitat, and other user groups in adjacent waters. For example, nets, cages or other equipment placed in close proximity to one another will impede access by workers and disrupt the activities of noncultured species. Rafts, FLUPSYs, and other floating structures may be allowed but usually with restrictions regarding the extent of coverage of the production area. An area is considered to be covered with floating equipment if normal navigation through the area is impeded.

### *Use durable materials for facility construction*

Purchase materials and equipment constructed with durable materials or those that can be reused for other purposes or recycled. Materials used to construct culture apparatus should be environmentally compatible. If possible, purchase recyclable or reusable materials or durable products with a long lifespan. Aquaculture operations can have influence on suppliers of aquaculture products and should encourage manufacturers and suppliers of aquaculture equipment and packaging materials to produce recyclable products and develop protocols for product disposal.

## General Facility Operation

Public perception of the benefits of bivalve mollusk aquaculture to the marine environment and the dependence of shellfish growers on fertile, but uncontaminated water in which to grow crops emphasizes the need to adopt practices that minimize or eliminate any activity that adversely affects environmental quality. Facilities must be designed, constructed, and operated to minimize adverse impacts on receiving waters, adjacent wetlands, and uplands.

### ***Better Management Practices for General Facility Operation***

#### *Minimize disturbance of substrate in shellfish growing areas during bed preparation and harvesting*

For shellfish that are cultured in or on the substrate, bed preparation may be required to increase the surface area and uniformity of the growing area and to increase seedstock survival. This preparatory effort may include removing algae, mussel mats, shell debris, or other growth, and mixing gravel with the sediment to create a more uniform substrate. Extreme disturbance of the seabed may negatively affect shellfish production and local environmental conditions.

The oyster drill—one or more species of univalve snails—can be highly destructive to oysters. In attempts to control oyster drill in highly infected areas, bottoms may be cleaned and plowed after harvest. These activities, particularly if conducted subtidally, can increase turbidity of surrounding waters and deposit sediments downcurrent of the planting area. Predator removal is necessary at some culture sites, and the extent to which this is allowed depends on state permitting and regulations, but an overabundance of shellfish predators also denotes a poor culture site. This should be addressed and considered during site selection. If predator removal is deemed necessary and proper regulatory processes have been followed, producers should use depredation methods and chemicals approved for use (see the section “Pest and Predator Control” later in this chapter).

Spat for some bivalve species may be dredged, and wild oysters and other bivalves often are harvested by dredging (Shumway et al. 2003). Impacts of bivalve dredging include changes in seabed topography and sediment structure, resuspension of sediment, and reduction in macrofaunal biodiversity. Mechanical harvesting of oysters using dredges and hydraulic-powered tongs extracts living oysters and the attached shell matrix and has been blamed for degradation of oyster reef habitat (Reise 1982; Hargis and Haven 1988; Rothschild et al. 1994; Dayton et al. 1995). This habitat serves as a refuge for many aquatic species, and dredging could indirectly cause the decline of aquatic life other than oysters. Oyster habitat may now be more economically valuable as habitat for other species than for the oyster fishery per se (Lenihan and Peterson 1998).

Scallop dredging has caused long-term changes in the structure and biodiversity of sponge assemblages in the Gulf of Kalloni, Aegean Sea (Kefalas et al. 2003). Most damage to large benthic invertebrates during scallop dredging occurs unobserved on the seabed, rather than in the by-catch (Jenkins et al. 2001). However, the yield of shellfish per unit area of the bottom in aquaculture sites is much higher than yields of natural scallop beds. Thus, the likely area of impacted sediment is much less per ton of harvest in shellfish aquaculture than in shellfish wild capture.

Harvesting shellfish beds can temporarily resuspend sediments and alter benthic communities. The use of suction dredges and mechanical drags or rakes remove or relocate sediments, creating surface irregularities that may require days to months to recover depending upon tidal, wave, wind, and current activity (Hall and Harding 1997; Jennings and Kaiser 1998; Kaiser et al. 1996). If necessary, culture gear should be removed from the area after harvest to allow time for the substrate to lie fallow and recover. Culture gear deployed on or immediately above the substrate can result in increased sedimentation from altered current velocities and direction.

Sediment with accumulated organic matter can be removed or plowed to facilitate oxidation of the surface sediment and reduce oxygen demand, although sediment removal is rarely necessary. Additionally, aquatic vegetation can be removed from some culture sites to reduce biofouling. Any organic matter that is removed should be deposited where there is minimal burden placed on the environment as a result of the oxygen demand associated with decomposition of this material. Creating spoil piles on shore may increase oxidation of organic matter, but the smells and sight of spoil piles could result in complaints from nearby residents.

In general, avoid resuspension of sediments as a result of bed preparation or harvesting activities. The effects of resuspension can be minimized by deploying sediment curtains or silt fences. Conduct harvest and bed preparation activities during slack tides to minimize downcurrent sedimentation. Employees should be trained in the proper techniques for planting and harvesting to minimize resuspension of sediments and other disruptions to the natural environment. Be aware of the attributes and limitations of culture sites and recognize that it may be advantageous in the long run to farm in harmony with existing site attributes (or select another site altogether) rather than attempting to create an ideal culture site.

Because wave action can disturb shoreline sediments, vessel speed should be adjusted to minimize the impact of wake on the intertidal area and foreshore. Additionally, wave action by boats may disturb shellfish plots and other marine users in the area. Thus, safe speed limits within shellfish growing areas should be posted to encourage boaters to reduce speed.

### *When collecting wild seed, use equipment and methods that will minimize potential adverse effects on surrounding ecosystems*

Placing oyster cultch bags along the intertidal zone is one popular method for collecting wild oyster spat. Examples of suitable cultch materials include clean, washed, and bundled oyster shell, fossilized shell, coral, crushed and graded limestone, granite, or concrete, or recycled materials that contain lithic and calcium carbonate fractions. Cultch bags should be placed where they will not disturb sensitive fish or wildlife habitat, including aquatic vegetation. Similarly, any nonnatural materials, floating structures, lines, or other temporary equipment should be appropriately anchored, visually unobtrusive, and marked in accordance with existing statutes and navigational requirements.

### *Remove and properly dispose derelict shellfish culture equipment and other solid wastes*

Netting, stakes, bags, lines, floats used during normal operations of a shellfish aquaculture site may be introduced into the environment or become derelict through mismanagement or the disruptive effects of adverse weather or sea conditions. Patrol the farm and adjacent shoreline areas regularly to retrieve marine debris and other solid waste, and dispose or recycle appropriately. Emphasize areas where waste accumulates from prevailing winds and currents.

Solid waste generated in the normal course of farm operations should be minimized through waste reduction, reuse, recycling, and recovery. All waste produced by the farm should be collected and disposed according to local, state, and federal guidelines. Solid waste should be separated into "burnables," organic, aluminum, plastic, and trash. Promote the responsibility of all marine resource users to collect and dispose of solid wastes in a proper and timely manner.

### *Properly dispose of wastewater generated by shellfish culture activities*

Shellfish farming operations generate wastewater from washing shellfish and equipment, cleaning tanks, human sewage, and human hygiene. Some of these activities occur on land, while a substantial portion may occur on vessels or on the culture site. The introduction of human fecal coliform bacteria into marine waters, particularly within areas certified for shellfish aquaculture, is an issue of particular importance and concern. Provide on-site sanitary facilities for employees and visitors and have a regular plan for proper pumpout, disposal, and cleaning of portable toilets. Operators should exercise all due diligence to ensure that all sewage, either onshore or onboard, is properly disposed. Many states require the pumpout and complete containment of black water and disposal at approved facilities or sites. Similarly, states may require containment and off-site disposal of gray water (i.e., sink, tub, shower, or laundry wastewater).

Efforts should be made to minimize all wastewater impacts from the site through wastewater reduction, reclamation, and recycling. Recycling wastewater where possible or conversion to irrigation water or other approved environmental enhancement projects will reduce environmental footprint and encourage other marine resources users to dispose of sewage and wastewater responsibly. Conserve water whenever possible; stop water flow when processing or cleaning operations are interrupted.

### *Remove grow-out equipment, such as cover nets, bags, and trays, from water during mechanical cleaning*

No mechanical or hydraulic cleaning equipment should be employed underwater; only hand tools are appropriate for cleaning submerged bags and equipment. This activity should occur over the farm site so that sediments remain in the local area and be scheduled during periods of low current flow to retain sediments on-site.

### *Maintain vessels and equipment in good working order*

Skiffs, marine vessels, and work rafts are used in shellfish aquaculture operations to transport employees and equipment, and for the handling and harvest of shellstock. The main purpose of vessels used in the harvest and transport of shellfish is to prevent contamination and/or deterioration of the product. Such vessels should be provided with false bottoms and bulkheads fore and aft to prevent product contamination from bilge water.

Typically, only small amounts of fuel and lubricants are carried on support vessels, but even the risk of small spills resulting from careless fueling, poor weather conditions, or the sinking of unattended craft can cause considerable environmental damage. Therefore, vessels and marine equipment should be maintained in seaworthy condition and properly used at all times.

### *Use fuels, lubricants, and other petroleum-based products in a responsible manner*

A variety of chemicals, fuels, lubricants, and cleaners, albeit in small quantities, are used in shellfish aquaculture operations. Maintain only the minimum amount of fuels and lubricants necessary for on-site operations. If practical, use nontoxic, biodegradable or food-grade oils, lubricants, cleaning agents, and other environmentally benign products. Separate fuel containers from product holding areas on vessels or land transport vehicles. Minimize the risk of contaminating spills through appropriate design of work craft and equipment and employ containment devices (such as drip pans) wherever possible. Transportable fuel tanks, oil canisters, and other hazardous materials should be removed from vessels when not in use for extended periods. Transition from two-stroke outboard engines to four-stroke engines.

### *Maintain proper containment of hazardous materials*

Store hazardous materials in lined and covered bins and have absorbents available for use in the event of spills. Precautions should be made to ensure that handling, storage, and disposal of these materials ensures protection of employees and prevents contamination of the marine environment. State and federal food-safety regulations require safe storage of hazardous materials to protect water quality and food safety in processing operations.

*Provide adequate training in waste management*

Employees should be trained in spill prevention and a rapid-response strategy for proper containment and cleanup of spills, and be able to coordinate spill cleanup with the appropriate regulatory agencies. Training should also include methods to prevent direct or indirect contact of toxic chemicals and compounds, such as creosote, wood preservatives, and tin-based antifouling paints, with the marine environment.

## Biofouling Control

Surfaces immersed in the marine environment or otherwise exposed to seawater become colonized by marine organisms, a process termed biofouling (Railkin 2004). The types, frequency, and severity of naturally occurring biofouling organisms depends on site location, type and location of crops and equipment, depth, seasonality, flow, nutrient loading, and water temperature. Most fouling organisms produce planktonic or free-swimming larvae that are carried by currents until they metamorphose or settle onto a suitable surface and adopt a benthic lifestyle.

Biofouling is a ubiquitous problem for shellfish farmers because fouling organisms can occlude the mesh openings on nets or bags, thereby restricting water flow to the crop (Claerboudt et al. 1994; Ross 2002) resulting in reduced food availability and dissolved oxygen supply (Huguenin and Huguenin 1982; Enright 1993; Lu and Blake 1997; Cronin et al. 1999; Dolmer et al. 2001; Mazouni et al. 2001). Most marine fouling organisms are filter feeders (Fig. 11.5) that compete with shellfish for food, a problem

**Fig. 11.5.** Mollusk cage fouled by tunicates. Colonial ascidians are particularly problematic as fouling organisms because they not only restrict water flow but, as filter-feeders, they also compete with shellfish for food. Equipment severely fouled with tunicates can become cumbersome and heavy enough to cause safety concerns. Photograph courtesy of Garth Arsenault, Atlantic Veterinary College, Prince Edward Island, Canada.

found not only on submerged structures but also in water intake pipes and tanks in land-based holding facilities, hatcheries, and nurseries. Fouling also restricts shell opening, thereby compromising respiration and feeding activity, and increases vulnerability to predation (Minchin and Duggan 1988; Lu and Blake 1997; Lodeiros and Himmelman 2000).

Severe biofouling can increase the weight of framing materials, complicate handling procedures, and compromise safety during regular cleaning and harvesting activities. The eutrophication of coastal waters from land-based runoff enhances production of most biofouling organisms and exacerbates the shellfish farmer's challenge to control the problem. Thus, nets, frames, and other equipment should be regularly monitored for accumulation of biofouling organisms.

There are strong economic incentives for shellfish farmers to implement practices that reduce the impact of biofouling organisms on crops and equipment and minimize the need to discard nontarget species in a sustainable manner. To that end, biofouling management is a primary activity of shellfish farmers, particularly during the warmer months of the growing season.

A research project funded by the European Union (*Collective Research on Aquaculture Biofouling*; www.crabproject.com) is developing and implementing effective biofouling management strategies for the aquaculture industry. These include biological control, new materials (coatings), husbandry practices, cleaning practices, and electrochemical antifouling methods (Lane and Willemsen 2004; Willemsen 2006).

### *Better Management Practices for Biofouling Control*

#### *Develop and implement an integrated biofouling management plan*

Integrated Pest Management (IPM) is the coordinated decision making and action process that uses the most appropriate biofouling control methods and strategies in an environmentally and economically sound manner, and in coordination with appropriate regulatory agencies. Elements of a comprehensive IPM include 1) early prevention and avoidance of biofouling problems; 2) regular monitoring for the presence and damages incurred by biofouling organisms; 3) establishing maximum densities for biofouling organisms based on levels that are economically, aesthetically, and environmentally acceptable; and 4) evaluating the effects and efficacy of biofouling control options (PCSGA 2002).

Careful selection of growing areas is the best method to avoid severe biofouling of shellfish crops and gear. Another cost-effective way to avoid or minimize biofouling is to adapt the timing of the crop production cycle to offset peaks in recruitment of nuisance species. For example, regular monitoring of barnacle larvae in spring and early summer can suggest an appropriate time to transfer shellfish from nurseries to grow-out sites to avoid barnacle sets.

High-quality seed, well-maintained production systems, and productive areas that promote rapid growth are the best insurance against overwhelming fouling events. Daily exposure to air in intertidal shellfish beds and regular maintenance and dessication of containers, nets and screens, and seed in land-based nurseries can be effective as a preventive approach to biofouling management.

### *Use mechanical methods to control biofouling*

If biofouling develops to the extent that it restricts flow to cultured shellfish, clean netting material sufficiently to return adequate water flow or replace with clean netting or bags. Air/sun desiccation or heat treatment of equipment and stock hoisted out of the water will decrease biofouling organisms but not remove them. Control methods usually employ physical removal of biofouling organisms through mechanical cleaning, scrubbing and scraping, or pressure spraying (Hodson et al. 1997). Limit the downstream effects of physical removal of biofouling organisms. Disrupting the benthos during physical removal of biofouling can lead to sediment suspension, which could have negative impacts on downcurrent water quality. Additionally, if pressure washers or motorized devices are used to remove biofouling organisms, conduct this activity so that it does not disturb neighboring communities. In Florida, all mechanized cleaning must occur above water, and high-pressure cleaning of biofouled equipment may not occur over sovereign submerged lands. Contact the appropriate regulatory agency to identify allowable methods in your locality.

### *Use brine or freshwater dips to control biofouling, especially by ascidians*

Dipping biofouled shellfish and equipment in brine (saturated salt solution) or freshwater is an effective and inexpensive method to control most biofouling organisms, particularly ascidians (Eno et al. 1997) (Box 11.3). Cleaning shell stock along with netting can be

## BOX 11.3
### Biofouling Control Methods

Brine dips are effective for controlling a variety of fouling and predatory species, including echinoderms (*Asterias* spp.), boring sponges, hydroids, various ascidians, the slippersnail (*Crepidula fornicata*) (Loosanoff 1961b), and macrophytic algae (e.g., *Codium fragile* and *Sargassum muticum*) (Minchin 1996; MacNair and Smith 1999). Brine dips associated with air drying or coupled with dips in quicklime have been effective in killing the common fouling ascidian *Molgula manhattensis* (MacNair and Smith 1999). Quicklime (CaO) has been used primarily to control echinoderms (starfish), but has also been successful in controlling ascidians (e.g., *Molgula*), particularly in combination with immersion in brine solutions (MacNair and Smith 1999).

Limited control of solitary and colonial fouling ascidians (*Botrylloides leachi*, *Styela* spp., *Ascidiella aspera*) has been achieved by immersion in freshwater, in most cases requiring at least 24 hours exposure for effective mortality (Brunetti et al. 1980; Lützen 1999; McEnnulty et al. 2001; Hewitt et al. 2002). Limited control of biofouling and predation by the green crab (*Carcinus maenas*) has been achieved by aerial exposure and high temperature water (Minchin and Duggan 1988; Lützen 1999; Hewitt et al. 2002).

accomplished by immersion in either hot seawater, freshwater, or saturated brine solution (Arakawa 1980).

### *Use biological methods to control biofouling*

An alternative method for treatment of biofouled equipment and shellstock is through some form of biocontrol using native predators or parasites. Several biological control agents have been tested over the years with varying success (Box 11.4). In view of the limited efficacy, expense, and potential for deleterious environmental consequences of chemical treatment, further efforts to develop biocontrol techniques are warranted.

### *Use appropriate chemical methods to control biofouling*

Several attempts have been made to control predators and fouling organisms on submerged structures in the marine environment through the use of chemicals. These include, but are not limited to, chlorine and bromine chloride (Burton and Margrey 1979), copper sulfate, Victoria Blue B stain, quicklime (MacNair and Smith 1999), 5% acetic acid (Carver et al. 2003) saturated salt solution (brine), insecticides (chlorinated hydrocarbons), and other pesticides (Loosanoff et al. 1960; MacKenzie 1979; Shumway et al. 1988; Brooks 1993). The use of chemicals, herbicides, or pesticides for control of biofouling is not permitted by the United States Food and Drug Administration. Application of biocidal coatings on net surfaces remains in wide use in shellfish aquaculture. Copper oxide (CuO) is commonly used in antifoulant coatings, although the effectiveness of copper oxide antifoulants is limited to one season and they contribute to elevated levels of copper in adjacent waters and sediments.

Coating materials should be handled and applied to ensure worker safety. Educate workers in the proper application and handling of these types of chemicals. Farm management should consult the *Guide to Drug, Vaccine, and Pesticide Use in Aquaculture* (Joint Subcommittee on Aquaculture 2004) for the regulatory framework and technical guidance. Coatings should be applied with adequate ventilation and drop cloths to collect any drip

## BOX 11.4
## Biological Control of Biofouling

Control of biofouling organisms has been attempted with biological agents. Blue mussel infestation of enclosed trays of European oysters can be controlled with juvenile rock crabs (*Cancer irroratus*) (Hidu et al. 1981). Addition of periwinkles (*Littorina littorea*) to lantern nets containing European oysters successfully dislodged and eliminated newly recruited ascidians (Enright et al. 1983). Similar successful demonstrations of biological control of fouling organisms include grazing gastropods (Ciguarria et al. 1998), hermit crabs (Enright et al. 1993), and sea urchins for scallop culture (Ross et al. 2004) to control algae; and fish (*Fundulus* spp.) to control ascidian fouling in a hard clam nursery (Flimlin and Mathis 1993).

loss. Also, adherence to the manufacturer's recommendations on the product label is mandatory. Farm workers and owners are advised to retain documentation of product labels and application instructions. Drying and curing times between application of coatings or prior to use must be in compliance with the manufacturer's recommendations as presented on the product label, usually 5 to 10 days. This will allow for minimal, nontargeted mortalities of cultured animals and other organisms downcurrent from the culture site. Coatings should be handled and stored in sealed and secured containers to prevent spillage.

### *Use caustic chemicals in accordance with manufacturers guidelines and neutralize the chemicals prior to disposal*

Biofouling organisms can be removed with quicklime (CaO). Application of quicklime in the marine environment is not regulated (Shumway et al. 1988) and, although there is little cumulative effect on the natural environment, quicklime is caustic, can cause serious burns, and may dramatically increase the pH of water and soil in the immediate vicinity of application. Inform workers about the dangers and environmental effects of working with quicklime and follow safety recommendation in the Material Safety Data Sheet (MSDS) for the chemical. Using acetic acid or chlorine dips or sprays under field conditions should be carefully evaluated to ensure personal safety and containment (or neutralization) of the chemicals to minimize environmental impacts.

### *When practical, remove biofouling organisms from the farm site*

Every effort should be made to avoid accumulation of material dislodged during biofouling control measures downcurrent from culture sites. Excessive accumulations of macroalgae should be removed and transported to appropriate inland disposal sites so they do not pose a nuisance to adjacent waters and landowners. If heavily fouled gear must be transported to an inland site for cleaning, drying, or disposal, these activities should be conducted at an approved and appropriate location. Public-access boat ramps, parking lots, or locations visible to neighboring land owners are not appropriate sites. Fouled nets and equipment should be thoroughly cleaned and dried prior to placing in storage.

## Pest and Predator Control

A healthy marine environment is richly populated with marine aquatic plants and animals, and their health and safety are necessary to preserve biodiversity and an environment that is beneficial to shellfish. Most naturally occurring plants and animals have little or no adverse effect on shellfish culture operations. Unfortunately, some organisms can have a significant impact on wild and cultured shellfish populations and, in the case of invasive species, on the marine environment generally. Because shellfish and other marine species share the marine environment, molluscan aquaculture operations have the potential for interaction with marine mammals, protected species, and their habitats.

Predation on commercial mollusks during grow-out remains one of the major hurdles to successful culture in many areas of the world. Molluscan predators range from polychaete worms to mammals, and can be further complicated by the introduction of invasive species, such as the Japanese oyster drill (*Ocenebra japonica*) in the Pacific Northwest of the United States and the introduction of the oyster drill (*Urosalpinx cinerea*) into Great Britain from the eastern United States (Table 11.2). Predation is usually not a limiting factor during hatchery and nursery phases of culture, when juvenile mollusks are reared in large numbers under controlled and secure conditions and the technology is reasonably well established (Jory et al. 1984).

Predation by birds and mammals can have a significant impact on bivalve aquaculture, in part because of depredation regulations on certain species that limit control options. Populations of sea otters have increased dramatically under protections afforded by the Marine Mammal Protection Act and a federal transplanting program. Resurgent sea otter populations have caused destruction of lantern nets of oysters, requiring growers to switch to wire-mesh cages or protective seine-net webbing.

Taking reasonable measures to prevent the destruction of crops from predators and pests is in the economic interest of shellfish producers. Thoughtful facility design, proper construction of equipment, and diligent management of farm operations can minimize the risk of major predation events and reduce the need for control efforts if and when they do occur. Methods to prevent, exclude, or control pests and predators is a function of the species cultured, location, time of year, and cultivation structures and methods.

Birds and mammals quickly become aware of farm routines for deterrence and can adapt to the surroundings by preying on mollusks when the likelihood of a threat is reduced. Because there is no completely effective deterrent or exclusion device, and the use of lethal methods is less effective in the medium and long term, using a variety of nonlethal methods in an atypical manner has thus far been the most effective means of predator control.

### *Better Management Practices for Pest and Predator Control*

#### *Develop and implement an integrated pest and predator management plan*

Integrated Pest Management (IPM) is the coordinated decision-making and action process that uses the most appropriate pest and predator control methods and strategies in an environmentally and economically sound manner and in coordination with appropriate regulatory agencies (PCSGA 2002). Elements of comprehensive IPM include 1) early prevention and avoidance of pest and predator problems; 2) regular monitoring for the presence and damages incurred by pests and predators; 3) establishing maximum densities for pests and predators based on damage levels that are economically, aesthetically, and environmentally acceptable; and 4) evaluating the effects and efficacy of pest and predator control options.

Careful selection of growing areas is the best method to avoid excessive predation on shellfish crops. Daily exposure to air in intertidal shellfish beds and regular maintenance and dessication of containers, nets and screens, and seed in land-based nurseries can be an effective preventive approach to predation problems. High-quality seed, well-maintained production systems, and productive areas that promote rapid growth represent the best combination of circumstances to minimize the effects of predation.

**Table 11.2.** Common predators of cultured mollusks.

| Common Name | Scientific Name | Location |
|---|---|---|
| **Invertebrates: platyhelminths** | | |
| Flatworms | *Stylochus ellipticus* | Atlantic |
| | *Pseudostylochus ostreophagus* | Pacific |
| **Invertebrates: crustaceans** | | |
| Blue crab | *Callinectes sapidus* | Atlantic |
| Stone crab | *Menippe mercenria* | Southeast Atlantic |
| Rock crab | *Cancer irroratus*, *C. borealis* | Atlantic |
| White-fingered mud crab | *Rhithropanopeus harrisii* | Atlantic |
| Black-fingered mud crab | *Eurypanopeus demissus* | Atlantic |
| Dungeness crab | *Cancer magister* | Pacific |
| European green crab[a] | *Carcinus maenus* | Atlantic |
| Hairy shore crab | *Hemigrapsus oregonensis* | Pacific |
| Japanese shore crab[a] | *Hemigrapsus sanguineus* | Atlantic |
| **Invertebrates: mollusks** | | |
| Channeled whelk | *Busycon caniculatus* | Atlantic |
| Knobbed whelk | *Busycon carica* | Atlantic |
| Moon shell | *Polinices duplicatus* | Atlantic |
| | *Lunatia lewisii* | Pacific |
| | *Euspira heros* | Atlantic (Canada) |
| Rapa whelk[a] | *Rapana venosa* | Atlantic |
| Japanese oyster drill | *Ocenebra japonica* | Pacific northwest |
| Eastern oyster drill | *Urosalpinx cinerea* | Atlantic, Pacific |
| | *Thais haemastoma, T. lapillus* | Atlantic |
| **Echinoderms** | | |
| Starfish | *Asteria vulgaris*, *A. rubens*, *A. forbesi* | Northeastern Atlantic |
| | *Pisaster ochraceus* | Pacific |
| | *Evasterias troschelii* | Pacific |
| **Finfish** | | |
| Cownose ray | *Rhinoptera bonasus* | Atlantic |
| Stingray | *Dasyatus* spp. | Atlantic |
| Eagle ray, bat ray | *Myliobatis* spp. | Atlantic, Pacific |
| Summer flounder | *Paralichthys dentatus* | Atlantic |
| Black drum | *Pogonias chromis* | Atlantic |
| Western Atlantic sea bream | *Archosargus rhomboidalis* | Atlantic |
| Starry flounder | *Platichthys stellatus* | Pacific |
| Rock sole | *Lepidopsetta bilineata* | Pacific |
| Pile perch | *Rhacochilus vacca* | Pacific |
| Striped sea perch | *Embiotoca lateralis* | Pacific |
| **Birds** | | |
| Common scoter | *Oidemia nigra* | Atlantic, Pacific |
| White-winged scoter | *Melanitta deglandi* | Pacific |
| American scoter | *Oidemia nigra* | Atlantic |
| Surf scoter | *Melanitta perspicillata* | Pacific |
| Long-tailed duck | *Clangula hyemalis* | Atlantic |
| Eider | *Somateria mollissima* | Pacific |
| Goldeneye | *Blucephela clangula* | Pacific |
| **Mammals** | | |
| Sea otter | *Enhydra lutris* | Pacific northwest |
| Marine otter | *Lontra felina* | Pacific northwest |
| Walrus | *Odobenus rosmarus* | Pacific northwest |

[a] Invasive species.

Another cost-effective way to avoid or minimize predation is to adapt the timing of the crop production cycle to offset peaks in recruitment of nuisance species. Once shellfish have achieved a size at which they are less vulnerable to predation, they can be transferred to sites with abundant predator populations. In general, planting larger seed is an effective means to reducing predation.

### *Comply with regulations that protect marine mammals and threatened and endangered species*

Comply fully with state and federal guidelines for protecting endangered and threatened species. Where appropriate, conditions designed to minimize interactions between farming activities and protected species should be clearly enunciated in permit applications. The Marine Mammal Protection Act (16 USC §1361) prohibits harassment of marine mammals or any farm activities that adversely affect them. Even the perception that marine mammals are adversely affected by aquatic farming operations may initiate restrictions on farming activities or siting of new operations. Permits are required if activities will result in the taking of a protected species, where "taking" includes killing, harming, or harassing. Construction activities can result in harassment. For example, aquatic farming operations in Alaska are not allowed within 1 mile of marine mammal haulout or calving areas. The Marine Mammal Protection Act has resulted in a resurgence of species that may impact shellfish grow-out site selection and operations. Exclusion methods should be emphasized in areas with sea otter populations to prevent access to the shellfish crop.

Although the Endangered Species Act (16 USC §1531) has had a minimal impact on molluscan aquaculture operations, the potential for future restrictions are real. For example, in 2001 the listing of eider ducks led the United States Army Corps of Engineers to suspend blanket permitting of aquatic farming in Alaska.

### *Use and maintain predator exclusion devices*

Although the type and method of deployment may vary according to culture equipment, species, marine conditions, and habitat, the installation of predator exclusion devices, such as netting or coated wire, are usually more successful in controlling predators than chemical treatment (Jory et al. 1984). Infaunal bivalves can be protected with gravel, rigid wire cages, flexible mesh bags (an enclosure with netting above and below), and direct planting in the sediment covered by plastic (polyethylene, polypropylene, or nylon) netting (Box 11.5). Bottom nets typically are 0.64 cm (1/4-inch) mesh secured to the sediment with weights or reinforcing steel bars or stakes with lead lines. Bottom nets should be buried into the substrate with lead lines or other weights to avoid fish, birds, or other animals from becoming ensnared under the net.

Ensure that nets, anchors, and other gear are in good condition and secured to the substrate by conducting regular inspections. Nets and bags should be routinely inspected for tears, burial by sediments, and biofouling, and they should be cleaned, repaired, or replaced as appropriate.

In warm subtropical waters, predator exclusion devices are in place year-round because the activities of predators are continuous, whereas in cooler temperate waters, they are often removed during winter when predators are less active. On-bottom methods for

## BOX 11.5
## Marine Mammals and Shellfish Aquaculture

Sea otter (*Enhydra lutris*), marine otter (*Lontra felina*), and walrus (*Odobenus rosmarus*) are the only marine mammals that habitually feed on shellfish. Therefore, predation on cultured mollusks by marine mammals is limited to the Pacific Northwest of the United States and Canada (in North America) where predation of oysters held in lantern nets has occurred (Würsig and Gailey 2002). In most instances, addition of seine webbing or switching to wire mesh trays has alleviated the problem. Many growers report that otters are helpful by grazing on biofouling mussels that set on lantern nets and other gear (PCSGA 2002).

oysters often include intertidal culture in bags or on slightly elevated trays to increase the surface area of the intertidal zone, making them inaccessible to predators. Use of PVC tubes with nets effectively excludes predators from subtidally cultured geoducks.

*Use predator exclusion nets with hardened coatings*

Hardened coatings for predator exclusion nets for shellfish aquaculture are under development and evaluation throughout the world. Generally, coatings that release pollutants—particularly oil-based products such as creosote, asphalt-based tars, and other tars—are prohibited, but coatings that do not release pollutants when fully cured are acceptable. Examples that are acceptable in most states when properly handled, dried, and cured include acrylic (water-based resins), latex (water-based emulsions), polyester, epoxy, or alkyd resins (synthetic resins). Coatings may be tinted various colors to help identify net ownership, camouflage nets for additional predator protection, or enhance security from theft. Most colorants and other additives are usually acceptable by law, provided they do not leach into the marine environment. Usually, the onus is on the coating manufacturers to provide information regarding the proper instructions for application, drying, and curing prior to use in farm-raised shellfish aquaculture operations (FDACS 2005).

*Avoid predator exclusion devices that can entangle waterbirds and other predators*

Placement and type of exclusionary devices to prevent predation should be guided by general principles to protect surrounding wildlife and the environment. Predator exclusion devices in mollusk culture seldom cause undue harm to predators (Box 11.6). However, devices should be properly secured to minimize the danger to fish, wildlife, or humans through entanglement or entrapment and to minimize the risk of becoming derelict. Use caution when exclusion devices are deployed to protect against predation by waterbirds because entanglement in excluding nets may lead to fines associated with the unintentional take of a regulated species. Therefore, use protective netting of a mesh size small

## BOX 11.6
## Controlling Bird Depredations in Shellfish Aquaculture

Scoter ducks and eiders prey on littleneck and Manila clam operations in the Pacific Northwest (Murton and Wright 1968; Guillemette et al. 1993). The presence of workers on shellfish farms—either harvesting, grading or conducting regular maintenance—and the sound of outboard motors during these activities is a powerful deterrent to bird feeding at shellfish farms, reducing feeding eiders on a mussel farms by over 90% (Ross 2000). A digital recording of outboard engine noises using an underwater playback system reduced eider feeding by 50 to 80% (Ross et al. 2001).

enough to avoid entanglement by diving birds. Additionally, exclusion devices should be easily visible to birds or marine mammals to minimize the risk of entrapment or injury.

Lost, abandoned, or improperly disposed nets and bags represent an entanglement threat to marine organisms and a nuisance to boaters. Thus, all old netting and associated materials should be removed from the marine environment (including derelict nets in the area) for proper disposal at a landfill. If possible, used materials should be cleaned, repaired, and recycled for further use. Fences, water column nets, and high-density stakes should not be used to exclude predators. This activity is prohibited in most states or may require special permitting in specific cases. Best Management Practices drafted by the state of Maryland specifically state, “Use of fencing, water-column netting, close-set stakes or other means that extend from the bottom to the water surface and restrict movement through site is strongly discouraged” (MACC 2006).

### *Use off-bottom culture technologies*

Elevating mollusks above the bottom is an effective, albeit expensive, form of protection from benthic predators. Off-bottom culture technologies include covered trays; floating or suspended cages and nets; and ropes suspended from floating structures, pilings, or moored surface lines (Fig. 11.6). These methods place the cultured mollusks out of range of benthic predators and use the entire water column, which increases yield per unit area of bottom. However, predators with pelagic larvae, such as starfish, can set on off-bottom structures and cause damage (Naidu and Scaplen 1979).

### *Use biological control methods where appropriate*

Biological control methods may reduce predator impacts on cultured shellfish (Box 11.7). Although it is unlikely that such efforts would have indirect effects on the ecosystem, predator control should be targeted to specific animals while minimizing collateral impacts.

**Fig. 11.6.** Off-bottom cultivation of oysters using ropes suspended between stakes. This method of culture can reduce crop loss caused by benthic predators.

## BOX 11.7
## Biological Control of Shellfish Predators

Biological control methods for mollusk predation have received much attention over the years, but seldom have been successful. Attempts to control starfish predation on oysters with a ciliate parasite that sterilizes the echinoderm and the introduction of a nonnative starfish that preyed upon local species were unsuccessful (Loosanoff 1961a). Attempts to use a digenetic trematode (*Parorchis acanthus*) to reduce the reproductive potential of the southern oyster drill (*Thais hemastoma*) failed because high infection rates in the laboratory could not be replicated in wild populations (Cooley 1962).

### *Use chemical control methods only when other methods are ineffective*

The use of chemical substances to control predators and pests was pioneered in the 1930s and continued for decades. These included using copper sulfate and quicklime to eliminate starfish predation on oysters and chlorinated oils such as trichloroethylene, insecticides such as Sevin® (Loosanoff et al. 1960; Loosanoff 1961a, b; Koganezawa 1978), and copper plates (Glude 1957). Unfortunately, potential environmental and public health risks implicit in the use of most chemicals to control predators outweigh the benefits and should be limited to controllable conditions such as hatcheries. Use of chemicals in public waters will often result in confrontation with environmental organizations and other stakeholders (Box 11.8).

### BOX 11.8

### Evolution of Control Strategies for Burrowing Shrimp

In some estuaries in the Pacific Northwest, populations of the burrowing shrimp *Neotrypaea californiensis* (ghost shrimp) and *Upogebia pugettensis* (mud shrimp) have increased significantly since the 1940s. Although not predators to oysters, shrimp populations have increased to the extent that sediments have been destabilized, converting tidal flats to soft mud and rendering these areas inhospitable to shellfish culture. In the 1960s, the State of Washington approved carbaryl (the pesticide Sevin® registered by the United States Environmental Protection Agency) to control burrowing shrimp (Feldman et al. 2000; Dumbauld et al. 2001). Although numerous studies have indicated no long-term negative impact from the use of carbaryl, in the short term there can be significant impacts to nontarget species. This has become a contentious issue in areas where the pesticide is applied, resulting in increasing efforts to ban the chemical in the production of oysters. In response to legal battles and contentious meetings, oyster growers have agreed to phase out the use of carbaryl to control burrowing shrimp. The phase-out of carbaryl use will be completed by 2012. A comprehensive integrated pest management program for burrowing shrimp on commercial oyster beds will provide alternative control approaches for these species (Dumbauld et al. 2006).

## Invasive Species

There is a long history of introduction of nonnative species in terrestrial agriculture, and it is also the basis of several highly successful aquaculture industries around the world. However, introduction of nonnative marine species often results in unanticipated ecological perturbations. These perils can generally be described in three categories: 1) cointroduction of organisms carried with, on, or within introduced species; 2) negative genetic consequences of interbreeding between introduced and native stocks; and 3) invasive species that impact the ecological health and carrying capacity of an ecosystem (Shumway and Kraeuter 2000).

Shellfish undergo a planktonic larval stage and can be introduced to other areas of the world with relative ease. For example, many different larval bivalves and other organisms are discharged when cargo ships dispose ballast water into the local environment (Carlton 2001), with the zebra mussel (*Dreissena polymorpha*) as one recent notorious example.

Ayres (1991) and Dinamani (1991) described several of the impacts and modes of introductions of the Pacific oyster in Australia and New Zealand, respectively. Displacement of native oysters has been one of the greatest impacts of Pacific oyster introductions. The spread of this introduced species has been to the detriment of some long-standing and valuable fisheries based on local rock oysters (Medcof and Wolf 1975). The Pacific oyster competes with native oyster species for space and food and may even smother them. This potential change in the species balance also has the potential to impact species other than shellfish through a modification of habitat.

Several scallop species have been introduced outside their native range, and, in China, a nonnative species (*Argopectin irradians*) is cultured; spat may be produced in one country and sold to farmers in another. The introduction of nonnative species and international trade in broodstock and seedstock for aquaculture can result in ecological perturbations such as competition with native species, loss of biodiversity, and the spread of pathogens.

Instances have occurred where introduced oyster species have spread parasites and disease to native oysters and have caused severe mortalities. Over 2 million bushels of seed oysters from public beds in the James River are transplanted annually to private beds in four major growing areas. The introduction of *Haplosporidium nelsoni* (the causative agent of MSX disease) in 1959 resulted in the death of most oysters throughout the Chesapeake Bay. Subsequently, private planting was abandoned (Andrews 1996).

In the early 1940s, oysters in the Gulf of Mexico began falling prey to a protozoan parasite, *Perkinsus marinus* (the causative agent of Dermo disease). In the mid-1980s, Dermo began killing oysters in the Chesapeake Bay, and over the next decade, the parasite spread throughout the Chesapeake Bay, sometimes inadvertently transported by replenishment programs and commercial operations that moved oysters from reproductively rich bottom grounds to areas more favorable for grow-out (Ewart and Ford 1993). By the early 1990s, Dermo had infested virtually every major oyster bottom in the Chesapeake Bay. In the mid-1950s, *P. marinus* was introduced into the Delaware Bay when infected seed oysters were transplanted from the lower Chesapeake Bay. Dermo has continued to move up the Atlantic coast and has been recorded as far north as Maine.

The eastern oyster populations in the Chesapeake Bay have fallen to approximately 1% of the original stock status, and part of this reduction is a result of the spread of Dermo and MSX (NRC 2004). Presently, the introduction of the Suminoe oyster (*C. ariakensis*) is being explored to restore the oyster industry in the Chesapeake Bay. As of July 2004, approximately 860,000 triploid Suminoe oysters have been tested in the Bay. The Virginia Seafood Council has received permits to conduct industry trials with triploid Suminoe oysters. The importation of *C. ariakensis* to the Chesapeake Bay may be yet another carrier of oyster parasites or diseases.

Most invasive species impacting shellfish aquaculture are fouling organisms, although many invasive species actively prey upon cultured shellfish—the oyster drill is a well-known example. Although endemic nuisance species may prey upon bivalves or foul cultured mollusks and equipment, nonnative invasive species tend to be more problematic. Invasive species can have a devastating impact on shellfish culture operations because predators, fouling organisms, or nuisance species interrupt regular farming activities or compromise production performance.

Eradication of established nonnative species is rarely effective. Invasive species can be controlled through diligent management of the transport and release of target organisms and water from distant areas. Nonnative introductions are a controversial subject that deserves considerable debate, not solely in regards to molluscan aquaculture, but as part of a broader systems approach to ecosystem management.

A precautionary approach to the intentional transfer and introduction of nonnative marine organisms was established in 1994 by the International Council for the Exploration of the Sea (ICES), through its Working Group on Introductions and Transfers of Marine Organisms (ICES 1994). In that document, and subsequently in the 2004 Code of Practice, ICES sets forth recommended procedures and practices to diminish the risks of detrimental effects from such scientific and commercial activities involved in introductions and transfers. The most responsible approach to marine aquaculture is to limit the species reared to those that occur naturally in the environment where the aquaculture activity is to be conducted.

## *Better Management Practices for Invasive Species*

### *Be knowledgeable of and comply with all regulations governing the importation and transport of bivalve mollusks*

Virtually all states that regulate molluscan aquaculture either prohibit the transport of shellfish from noncontiguous bodies of water or mandate rigorous protocols for inspection and certification of them. However, nonuniformity in state rules concerning the transport of shellfish seed and stock has resulted in confusion, misinformation, and noncompliance. In turn, this has resulted in the unintended introduction of nonindigenous species and their diseases and parasites. The commerce clause of the United States Constitution, designed to maintain and protect interstate commerce, may preempt state aquaculture importation restrictions, and many states may run afoul of federal regulations. These inconsistent policies for interstate transport of shellfish aquaculture products reinforce the need for development of a comprehensive transport strategy (Duff et al. 2003).

### *Carefully inspect all shellfish seedstock received from hatcheries and remove nontarget species*

In most states, aquaculture products must have an Aquaculture Certification or Registration Number that allows tracking of product from origin to point-of-sale in containers that are identified by tags or labels that are securely attached and clearly displayed (FDACS 2007). Shellfish should be transported in solid, sealed, distinct containers identified by aquaculture certification number and other appropriate documentation.

Inspection of all shellfish seed received from a hatchery and removal of nontarget species is required because the responsibility for inadvertent introductions will fall on the producer. Additionally, do not store nonlocal shellfish or nonnative aquatic species where there is potential for escape into local waters.

### *Assure that all nonlocal organisms are nonviable when disposed*

Disposal of excess cultured algae or shellfish larvae into the marine environment should be carefully controlled to ensure that stocks from nonlocal sources are rendered nonviable before being discharged. A typical protocol would be to divert effluent to a holding tank that is treated with a chlorine bleach solution for 24 hours, followed by dechlorination with sodium thiosulfate (Allen and Burreson 2002).

### *Use broodstock and seed from verified sources*

Hatchery operators must verify the source of broodstock and should sell or use seedstocks from a genetic selection program that are compatible with parent stocks at the grow-out location. In Florida, the seedstock of oysters and other bivalves (with the exclusion of hardshell clams) can not be transferred between waters of the Atlantic coast and the Gulf of Mexico.

# Disease Prevention, Control, and Eradication

Over the past decades, the shellfish industry has experienced major disease outbreaks that have had significant adverse impacts on environmental quality, the value of natural resources, and the economies of coastal communities. A disease is a debilitating condition caused by a variety of biotic and abiotic factors that compromise survival, growth, and marketability of affected stocks (NAA 1998). Diseases might be the result of genetic defects in the stock or infectious pathogens that may prevail under stressful environmental conditions. Most genetic diseases can be avoided through careful broodstock selection programs that avoid inbreeding. Stress related to poor water quality, nutritional deficiencies, overcrowding, predator harassment, and inappropriate handling procedures can predispose shellfish to invasion by pathogens resulting in disease episodes.

The transport of shellfish across national or state boundaries is a necessary activity to maintain the viability of commercial shellfish aquaculture. It is incumbent upon resource managers and shellfish industry representatives to establish protocols for the transfer of shellfish stocks for husbandry purposes and rigorous animal health standards that reduce the risk of dissemination of infectious diseases through aquaculture activities. To protect native and cultured shellfish populations from the introduction of infectious diseases and parasites, responsible resource management agencies in most states have developed inspection and certification requirements, or they prohibit the transfer of seed or broodstock from locations where pathogens are prevalent.

## *Better Management Practices for Disease Prevention, Control, and Eradication*

### *Adhere to state regulations regarding importation of mollusk broodstock or seed*

Most states have established strict guidelines for the transport of broodstock and/or seed from nonlocal waters or the complete prohibition of imported stock. A review of hard clam seed importation requirements for the southeastern United States (Tuckey and Sturmer 2001) illustrates the similarities and disparities in certification requirements, monitoring, and disease testing. Most states require that bivalves imported from another state for aquacultural purposes must be certified by a licensed veterinarian that the stock is free of several pathogens, primarily (but not limited to) Quahog Parasite Unknown (QPX) in clams and *Haplosoridium nelsoni* (MSX) and *Perkinsus marinus* (Dermo) in oysters. An exception to disease testing may be made for animals originating from hatcheries that have been preapproved based on documentation of operating procedures and prior history of high-health seed. Preapproved certification of hatcheries is usually renewed annually.

Health certification requirements for 14 east coast states is summarized in the *Eastern United States Interstate Shellfish Seed Transport Workshop* (Anderson et al. 2002). Regulations, policies, and best management practices have evolved in each state with little coordination among states. They are subject to oversight by different agencies with responsibility for permitting and inspecting imported shellfish (e.g., departments of agriculture, natural resources, and environmental health). It is the responsibility of the shellfish farmer to comply with all existing inspection procedures and documentation. Procedures should be established in consultation with the appropriate agency personnel well in advance of any importation of seed or broodstock.

### *Isolate the culture facility from sources of infection*

A key strategy in preventing the occurrence of disease is to locate a culture facility in an area with high-quality water and avoid areas that appear to be sources of infection. Screening indigenous shellfish for pathogens at the prospective site might provide insight about potential problems.

### *Minimize stress through good husbandry practices*

Maintaining cultured animals in favorable growing conditions promotes effective defense mechanisms, enabling resistance to pathogen invasion and the progression to disease. Stocking densities, whether in land-based nurseries or in field sites, should be appropriate to ensure an adequate food supply. On-shore facilities should be regularly cleaned and disinfected. Offshore grow-out sites also require routine service, predator exclusion, and biofouling control, outlined earlier in this chapter.

### *Properly quarantine or dispose of infected stock and contaminated materials*

If infectious pathogens are identified as a cause of disease or mortality, all necessary measures should be undertaken immediately to reduce or eliminate the potential transfer of infectious material to other areas of the facility, other stocks, and animals intended for culture in subsequent production cycles (NAA 1998). Dispose of all products in an appropriate waste facility; disinfect all nets, tanks, and equipment if possible; and adequately sterilize infected water prior to release. Proper chlorination (neutralized prior to discharge), ozonation, and heat treatment (pasteurization) will effectively prevent the introduction of commensal or parasitic organisms and diseases (Allen and Burreson 2002).

### *Limit wet-storage activities*

Wet storage, although not always considered aquaculture, is the holding of shellfish from other regions or bodies of water in land-based, flow-through systems, or placed overboard in natural waters for storage or product enhancement prior to marketing. Animals relayed and wet-stored are tested only for human health pathogens, but not shellfish pathogens that could exacerbate the spread of molluscan diseases. Wet-storage practices should be limited to stock that has been thoroughly and properly screened, and the proper permits obtained.

*Maintain good records*

A record-keeping system is a necessary component of regular operations in shellfish production. Many states require hatchery operators to maintain records of broodstock or seedstock purchases and sales for at least 2 years. Detailed records of stock growth and survival at all stages of the production cycle, logged daily and evaluated frequently, can alert the culturist to imminent problems related to the spread of pathogens. In particular, an alarm provision within these records—when animal behavior, poor growth, or mortality exceed preestablished limits—should activate further examination and initiate corrective action.

## Drugs and Therapeutic Agents

The use of drugs and therapeutants in molluscan shellfish culture is unique among the various forms of aquaculture because it is not at all practical to attempt treatment during the grow-out phase. Therapeutic agents delivered to shellfish beds would be quickly dispersed by water currents, reducing effectiveness and exposing nontarget organisms to the agent. Drug and therapeutant use to control pathogens and sterilize equipment is therefore limited to hatchery and nursery operations. The proper handling, application, and disposal of aquaculture chemicals and drugs can prevent contamination of soil, surface waters, and groundwaters. Chapter 12 provides additional information on the proper use of drugs and therapeutants to manage disease.

### *Better Management Practices for the Use of Drugs and Therapeutic Agents*

*Minimize drug and therapeutic use in the shellfish hatchery*

Therapeutic agents for disease control in the hatchery should be used as a last resort. Optimizing water quality, using appropriate stocking densities, and feeding high-quality algal cultures during larviculture will minimize stress and favor natural defenses to pathogens. Good housekeeping procedures, such as routine cleaning and sanitation of all hatchery components, are also critical to maintaining quality production. If pathogens are identified as a source of mortality in larviculture, infected animals should be moved to other areas of the facility and quarantined or discarded. The affected culture vessels and equipment should then be thoroughly disinfected.

In the United States, restrictions on the use of chemicals and drugs in food production fall under the jurisdiction of the Food and Drug Administration (FDA). As of this writing, there are no FDA-approved drugs for use in bivalve shellfish hatcheries. Common chemical disinfectants—such as bleach, or alkaline or acidic reagents—are generally not prohibited by FDA, although their presence in discharged effluents might be regulated (NAA 1998).

*Store drugs and chemicals in appropriate locations*

Disinfectants, pesticides, and most drugs should be stored in a dark, locked container in a dry, well-ventilated area and away from children, animals, food, and living areas. An inventory of chemical agents (e.g., therapeutants and spawning inducers) is required. Follow all product label directions for use, storage, and disposal to ensure compliance with all applicable federal and state guidelines and laws. Immediately contain and dispose of all spilled or leaking chemical containers utilizing barriers and/or absorbent materials in accordance with federal and state laws. Never leave a chemical spill or leak unattended.

### *Use and dispose drugs and therapeutic agents as labeled*

Determine the toxic effects of all chemicals on cultured organisms. Do not use antibiotic drugs for disease control or prevention unless specifically approved for that purpose. Accurate records must be kept to allow for tracking of cultured products back to specific times or batches. This will also aid in the tracking of expired or mislabeled products. Thoroughly rinse all contact surfaces after using cleaning and sanitizing agents. Unused portions of regulated products and their empty containers should be properly disposed of in accordance with the product label.

### *Neutralize disinfecting agents and wash water containing disinfecting agents prior to disposal*

Chemicals such as sodium hypochlorite (chlorine bleach), caustic lye (NaOH), or acids (acetic or muriatic) used to disinfect tanks and equipment should be neutralized prior to disposal. Water used to wash disinfected surfaces should also be neutralized to eliminate adverse effects on effluent-receiving water bodies. Chlorine disinfectants can be neutralized with an appropriate amount of sodium thiosulfate; basic and acidic compounds can be treated with weak acids (for basic compounds) or weak bases (for acidic compounds) to return them to near-neutral pH. Effectiveness of neutralization can be assessed with colorimetric test strips.

## Genetic Diversity

To the best of our knowledge, we are not aware of genetically modified organisms being used in molluscan shellfish farming in the United States. However, the role of domestication and genetic improvement of cultured stocks has raised concerns regarding the potential impact on the genetic integrity of wild stocks. Regardless of the absence of genetic modification within the United States shellfish industry, the term *genetic improvement* will attract attention from those with negative perceptions of *genetic modification*. Thus, it is important to distinguish between genetic modification and genetic improvement and to offer guidance for domestication and genetic improvement programs while minimizing effects on the genetic diversity of both cultured and wild stocks.

Genetically modified organisms are defined here as those whose genetic material has been altered with genetic material from a different species by genetic engineering techniques. Therefore, organisms resulting from the conventional breeding techniques of selective breeding, hybridization, and polyploid induction are not considered genetically modified organisms. The basic breeding techniques used in genetic improvement programs exploit natural heritable variation to improve performance characteristics such as growth rate, survival, disease resistance, and product quality.

### *Better Management Practices for Maintaining Genetic Diversity*

#### *Plan genetic programs to ensure adequate genetic diversity of the cultured organism*

Poorly planned selection programs can inadvertently result in high levels of inbreeding and loss of genetic diversity of the gene pool being used for culture. This may also impact the regional genetic integrity of wild stocks, should adequate genetic variability be absent. Shumway and Kraeuter (2000) recommend these breeding strategies to ensure adequate genetic diversity of cultured species:

1) Identify the available genetic stocks and choose the best one for improvement.
2) Separate the breeding effort from production.
3) Clearly identify the traits to be improved and know their economic value.
4) Determine the nature of genetic variation in traits of interest. If heritable, design a selection program. If nonheritable, as in the case of traits showing hybrid vigor, develop inbred lines for crossbreeding.
5) Design a long-term, sustainable breeding program. These programs are based on adequate numbers of genetic lines of culture strains and will vary depending on region and species cultured.
6) Multiply the improved stocks for the broadest possible application.
7) Develop control populations or methods with which to assess the success of the program (gain).

#### *Use performance-improvement programs that reduce risks of negative impacts*

There are primarily two methods now employed to improve performance of shellfish: 1) traditional selective or cross-breeding programs and 2) the use of polyploidy induction to render shellfish sterile. Both methods promote fast growth, attractive shape, high meat-to-shell ratio, and disease resistance. Selective breeding (also referred to as crossbreeding or hybridization) is the mating of stocks to produce progeny exhibiting selected traits (e.g., disease resistance or growth), hybrid vigor, or other market qualities. Selective breeding may result in inbreeding depression, which is the loss of genetic diversity and usually increased mortality. In some instances, breeding stocks are inbred to focus on a specific trait, but otherwise they are healthy organisms. Polyploidy is a genetic technique that prevents the loss of a set of chromosomes that would normally be lost during meiosis, but after fertilization. The result is progeny having three or more sets of chromosomes (Beaumont and Fairbrother 1991). Triploid organisms have three sets of chromosomes, typically two from the female and one from the male, and results in an organism that is virtually sterile, thus potentially improving meat quality and growth rate.

Traditional selective breeding relies on identifying and selecting genetic lines that perform better. Selective breeding, or artificial selection, is based on choosing specific individuals to contribute to the gene pool of the next generation. Producers or hatchery technicians choosing to use these genetic lines must do so in a manner that reduces the likelihood of selection of disease-prone organisms that may perform poorly in culture and could be detrimental if introduced into wild stocks. Appropriate management practices to reduce these impacts largely focus on precise record-keeping techniques and close working relationships with local extension and shellfish genetics professionals. An example of the practical use of selected culture lines is provided in Box 11.9.

### *Use appropriate chemicals for polyploid induction*

Polyploidy is one of the most promising technologies for improving shellfish growth and survival. As mentioned earlier, the production of sterile shellfish allows the culture organism to redirect energy that would normally be used for reproduction (i.e., gamete production) into growth and immuno-response processes. This provides a significant advantage over the conventional culture of some shellfish as the organism will grow much faster and to a larger size.

The use of chemicals to induce polyploidy in shellfish in the United States is strictly regulated; therefore, there are no specific BMPs for using these chemicals, but rather a legal framework that producers must follow to be in compliance with FDA regulations. Producers should ensure that their hatchery (or the hatchery from which they are sourcing triploid shellfish) is achieving adequate polyploid induction. Because chemical methods are not 100% effective at inducing triploidy, research has focused on producing tetraploid broodstock for mating with diploid broodstock to produce “natural” triploids. Mating tetrapoids with diploids produces virtually 100% triploid offspring without chemical exposure to the final organism (Guo et al. 1996).

## BOX 11.9

### Disease-Resistant Haskin Oyster Lines

According to Allen et al. (1993), the New Jersey Agricultural Experiment Station has agreed to release the Rutgers MSX-resistant oyster lines as the Haskin Lines (HaLs) to interested growers in the northeastern region on a quid pro quo basis. Specifically, in exchange for using HaLs, growers (hatchery or growout) must agree to act as custodians of the broodstock. Although the details of this arrangement are still being formulated, the essential function of a custodian or user group will be to keep a HaL broodstock distinct from other broodstocks and to keep records of its spawnings and distribution. This relationship between breeder and oyster farmer is mutually beneficial. The benefits to the grower are obvious. The benefits to the breeding program at the Haskin Shellfish Research Laboratory are sanctuary from Dermo disease and long-term maintenance of this unique genetic resource. There will be no licensing fees associated with the use of HaLs.

## Aesthetic Values

Aquaculture enterprises operating on public waters are subject to a range of permits, regulations, and operational protocols that are either mandated by regulatory agencies or requested through voluntary industry initiatives. Voluntary initiatives, such as Codes of Practice, are designed to provide a sustainable industry while addressing public concerns regarding environmental integrity and visual impacts. Visual quality issues are often a significant public concern related to shellfish farming in public waters. The adage “all politics are local” can have special meaning in the context of shellfish aquaculture: Despite compliance with all state and local regulations, a shellfish farm that is not aesthetically appealing to neighboring property owners or other user-groups may find operations jeopardized by negative publicity and complaints to local authorities.

Consistent with environmental compatibility and aesthetics is attention to lifespan of the facility; durability and quality of materials used in construction and equipment; and safety of employees, visitors, and other marine users. An orderly, thoughtfully designed, and well-maintained site represents a responsible and efficient enterprise that will be more acceptable to neighbors and other marine resource users.

### *Better Management Practices for Maintenance of Aesthetic Values*

#### *Avoid excessive visual disruption of sites*

With the exception of navigational safety aids, select subdued natural colors for materials used for flotation and floating structures. The use of dark or muted colors for buoys, markers, netting, and other equipment will reduce visual impact, although the United States Coast Guard and some regulatory agencies require the use of brightly colored buoys at specified distances along the perimeter of submerged leases or suspended culture longlines. Remove all unnatural materials (e.g., stakes and buoys) used in cultivation activities as soon as practical.

Buildings (hatchery and other production areas, offices, storage) and properties (parking, walkways) should be attractive and well-maintained, particularly building fronts exposed to the public and viewed from the water. Seed storage piles, transport containers, and materials and gear stored on intertidal sites should be neatly organized and tidy. Abandoned or damaged equipment should be removed and disposed of properly.

#### *Operate facilities to minimize noise*

Noise often attracts attention and may lead to user conflicts. Efforts to improve the productivity and efficiency of shellfish farming has led to an increased reliance on motorized equipment, resulting in incidental noise generated by these activities. Shellfish nurseries—such as floating upwelling systems—may require continuous diesel, electric, or propane power, which generates noise that could travel considerable distance from the farm site. Where possible, employ sound-suppression devices such as mufflers, baffles, and barriers on operating equipment. Vessels should be maintained and equipment kept in good working order to minimize noise levels. Operating vehicles and boats at appropriate speed limits will assist in noise reduction.

Operations conducted in intertidal areas, particularly in the fall and winter when minus tides occur at night, should give consideration to the impacts of noise generated by equipment and personnel on nearby residents. Efforts should be made to minimize nighttime noise to a level that is respectful to adjacent residents. Caution employees to reduce verbal communication to the minimum necessary, particularly at night in areas adjacent to coastal residents.

#### *Reduce smells and odors emanating from shellfish facilities*

Normal shellfish farming operations generate odors related to handling stocks and natural biofouling. This can become offensive if large amounts of nets and equipment are being air-dried. Isolate shell piles and heavily fouled equipment being air-dried to minimize odor. Be courteous about storing and drying equipment in areas adjacent to coastal residents and other users.

#### *Minimize lighting disturbances*

Shellfish farming is conducted year-round, regardless of limitations caused by weather and visibility. To accommodate the seasonal shift of working tides for intertidal farming to nighttime activities, artificial lights may be necessary during several months of the year and can create a visual disturbance outside the farm area. Lights may be required at night on a site to facilitate normal operations, to comply with navigational safety issues as required by law, or to provide safety and security. Light that is intense, poorly directed, or reflecting off the water surface can create a hazard for ocean navigation and constitute a nuisance for upland owners several miles away. Minimize external light at night to the extent consistent with safe operations, and point directional lights seaward so that they do not interfere with safe navigation and offend coastal residents.

## Community Relations

The continued growth of commercial shellfish aquaculture is linked to public support for that activity. Support can be facilitated by the grower adopting a "responsible neighbor" policy that acknowledges the concerns of others and seeks to achieve a reasonable compromise among stakeholders with diverse interests related to marine resource utilization. Educating the general public about shellfish aquaculture activities, reliance and commitment to protecting and enhancing the marine environment, and shared commitment to environmental stewardship will foster public goodwill toward the activity.

### *Better Management Practices to Foster Good Community Relations*

#### *Raise awareness and educate the public with respect to farming activities*

The molluscan aquaculture industry depends more than any other form of aquaculture on public resources. A significant challenge facing shellfish farmers is educating the public about the industry and explaining that its operations affirm a commitment to protecting and enhancing water quality and the marine environment. In many cases, the public is unaware of land-based anthropogenic impacts on the marine environment and the commercial shellfish aquaculture it supports; nor do they understand that successful molluscan aquaculture is dependent on clean water and a healthy marine environment. It is incumbent upon commercial shellfish producers to be good stewards of coastal waters. As vested users of a natural resource, owners, operators, and employees of shellfish facilities must report the abuse of natural resources (e.g., pollution and poaching) to the appropriate authorities. Moreover, shellfish farm personnel should volunteer to participate in community shoreline cleanup activities adjacent to the aquaculture site and use the opportunity to familiarize other stakeholders about aquaculture operations and the commitment to environmental stewardship.

### *Maintain regular communication with surrounding communities*

Maintaining dialogue with adjacent residents and other stakeholders to resolve concerns will help provide a stable level of corporate social responsibility. Informing neighbors of operations that may adversely affect them—such as noise, lights, and odors—and taking complaints seriously and in a responsive, constructive manner will position shellfish producers to better address conflicts that arise in the future.

The industry should aspire to educate the public regarding sound stewardship policies through community discussions to provide information regarding operations and respond to concerns in a timely fashion. Offer scheduled tours of facilities to allow stakeholders to observe the culture activities firsthand. Produce informational brochures for distribution at meetings, tours, schools, and public events.

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## Chapter 12

# Fish Health Management and the Environment

*Scott E. LaPatra and John R. MacMillan*

## Introduction

With very few exceptions, aquaculture systems are hydrologically connected to the aquatic environment near the facility. Therefore, processes or activities occurring within an aquaculture facility may impact the surrounding environment. In the context of fish diseases, potential impacts include pathogen transfer from farmed to wild fish populations and nontarget impacts of disease treatment. Loss of fish to disease is also a waste of resources used to grow fish and, therefore, disease reduces the environmental efficiency (and profitability) of food production. These issues are common to terrestrial and aquatic animal husbandry. Aquaculturists, however, face unique challenges because 1) identical or closely related species of wild and farm-raised animals may live in close proximity; and 2) chemicals, pathogens, and animals easily can be transported or move about in the aquatic environment.

In many countries, domestication of terrestrial animals and steady urbanization has displaced wild terrestrial animals. The interface between terrestrial wildlife and livestock has significantly diminished over time. Free-range chickens are no longer common and widely dispersed, and ungulates no longer roam wide open areas. The movement of horses and cattle between states is closely controlled in the United States—not because of concerns related to interactions with wildlife but out of concern for other farmed animals. In contrast, free-ranging wild fish are present in almost all waters of the United States. These wild fish communities are potentially subject to impacts from fish farms, especially considering the ease with which chemicals and microorganisms can be carried in water. This creates a special need for judicious animal health management on aquaculture facilities and special care in the movement of farmed fishes.

The relationship among pathogens, fish, and the environment is complex and the mere presence of a pathogen does not necessarily induce disease, even in a potentially susceptible species. Pathogen and fish may coexist with no economic, physiological, or ecological consequence. Most often the interaction among the fish host, pathogen, and environment determines the consequence of infection (Snieszko 1973; Hedrick 1998). This interaction, while complicating the epizootiology of fish diseases, provides opportunities to minimize the consequences of infection by maintaining conditions that are not condu-

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cive to widespread development of disease within the population. This is important because appropriate fish health management practices can be effective at reducing farm-level impacts of infectious disease as well as reducing potential effects outside the farm.

This chapter presents management practices that can reduce risk of environmental impacts of fish diseases and fish disease management in aquaculture systems. Environmental interactions related to cultured molluscan shellfish diseases are unique and are discussed in Chapter 11. The farm-level practices discussed in this chapter cannot be expected to solve or minimize all potential environmental risks related to fish diseases in aquaculture. Because of the confluent nature of the aquatic environment, risk-reduction programs for fish health-related issues, especially disease transfer, should be developed on a larger scale, such as watersheds or within other hydrographic boundaries. Farm-level management plans should be considered only as part of a program developed within a regional framework, possibly even crossing national boundaries (Subasinghe et al. 2004). Furthermore, some disease-management practices must rely on development of regulations and policies that can be implemented only within a federal or state regulatory framework. These practices may go beyond what can be accomplished on a particular facility or may not even be in the immediate best financial interest of the producer. For example, issues such as facility siting restrictions to avoid sensitive wild populations or restrictions on the movement of animals from state to state are issues typically addressed outside a farm-level environmental management plan. Considerations for the development of federal and state fish health policies and regulations are described by Mitchell and Stoskopf (1999).

## Disease Transmission Between Cultured and Wild Fish

Public and private aquaculture may impact wild aquatic animal populations with infectious disease. Importation of indigenous and nonindigenous species can introduce new pathogens or pathogen strains in a particular area, and transfer of fish among facilities within an area can enhance the spread of existing pathogens. Although fish farms do not create pathogens, intensive culture may magnify or amplify the potential effects of pathogens by increasing their local abundance.

The risk of disease transfer between captive and wild stocks depends on a complex set of factors that includes culture system type, degree of hydrological connectivity between the aquaculture facility and the environment, health of the captive stock and wild fish population, environmental quality inside and outside the aquaculture facility, and characteristics of the pathogenic microorganism—such as pathogenicity, ability to multiply and remain viable in the aquatic environment, survival time outside the host, and the number of infectious units required to cause infection and pathogenicity (LaPatra 2003; NMFS 2005). Little is known of the distribution of pathogens in wild fish populations, so it is difficult to establish baseline conditions to determine the origin of fish pathogens and the role played by aquaculture in increasing the risk of infection (Coutant 1998; Moffitt et al. 1998; Blazer and LaPatra 2002). This uncertainty is exacerbated by the wide geographical variation in the prevalence of disease among wild stocks and the effect of natural and anthropogenic factors on the health of individuals and populations of wild fish (Reno 1998). As such, the hazard of fish farming to wild populations is not clear and risk assessment is complicated by site-specific factors (Box 12.1).

## BOX 12.1

## Disease Transfer between Captive and Wild Populations: A Case Study

Infectious hematopoietic necrosis virus (IHNV) causes epizootics in wild, hatchery-reared, and farmed salmonids throughout the world. It is considered the most important viral pathogen of salmonid fish (Wolf 1988). The disease has been a significant problem in chinook salmon (*Oncorhynchus tschawytcha*) at the Coleman National Fish Hatchery (CNFH) in northern California since it began operations in the 1940s (Ross et al. 1960). The hatchery is operated as a flow-through system with water supplied from and then returned to the Sacramento River. The river contains adult salmonids that are carriers of IHNV. Prior to 1999, epizootics of IHNV were common in hatchery-reared smolts of fall-run chinook salmon and, when disease was detected in hatchery-reared smolts, infected fish were released into the river in an effort to reduce losses. Of course, the practice of releasing large numbers of IHNV-infected smolts into the river raised concerns about possible impacts on the wild salmon population. Foott et al. (2000) conducted three cohabitation experiments wherein uninfected wild chinook salmon juveniles were held at different ratios with juvenile chinook salmon that were intentionally infected with IHNV. Virus was not isolated from wild salmon in any of the experiments. In another study, no virus was detected in wild fall-run chinook salmon alevins collected from redds within a stream reach containing high numbers of IHNV-positive adult salmon carcasses. Despite the high prevalence of IHNV infection in adult salmon in the upper Sacramento River, no virus was detected in more than 500 wild alevin and parr collected over 2 years. Foott et al. (2000) concluded that hatchery effluent and the release of IHNV-infected fish from the hatchery posed a low risk to the wild chinook salmon population. The practice of releasing IHNV-infected fish was stopped in 1999 when an ozone-treatment unit was installed to disinfect the water supply and prevent infection of fish within the facility.

This case study illustrates three important points. First, it can be difficult to assess the risk of disease transfer from captive stocks to wild populations. Second, the nature of the Coleman facility provided ideal hydrological conditions to show that disease transfer between captive and wild populations can occur in both directions. Third, the eventual resolution of the problem demonstrates that facility biosecurity measures (ozonation of the water supply in this instance) can prevent infection of captive stocks by pathogens derived from wild populations. This solved two problems: it reduced juvenile salmon losses to IHNV at the Coleman facility—which made the hatchery more efficient—and it reduced disease incidence within the facility, which clearly reduced the risk to wild salmon populations in the river.

Currently the most thorough assessment of the interactions between farmed and wild aquatic organisms is the report sponsored by the Commission of the European Communities (Raynard et al. 2007) for conditions in Europe and the Mediterranean. Interactions and risks were evaluated for 80 fish, crustacean, and molluscan shellfish pathogens of concern in marine and freshwater ecosystems. Pathogen exchange between farmed animals and wild populations was documented for most of the disease organisms studied. However, harmful effects were more commonly documented for pathogens transmitted from wild to farmed populations than vice versa. Overall, pathogen transmission from farmed to wild animals was rarely documented and there was even less evidence that transmission resulted in disease. For example, of 22 pathogens affecting marine fish in the North Atlantic, disease interactions between farmed and wild fish were documented for nine. Seven pathogens had documented transmission from wild to farmed fish, whereas transmission from farmed to wild populations was documented for four pathogens (infectious pancreatic necrosis virus, *Gyrodactylus salaris*, *Lepeophtheirus salmonis*, and *Aeromonas salmonicida*). Of those four, farm-to-wild transmission of only two pathogens—sea louse *Lepeophtheirus salmonis* and the trematode *Gyrodactylus salaris*—were thought to pose significant risks to wild populations.

Clearly, pathogens are exchanged between captive and wild populations, particularly for "open" systems such as net pens and flow-through facilities. The more difficult question is whether the interchange of potential pathogens has significant effects at the population level—even for aquaculture systems with high potential risk. Perhaps the best example of this uncertainty is the debate surrounding transmission of sea lice from net-pen cultures of Atlantic salmon (*Salmo salar*) to wild salmon populations (Box 12.2).

Uncertain risk of disease transmission is never an argument against developing and employing risk-reduction measures. To the contrary, uncertainty argues strongly for implementing strong and effective international safeguards, regional policies, and farm-level practices to reduce opportunities for pathogen transfer. The two central themes for reducing the risk of pathogen transfer are to reduce disease incidence within an aquaculture facility and eliminate escape of farmed animals. These are common objectives for efficient, profitable aquaculture and sound environmental management.

## BOX 12.2

## Salmon Farming and Sea Lice

Sea (or salmon) lice (*Lepeophtheirus salmonis* and, to a lesser extent, *Caligus* spp.) are ectoparasitic caligid copepods that infect the external surfaces of marine salmonids. Lice graze the mucus and skin and ingest blood of the fish host, causing lesions, hemorrhaging, scale abrasion, and tissue necrosis in extreme cases. Infection of wild adult salmon is common but seldom debilitating. However, high infection rates can cause extensive dermal damage and osmoregulatory disturbances leading to death. Sea lice may cause fish losses indirectly by increasing susceptibility to secondary infections through stress-associated immunosuppression or by serving as vectors for bacterial and viral pathogens (Nylund et al. 1991; Rolland and Nylund 1998). Sublethal infections and chronic stress may also affect the health and survival of wild salmonids by reducing the ability of infected fish to forage or escape predation (Wagner et al. 2003). All pathological effects are most pronounced in juvenile salmon. The source of sea lice on farmed salmon is wild fish because salmon smolts are louse-free when transferred to farms (Saksida et al. 2007). If the farmed population is infected, culture conditions (stationary, high-density host populations) are conducive to rapid, internally generated reproduction of lice. Uncontrolled sea lice epizootics in farmed salmonid populations can cause significant economic loss through mortality, poor growth, or product unmarketability due to disfigurement from wounds caused by the parasite. Germane to this chapter, once sea lice populations are established in farmed fish, the direction of transmission may reverse and the farm can become a source of pathogens for wild fish populations.

Research has substantiated the exchange of lice between farmed and wild populations and shown that lice infestations are threats to individual fish. There is also evidence that infection rates of wild fish are higher in areas near salmon farms, suggesting that the source of increased infection rates in wild salmon is the captive, farmed population (see, for example, Bjørn and Finstad 2002; Morton et al. 2004; Krkošek et al. 2006a, b). The issue of sea lice transmission between farmed and wild salmon is, in the words of McVicar (2004), ". . . one of the most intensively studied topics in aquatic biology." Yet McVicar (2004) concludes that, despite abundant research and several international symposia convened to assess the risk, it is not possible ". . . to conclude that there is a cause-effect relationship between salmon lice on farms and variations in wild salmon populations." This view was reaffirmed for the relationship between farmed Atlantic salmon and wild pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon in British Columbia (Beamish et al. 2006; Fisheries and Oceans Canada 2006).

Sea lice epizootics in salmonids have been documented long before salmon farming began, so the link between salmon farming and sea lice epizootics is not straightforward. Further complicating the issue, sea lice epizootics in wild fish are a complex function of temperature, salinity, currents, the life cycle of sea lice, and density of suitable fish hosts (Brooks 2005). Nonetheless, there is reasonable certainty that the presence of salmon farms increases infestation rates of wild fish, at least in some regions. The effect on the health and survival of salmon in wild populations is much less certain. Reviews of the broader risks of disease transfer (i.e., not limited to sea lice) between net-pen farmed salmon in eastern Canada (Ritter 1999; Olivier 2002) and Washington state (Nash 2003; Waknitz et al. 2003) conclude that the risks of significant ecological impacts from transmission of pathogens from farmed to wild stocks are low.

## *Better Management Practices for Reducing Transfer of Disease from Farmed to Wild Populations*

### *Comply with all applicable fish health regulations*

State, federal, and tribal fish pathogen-control programs in the United States have existed for a long time. Their goal is to prevent the introduction of significant fish pathogens into the country, regions, specific states, or facilities. Pathogens are regulated that meet criteria such as 1) serious pathogens exotic to an area, 2) pathogens known to cause serious problems, 3) pathogens that are highly infectious and easily transmitted, or 4) pathogens that regional watershed compacts have agreed are of concern in that region. Additionally, pathogen inspections may be required before fish are brought to an aquaculture facility and routine disease inspections may be required of fish in the facility. State resource management agencies and/or state agriculture departments oversee these programs in public and private aquaculture operations (Box 12.3). The United States Fish and Wildlife Service also has authority to regulate importation, shipment, and inspection programs to prevent the introduction of foreign animal pathogens into the United States (50 CFR 16.13). The National Marine Fisheries Service (NMFS) and the United States Department of Agriculture—Animal and Plant Health Inspection Service (APHIS) may also become involved under certain circumstances. These regulatory control programs have been successful at limiting the introduction of important fish pathogens. Regulatory control programs are also being revised or established to prevent the introduction of important shellfish pathogens.

### BOX 12.3
### A State-Level Policy for Reducing Salmonid Disease Risks

The Northwest Indian Fisheries Commission and the Washington Department of Fisheries developed a comprehensive policy (NWIFC/WDF 2006) to protect wild and cultured salmonids within the state of Washington. The policy was developed to reduce the risk of spreading diseases within the borders of the state and includes requirements for surveillance of facilities and populations for regulated pathogens; health monitoring of cultured stocks; hatchery sanitation; transfer of eggs, live and dead fish, and water; and site-specific containment practices for pathogens of concern. All public and private growers of salmonids must adhere to strict disease-control polices that regulate all phases of fish culture, from egg procurement to harvest or release. Broodfish at public and private hatcheries must be sampled annually for viral, bacterial, and parasitic organisms. If reportable pathogens are detected in fish at a hatchery, or have been detected within the past 5 years, transfer of eggs or fish from that facility is prohibited. Similar policies exist in many states.

### *Use concepts of Integrated Pest Management (IPM) to develop pathogen-specific management plans to reduce risk of disease transfer*

The concept of IPM was originally developed to reduce the environmental impacts of insect control in terrestrial crops by making use of a variety of methods that, taken together, reduce reliance on chemical pesticides while still affording a desired level of pest control. The scope of IPM has expanded over the years to include almost any injurious organism as a "pest," and the concept has been broadened to mean the planned, coordinated use of multiple strategies to manage pests below the economic injury level while minimizing risks to the environment. In the context of fish diseases, IPM involves the use of measures that reduce the risk of infection so that outbreaks are easier to control when they occur. Lower disease incidence reduces opportunities for pathogen spread outside the farm.

IPM programs for fish disease include facility biosecurity measures, surveillance and early detection, timely treatment, and use of nonchemical methods of reducing disease incidence. Nonchemical disease management strategies include, among others, proper site selection, the use of vaccines, pathogen vector control, and site fallowing and stock management to break pathogen life-cycles. IPM plans must be pathogen-specific and, although the concepts can be applied to any disease, IPM works particularly well for pathogens with complex life cycles providing multiple opportunities for intervention (Box 12.4).

### *Select sites that reduce the risk of disease transfer*

Depending on the type of culture system and the species cultured, proper site selection can significantly reduce the risk of disease transfer. Appropriate sites provide environmental conditions (water temperature, salinity, and so on) that minimize physiological stress, thereby reducing the incidence and severity of infectious diseases on the facility. The quality of the available water should also be considered. The volume of water and its varying availability over time may limit production capacity. Facilities with insufficient water supplies are often plagued by poor fish performance, more disease problems, and reduced profitability. For earthen pond facilities, it is important to ensure that soils are not contaminated with compounds that might enter the water column and adversely impact fish health or otherwise contaminate fish flesh.

Appropriate sites also reduce the probability that natural phenomena (such as floods, storm surges, or large seas) will cause facility biosecurity breaches that allow pathogen release or escape of infected fish. Site selection should also consider whether sensitive populations of wild fish are placed at risk. Sensitive populations may include threatened or endangered species or migrating populations of susceptible species.

### *Manage the facility to reduce disease incidence*

Infectious diseases inevitably occur in aquaculture, but the risk of pathogen transfer obviously is reduced if disease incidence within the facility is low. Fish diseases are less common in high-quality environments. Obtain and use fish strains with good growth performance and disease resistance, avoid overcrowding, maintain the best possible environmental conditions, feed properly, and use high-quality diets. The water supply should be of adequate quality and quantity to ensure the well-being of the species cultured. Inspect

## BOX 12.4
## Integrated Pest Management of Sea Lice

Although the ecological risk of sea lice transfer from farmed to wild salmon remains uncertain, the goal of reducing the level of sea lice infection on farmed salmon is desired by farmers as well as by wild salmon managers and stakeholders. Sea lice have a complex life cycle involving several developmental stages (Johnson and Albright 1991), and the rate of development depends strongly on water temperature and salinity (Boxaspen and Naess 2000; Brooks 2005). Although oral and bath treatments are available to treat sea lice infections, management of the parasite poses special problems because farmed stock may be persistently reexposed to infection from wild salmon. It is not economically possible, nor environmentally sound, to treat fish at frequent intervals to maintain very low levels of infection. Accordingly, a planned, integrated program using a variety of tactics should be used to reduce costs, avoid development of chemical resistance, and reduce the risk of environmental contamination. Research has provided an increasingly detailed understanding of sea lice epidemiology (see, for example, Revie et al. 2002, 2005) that can be used to develop effective sea lice management plans, which function best when implemented and coordinated within an area, rather than farm by farm (Grant and Treasurer 1993).

In Europe, sea lice management programs include close monitoring of infection levels in farmed stock, early spring treatment before rising water temperatures allow for high sea lice reproduction rates, alternating different chemotherapeutants, using single-year class populations on facilities to break the cycle of within-facility reinfection, and fallowing areas between salmon generations. In Norway and elsewhere in Europe, species of “cleaner” fish in the wrasse family (Labridae) are widely used as a biological-control component of sea lice management programs (Sayer et al. 1996; Treasurer 2002). Effective “cleaner-fish” wrasse species are not native to the coldwater coasts of the United States and Canada, and this approach to sea lice control does not appear promising in North America (Health Canada 2003).

The Canadian government (Health Canada 2003) recommends an integrated approach to sea lice control that includes 1) prevention, 2) monitoring, and 3) control. Preventive steps include proper site selection, good husbandry, year-class separation, and site fallowing. Then, throughout the culture period, pest populations and damage are systematically monitored. Treatment “triggers” are established based on numbers of the different life stages of sea lice observed on salmon during routine monitoring, and when treatment triggers are exceeded, biological, mechanical, or chemical control measure are implemented. Using chemical therapeutants is the most common control measure, and the choice of therapeutant is based on which products are currently registered or licensed and the recommendation of the attending fish health expert.

and evaluate fish daily for unusual behavior or physical changes that could indicate early manifestation of infectious disease. Keep daily records of mortalities and feeding activity as additional early indicators of disease. This will ensure that if a disease does occur it will be acted upon promptly, which will reduce opportunity for pathogen spread to other culture units or to the external environment. When problems occur, consult appropriate fish health experts as soon as possible for advice on how to treat the disease and whether the disease poses a threat to wild fish.

Factors that stress aquatic animals should be systematically minimized. Each production system will have optimal aquatic animal stocking rates that maximize production yet minimize stress-associated morbidity and mortality. If complete harvest is not practiced, grading practices should be designed to minimize stress and aquatic animal injury. When disease incidence increases, every effort should be made to identify and address all predisposing (i.e., immunosuppressive) stressors. General guidelines can be obtained from scientific and extension literature, but trial and error may be needed for adaptation to site-specific conditions.

The type of aquatic animal and extent of domestication may also impact individual husbandry practices and production expectations. Domestication with selective pressure exerted on fast growth may impact various behavioral traits (Huntingford 2004). These traits may influence innate learning skills that enhance learning and decrease sensitivity to novel stimuli associated with farming (Fernö et al. 2006). Wild-captured aquatic animals and those only recently introduced into farming conditions may be more sensitive to trauma from the novel stimuli (compared to conditions in nature) associated with farming. These animals will likely be more sensitive to any stresses associated with farming.

### *Develop and implement a biosecurity plan for each facility*

Implement biosecurity practices to reduce the probability of pathogen introduction to the facility through management actions, transfer among culture units on the facility, or transfer from the facility to neighboring waters (Scarfe et al. 2005). Limiting traffic of people and animals into areas where early life-stage rearing occurs may be helpful. Practice good hygiene in all production systems. Carefully scrutinize movement of aquatic animals, germplasm, and fertilized eggs between farms to ensure new aquatic animal diseases are not introduced.

There are some unique aspects of cage and net-pen culture that warrant specific recommendations. For example, growers operating in an area that is linked hydrologically should develop cooperative aquatic animal health and biosecurity agreements. Additionally, site fallowing, site rotation and year-class separation should be considered as potential methods for disease and pest control. Depending on the species cultured and the production strategy employed, these control methods may require between one and three sites per production cycle.

For some aquaculture species, specific pathogen-free stock (SPF) can be used. Large-scale availability of SPF Pacific white shrimp (*Litopenaeus vannamei*) has led to widespread use of these animals in Asian shrimp production and enabled dramatically increased production success (Jaenike et al. 1992; Lightner 2003).

Include a communications plan in the biosecurity program to ensure effective and timely cooperation among growers within the same watershed, bay, or estuary. Farmers operating in the same area should agree on a clear set of procedures and criteria describing when and how they should share information on test results, disease incidents, animal performance, and environmental conditions. The communications plan should also include guidelines on how and when to communicate with regulatory authorities and the public in order to assist in distributing accurate information.

Farmers using open aquaculture systems such as net pens should consider third-party biosecurity audits to identify sources and vectors for potential pathogens. Use biosecurity audits to assess all farm operations and facilities relative to potential impacts on disease transfer into and out of the facility. Audits should be unannounced and auditors should be given unrestricted access to all animal husbandry and health records, as well as unrestricted access to all employees. Inform employees of their responsibilities and explain that the object of biosecurity interviews is to improve disease management; employees should respond to all questions in an open and honest fashion. Belle (2003) discusses the utility of biosecurity audits as a disease control tool. Allen and Opitz (1999) and Merrill (2000, 2001) present the results of audits and discuss the design and implementation of a biosecurity audit program for net-pen facilities.

### *Reduce the risk of introducing disease organisms into an aquaculture facility*

Obtain fish from reputable sources. Maintain containment during transfers or transport of aquatic animals. Fish should be in good health and, whenever possible, inspected for health status prior to being brought onto a facility. In many states, disease inspection permits or health certificates are required when importing aquatic animals from out of state. Maintain appropriate records and documentation of all shipments into or out of the facility. Some states require that such records be kept for a minimum period, depending on the species being cultured. If possible, quarantine fish upon arrival at the facility to ensure good health and do not share equipment among farms. If practical, disinfect the water supply to the facility or use pathogen-free water supplies. Do not allow unauthorized persons to have access to the farm. Keep a log of all visitors and implement procedures to minimize the risk of human spread of disease organisms. Develop and implement a predator-control program. Predators may stress fish, thereby increasing susceptibility to disease, but may also serve as a disease vector. Predator control measures have been discussed for freshwater ponds (Chapter 6), marine shrimp ponds (Chapter 7), net-pen facilities (Chapter 8), flow-through facilities (Chapter 9), recirculating aquaculture systems (Chapter 10), and shellfish culture facilities (Chapter 11).

### *Reduce the risk of transferring disease organisms among culture units within the facility*

Infectious disease outbreaks inevitably occur in aquaculture, but the risk of pathogen transfer to the outside environment can be reduced by localizing and isolating the outbreak on the facility. Closely monitor the behavior of animals in individual culture units (ponds, tanks, raceways, net pens) and take action to control the disease as soon as appropriate.

## BOX 12.5
### Disinfection in Aquaculture

Disinfection can reduce the risk of disease transmission within aquaculture facilities and from facilities to the environment by deactivating or destroying pathogens with disinfecting agents. Disinfection can be done routinely, but also in response to the outbreak of specific diseases. Routine disinfection can prevent or reduce the release of pathogens from an aquaculture facility. A range of chemical compounds and other techniques can be used to achieve disinfection, including chlorine, chloramine-T, iodophors, hydrogen peroxide, heat, ozone, and ultraviolet light. To the extent possible, disinfectants should be targeted to specific pathogens. Depending on the chemical or technique, the effectiveness of disinfection will vary as a function of temperature, pH, and organic matter concentration. Follow the manufacturers instructions for safe use and disposal of disinfectants. Protocols and procedures for cleaning and disinfection are described by Torgersen and Håstein (1995) and Fraser et al. (2006). In addition, Section 3.2 of the *Aquatic Animal Health Code* developed by the World Organization for Animal Health (OIE) has information about inactivation of pathogens (www.oie.int/eng/normes/fcode/A_summry.htm). Finally, volume 3 of the *United States Fish and Wildlife Service Handbook of Aquatic Animal Health Procedures and Protocols* has information on iodophor disinfection of eggs, facility disinfection guidelines (including effluent disinfection), and isolation and quarantine guidelines (www.fws.gov/policy/fh_handbook/Volume_3/Volume3.htm).

To the extent possible, isolate the culture unit with infected fish from other culture units by disinfecting all equipment between uses and otherwise preventing the transfer of water, mud, wastes, and animals from the affected units to units with healthy animals (Box 12.5). Make employees aware of which culture units contain infected fish.

### *Remove dead fish at once*

Dead fish can be vectors for pathogen spread among culture units and between the facility and the outside environment. Prompt removal of dead fish can reduce risk of pathogen transfer. Disinfect all equipment that comes in contact with dead fish and never allow dead fish to enter public waters. Mortality removal and disposal options for the major aquaculture systems are discussed in Chapters 6 through 10.

### *Prevent fish escape*

Commingling of escaped farmed fish with specific pathogen-susceptible wild populations is a controllable risk factor for disease transfer. Escape prevention for each of the major aquaculture systems is discussed in Chapters 6 through 10.

### *If possible, do not discharge water from culture units with active infectious disease epizootics*

Pathogens are often shed into water in waste products from animals with active infections. Pathogens may also be released into water when dead fish decompose. As such, waterborne pathogens can be released to the environment in facility effluents. Water discharge from some systems, notably embankment ponds, can be stopped for long periods without affecting the culture unit environment. If possible, water should not be discharged from ponds during infectious disease outbreaks. This is not a management option with open systems, such as net pens and flow-through systems.

## Drug and Therapeutant Use

Although the incidence of infectious disease can be significantly reduced by using good husbandry practices as described above, epizootics are inevitable in all but the most biosecure culture facilities. The inevitable stress and ease of pathogen transfer associated with maintaining fish at high densities predispose fish to disease if the appropriate pathogen is introduced. Pathogen introduction is difficult to prevent because most aquaculture systems are, to a varying degree, open to the external environment. Depending on the culture systems and husbandry practices, pathogens may be introduced to a facility in water, by introducing infected fish into the facility, by vectors such as birds or snails, or on equipment that has been in contact with infected fish. When epizootics occur, drugs and chemical therapeutants are often the most effective means of managing the disease and reducing the opportunities for transmission of pathogens and spread of the disease outside the culture unit.

The use of drugs and therapeutants in aquaculture has raised concerns that substances may contaminate the environment, leading to development of resistant microorganisms (both pathogenic and environmental) and adverse impacts on nontarget species, and cause other environmental disturbances. Antimicrobial resistance, for example, is of considerable worldwide concern (WHO 2006) because of the potential for drug resistance to be transferred from an animal pathogen or commensal organism to human pathogens. Prevalence of antimicrobial-resistant human pathogens has been increasing since the first use of the antimicrobial penicillin in 1948 (Levy 1997). All potential sources or causes of antimicrobial resistance are suspect, including use of drugs in agriculture and aquaculture. Regulatory approval programs have been designed to prevent or minimize potential impacts.

### ***Federal Drug Approval and Pesticide Registration Requirements***

Federal drug and pesticide approval programs are intended to ensure that use of approved drugs and pesticides according to label instructions will protect public health and the environment. Such approval programs are well established in countries such as the United States (discussed below) and European Union (Costello et al. 2001). This protection is dependent upon user adherence to label requirements and is assisted by regulatory enforcement. Nevertheless, controversy regarding the public health and environmental significance of drug and pesticide use in aquaculture arises because of public misunderstanding of federal drug and pesticide approval requirements, changing perceptions about the adequacy of such approval processes, potential misuse of drugs and chemicals by aquatic animal producers, and differing drug and chemical uses or approval and enforcement processes in other countries.

In the United States, drug approval requirements are authorized in the Federal Food, Drug, and Cosmetic Act (FFDCA; 21 USC §301) as described within the Code of Federal Regulations (21 CFR §500–589) and various Food and Drug Administration (FDA) regulatory guidance documents (Guidance 152, for example) that can be obtained from the FDA or accessed from the FDA website (www.fda.gov/cvm/guidance/fguide152.doc). Chemicals used in the United States, which for regulatory purposes are called pesticides, must pass scientifically, legally, and administratively rigorous registration processes overseen by the United States Environmental Protection Agency (USEPA). The USEPA regulates pesticides used in the United States under broad authority of the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA; 7 USC §136 et seq.) and the Federal Food, Drug and Cosmetic Act. Regrettably there is little international harmonization in either the drug-approval process or enforcement of drug regulations, which leads to confusion and public misperceptions.

The FDA Center for Veterinary Medicine (CVM) is responsible for ensuring that animal drugs and medicated feeds used in United States aquaculture are safe and effective for their intended uses and that food from treated animals is safe for human consumption. The FDA has established a rigorous (and expensive) drug-approval process that includes, among other things, various laboratory and field studies to demonstrate drug effectiveness, target animal safety, good manufacturing procedures, adequate methods to detect drug residues, drug metabolism and depletion, and specific labeling requirements. If the drug is proposed for use in a food animal its use must be scientifically proven safe for humans consuming the food. Mandatory drug withdrawal times before animal harvest may be required if potential drug residues pose a health hazard.

In response to concerns about antimicrobial resistance, the FDA established specific guidance relative to how antimicrobial drugs should be evaluated (Guidance for Industry 152—Evaluating the Safety of Antimicrobial New Animal Drugs with Regard to their Microbiological Effects on Bacteria of Human Health Concern; www.fda.gov/cvm/Guidance/fguide152.pdf). Additionally, the FDA requires an environmental assessment of new drugs to help ensure compliance with Sections 318, 402, and 405 of the Clean Water Act (40 CFR §122.44). An environmental assessment usually involves determination of environmental fate of the drug and its toxicity to various aquatic animals and plants. Once approved drugs are on the market, the CVM monitors product use through surveillance and compliance programs.

Congress passed the Minor Use and Minor Species Act (Public Law 108–282) that provides incentives for pharmaceutical companies to seek drug approvals. The law creates limited flexibility in the approval requirements but maintains environmental and public health protection. Additionally, FDA has established a list of low regulatory priority aquaculture drugs, such as ice ($H_2O$) and salt (sodium chloride), that the agency determines to be *generally regarded as safe (GRAS)* and would not likely require a sponsor to invest in the drug approval process (Policies and Procedures 1240.4200; www.fda.gov/cvm/policy_procedures/4200.pdf).

The USEPA also uses a rigorous process to evaluate and register pesticides (www.epa.gov/pesticides). Registration is required for all pesticides sold or distributed in the United States. Registration involves review of ingredients; the particular site or crop on which the pesticide is to be used; the amount, frequency, and timing of its use; pesticide storage and disposal practices; and the range of potential human health and environmental effects associated with use of the product.

Review is required to evaluate whether a pesticide may cause adverse effects on humans, wildlife, fish, and plants—including endangered species and nontarget organisms. The review also examines the potential for contamination of surface or groundwater from leaching, runoff, and spray drift. Assessment of potential human health risks ranges from short-term toxicity to long-term effects such as cancer and reproductive system disorders. The language that appears on each pesticide label must also be approved by USEPA. A pesticide product can only be used legally according to the directions on labeling accompanying the product at the time of sale.

Pesticides registered for use in United States aquaculture can be found in the document *Guide to Drug, Vaccine, and Pesticide Use in Aquaculture* (Joint Subcommittee on Aquaculture 2004). Pesticides registered for use in domestic aquaculture include algicides and herbicides. Under some circumstances, pesticides may have therapeutic value (FDA Policies and Procedures 1240.4220; www.fda.gov/cvm/policy_procedures/4220.pdf) or may mitigate environmental conditions that promote disease development. The FFDCA requires USEPA to set pesticide tolerances for all pesticides used in or on food. A tolerance is the maximum permissible level for pesticide residues allowed in or on commodities for human food and animal feed. Concern about pesticide residues in all foods led to passage of the Food Quality Protection Act of 1996 (FQPA; Public Law 104–170), which amended FIFRA and FFDCA and required that the USEPA determine that a pesticide poses a “reasonable certainty of no harm” before the pesticide can be registered for use on food or feed. Factors the USEPA must evaluate include possible exposure of humans to pesticides from diet, cumulative effects of different pesticides on humans, effects on infants and children, and potential endocrine-disruption effects. As part of the FQPA, the USEPA is reassessing the safety of all pesticide residues currently allowed in foods.

### *Antimicrobials*

The use of antimicrobials in aquaculture has engendered considerable public concern (Goldburg and Triplett 1997; Goldburg et al. 2001; Benbrook 2002, cited in Boxall 2004). The global prevalence of human bacterial pathogens resistant to antimicrobials has increased over time, raising concern that antimicrobial use in animal and plant agriculture, including aquaculture, might contribute to this problem (Schnabel and Jones 1999; Singer et al. 2003). Proving a direct connection of animal agriculture with human bacterial pathogen resistance or risk to human health (Phillips et al. 2004) is difficult because of various technical or experimental limitations (Isaacson and Torrence 2002). The absence of credible data and scientifically rigorous research fosters uncertainty and speculation regarding the environmental impacts of antimicrobial use in agriculture (Mellon et al. 2001; Benbrook 2002, cited in Boxall 2004).

While there is little data to rigorously assess environmental impacts of antimicrobial use in aquaculture, the presence of violative drug residues in farmed fish and shellfish are cause for concern. The occurrence of violative antimicrobial residues (e.g. www.fda.gov/ora/oasis/4/ora_oasis_c_cn.html) in some farmed fishes (e.g., channel catfish, eel, and shrimp) detected during import inspections into the United States indicates that not all international regulatory and compliance programs are sufficiently rigorous or that producer or seafood processor noncompliance rates are high. Some residues are regarded as unsafe if they occur in food animals. For example, chloramphenicol may cause bone marrow depression and the nitrofurans may be carcinogenic and genotoxic in humans. These issues highlight the importance of using antimicrobial drugs judiciously and in compliance with federal regulatory programs. There is obvious need for harmonization of international drug-approval programs.

### *Environmental significance of antimicrobial use*

The environmental and public health significance of antimicrobials used in domestic aquaculture is not known. The World Health Organization (WHO 2006) has recently assessed antimicrobial use in global aquaculture by using qualitative risk assessment tools. The significance of antimicrobial use is dependent on a number of factors, including environmental fate and the probability that human pathogens might become resistant to a particular antimicrobial or class of antimicrobials used in aquaculture. Considerable evidence has accumulated to demonstrate that aquatic animal bacterial pathogens and aquatic bacteria can develop resistance to antimicrobials used in aquaculture (Tsoumas et al. 1989; Cooper et al. 1993; Starliper et al. 1993; Alderman and Hastings 1998; Lee et al. 2005; Sørum 2006). Interestingly, antimicrobial resistance may also develop in the absence of antimicrobial use (Smith et al. 1994; Kapetanaki et al. 1995; Vaughn et al. 1996). Antimicrobial-resistant bacteria may also be detected in wild fish not near aquaculture facilities (Pettibone et al. 1996). In this study brown bullhead (*Ictalurus nebulosus*) were presumed to have obtained antimicrobial-resistant bacteria as a consequence of exposure to river water contaminated by sewage.

The potential for transfer of an antimicrobial resistance factor from aquatic bacteria or aquatic animal pathogens to human pathogens has been demonstrated in laboratory studies (Kruse and Sørum 1994; Kruse et al. 1995). The probability of such transfer under natural conditions cannot be determined, and there is currently no scientifically credible evidence to demonstrate a direct link between the use of antimicrobials in fish farming and the occurrence of human pathogens resistant to antimicrobials. There are also no publicly available reports to suggest that violative (i.e., does not comply with FDA standards) antimicrobial residues occur in domestically produced aquaculture products marketed for human consumption, although there are occasional reports stating that drug residues are present on some imported seafood, including farm-raised channel catfish *Ictalurus punctatus* from China (www.fda.gov/ora/oasis/4/ora_oasis_c_cn.html). MacMillan (2001) provides reasons why the public health significance of antimicrobial use in the United States aquaculture industry may be negligible. These include various natural barriers to transfer including temperature, itinerant microbial flora of fish, and physiological and evolutionary differences of fish that impact microbial flora, physical barriers such as rare contact, and the rarity of human pathogens in fish or shellfish.

Limited data exists documenting the concentration of antimicrobials in water as a consequence of the use of antimicrobial-medicated feed used in aquaculture. Some information has been collected regarding the concentration of antimicrobials discharged from flow-through systems (Thurman et al. 2002). These studies documented very low concentrations of oxytetracycline (0 to 2.3 μg/L) or ormetoprim and sulfadimethoxine (0 to 5 μg/L) in raceway discharge waters of public hatcheries using medicated feeds to treat diseased fish. The frequency of medicated feed use was not documented. The type of waste management systems in place at these facilities was not clear, and waste capture may be an important mechanism to limit discharges of antimicrobials. The environmental significance of these concentrations was not investigated and the implications of a low environmental concentration of animal or human pharmaceuticals have only recently attracted research effort (Barnes et al. 2002; Boxall et al. 2003; Kummerer 2004; Dietze et al. 2005). Gordon et al. (2007) also documented the presence of antimicrobial-resistant aquatic bacteria downstream of flow-through fish farms and a waste treatment plant.

The significance of antimicrobial use in aquaculture production is unknown. Nevertheless, the potential exists for transfer of resistance factors to human pathogens and judicious use of antimicrobials in all uses (including human health management) is warranted. Recognizing this potential, several associations (the American Veterinary Medical Association and the National Aquaculture Association, as examples) and individuals (Serrano 2005, for example) have promulgated practices for responsible antimicrobial use in aquaculture. Useful websites with guidelines for the judicious use of antimicrobial therapeutics or the use of drugs include that of the American Veterinary Medical Association (*Judicious and Prudent Antimicrobial Drug Use for Food Fish Veterinarians*; www.avma.org/reference/jtua/fish/jtuafish.asp) and that of the National Aquaculture Association (*Judicious Antimicrobial Use in U.S. Aquaculture: Principles and Practices*; www.nationalaquaculture.org/pdf/Judicious%20Antimicrobial%20Use.pdf).

### *Better Management Practices to Minimize and Correctly Use Drugs and Therapeutics*

Prevention of disease must be the primary goal of health management in fish culture. Disease prevention is important for economic reasons, but also because there are few therapeutic agents approved for use in aquaculture in the United States. As such, once disease occurs, treatment options are limited and are rarely completely successful. Good husbandry practices to reduce disease incidence are also important to reduce environmental risks associated with disease and disease treatment.

When disease occurs, use of vaccines or drugs may be warranted if it is economically justified and the environmental impacts can be minimized. Vaccines may be used to prevent significant endemic diseases, and drugs may be useful for curing disease or limiting conditions that cause disease within individual rearing units. If therapeutic drugs are used, they must be used according to labeled requirements to assure safety and protection of public health and the environment. Careful economic analysis is also required because it may be more cost-effective not to treat and instead focus management efforts on optimization of rearing conditions.

Various farm-level management practices are presented below that can minimize drug and chemical use, thereby reducing potential environmental impacts. Note, however, that practical considerations already play a role in limiting indiscriminate use of therapeutic agents in aquaculture:

1) Federal and state regulations regarding drug and chemical use are based on risk-reduction measures that limit or specify, among other things, the diseases that can be treated, the animals on which the agent can be used, the types of culture systems in which the agent can be used, treatment rates, treatment duration, and withdrawal period before slaughter. These considerations limit the legal use of health-management agents to highly specific conditions.
2) Drugs and chemicals used in aquaculture are expensive. Cost considerations alone argue strongly against haphazard use. The use of approved drugs and chemicals is the responsibility of the grower in conjunction with an aquatic animal health specialist.
3) Many producers or producer associations have developed voluntary quality assurance programs that provide guidance on the legal and proper use of drugs and chemicals.
4) All processors of fishery products must develop and implement a Hazard Analysis and Critical Control Point (HACCP) plan under FDA food-safety regulations. Included in all plans are requirements to ensure that there is no hazard from use of aquaculture drugs at aquaculture facilities. Hazard Analysis and Critical Control Point plans cover use of approved drugs, drugs under review in the investigational new animal drug (INAD) program, extralabel use, and use of low regulatory priority drugs by producers. The processor may require a receipt of evidence (certificate of compliance) that the producer operates under a third-party audited Quality Assurance Program for aquaculture drug use (FDA-CFSAN 2001). This scrutiny ensures that the producer is not using an unapproved drug or an approved drug in a manner that will cause hazards.

### *Use good husbandry practices*

Reducing the incidence of disease by using good husbandry practices is perhaps the most effective way to reduce antibiotic and therapeutant use in aquaculture. Although good husbandry practices must be tailored to an individual facility, certain general guidelines can be identified. Factors to consider include production system water quality and quantity, production system (pond, flow-through, net-pen, or recirculating), type of aquatic animal raised and its degree of domestication, production requirements, feed quality and feeding practices, and availability of approved drugs. These factors are discussed above in the section “Better Management Practices for Reducing Transfer of Disease from Farmed to Wild Populations.”

### *Obtain an accurate diagnosis before treating a disease*

Timely and accurate disease diagnosis is essential to optimize resources and to implement effective management practices. Many fish diseases are caused by viruses, protozoan or metazoan parasites, or fungi, not bacteria. Antimicrobial treatments are ineffective against these diseases and are expensive. Morbidity or mortality may be associated with a complex of pathogens, making identification of the primary etiologic agent imperative. Accurate diagnosis can be obtained only if representative diseased animals are examined and the animals are submitted for diagnosis in a fresh condition. Representative water samples should also be tested because water quality can be a significant contributor to disease outbreaks. Farmers should work with aquatic animal health professionals to develop written standard operating procedures for initiating disease diagnostic activities and implementing treatment. The protocols should include specific instructions for procedures to follow when administering antimicrobials at aquatic animal production facilities. Diagnostic guidelines can be obtained from such publications as the American Fisheries Society, Fish Health Section "Blue Book" (AFS-FHS 2005).

### *Use vaccines to prevent diseases*

Prevention of infectious disease through successful vaccination can be a key practice for some aquaculture species. Vaccination is also important because the availability of antibiotics that can legally be used in the United States and the effectiveness of the few available drugs are limited. Further, the prospects for increasing the availability of drugs in the domestic aquaculture industry are poor because of the expensive federal approval process and increasing concerns that antibiotic resistance might be transmissible to microorganisms of public health importance. Finally, viral diseases and many of the bacterial, fungal, or protozoan infections in aquatic animals cannot be successfully treated using the antimicrobial or protozoacides currently available.

Vaccination does not generate antimicrobial-resistant microorganisms and can be used to control viral as well as bacterial diseases. Aquatic animals can be vaccinated economically and conveniently while small. Protection conferred by vaccination is often durable, thus eliminating the need to treat diseased animals repeatedly. Finally, with killed vaccines the requirements for licensing vaccines are considerably less problematic for the manufacturer than those required for the licensing of drugs.

Vaccination of aquatic animals has improved in recent years, making immunization of large numbers of animals more economical and practical. In addition, improvements in adjuvant formulations and the development of multivalent vaccines have led to the widespread use of vaccines for prevention of several of the most important bacterial diseases of fish. In Norway, the use of effective vaccines revolutionized and stabilized Norwegian salmon farming. The use of antibiotics per unit biomass of fish produced was reduced by more than 99.9% (Fig. 12.1; Håstein and Gudding 2005) while production costs were reduced and financial predictability stabilized (Lillehaug et al. 2003). Recent advances in the molecular biology of fish pathogens and the development of novel approaches in vaccination have opened the way for a new generation of fish vaccines that promise further improvements in the ability to protect populations of cultured fish against significant diseases (Lorenzen and LaPatra 2005). The availability of new vaccines for important finfish pathogens should improve over the next several years. Individuals may also contract with a veterinarian to develop autogenous vaccines (site-specific) to meet particular needs (Table 12.1). Autogenous vaccines are not subject to USDA licensing requirements.

### *Use only approved antimicrobials*

Although vaccines have an important role in disease prevention, drug treatments may occasionally be required. It is essential that drugs be used judiciously and with thorough understanding of how they can be safely used. The availability and conditions of use should be checked to ensure particular drugs can be safely used (www.fda.gov/cvm/drugsuseaqua.htm).

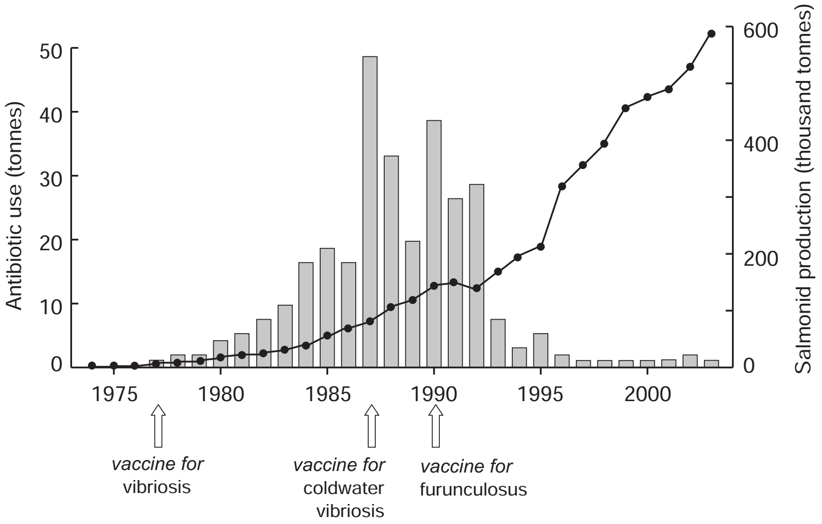

**Fig. 12.1.** The impact of vaccine development on antibiotic use in net-pen aquaculture of Atlantic salmon in Norway. Adapted from Håstein and Gudding 2005, with permission.

**Table 12.1.** Biologics for use in the United States in 2007.

| Biologic | Year Licensed |
|---|---|
| *Aeromonas salmonicida* bacterin | 1990 |
| *Aeromonas salmonicida* bacterin | 1991 |
| *Aeromonas salmonicida* bacterin | 1996 |
| Autogenous bacterin | 1991 |
| *Aeromonas salmonicida-Vibrio anguillarum/ordalli/salmonida* bacterin | 1994 |
| *Aeromonas salmonicida-Vibrio anguillarum/ordalli/salmonida* bacterin | 1997 |
| *Aeromonas salmonicida-Vibrio anguillarum/ordalli/salmonida* bacterin | 2001 |
| *Arthrobacter* vaccine, live culture | 2002 |
| *Edwardsiella ictaluri* bacterin | 1993 |
| *Flavobacterium columnare* bacterin | 1997 |
| Infectious salmon anemia virus vaccine (killed virus); *Aeromonas salmonicida-Vibrio anguillarum/ordalli/salmonida* bacterin | 2001 |
| *Yersinia ruckeri* bacterin | 1987 |
| *Vibrio anguillarum/ordalli* bacterin | 1987 |
| *Vibrio anguillarum/ordalli* bacterin | 1990 |
| *Edwardsiella ictaluri* vaccine, avirulent live culture | 1999 |
| *Flavobacterium columnare* vaccine, avirulent live culture | 2005 |

In the United States, there are four FDA-approved antimicrobials for use in aquaculture, although their approved uses are limited to specific foodfish (catfish, salmonids and lobster) and specific diseases. These antimicrobials are oxytetracycline (Terramycin for Fish®, oxytetracycline monoalkyl trimethyl ammonium), a potentiated sulfonamide (Romet-30®, ormetoprim and sulfadimethoxine), and Aquaflor® (florfenicol). These drugs can only be administered through feed in a specific feed formulation. A fourth antimicrobial, sulfamerazine, is approved but not currently manufactured.

Terramycin for Fish® is the only approved therapeutic oxytetracycline product and is approved to treat certain diseases in catfish, salmonids, and lobster. Oxytetracycline-medicated feed can be used to treat bacterial hemorrhagic septicemia and pseudomonas disease in catfish at a dose of 2.5 to 3.75 g active ingredient/45.4 kg of fish per day for 10 days when the water temperature is above 16.7 °C. For salmonids, when the water temperature is above 8.9 °C, Terramycin for Fish® can be used to control ulcer disease, furunculosis, bacterial hemorrhagic septicemia, and pseudomonas disease. The treatment duration is 10 days. Terramycin for Fish® is not currently approved for use in salmonids at temperatures below 8.9 °C. Lobster can be treated with Terramycin for Fish® to cure gaffkemia caused by *Aerococcus viridans*. The treatment duration is 5 days at 1 g active ingredient/0.45 kg of medicated feed. This product has a withdrawal time of 21 days for catfish and salmonids and 30 days for lobster. The withdrawal time is the period between the last administration of the drug to the aquatic animal and the time when the aquatic animal can be harvested and offered for food (human or animal). The withdrawal time ensures no harmful drug residues are present when the animal is harvested for human consumption.

Romet-30® can be used in medicated feed to treat enteric septicemia of catfish (ESC) and furunculosis in salmonids. The dose is 50 mg active ingredient/kg body weight per day for 5 days. In catfish there is a 3-day mandatory withdrawal time and a 42-day withdrawal time for salmonids. The shorter withdrawal time for catfish occurs because any Romet-30 residues that might be present are removed with the skin of catfish during processing.

Aquaflor® can only be used under a Veterinary Feed Directive (VFD) in catfish for the treatment of ESC caused by *Edwardsiella ictaluri* or in freshwater-reared salmonids for the treatment of coldwater disease caused by *Flavobacterium psychrophilum*. Aquaflor® has also been conditionally approved by the FDA to treat columnaris disease in catfish caused by *Flavobacterium columnare*. Conditional approval allows use of a drug while a complete approval package (full demonstration of effectiveness) is generated in conformance with the Minor Use and Minor Species Act (Public Law 108–282). A Veterinary Feed Directive requires that the medicated feed can only be fed on the order of a licensed veterinarian. Extralabel use of a Veterinary Feed Directive-approved drug is prohibited by regulation.

There is only one approved antibiotic for ornamental fish (nifurpirinol). The drug is approved for treatment of columnaris disease in freshwater aquarium fish that are not reproducing. There are no drugs approved for other nonfood aquatic animals (Table 12.2).

### *Use therapeutic agents only for their approved purposes*

Drugs used in aquaculture are not approved for use as growth promoters. In fact, fish fed diets supplemented with antibiotics tend to grow slower than fish fed unmedicated diets (Rawles et al. 1997). Antibiotics are to be used only for the specific therapeutic purposes described in the previous section and should never be used prophylactically. Spawning hormones are used on selected adult broodstock (that are not processed for human consumption) in confined and controlled situations using FDA-approved drugs (e.g., reproduction). Some EPA-registered chemicals are used according to label to mitigate further outbreak of disease (i.e., disinfection).

**Table 12.2.** Drugs for aquatic animals approved by the United States Food and Drug Administration, 2007.

| Active Ingredient | Trade Name | Uses and Species |
|---|---|---|
| Tricaine methanesulfonate | Finquel® (MS-222) | Temporary immobilization of aquatic cold-blooded animals (poikilotherms), including finfish and amphibians |
| Tricaine methanesulfonate | Tricaine-S® (MS-222) | Temporary immobilization of aquatic cold-blooded animals (poikilotherms), including finfish and amphibians |
| Formalin | Formalin-F® | Control of external protozoa (*Chilodonella* spp., *Costia* spp., *Epistylis* spp., *Ichthyophthirius* spp., *Scyphidia* spp. and *Trichodina* spp.), and the monogenetic trematode parasites (*Cleidodiscus* spp., *Dactylogyrus* spp., and *Gyrodactylus* spp.) on all finfish. Control of fungi of the family Saprolegniaceae on all finfish eggs. Control of external protozoan parasites (*Bodo* spp., *Epistylis* spp., and *Zoothamnium* spp.) on penaeid shrimp. |
| Formalin | Paracide-F® | Control of external protozoa (*Chilodonella* spp., *Costia* spp., *Epistylis* spp., *Ichthyophthirius* spp., *Scyphidia* spp. and *Trichodina* spp.), and the monogenetic trematode parasites (*Cleidodiscus* spp., *Dactylogyrus* spp., and *Gyrodactylus* spp.) on salmon, trout, catfish, largemouth bass, and bluegill. Control of fungi of the family Saprolegniaceae on salmon, trout, and esocid eggs. |
| Formalin | Parasite-S® | Control of external protozoa (*Chilodonella* spp., *Costia* spp., *Epistylis* spp., *Ichthyophthirius* spp., *Scyphidia* spp. and *Trichodina* spp.), and the monogenetic trematode parasites (*Cleidodiscus* spp., *Dactylogyrus* spp., and *Gyrodactylus* spp.) on all finfish. Control of fungi of the family Saprolegniaceae on all finfish eggs. Control of external protozoan parasites (*Bodo* spp., *Epistylis* spp., and *Zoothamnium* spp.) on penaeid shrimp. |
| Sulfadimethoxine and ormetoprim | Romet 30® | Control of furunculosis in salmonids (trout and salmon) caused by *Aeromonas salmonicida*. Control of enteric septicemia of catfish caused by *Edwardsiella ictaluri*. |
| Sulfamerazine | Sulfamerazine in Fish Grade® | Control of furunculosis in rainbow trout, brook trout, and brown trout. Comments: According to sponsor, this product is not presently being distributed. |
| Oxytetracycline (monoalkyl trimethyl ammonium salt) | Terramycin for Fish® | Control of ulcer disease caused by *Haemophilus piscium*, furunculosis caused by *Aeromonas salmonicida,* bacterial hemorrhagic septicemia cause by *Aeromonas liquefaciens*, and pseudomonas disease in salmonids. Control of bacterial hemorrhagic septicemia caused by *Aeromonas liquefaciens* and pseudomonas disease in catfish. Control of gaffkemia caused by *Aerococcus viridans* in lobsters. Marking of skeletal tissue in Pacific salmon. |
| Chorionic gonadotropin | Chorulon® | Spawning aid in all brood finfish. |
| Florfenicol | Aquaflor® | Enteric septicemia of catfish, coldwater disease of salmonids, and conditional use for columnaris of catfish. |

There are limited circumstances, under supervision of a licensed veterinarian, where Terramycin for Fish® or Romet-30® medicated feed can be used for other aquatic animals not listed on the label. This is considered extralabel use, meaning that the drug is being used not in accordance with approved product labeling. In 1994, the United States Congress passed the Animal Medicinal Drug Use Clarification Act (AMDUCA) to allow veterinarians to prescribe FDA-approved drugs in an extralabel manner under specific conditions. The regulations that implement AMDUCA can be found in 21 CFR §530. These extralabel uses have limited utility in most commercial aquaculture, but might be feasible for valuable brood stock or ornamental fishes.

While AMDUCA prohibits the use of an FDA-approved drug in or on feed, FDA recognized that there was a need for certain animal populations. The FDA exercised its regulatory discretion to allow extralabel use of medicated feeds under specific conditions. If the conditions are met, FDA is unlikely to take regulatory action. These conditions are identified by FDA in compliance policy guide 1240.4210 (www.fda.gov/cvm/policy_procedures/4210.pdf). The guide describes how a veterinarian can prescribe medicated catfish or salmonid feeds to treat bacterial diseases in other aquatic animals or for different bacterial diseases than what the products are approved for. A veterinarian can prescribe the extralabel use of medicated feed when the health of animals is threatened and suffering or death would result from failure to treat affected animals. To use a medicated feed in an extralabel manner, the following conditions must be met:

1) There is express written recommendation and oversight of an attending licensed veterinarian within the context of a valid veterinarian-client-patient relationship.
2) The medicated feed is already approved for use in aquatic species, meaning only medicated catfish, salmonid or lobster feed.
3) There cannot be any reformulation of the feed and it must be labeled for the approved species.
4) Extralabel use can only be for therapeutic purposes (i.e., to treat a disease).
5) The aquaculturist is required to:
    a) Keep complete and accurate records of feeds received, including labels, invoices, and dates fed. Records must be kept for at least 1 year.
    b) Keep a current copy of the veterinarian's written recommendation.
    c) Institute procedures to assure that the identity of treated animals is carefully maintained.
    d) Take appropriate measures to assure that the withdrawal time provided by the veterinarian is met and no unsafe drug residues occur in any food-producing animal.
    e) Use the medicated feed in accordance with federal, state, and local environmental laws and regulations.
    f) Follow user safety provisions.

Additionally, as part of the FDA scientific data gathering requirements needed to approve a new antibiotic or other drug, an investigational new animal drug (INAD) exemption may be issued by FDA. The exemption allows a scientist or aquatic animal producer involved in generating data to support a specific drug approval to test the safety and effectiveness of the drug. INAD exemptions must be approved from FDA Center for Veterinary

Medicine prior to drug use and entail considerable scrutiny to assure that the testing will be valid and that human, animal and environmental safety are protected.

### *Assess antimicrobial resistance before using antimicrobials*

Bacteria causing the aquatic animal disease must be sensitive to the antimicrobial considered for use. If bacteria are isolated from representative, clinically diseased animals, the diagnostic laboratory should determine the sensitivity of the bacteria to available antimicrobials before treatment is initiated. Use only a federally approved antimicrobial to which the pathogenic bacteria are clearly sensitive. This determination is best done in consultation with aquatic animal health professionals. Internationally harmonized sensitivity standards are under development (Schnick 2001).

### *Use medicated feeds properly*

The primary means of delivering antibiotics to aquatic animals is through the feed. Successful use of medicated feed requires that aquatic animals have sufficient appetite to consume feed. Bacterial diseases often cause diminished feeding, so care must be exercised to feed amounts that can be consumed. Early disease diagnosis helps ensure that treatments can begin before aquatic animals cease feeding. Operators should routinely visually monitor feeding activity. In some circumstances, the best treatment is to stop feeding rather than to administer a medicated feed. The aim of treatment is to treat diseased fish, not to feed the water. Applying medicated feed when fish are not eating results in more of the antimicrobial agent reaching the environment. Medicated feed should never be used as a prophylactic treatment against disease. Use of prescription, Veterinary Feed Directive, or extralabel drugs should be done only under the direction and supervision of a licensed veterinarian.

### *Use only approved water-treatment chemicals*

The use of chemical therapeutics or disease treatments must consider federal or state discharge limitations and the impact of the chemical on the fish rearing environment. Federally approved chemicals for use as a drug include formalin, hydrogen peroxide ($H_2O_2$) and tricaine methane sulfonate (MS-222). Only those chemicals manufactured by specific companies with specific drug approvals can be used. Formalin (Formalin-F®, Paracide-F®, and Parasite-S®) is approved as a parasiticide to treat all finfish and penaeid shrimp and as a fungicide to treat eggs of all finfish. Hydrogen peroxide (35% Perox-Aid®) is approved as a treatment for saprolegniasis on freshwater-reared finfish eggs, for the control of bacterial gill disease associated with *Flavobacterium branchiophilum* in freshwater-reared salmonids, and for the control of mortality in freshwater-reared coolwater finfish and channel catfish due to external columnaris disease associated with *Flavobacterium columnare*. Tricaine methane sulfonate (Finquel® and Tricaine-S®) is approved as an anesthetic for the temporary immobilization of fish, amphibians, and other aquatic cold-blooded animals. It has a 21-day withdrawal time prior to any harvest of foodfish for human or animal consumption.

FDA has also developed a list of Low Regulatory Priority Compounds (Table 12.3) that, while not approved drugs, could be used under some circumstances (Policies and Procedures 1240.4200; www.fda.gov/cvm/policy_procedures/4200.pdf). Use of the low regulatory priority drugs requires careful consideration before use to ensure such use complies with EPA or state regulatory requirements. Labeling for low regulatory priority use is not required for a chemical that is commonly used for nondrug purposes, even if the manufacturer or distributor promotes the chemical for the permitted low regulatory priority use. However, a chemical that has significant animal or human drug uses in addition to low regulatory priority aquaculture use will be required to be labeled for the low regulatory priority uses if the manufacturer or distributor establishes the intended low regulatory priority use for its product by promotion or other means. Low regulatory priority compounds may be marketed for aquaculture use with drug claims (the claims permitted for such compounds) but must be of an appropriate quality for use in food animals.

In the United States, some chemicals are federally approved as pesticides but may have an ancillary use as a drug. A good example is the various copper-based algicides, particularly copper sulfate pentahydrate. The FDA recognizes that copper sulfate has use as a parasiticide, as well as its well-known algicidal properties. The FDA has decided to allow use of these types of compounds when they are used as a drug in the same manner (dosage) as for a water treatment. Copper discharges are also closely regulated by federal and state effluent discharge criteria to ensure that water quality criteria are maintained. The EPA has established aquatic life criteria for toxins such as copper (40 CFR §131.36) and these should be followed at a minimum.

### *Follow label instructions*

Whether a drug, vaccine, or water treatment chemical is used, it is essential that complete label instructions are followed. It is important to provide the medicated feed for the full duration of time indicated on the label and to minimize development of antimicrobial resistance. For example, Terramycin for Fish® is a broad-spectrum, short-lived (does not persist in the body) bacteriostatic antibiotic. Because this antibiotic does not directly kill disease-causing bacteria, the aquatic animals own host defenses must work if therapy is to be successful. Reduction of aquatic animal stress can enhance host defenses. Although the potentiated sulfonamide Romet-30® is generally bactericidal and broad-spectrum, it is crucial to also reduce aquatic animal stress if therapeutic success is to be expected. Copper sulfate can be used only if it is an approved algicide and must be used according to label requirements. The label prescribes maximum application rates, safe usage, and chemical disposal requirements.

### *Keep accurate and complete records of all health management activities*

Complete records should be kept documenting animals treated with antimicrobial or other drugs. Food animal producers should maintain these records to ensure compliance with mandatory FDA seafood inspection regulations and any information required by processors.

**Table 12.3.** Drugs for aquatic animals listed as "Low Regulatory Priority" by the United States Food and Drug Administration, 2007.

| Common Name | Permitted Use |
|---|---|
| Acetic acid | Used as a dip at a concentration of 1,000–2,000 milligrams per liter (mg/L) for 1–10 minutes as a parasiticide for fish |
| Calcium chloride | Used to increase water calcium concentration to ensure proper egg hardening. Dosages used would be those necessary to raise calcium concentration to 10–20 mg/L calcium carbonate. Also used to increase water hardness up to 150 mg/L to aid in maintenance of osmotic balance in fish by preventing electrolyte loss. |
| Calcium oxide | Used as an external protozoacide for fingerling to adult fish at a concentration of 2,000 mg/L for 5 seconds |
| Carbon dioxide gas | Used for anesthetic purposes in cold-, cool-, and warmwater fish |
| Fuller's earth | Used to reduce the adhesiveness of fish eggs in order to improve hatchability |
| Garlic (whole) | Used for control of helminth and sea lice infestations in marine salmonids at all life stages |
| Ice | Used to reduce metabolic rate of fish during transport |
| Magnesium sulfate (Epsom salts) | Used to treat external monogenic trematode infestations and external crustacean infestations in fish at all life stages. Used in freshwater species. Fish are immersed in a solution of 30,000 mg/L magnesium sulfate and 7,000 mg/L sodium chloride for 5–10 minutes. |
| Onion (whole) | Used to treat external crustacean parasites and to deter sea lice from infesting external surface of fish at all life stages |
| Papain | Used as a 0.2% solution in removing the gelatinous matrix of fish egg masses in order to improve hatchability and decrease the incidence of disease |
| Potassium chloride | Used as an aid in osmoregulation to relieve stress and prevent shock. Dosages used would be those necessary to increase chloride ion concentration to 10–2,000 mg/L. |
| Povidone iodine compounds | Used as a fish egg disinfectant at rates of 50 mg/L for 30 minutes during water hardening and 100 mg/L solution for 10 minutes after water hardening |
| Sodium bicarbonate (baking soda) | Used at 142–642 mg/L for 5 minutes as a means of introducing carbon dioxide into the water to anesthetize fish |
| Sodium chloride | Used as a 0.5–1% solution for an indefinite period as an osmoregulatory aid for the relief of stress and prevention of shock. Used as a 3% solution for 10–30 minutes as a parasiticide. |
| Sodium sulfite | Used as a 15% solution for 5–8 minutes to treat eggs in order to improve hatchability |
| Urea and tannic acid | Used to denature the adhesive component of fish eggs at concentrations of 15 g urea and 20 g NaCl/5 L of water for approximately 6 minutes, followed by a separate solution of 0.75 g tannic acid/5 L of water for an additional 6 minutes. These amounts will treat approximately 400,000 eggs. |

### *Properly handle, store, and dispose of drugs and chemicals*

All chemicals and drugs should be secured to prevent unauthorized use. Chemical storage facilities should be locked to prevent vandalism (contamination of drugs) or unauthorized uses. Certain chemicals used at aquaculture facilities may be toxic when directly applied to aquatic animals. Securing these chemicals from unauthorized use may limit such exposure and opportunity for toxicity.

Unused medicated feed and medicated articles should be properly disposed. Applicable federal and state statutes and regulations do not generally consider ready-to-feed or complete medicated feed as a hazardous substance requiring special disposal. It is the producers' responsibility to confirm this requirement because requirements do change. In fact, feed in general does not require a Material Safety Data Sheet (MSDS), which is the best guide to identifying hazardous substances. On the other hand, feed supplements or concentrates (feed with higher levels of medications and nutrients) may require special handling and disposal. There should be an MSDS for these products indicating whether the supplements or concentrates contain hazardous substances, thereby requiring special handling and disposal. Such disposal must meet local, state, and federal requirements. Contact a commercial waste disposal provider for compliance procedures. Some drug sponsors may also accept the return of product on a case-by-case basis. The last and most potent category of feed products is medicated articles, commonly referred to as *drug premixes*.

For those medicated articles approved for use in aquatic animal feed (antibiotics), contact the pharmaceutical manufacturing firm listed on the label for specific disposal instructions. Some firms will accept return of the products for disposal. The USEPA's "List of Lists" identifies ingredients deemed hazardous along with the permitted threshold amounts (*List of Lists: Consolidated List of Chemicals Subject to the Emergency Planning and Community Right-to-Know Act (EPCRA) and Section 112(r) of the Clean Air Act*; www.epa.gov/swercepp/pubs/title3.pdf).

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## Chapter 13

# Economics of Aquaculture Better Management Practices

*Carole R. Engle and Ada Wossink*

## Introduction

Economics is often defined as the allocation of scarce resources to meet the unlimited wants and needs of human beings. This definition illustrates the breadth of the economics discipline and the basis for the tools of economic analysis that are used to address issues that extend well beyond business activities. In the context of environmental regulation, better management practices (BMPs), and aquaculture, economics provides theoretical and analytical models that can identify optimal or best choices given particular sets of environmental and business objectives.

To an economist, pollution is an externality. An externality exists when the welfare of a firm or individual depends directly on activities under the control of some other firm or individual. Regulations may be promulgated when pollution causes damage to enough people so that attention is drawn to the problem. This is particularly true if the society is wealthy enough or if there is potential to direct resources toward alleviating damages or preventing future damages.

This chapter will first provide a brief overview of an economics perspective on the adoption of environmentally friendly technologies. Better management practices will then be compared to other policy approaches designed to enhance environmental management. The chapter then moves on to describe several empirical examples of the use of BMPs in row crop farming, urban stormwater control, and swine producers' perceptions of alternative waste management systems. The aquaculture economics literature includes several studies on the economics of BMPs and BMP-type practices in aquaculture that are reviewed in this chapter. Relevant studies have examined various aspects of BMPs recommended for marine shrimp production in Honduras, Mexico, and Nicaragua; trout farms in Idaho and North Carolina; and hybrid striped bass, baitfish, and catfish production. The final section of the chapter compares the relative costs associated with the use of various components suggested for BMPs in aquaculture.

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## An Economics Perspective on Adoption of Environmentally Friendly Technologies

From an economics perspective, the cost of achieving water quality goals must be balanced with the benefits (Marra and Zering 1996). The goal is to internalize (charge costs to the firm generating the pollution) the externality (the pollution) so that the costs of pollution are charged to those consumers who wish to purchase the good that is generating the pollution (Baumol and Oates 1988). However, creating policy to do this is not simple. The appropriateness of regulatory options is case-specific and depends on the relationship between the benefits to be achieved through environmental improvements and the costs that result from regulation. These costs may be incurred by the private businesses affected but may also be incurred by various state and federal agencies.

There are two ways to build environmental concerns into economic analysis. One way is to assign monetary values to environmental attributes and include them in monetary analyses. This approach is known as *cost and benefit analysis (CBA)*. Critiques of CBA are abundant and point to the difficulty of assigning values to public goods like water quality. Because of a lack of relevant data, many studies describe benefits of control efforts but monetarize only a single impact category or provide no monetarization at all. The inherent shortcomings of CBA have led to revised evaluation methods. These other evaluation methods can be more appropriate particularly when the ecological and environmental impacts of decisions are important to decision makers. In the context of BMPs, the relevant decision frequently is which BMP to choose for a specific location. In that case information on the trade-off of costs and environmental effectiveness in situ is most relevant. This approach is known as *cost-effectiveness analysis* and examines tradeoffs between environmental attributes and costs.

Environment-economic trade-offs can offer two useful kinds of results. First, mapping alternative practices by these two criteria can identify those that are “efficient” in the sense of giving the best economic performance for a given level of environmental performance, or the best environmental outcome at a given cost level. In Fig. 13.1, the least-cost solution results in lower costs but also lower emission reductions than the other alternatives. The alternatives located above and to the right of the solid line are not efficient because they would create either more emissions or higher costs than a mix of two of the efficient alternatives (those circles that lie on the connecting line). Efficient choices will lie on a frontier, where there is a trade-off between improving economic and environmental performance. The “knee of the curve” is where the cost for further environmental improvements significantly increases. This kind of information can be particularly helpful in stakeholder negotiations.

Decision-making regarding BMPs consists of the selection of a feasible and acceptable option out of the set of efficient alternatives. Collaboration among economists, other scientists, and policy makers is required to find the “best of the best.” Practices can be expected to be successful when they meet technical, economic, and environmental criteria and are also socially acceptable. Farmers’ opinion of the alternative options is particularly relevant. Sustainable practices must fit a broader farm decision-making context that incorporates social and personal considerations in addition to economic and environmental aspects. Thus, in the analysis of feasible and acceptable BMPs, not only environmental

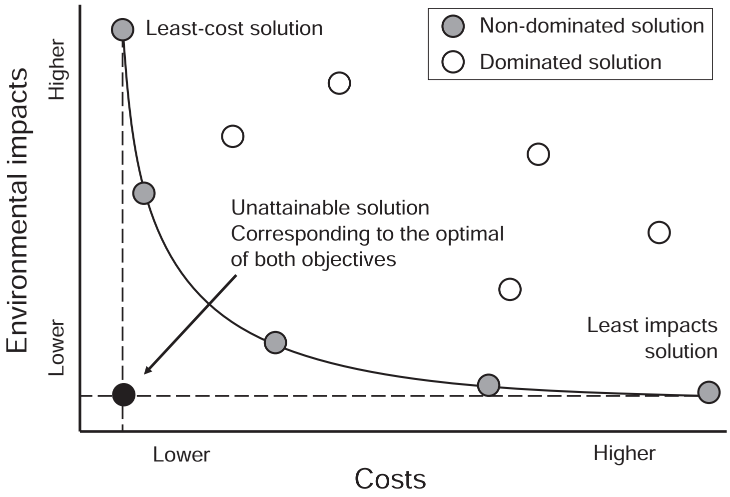

**Fig. 13.1.** Graph of the trade-offs between improving environmental quality and the costs associated with the improvement. The least-cost solution has lower costs but reduces pollution less than other alternatives. When environmental quality is poor, even inexpensive treatment options can reduce pollution rapidly. The least impacts solution is a point from which it becomes very expensive to remove the last bit of remaining pollution.

benefits and economic costs should be assessed, but also farmers' knowledge and perceptions of these practices.

Behavioral economics can provide insights into these constraints. In this type of economic analysis, not only do the objective characteristics of goods or actions matter, but also subjective characteristics as perceived by the decision maker. Hence, perception plays an important role in guiding choices. Furthermore, each option may be considered as a bundle of attributes. Depending on the valuation of these attributes by the decision maker, different choices will result. The use of analytical techniques based on these theoretical insights has a long history in the marketing literature and in the analysis of consumer behavior (Sherrick et al. 2003). These techniques have only recently been applied in the ex ante assessment of the impact of farmers' subjective assessments of future adoption decisions of sustainable practices (Adesina and Baidu-Forson 1995; Wossink et al. 1997) and for environmental and conservation issues in general (Holmes and Adamowicz 2003).

## Comparing BMPs to Other Policy Approaches for Enhanced Environmental Management

The choice of the most effective type of policy in terms of protecting the environment and having sustainable industries depends on the nature of the problem, the costs of abatement, and the transactions costs associated with administering the policy (Brennan 2002). New policies may require additional investment costs if any new structures must be built, additional operating costs in the form of additional inputs or labor for record keeping, and additional monitoring and enforcement costs incurred by the agency charged with administering the program (Hishamunda and Ridler 2003).

Better management practices define a recommended set of activities that take environmental and economic factors into account and have been a principal policy instrument to balance agricultural and resource policies (Leathers 1991). Costs and benefits of any given practice vary substantially from farm to farm, making a broad prescription of practices impossible (Leathers 1991). By definition, a practice is a BMP if installation and maintenance costs do not exceed the sum of private and public benefits (Dempster and Stierna 1979; Leathers 1991). The following section will review a variety of policy approaches used for environmental management and will conclude with a discussion and comparison of these approaches with BMPs.

The literature on environmental management policy is confusing due to the large number of classification systems (Table 13.1). One such classification is as either command-and-control (governmental) regulation or incentive-based policy. Command-and-control (C&C) regulations have been used more commonly in aquaculture than in other industries (Thongrak et al. 1997; Hishamunda and Ridler 2003). Common examples of C&C policy instruments in aquaculture include emission standards, environmental impact assessments, effluent discharge permits, limitations on nonnative species, restrictions on drug and chemical uses, standards for feed consumption, restrictions on feed use, and restrictions on certain management practices.

Policies can also be classified as either direct (applied to the effluent itself) or indirect (applied to inputs or outputs). For example, a direct regulation may require a specified area of effluent treatment per unit area of production ponds. Other direct types of policies may include bans, restrictions, land use classification, zoning, permits, taxes, and user fees (Boyd and Schmittou 1999). Some C&C types of policies (emission standards, direct load limits, quotas) fall into this category. The disadvantage of direct regulations is that other factors that affect effluent output (such as feed conversion ratios, total production, and site location) are not taken into account (Brennan 2002). For example, the optimal number of effluent treatment ponds varies among farms and requires case-by-case control measures. Implementation of direct regulations often includes environmental impact assessment, mitigation plans, and monitoring. However, if there is a great deal of risk or uncertainty or if monitoring efforts are limited, direct regulations and controls will not result in the types of benefits expected (Mathis and Baker 2002).

Policies also can be either price-based or quantity-based (Brennan 2002). Price-based policies include taxes, emission charges, performance or assurance bonds, and subsidies. Quantity-based policies include emission standards, direct limits on nutrient loads, tradable emission permits, quotas, zoning, standards for feed consumption, restrictions on drugs and chemicals, limitations on nonnative species, and mandatory production practices (Table 13.1) (Hahn and Stavins 1991, 1992). How a given policy affects prices or quantity is independent of whether it is C&C or incentive-based, direct, or indirect.

### Emission Standards and Charges

*Emission standards* is a command-and-control approach used in the United States for point sources of pollution. Establishing emission standards requires the regulatory authority to set an environmental standard for each emission source and to monitor emissions for

**Table 13.1.** Summary of the principal policy types to regulate pollution.

| Policy | Definition | Description | C&C[a] or Incentive-based | Direct or Indirect | Price or Quantity-based |
|---|---|---|---|---|---|
| Emission standards | Establishment of environmental standard for each emission source and monitoring emissions for compliance | Most popular method in U.S. for point sources. Enforcement involves penalties for violating the standard. | C&C | Direct | Quantity |
| Direct load limits/ minimum nutrient concentrations | | | C&C | Direct | Quantity |
| Quotas | | | C&C | Direct | Quantity |
| Emission charges | Charge is the price that the polluter pays for using the assimilative capacity of the environment. Charge is adjusted until the standard is achieved. | Requires regulatory authority to establish environmental standard and a uniform charge per unit of emission for each source | C&C | Direct | Price |
| Permits | | | C&C | Direct | Quantity |
| Tradable emission permits | Specifies maximum emission level | Restricts contribution that different sources make to ambient concentrations of a pollutant. Permits can be bought and sold like emissions standards | Incentive | Direct | Quantity |
| Taxes on discharges | Pigouvian tax is the difference between marginal social benefit and the marginal private benefit of pollution abatement at the socially efficient level of abatement | Used to reduce municipal solid waste, congestion on highways, and to encourage recycling | Incentive | Direct | Price |
| Taxes on inputs or production | | Implementation difficult. Must know marginal cost and marginal benefits and emission levels. Not possible to determine tax without it. | Incentive | Indirect | Price |

*(Continued)*

**Table 13.1.** *Continued.*

| Policy | Definition | Description | C&C[a] or Incentive-based | Direct or Indirect | Price or Quantity-based |
|---|---|---|---|---|---|
| Environmental liability | Lawsuits | Makes acting parties financially responsible for pollution damage, usually via lawsuits | Incentive | Indirect | Price |
| Performance/assurance bonds or deposits | | | Incentive | Direct | Price |
| Other financial incentives and subsidies | Subsidizing defensive expenditures | Use of bottled water instead of polluted water | Incentive | Indirect | Price |
| | Compensation for affected parties | For damages inflicted by acting parties | Incentive | Indirect | Price |
| | Subsidizing emissions-reductions by acting parties | Increases profits | Incentive | Indirect | Price |
| Limitations on nonnative species | | | C&C | Direct | Quantity |
| Restrictions on drugs and chemicals | | | C&C | Direct | Quantity |
| Standards for feed consumption | | | C&C | Indirect | Quantity |
| Mandatory production practices | | | C&C | Indirect | Quantity |
| Zoning | | | C&C | Indirect | Quantity |
| Voluntary agreement | | | C&C | Indirect | Quantity |
| Cost sharing of BMPs | Society pays for part of pollution abatement because pollution is an external diseconomy; someone other than polluter primary beneficiary of pollution reduction. | Examples include terraces, conservation tillage, soil-nitrogen testing, split application of pesticides. | Incentive | Indirect | Quantity |

[a] Command-and-control (government-dictated regulation).

compliance. Enforcement frequently involves charging fees and penalties for violating the standard. The amount of the fees charged can be adjusted until the environmental standard is achieved. The primary emissions from aquaculture are effluents. Standards for effluent discharge can focus either on the concentration of nutrients in the effluent or the quantity of effluent discharged. Either requires monitoring by individuals with the appropriate expertise. Better management practices can provide a lower cost option by not requiring expensive monitoring (Hishamunda and Ridler 2003).

Pongthanapanich (2006) examined effects of a discharge tax on uncertified shrimp farms in Thailand as part of a three-pronged tax. The other two components of the tax were a "mangrove" tax that would be levied on new farms that encroach on existing mangroves and an "abandoned farm tax" that would be used as social insurance for abandoned shrimp farms that leave behind salinization problems. The analysis indicated differing environmental costs, depending on the receiving water body. In the near term, the benefits in net welfare and trade from shrimp offset the environmental costs. However, over time, the model indicated higher net gains from trade with environmental taxes. The effect on net welfare over time was ambiguous.

Australia has placed discharge standards for prawn farms that include loading limits and minimum nutrient concentration levels on farms with licenses (Brennan 2002). New licenses are subject to a specific environmental impact assessment. The limits establish a threshold level that farms must achieve, but do not provide an incentive to adopt technological improvements that reduce the effluent load below the limit established by the discharge standard. Uniform discharge standards like these do not account for varying compliance and efficiency costs among farms. For example, in this Australian case, the cost of reducing effluent on a prawn farm is considerably higher than the cost of abating effluent from a sugar cane farm. Sugar cane farming contributes more nutrients in its runoff, but is not restricted under Australian policy.

Emissions standards are often implemented through permit systems. Economists frequently view tradable emissions permits as a more efficient policy than an absolute limit or quota system. Tradable emissions permits specify a maximum emission level and can be bought and sold. Firms with permits are allowed to discharge a proportion of their historical discharge and are further allowed to trade permits. Firms that can control their discharge inexpensively can sell their permits at a profit to firms whose costs of reducing discharge is high.

### *Taxes*

A tax referred to as a *Pigouvian tax* is considered the most economically efficient type of environmental policy (Ulph 2000). A Pigouvian tax is a levy charged on a firm equal to the environmental damages caused by its activity (Pigou 1932; Mathis and Baker 2002). The goal of imposing such a tax is to reduce implementation costs of command-and-control policies and to reduce pollution in the least-cost manner (McMorran and Nellor 1994). Such taxes have been used to reduce municipal solid waste, reduce congestion on highways, and encourage recycling. Tax revenue can be used to compensate affected parties and to conduct research to identify ways to improve the environment.

Be et al. (1999) examined application of a Pigouvian tax on shrimp farms in Vietnam that cause damage to rice farmers through increased salinization. The tax was applied in the form of a penalty for damages and tax revenue was distributed to rice growers who were affected negatively by increasing salinization. The level of shrimp yield and its variability affected the choice of a socially optimum policy (with environmental costs considered). Integrated rice-shrimp technologies were socially and privately (without considering environmental costs) preferable when shrimp yields were high. However, if yields were only average, monoculture of rice was optimal from societal and private viewpoints in considering environmental and economic effects.

### Environmental Liability

Environmental liability refers to the use of lawsuits to make acting parties responsible financially for pollution damage (Segerson 1988). To pursue such an action, data on abatement costs to the individual, costs of the damages, and knowledge of how an individual's abatement efforts affect environmental levels must be available. Environmental liability is an indirect, price-based option that provides a negative feedback incentive to improve environmental performance.

### Performance Bonds

Performance bonds are funds deposited for a certain period of time that are linked to some level of environmental performance (Hishamunda and Ridler 2003). At the end of the time period, the company receives a refund depending on its environmental performance (Mathis and Baker 2002). This deposit-refund system provides an incentive to prevent environmental damage and encourages recycling of pesticide containers (Malik et al. 1994). Deposit-refund systems have been suggested for water quality issues, particularly if tied to farmer adoption of an approved BMP.

Environmental assurance bonds differ from deposit-refund systems in that lump-sum payments are made in anticipation of environmental damage (Malik et al. 1994). Bonds have been used in industrial hog farming (NCEMC 1998; State of Colorado 1998), to reduce space debris (Macauley 1992), and with surface coal mining in Pennsylvania and West Virginia (Shogren et al. 1993). These bonds work best with a small number of sources or where there is a history of cooperative action. However, environmental bonds can tie up a large portion of a firm's assets (Shogren et al. 1993). Such financial constraints can force firms out of business or restrict new firms from entering. Moreover, a regulator may have incentive to confiscate the bond regardless of the firm's performance or to write terms to more easily capture the bond (Shapiro and Stiglitz 1984).

### Other Financial Incentives

Financial incentives, such as tax exemptions or subsidies, can be effective in enhancing environmental management and can reduce expenses of monitoring and enforcement (Bailly and Willman 2001; Hishamunda and Ridler 2003). For example, Ecuador offers tax exemptions if pond wastewater is treated.

Subsidies may provide incentives to adopt environmentally friendly measures, but have the disadvantage of incurring a cost to governments (Hishamunda and Ridler 2003). Subsidies are justified with the rationale that new regulatory policies may cause financial hardship to farmers, especially those on a small-scale who lack necessary collateral or cash flow to adjust (Ervin and Ervin 1982; Holik and Lessley 1982; Just and Zilberman 1983; Lee and Stewart 1983; Rahm and Huffman 1984; Feder et al. 1985; Norris and Batie 1987; Gould et al. 1989; Lichtenberg et al. 1991). However, economists tend to view subsidies as poor policy instruments for pollution control (Baumol and Oates 1988). Subsidies increase the rate of return in the polluting industry and can lead to industry expansion. If subsidies attract new investment, total pollution may increase even though individual firms are polluting less.

United States' agricultural policy has provided partial subsidies that share the cost of conservation practices with farmers. The rationale for these cost-share programs is that, to the farmer, pollution is an external dis-economy. As such, someone other than the polluter is the primary beneficiary of pollution reduction, and, thus, society should pay for part of the pollution abatement. Cost-sharing subsidies have been used to encourage conservation practices such as terraces, conservation tillage, soil nitrogen testing, and split application of pesticides. The Environmental Quality Incentives Program (EQIP) is a federally subsidized cost-share program in the United States. The program was created in the Federal Agriculture Improvement and Reform Act of 1996 to provide financial incentives to farmers to adopt nutrient, manure, integrated pest, irrigation, and wildlife habitat management programs.

Subsidies in the form of grants or loans have been suggested in Thailand to encourage shrimp farmers to invest in sedimentation and treatment ponds to improve water quality (Thongrak et al. 1997). Construction costs of a water supply system would be shared between the government and participating farmers. Participation would be voluntary and the incentive to participate would be access to high-quality water for participating farmers. The environmental benefit would be the condition that water is discharged through a treatment pond. Sri Lanka offers loans at subsidized interest rates for installing water treatment systems (Hishamunda and Ridler 2003).

### *Input Taxes*

Taxes on inputs are an indirect method to regulate effluents in some countries because of the practical difficulties of effectively monitoring effluent discharge. Fertilizer taxes, for example, are popular in Europe (Shortle and Dunn 1986). A tax on feed would provide an incentive for farmers to reduce feed conversion ratio and effluent output. Farms with high feed conversion ratios would have a greater incentive to implement changes. However, the feed conversion ratio can be lowered only to the biological limit of the species raised. The potential environmental improvement from a feed tax may be small because farms already have strong incentives to produce at a low feed conversion ratio. Taxes on shrimp postlarvae have been suggested to induce farmers to stock at lower rates (Thongrak et al. (1997). However, these are less desirable than a feed tax because they do not distinguish among producers who use cleaner technologies. Taxes to discourage overuse of drugs and chemicals can be effective if demand for the aquaculture product is price-elastic (an increase in price results in a proportionately greater decrease in quantity purchased).

Input taxes have rarely been used in the United States. For an input tax program to be effective, the regulatory agency must be able to quantify the additional costs to be incurred, the additional benefit to be gained, and the emission levels to determine the appropriate amount of the tax.

Fernandez-Cornejo (1993) and Larson and Vroomen (1991) concluded that very high tax rates would be required on chemical input use to achieve significant reductions. Moreover, input taxes can have perverse effects. For example, Love and Buccola (1991) demonstrated that pesticide use could increase following a pesticide tax. If the tax on pesticides increased costs that resulted in decreased wealth, producers could become more averse to risk and use more pesticides.

### *Mandatory Production Methods*

The United States Environmental Protection Agency (USEPA) has relied on mandatory production methods in its Effluent Limitation Guidelines program through the Best Available Technology designation for reducing emissions. A regulatory option of mandating animal waste storage facilities, for example, provides no economic incentives to continue to seek additional improvements. Moreover, mandatory production methods result in difficulties that arise from site-specific variations and compliance cost differences across farms.

### *Zoning*

Zoning and permits are commonly used to resolve conflicts over public land and waterways used for aquaculture (Millar and Aiken 1995). With zoning, salmon cages have been assigned to more distant locations off northwest Spain where shallow seas preclude extensive flushing. In Chile, marine zoning has designated separate areas for salmon farming and capture fisheries. Protected areas exist in Zambia from concerns over water conservation, and, in Ecuador, for defense. In Malawi, distinctions are made between public and private water. Land zoning could prohibit shrimp farming in areas of high ecological importance and install appropriate dike systems to avoid overflow of saline water (Be et al. 1999). For example, in Australia, prawn ponds cannot be constructed in coastal mangrove areas (Brennan 2002). Zoning of areas suitable for aquaculture development will help improve information to investors about where and under what conditions approval would be granted for aquaculture investments and would reduce transaction costs (Brennan 2002).

### *Voluntary Agreements*

Voluntary agreements can be attractive alternatives to mandatory pollution controls (Segerson and Miceli 1998). There is a history of voluntary approaches used in agriculture, particularly in soil conservation and erosion control. Results imply that achieving an optimal abatement is possible, but the outcome depends upon the magnitude of the background threat, the social cost of funds, and the allocation of bargaining power. Voluntary agreements are those that induce participation with either positive incentives or by threatening a harsher outcome, such as direct controls, if an agreement is not reached.

Fish farmers have an incentive to produce responsibly and are more likely to internalize environmental externalities because environmental damage directly affects their own output (Hishamunda and Ridler 2003). In Yokohama, enforcement of Best Management Practices is community-based (Bell 1999; Adams et al. 2000). Because salmon farmers are affected more directly by their own production activities than producers in other industries, Asche et al. (1999) argued that negative externalities are internalized to a greater extent than in agriculture and manufacturing sectors. Improved feed quality for salmon has reduced nitrogen and phosphorus emissions, and the industry has reduced use of antibiotics and reduced accumulation of organic sediments below farms. The use of antibiotics in Norwegian salmon farming was a negative environmental externality but was also a threat to the image of and markets for Norwegian farmed salmon (Bjorndal et al. 2003). Farmers have voluntarily reduced antibiotic use and overall rates have fallen dramatically since 1987 to almost negligible levels.

Self-policing through peer pressure can be effective particularly for those farmers with a long time horizon (Hishamunda and Ridler 2003). An example of self-policing is the decline in environmental damage to coastal waters from salmon feed waste. Feed accounts for approximately 50% of total costs in Norwegian salmon. Increased feed costs and declining yields caused by pollution from excess waste resulted in lower feeding rates that reduced environmental effects (Asche et al. 1999).

### *Nonpoint Source Pollution*

Criteria for managing nonpoint source (NPS) pollution are defined less clearly than for point sources because of the difficulty in determining the source of the pollutant and in monitoring at the farm level (Malik et al. 1994). Effluent taxes are not well suited for NPS pollution because of the difficulty of identifying the origin of pollutants. Pollution trading or deposit/refund systems may not be broadly applicable for complex pollution situations. There may be no single, ideal policy instrument for nonpoint sources of pollution (Malik et al. 1994). Voluntary BMPs are considered effective with nonpoint source pollution (Stanley 2000).

### *Best Management Practices*

Best management practices (or, as used in this book, better management practices) are self-regulating management codes that may be developed by a government agency or a producers' organization (FAO 1999). They were developed as a way to balance policies related to environmental concerns and those affecting agriculture (Leathers 1991). The focus of BMP development, thus, should be to identify technologies and practices that enhance profit and reduce pollution. Examples that reduce costs and prevent waste can be found in the industrial ecology and green manufacturing literature (Hawken 1993). Industry involvement in development of BMPs will increase adoption rates.

In the United States, BMPs were introduced in the 1970s in response to growing concerns over agriculture as the main nonpoint source of pollution (Leathers 1991). Lichtenberg et al. (1991) defined BMPs as cultural practices that reduce soil and nutrient losses at a reasonable cost. The USDA and land-grant university agricultural experiment stations have developed, tested, and adapted BMPs to local conditions. Extension services have demonstrated the uses of BMPs and helped farmers incorporate BMPs into their production systems.

In 1985, the "conservation compliance" provision of the 1985 Farm Bill required farming practices to conform to conservation plans (BMPs) approved by the Soil Conservation Service or lose eligibility for farm program payments. The USDA Agricultural Cost Sharing program reimbursed farmers for 50 to 75% of the cost of installing BMPs as mandated in the 1985 Farm Bill.

Better management practices related to selecting nitrogen application rates based on crop growth requirements and soil nitrogen levels has allowed nitrogen application rates in some states to be reduced by as much as 30% with no loss in crop yields (Mitchell and Hennessy 2003). These BMPs generate savings through reduced input use that more than covers BMP costs. Better management practices have been used to improve water quality in the Chesapeake Bay region. The Chesapeake Bay Program and USDA cost share the BMPs for farms and provide technical assistance.

However, not all growers readily adopt these BMPs. The adoption and use of BMPs and their specific components will depend upon their feasibility, which depends in turn upon the details and consequences of their implementation. Careful study and analysis is required because the consequences (intended and unintended) of adoption may be far-reaching in terms of management of the farm and of the types of effects these have on the environment. For BMPs to work well, be adopted, and achieve the desired goals, thorough economic analysis is needed of each BMP component and its interactions (Stanley 2000; Brennan 2002). Unfortunately, few detailed empirical studies have been done on aquaculture-environmental conflicts. The majority of this literature is theoretical or conceptual.

Better management practice adoption will entail additional costs for farmers. Lichtenberg et al. (1991) separated BMP costs into structural and management costs. Structural BMPs require significant capital outlays for investment in structures such as rock-lined waterways, grade stabilization, sediment basins, ponds, or waste storage structures. Management BMPs resulted in changes in variable input use. For example, Integrated Pest Management BMPs reduced pesticide application rates but required more intensive management and increased overall management costs.

Several studies allege that voluntary BMP programs have not been effective (Cook et al. 1991; Browner 1993). Better management practices have failed primarily from too much or too little of an input applied, resulting in profit loss (Mitchell and Hennessy 2003). Better management practices that result in a greater impact on optimal input use are those that are more readily adopted.

Demographic factors also affect adoption rates. Full-time farmers were more likely to use structural practices. Older farmers were less likely to adopt managerial BMPs whereas farmers with more experience and education were more likely to use them. Farm size also affects the type and number of BMP practices adopted. Larger farmers were more likely to adopt BMPs even without cost sharing (Lichtenberg et al. 1991). Farmer perceptions of the risks associated with BMPs can also affect adoption and can be more important than a study indicating that the practice is profitable (Ramaratnam et al. 1987; Babcock and Blackmon 1992).

Moreover, farmers may adopt a BMP more readily if insurance is available (Mitchell 2004). Best Management Practice insurance reduces actual risks of adoption and encourages adoption among farmers who believe the BMP will decrease their welfare. The induced adoption provides an opportunity to gain experience with the BMP and observe the benefits first hand.

Green insurance is a single peril insurance that covers losses from BMP failure (Mitchell and Hennessy 2003). Best Management Practice failures tend to result in small yield losses that do not trigger crop insurance indemnities, but green insurance uses triggers other than yields. For example, rainfall insurance is sold for producers using split nitrogen applications and postemergent weed control; excessive rain delays these activities.

Although created in the United States as a voluntary measure, BMPs can be mandated directly and enforced through civil or criminal sanctions. As with other types of direct controls, mandated BMPs may not be cost effective in all situations (Malik et al. 1994). Offering a wide range of acceptable BMPs improves the chances of cost effectiveness.

## Economics of BMP Use in Environmental Management

### *Cost-Benefit Analysis of BMPs in Field-Crop Farming*

The Neuse River Basin in North Carolina became a nitrogen-regulated drainage area in 1998 after 2 years of rule making. The intent was to improve water quality by reducing nitrogen loading in the Neuse River by 30%. These rules addressed all sources of nitrogen, particularly agricultural sources. A set of agricultural BMPs was decided upon by the Neuse River Basin Oversight Committee. Wossink and Osmond (2002) performed an ex post evaluation of this BMP program; no economic analysis was conducted before the BMPs were mandated or the specific cost-share program (NC-CREP) was installed. Their approach combined partial budgeting with Net Present Value (NPV) assessment and break-even analysis.

Partial budgeting requires a BMP to be treated as a stand-alone activity or enterprise to calculate the annual net cash flow coming from the BMP. The costs could be in the form of reduced revenue (lower yields or prices) or higher costs. Benefits expected from a proposed change could be higher revenue (cost share payments) or lower costs (Fig. 13.2).

The results of a partial budget analysis for BMPs were used as the basis for NPV calculation. The NPV approach enables comparison of BMP opportunities with other current crop options or other land uses. Three ingredients are needed to calculate this value: cash inflows, $R_t$, and outflows, $C_t$, for each year $t + 1, \ldots, T$ of the duration of the project, and the discount rate $i$:

$$\text{NPV} = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+i)^t} \tag{13.1}$$

In addition, the NPV values can be converted to annuities (annual profit), to enable cost-shared BMPs of different durations to be compared.

Additional NPV calculations were used in a break-even analysis. Traditionally, break-even analysis is conducted to find price or yield levels (i.e., minimum returns) required to cover the cost of crop production. For cost-shared BMPs, the sensitivity assessment focused on the cost components. By far the most important cost component of the cost-

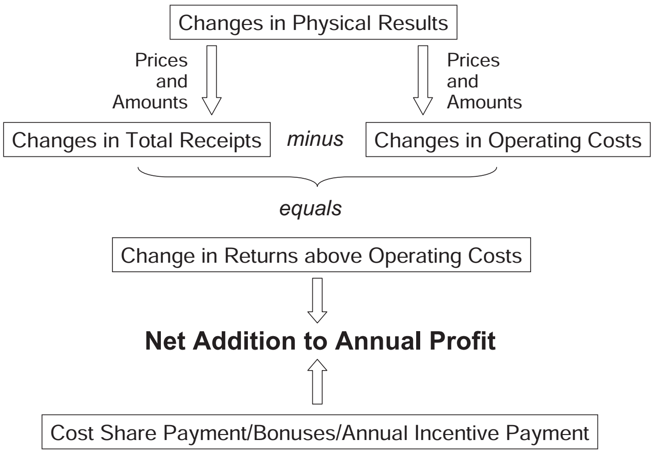

**Fig. 13.2.** Partial budget (schematic) of the annual economic effect of a cost-shared BMP.

**Table 13.2.** Best management practices by physiographic region, Neuse River, North Carolina.

| Best Management Practice | Physiographic Region: Piedmont | Physiographic Region: Upper and Middle Coastal Plain | Physiographic Region: Lower Coastal Plain | Expected Nitrogen Reduction |
|---|---|---|---|---|
| Buffer: trees 9 m + grass 6 m | — | — | | 85% |
| Tree buffers ≥6 m | — | — | | 75% |
| Shrub buffers ≥6 m | | — | | 75% |
| Grass buffers ≥9 m | — | — | | 65% |
| Filter buffers ≥6 m | — | — | | 40% |
| Nutrient management | — | — | — | Variable |
| Cover crop | — | — | — | 5 to 15% |
| Controlled drainage | | — | — | 40% |

*Source:* Based on decisions by the Neuse River Oversight Committee.

shared BMPs in Table 13.2 is the lost production of the land used for buffer strips. Setting NPV values at zero during estimation and keeping fixed all other cash flow elements except land opportunity costs provides the land opportunity cost level at which a BMP arrangement would break even. The break-even opportunity costs indicate the competitiveness of the various cost-shared BMPs. This economic ranking was compared to the ranking of the BMP by their expected ecological impacts. These two relative rankings have to be identical for cost-share programs to be effective. Controlled drainage does not involve the removal of land from production, and the break-even analysis was not conducted for this type of cost-shared BMP.

The Neuse River Basin Oversight Committee selected eight BMPs for implementation (Table 13.2). The costs of these BMPs include installation and maintenance costs. The first category of costs occurs in the first year when the BMP is installed. The other costs—such as land, labor, and equipment—occur yearly. Land opportunity costs are the gross margins (value of output minus variable costs) of the crops and rotation common in the physiographic region considered.

The NPV calculations for BMPs indicate that the economics of the cost-shared BMP differed considerably for the three physiographic regions distinguished in the Neuse River Basin (Table 13.2). In addition, the break-even analysis indicated that the economic ranking was not in line with the nitrogen reduction expected from the BMPs (last column of Table 13.2). Thus, the cost-share payments did not reflect the relative reduction in nitrogen emissions offered by the BMPs.

Adoption of nutrient BMPs has a significant positive effect on net farm income (Valentin et al. 2004) for wheat and corn, whereas herbicide BMP adoption, particularly use of BMPs related to application of atrazine on corn, resulted in a small but significant negative impact on income. Adoption of soil conservation BMPs does not have a statistically significant impact on farm income.

Many BMPs incorporating or splitting application of nutrients and pesticides require additional machinery operations and may result in increased production costs. Several herbicide BMPs require substitute herbicides with limited efficacy information. Most studies evaluating producer adoption of water quality management practices implicitly assume that the practices are profit-neutral. This condition prevails because the farming practices are developed with this goal in mind and presented to producers as not adversely affecting income.

### *Costs and Benefits of BMPs for Urban Stormwater Control*

Construction of pavement, buildings, and land clearing increase the volume and speed of stormwater. This contributes to flooding and increases damage to property and habitat (stormwater quantity impacts). It also increases the flow of pollutants such as oil, fertilizers, and pesticides and the flow of natural elements such as nitrogen, phosphorus, and sediment into the water (stormwater quality impacts). Urban stormwater runoff can be controlled by various better management practices. Wossink and Hunt (2003) presented an economic approach to identify the BMP to choose given a particular size and type of watershed as described by curve number range, soil type, and pollutant type. Table 13.3 summarizes BMP alternatives for structural stormwater in North Carolina, keying on the size of the drainage area. Wet ponds are runoff-holding facilities with continuous water volume that can be designed to look like natural lakes to enhance the value of surrounding property. Stormwater wetlands, or constructed wetlands, are comparable to wet ponds but are much shallower and more heavily vegetated with wetland plants. Wetlands consume a large amount of space and thus have limited applicability in highly urbanized settings. Sand filters are particularly well-suited to treating stormwater runoff in ultra-urban areas because they can be designed for pedestrian or vehicular traffic, thus preserving expensive land. Bioretention areas/rain-gardens are landscaped and vegetated filters and are ideally suited to many ultra-urban areas such as parking lot islands and other landscaped areas.

The costs of structural stormwater BMPs include installation (construction and land) and annual operating costs (inspection and maintenance). Stormwater BMPs commonly reduce the availability or the size of a (re-)development site, a frequent concern of real-estate interests. An important indicator for land requirements is runoff, which is determined by precipitation and curve number (CN). Curve number reflects the ability of a

**Table 13.3.** Structural stormwater BMPs by relative size of commercial/residential drainage areas.

| | Relative Size of Commercial/ Residential Drainage Area | |
|---|---|---|
| Best Management Practice | Large Area | Small Areas |
| Wet pond | — | — |
| Stormwater wetland | — | |
| Sand filter[a] | | — |
| Bioretention/raingarden[b] | | — |

[a] Only effective with a significant drop in elevation (for perimeter sandfilter at least 0.6 m).

[b] In clay soils a significant drop in elevation (1.3 m) is typically required.

watershed to store water through initial storage and subsequent infiltration. A high CN suggests a very impervious area with limited storage capacity. Wossink and Hunt (2003) distinguish among different surface areas of BMPs in North Carolina by Piedmont, Coastal Plain, highly impervious areas (CN 80), and areas that are 100% impervious. Three price scenarios were considered: \$5 per square foot for undeveloped land for commercial use; undeveloped land for residential use at \$50,000 per acre, and land with zero cost (from the requirement for open space).

Data on construction costs, maintenance costs, and inspection of the practices were collected by means of a telephone survey and site contacts with designers and property owners. Construction and maintenance costs were established from Raleigh-Durham, North Carolina by means of the R.S. Means (2001) Building Construction Cost Data handbook. The Means book provides a comparison of installation, material, and total costs estimation for cities across the United States to facilitate cost estimation of construction projects. A large body of national research data was available on the removal effectiveness of the four BMPs. The out-of-state cities' weather was compared to the weather of Charlotte, Raleigh-Durham, and Wilmington in North Carolina. Based on this comparison, pollutant removal information from the Austin, Texas, region; the Baltimore-Washington area; and the northern two-thirds of Florida was added to what had been collected in North Carolina and Virginia.

To capture potential scale effects, cost curves were developed for the four types of BMPs (Wiegand et al. 1986). The cost curves were specified as $C + \mathrm{a}x^{b}e^{u}$, where $C$ denotes costs (construction or maintenance costs) of the BMP; $x$ is the size of the watershed in acre, and $e^{u}$ is the error term. For estimation purposes the cost curves were reformulated as $\ln y = \mathrm{a} + \mathrm{b} \ln x + u$; parameters can then be estimated by conventional linear regression. The associated correlation coefficients were examined to determine the validity of size effects on construction and maintenance costs. All BMPs, except bioretention not in sandy soil, displayed large economies of scale within the practice for construction and maintenance costs. It was assumed that the BMPs analyzed were all optimally sized and designed from an engineering point of view.

To capture the differences in cost components over the lifetime of the BMPs the stream of costs was discounted to provide a Present Value of Costs (PVC):

**Table 13.4.** Cost comparison of four BMPs for a 10-acre watershed in a highly impervious area (CN 80).

| | Cost (dollars) | | | |
|---|---|---|---|---|
| Best Management Practice | Wet Ponds | Wetland | Bioretention in Clay Soils | Bioretention in Sandy Soils |
| Construction | 65,357 | 11,740 | 124,445 | 7,843 |
| Annual maintenance | 4,411 | 752 | 583 | 583 |
| Opportunity cost of land ($217,800/acre) | 43,560 | 65,340 | 65,340 | 65,340 |
| Present value of total costs | 146,474 | 83,486 | 194,751 | 78,137 |
| Annualized costs per acre of watershed | 1,721 | 981 | 2,288 | 918 |
| Annualized cost per % or TSS[a] removed | 26 | 15 | N/A[c] | N/A |
| Annualized cost per % or TN[b] removed | 61 | 45 | 51 | 20 |

[a] TSS = total suspended solids.
[b] TN = total nitrogen.
[c] N/A = not applicable.

$$\mathrm{PVC} = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} \tag{13.2}$$

where $C_t$ denoted the expenditures for each year $t + 1, \ldots, T$, and $i$ is the discount rate. Next, PVC values were converted to annualized costs per acre treated and annualized costs per percent of pollutant removed; this conversion is to facilitate the comparison of BMPs with different duration, treatment area, and removal effectiveness. For the PVC and annuity calculations, a spreadsheet model was developed in Excel.

Based on a series of systematic analyses by size of watershed, location, and cost of land, there are large differences in the annualized costs for each BMP per acre treated and the proportion of pollutant removed (Wossink and Hunt 2003). As an example of these calculations, the installations of a wet pond, a stormwater wetland, and a bioretention area for a 10-acre watershed with CN 80 are compared (Table 13.4). A sand filter is not an option: such a practice is applicable only to areas that are 100% impervious (Table 13.3). A bioretention area would be the least expensive BMP if this practice could be installed in sandy soil (Table 13.4). A stormwater wetland would be the least expensive solution if clay soil should prevail.

### *Swine Producers' Perceptions of Alternative Waste Management Systems*

Controversy surrounds the lagoon and spray-field system used on large-scale swine operations in the southeastern United States. Well-managed lagoons are a particularly economical method of treating animal waste, but the geographic concentration of hog production has led to water pollution through spills and leakage from large lagoons. Surface water can also be contaminated by runoff from spray-fields. In the late 1990s, the state government of North Carolina proposed the widespread conversion of swine waste lagoons and spray-fields to new technologies. Research efforts to identify environmentally superior technologies were initiated in 2000. Environmental performance verification and economic analysis of the selected technologies are in progress as of the spring of 2007.

In this verification process the focus is on the environmental advantages and costs of the new technologies.

Cates et al. (2005) analyzed North Carolina swine producers' perceptions of current and alternative hog waste management technologies. The study uses survey and statistical techniques based on behavioral economics. This type of analysis can be used to assess 1) farmers' knowledge of the technologies, 2) the technology characteristics perceived by farmers as important in the adoption of the sustainable practices, and 3) the extent to which cost and environmental performance as perceived by the farmers differs from the findings of the normative verification process.

In-depth interviews were conducted with swine producers to collect qualitative information on perceived benefits and limitations of the current system. Based on the interview findings, a questionnaire was developed and administered to a sample of North Carolina swine producers using a mail survey. The swine producers interviewed represented different sizes and types of operations (e.g., farrow to wean, feeder to finish). The in-depth interviews revealed that participants had difficulty expressing their preferences for the 16 individual waste management technologies. Therefore, the mail survey was limited to collecting information on producers' preferences for four categories of alternative waste management systems (Box 13.1).

Despite some limitations, swine producers were content with the current system and reluctant to install a new waste management system because of the financial burden it would impose and other concerns such as additional labor requirements. Producers had some interest in a system that would produce a marketable by-product, but they wanted more information and assurance that a market exists for the product. The most important other factors were level of management/oversight required by the owner/operator, amount of labor required for operation and maintenance of the system, and compatibility with the producers' farm and existing waste management system. Additionally, producers preferred a system that has a proven track record, is "low-tech," and is easy to operate and maintain. Interestingly, although respondents expressed interest in a waste management system that would reduce the volume of solid waste to be applied, and the sprayfield size needed, they were not particularly interested in installing waste management systems with the components (e.g., mechanical solids separator) that would accomplish these functions. Cates et al. (2005) also found that producers were not very knowledgeable about the different technologies and suggest educational efforts should address producers' concerns about the technologies. Their concerns may be based on misperceptions that need to be corrected.

## Economics of BMPs for Aquaculture Effluents

Costs associated with the implementation of BMPs in aquaculture include structural and management costs. Structural costs for aquaculture BMPs would include the capital investment costs and annual fixed costs associated with any new construction. Structures proposed for aquaculture BMPs that might require new construction include settling basins and constructed wetlands for pond aquaculture and offline settling basins for flow-through systems. Management costs include changes in operating costs that result from changes in management as farmers adopt the BMPs. These might include reduced yields (either from reduced inputs or from reduced production area if production ponds were removed

## BOX 13.1
## Waste Treatment Alternatives: Examples from Swine Production

Four alternative swine waste management technologies are evaluated by Cates et al. (2005). In most cases, the original lagoon is used with the new waste management system; however, the lagoon is modified to serve as a holding pond for treated waste or converted into a digester. The four technologies perform one or more of the following functions:

**Digestion and Energy Production:** Digestion is a microbial process that converts the organic carbon in swine waste into biogas, which consists of methane and carbon dioxide. The methane can be used to generate electricity for on-site use or sale or for other green energy applications. The digestion process is carried out in a closed container or covered lagoon (digester), which significantly reduces odor.

**Solids Separation (Phosphorus Removal):** Most of the phosphorus in swine waste is contained in the solid fraction of barn discharge. Solids separation involves installing a mechanical solids separator or a belt system (installed underneath slatted floors in hog houses) that removes the solid portion of the waste, and with it most of the phosphorus. After the separation process the solid waste is lighter and smaller in volume and can be hauled to off-farm crops at less expense or to a central processing facility for treatment (see "Treatment of Separated Solids" below).

**Liquid Treatment (Nitrogen Removal):** Most of the nitrogen in swine waste is contained in the liquid portion of barn discharge. Liquid treatment technologies remove a portion of the nitrogen through a process of combined nitrification-denitrification. The process involves a series of biological treatments that eventually release nitrogen as harmless elemental nitrogen gas. Generally, the liquid is treated in above-ground tanks or in-ground cells. Liquid treatment lowers ammonia emissions (and odor) and reduces the sprayfield size needed for applying lagoon effluent when waste is applied on a nitrogen basis.

**Treatment of Separated Solids:** Solids treatment technologies can be either on-farm systems or central processing facilities. These technologies use a variety of processes to convert separated solids into a product that is easier to transport and apply to land or into a sellable by-product. By-products include ethanol, compost, ash for fertilizer, and an animal feedstuff.

from production to construct settling basins) (Brennan 2002) or increased labor costs required for implementation, monitoring, and reporting. Complete economic analysis would also account for economic benefits that might be derived from adopting the BMP. Benefits might include increased feed efficiency or decreased costs associated with reduced pumping (if water exchange rates were reduced).

### *Economics of Better Management Practices for Freshwater Pond Aquaculture*

Many of the better management practices for freshwater pond aquaculture (as presented in Chapter 6) have been adopted by fish farmers in the United States. Many of these practices result in greater profits through improved efficiencies of input use or greater yields. Site selection practices as described in Chapter 6 will result in reduced pond construction costs (by siting in areas with suitable topography, allowing for less earth moving), reduced water supply costs (by selecting sites with suitable hydrology), reduced pumping costs (through proper compaction that minimizes water losses from seepage), and lower renovation costs (less erosion of levee fill material that results in longer-lasting levees). Use of the better management practices for overflow effluents increases profits by reducing costs: reducing or eliminating pumping costs to exchange water, reducing pumping costs by capturing rainfall, and reusing water for multiple crops. Proper feed management practices reduce nutrient discharge and reduce the largest cost in pond aquaculture through improved feed conversion ratios. Fertilizing appropriately and efficiently similarly reduces nutrient discharge and simultaneously reduces costs of inputs.

Because many of these practices are prevalent on fish farms, little formal economic analysis has been done on these individual management components. Much of the research literature on BMPs in aquaculture consists of analyses of proposed new practices, many of which entail new investment in farm infrastructure for treating pond discharges.

### *Shrimp*

The growth of shrimp farming worldwide has been accompanied by increasing criticism over the potential for shrimp farming to generate negative environmental impacts. Policy discussions related to the discharge of effluents from shrimp farms have prompted a wide variety of suggestions that range from proposed regulations to economic incentives to reduce discharges. A variety of Better Management Practices, Good Management Practices, and Codes of Conduct have been developed by a number of different groups. These range from industry groups such as the Global Aquaculture Alliance (GAA) to nongovernmental organizations (NGOs) like the Industrial Shrimp Action Network and Environmental Defense. International entities such as the Food and Agriculture Organization (FAO) and the Association of Southeast Asian Nations (ASEAN 1997) have formulated codes of practice for shrimp farming (FAO 1997; Boyd 1999; Donovan 1998). Boyd et al. (2001) described Good Management Practices with potential to improve production efficiency and reduce negative impacts on the environment.

Various BMPs, GMPs, and Codes of Practice have included a variety of alternative recommendations. Most include some sort of treatment of either influent or effluent through settling basins or forms of constructed wetlands; effluent volume reduction by reducing water exchange; or reducing nutrient concentrations by improving feed conversion efficiency, reducing stocking rates, or both. There are varying degrees of compliance currently with these types of recommendations. For example, Boyd et al. (2001) reported overall adoption of BMPs of 70% in Honduras. However, the adoption of voluntary instruments such as these may require a high level of farming knowledge, technical skill, and investment (Funge-Smith and Briggs 1998; Stanley 2000). Small-scale farmers may have less access to new technology and information than large-scale producers (Engle and

Valderrama 2006) and are less likely to adopt new technologies than large-scale farmers (Ervin and Ervin 1982; Just and Zilberman 1983; Lee and Stewart 1983; Rahm and Huffman 1984; Norris and Batie 1987).

The Thai government has used a combination of mechanisms to encourage shrimp farmers to adopt recommended practices (Pongthanapanich 2006). These include command-and-control instruments like effluent standards, and voluntary measures. In Thailand, common shrimp farming practices that maximize profits tend to also be those with high discharge rates of effluent (Thongrak et al. 1997; Clay 2004). Reductions in effluent discharge are associated with lower net returns. These trade-offs are difficult because production systems that reduce water pollution at the expense of lower net returns are not likely to be adopted by farmers without economic incentives.

Few farms in Thailand currently use settling ponds or sedimentation ponds to treat effluents because a production pond would need to be converted into a settling pond. This overall reduction in production area would clearly not be feasible for small farms with only one or two ponds (Thongrak et al. 1997). Yoo and Boyd (1993) indicated that use of sedimentation ponds to produce other aquaculture species may not be practical or economically efficient.

Managing farms to meet dual goals of economic and environmental sustainability can be complex because the relevant factors interact in a variety of ways. Better management practices are thought to be the most effective and practical method of reducing environmental impact levels to those compatible with resource management goals (Hairston et al. 1995). In some cases, a single practice may solve the problem, but usually a collection of practices is needed (Boyd and Schmittou 1999). Systems of BMPs need to be customized for species, production goals, national interests, and site characteristics.

Engle and Valderrama (2004) evaluated effects of five selected BMPs on farm profitability, selection of optimal management strategies, and the corresponding quantities of net nutrient discharge from semi-intensive shrimp farms in Honduras. An economic optimization model was extended (Valderrama 2000; Valderrama and Engle 2002, 2004) to evaluate five BMP practices. These included 1) reduction of water exchange rates from 10 to 5%, 2) establishment of predetermined nutrient discharge limits, 3) use of feed trays to avoid excess feed applications, 4) construction of settling basins for treatment of the last 10% of drainage effluents, and 5) use of mangrove biofilters for effluent treatment.

Adoption of some BMPs caused changes in the fundamental management of the farm while others did not. For example, the construction and use of settling basins and mangrove biofilters caused a switch from production in blocks (more profitable) to continuous production caused by changes in the harvesting schedule and volumes of water to be treated at one time. Use of settling basins caused an extension of the culture period and a reduction in the stocking rate.

Reducing the water exchange rate, however, resulted in few changes in management strategy. Moreover, model results indicated that farms can meet initial discharge requirements to meet GAA requirements even with an effluent volume of 2% if water exchange is reduced to 5%. When the discharge limits were restricted based on the GAA target standards and 2% of the total farm volume, the management switched to a lower stocking rate and a longer production cycle during the wet season.

The model identified two practices that increased net returns and reduced net nutrient discharges: reduced water exchange and use of feed trays. These meet the criteria of high potential for successful adoption by farmers. However, additional research may be needed to identify the optimum amount of water exchange. Martinez-Cordova et al. (1995) measured a substantial decrease in yield of Pacific white shrimp (*Litopenaeus vannamei*) from shrimp farms in Sonora, Mexico, when water exchange rates were reduced from 10–15% to 5–7.5%. The most rapid, effective, and feasible approach to reduce effluent discharges from shrimp farms in Honduras is through a strong extension effort that demonstrates the economic incentives of feed tray usage and reduction in water exchange rates to those farmers who have not yet adopted these practices.

Shrimp farmers face an environmental externality that results from discharges of municipal, household, and industrial wastes upstream from shrimp farms. Influent concentrations add additional complexity to management practices, particularly if numeric discharge standards are required. In shrimp ponds in Honduras operated with a 10% water exchange rate, only 21 to 38% of the discharged total nitrogen, total phosphorus, and organic matter result from shrimp production; the balance arrived in the influent (Engle and Valderrama 2004). Imposing set standards with high nutrients in the influent caused small farms to lower stocking rates and shorten the growing cycle, decreasing net returns.

Other practices demonstrated clear trade-offs and conflicts between farm profitability and environmental effects (Engle and Valderrama 2004). Settling basins, for example, resulted in the lowest net discharges, but decreased net returns. Settling basins result in high annual fixed costs that directly affect cash flow and interest expenses.

The use of mangrove biofilters is an appealing, innovative approach, but very costly to implement and is, as yet, unproven in terms of potential improvement in water quality. The construction of mangrove biofilters was six to ten times more expensive than construction of settling basins (Engle and Valderrama 2004). The annual costs associated with the construction of mangrove biofilters caused small-farm scenarios to become unprofitable and decreased net returns (profits) by 26% on medium farms and by 20% on large farms.

Artisanal shrimp farms in Honduras and Nicaragua grow shrimp extensively with lower stocking and feeding rates (Engle and Valderrama 2006). Their methods of production were rudimentary and extensive, utilizing tidal inflows to stock ponds, exchange water, and supply nutrients. Small-scale shrimp growers sell to local, open-air markets. Engle and Valderrama (2006) considered the same set of BMP practices as those analyzed in Engle and Valderrama (2004) for artisanal shrimp growers, using enterprise budget analyses. The fundamental relationships among the BMP practices were the same as those identified for semi-intensive farms. Net returns increased with the use of the BMP components of reducing water exchange rates, applying the entire feed ration on feed trays, and combining water exchange rates and the use of feed trays. Of the individual components considered, feed tray use resulted in the greatest increase in net returns (56%) on Honduran farms and on the Nicaraguan cooperative (105%) because feed tray use reduced the feed conversion ratio. The proportionate effect was greater than that for larger farms (Engle and Valderrama 2004) due to the lower production base.

Thus, the use of feed trays presents an economic incentive for adoption of BMPs that is particularly important given the overall low profit margins on small-scale shrimp farms in Central America. Net returns were reduced with the installation of settling basins or mangrove biofilters, caused primarily by increased fixed costs. Net returns became negative on both farm scenarios.

In contrast to these analyses, Martinez and Seijo (2001) found the traditional water exchange system to be slightly more profitable than a low water exchange system on semi-intensive farms in Mexico. Additional investment capital was required to purchase aerators, but overall electricity cost was lower to aerate than to pump water.

Decisions related to development of BMPs can be complex and can have unintended consequences if the wide variety of relevant factors is not accounted for in the decision-making process. For example, some authors have argued for intensification of shrimp farming to reduce environmental impacts. However, Martinez-Cordero and Leung (2004) demonstrated that semi-intensive farms in Mexico promote sustainability. A multicriteria decision-making model was developed that incorporated planning objectives to enhance employment and foreign exchange earnings, maximize profits of farmers, and minimize total pollution subject to land availability and local market demand. Model results indicated that intensification of shrimp farming reduced employment and increased pollution but semi-intensive systems produced more employment and wealth and lower levels of pollution. This underscores the need for sophisticated and comprehensive economic analysis when developing BMPs, other recommendations, or regulations.

### *BMPs for Trout Production in Idaho and North Carolina*

Most trout produced in the United States are raised in flow-through raceway systems (Chapter 9). The 2004 rule on aquaculture effluents by the USEPA (Federal Register 2004) included flow-through and recirculating aquaculture systems in the scope of the rule and excluded static pond aquaculture. Development of facility-specific BMP plans were required for trout production in the 2004 rule.

Engle et al. (2005) developed an economic analysis of the impacts of several proposed effluent treatment options for the production of trout in flow-through systems in the United States. Several BMPs were evaluated explicitly in the analysis, including a BMP plan for the facility, for drugs and chemicals, for escape prevention, and for solids control. The drug and chemical BMP plan documents the use of drugs and chemicals on the farm and site-specific activities to control inadvertent spillage or release of drugs and chemicals. A solids control BMP requires that the farm develop and incorporate site-specific activities to limit the release of solids from the farm. These activities typically include a description of the feeding methods, pollution control technologies and equipment, operation and maintenance of equipment, a cleaning schedule, personnel training, and record keeping.

The Engle et al. (2005) analysis was based on surveys of trout farms in Idaho and North Carolina. Data were collected on fixed and variable costs associated with trout production, waste management, and effluent monitoring costs. Farm sizes analyzed included medium-sized farms in North Carolina (68,182 kg/year of production) and Idaho (90,909 kg/year production) and large-sized farms in Idaho (1,136,364 kg/year production).

Enterprise budgeting techniques were used to estimate costs associated with the various treatment options and the effects on net returns for each farm scenario. A Monte Carlo simulation model further evaluated effects of economic risk of proposed alternatives, and mixed-integer whole-farm programming models were developed to identify optimal management plans for trout production subjected to the various policy options proposed.

Resources required to implement the various BMP components considered in the analysis are presented in Table 13.5. Implementation of the BMP plans themselves required

**Table 13.5.** Resources required to implement the various BMP components considered for trout culture in flow-through systems in the rule making process that eventually resulted in the USEPA effluent limitation guidelines and new source performance standards for concentrated aquatic animal production facilities (Federal Register 2004).

| | Labor and Management (hours) | | Capital (dollars) | |
|---|---|---|---|---|
| BMP Component | First Year | Every Year | Ownership | Operating |
| Drug and chemical BMP plan | 64 | 2 | | |
| Solids control BMP plan | 96 | 24 | | |
| Escape prevention BMP plan | 66 | 66 | | |
| INAD[a] reporting | 119 | 119 | | |
| Compliance monitoring | | | | |
| with labor | 204 | 204 | | 4,008 |
| with composite sampler | 120 | 120 | 250 | 9,936 |

*Source:* Engle et al. (2005).
[a] INAD = Investigational New Animal Drug.

primarily time of management and labor. However, compliance monitoring may also require capital investment (depending on sampling methods required) and supplies for water quality analyses. If a BMP would require construction of additional treatment facilities, additional capital investment and land might be required along with increased operating costs.

The addition of a quiescent zone would require land and capital costs and vacuum components for removal of sediments. Offline settling ponds would require investment capital for the structure, land for field application of wastes, and operating costs. Proper operation requires either a front-end loader or a vacuum tank.

Implementation costs for BMPs were much higher in the first year, as the plan was developed, than in subsequent years, particularly for the drug and chemical and solids control plans. Tax or other financial incentives may encourage farms to invest the time needed in BMP development. Compliance monitoring entailed significant labor expense.

In the Engle et al. (2005) study, all effluent treatment options considered resulted in negative net returns for the medium-sized farms in North Carolina and Idaho. Although positive, net returns for the large-size farm scenario in Idaho reduced returns to average investment to only 4%, less than the opportunity costs of capital in the United States of 9 to 12% (Barry et al. 1995; Kay and Edwards 1999). The probability of achieving positive net returns decreased from 40% to 0% for the medium-sized farms in North Carolina and Idaho. For the large-sized farm in Idaho, the probabilities were 0% under the high-cost options and 10 to 11% under the lower-cost options.

Trout production was particularly sensitive to the level of credit reserves for operating and investment capital. Reductions in total available capital (equity plus borrowing capacity) resulted in reducing the number of tanks in production that, in turn, reduced net returns. The whole farm models were not feasible under any proposed effluent treatment options when full costs of quiescent zones and offline settling basins were used in the model.

Construction of offline settling basins required higher levels of capital investment than is likely to be available for trout farms in North Carolina. The model could not find a feasible solution when credit reserves were specified in the model at levels commonly used by rural banks for aquaculture loans.

### *Hybrid Striped Bass*

Wui and Engle (2004) used a mixed-integer linear programming model to evaluate several effluent treatments considered for hybrid striped bass (*Morone chrysops* × *M. saxatilis*) production in ponds. Settling basins and constructed wetlands entailed high costs for farmers, with high reduction in effluents. Costs were estimated for either constructing new settling basins or converting existing ponds into settling basins. Converting a production pond to a settling basin reduces total farm production from reduced pond area. Filtering treatments incurred high cost with little reduction in nutrient concentration in effluents. Not flushing water from the pond or not draining the pond annually reduced effluent volume. Reduction in water exchange also decreased operating costs with no additional investment cost. The various effluent treatment options increased production costs on average by $0.00 to 6.79/kg.

Results indicated that the only feasible treatment alternatives for hybrid striped bass effluents were 1) not draining the pond and 2) not flushing ponds. Overall, no treatment and no annual draining resulted in higher net returns while constructed wetlands, settling basin, and converting existing ponds into settling basins options resulted in lower net returns for hybrid striped bass farmers. However, more research is needed to identify the production risks of not flushing or draining hybrid striped bass ponds.

## Major Economic Effects Associated with BMPs in Aquaculture

### *Investment Capital*

Better management practices that require construction of a new structure will increase the total amount of capital investment in the business. Through annual depreciation and interest charges on the increased amount of investment capital, annual fixed costs increase, which increases total costs, reduces net returns (profits), and increases break-even prices (cost/kg of production). For example, in Idaho, BMPs that required quiescent zones and offline settling basins were estimated to be $212,700, or $5,908 per quiescent zone, for a farm with 36 raceways.

The use of settling basins for treatment of effluents from pond aquaculture has been proposed frequently. Several studies have evaluated the costs associated with settling basins on aquaculture farms. Brennan (2002) developed an economic analysis of settling ponds on shrimp farms in Australia. Given that land on the farm was scarce and that effluent ponds could only be created by giving up pond space, the main cost was the opportunity cost of pond space. Effluent pond cost was estimated to be from $9,200 to $20,000/ha. The opportunity cost of lost production ranged from $13,162 to $42,458/ha for total effluent treatment costs of $22,362 to $51,658/ha. The average cost per kg of nitrogen removed was $26.49 to $61.36.

Engle and Valderrama (2003) also estimated farm-level costs of settling basins for treatment of pond effluents, but from catfish ponds in the United States. Costs increased dramatically as the number of different farm drainage directions increased. Larger pond sizes, percentage of effluent volume treated, and increased hydraulic residence times increased costs. For situations where existing ponds were converted to settling basins, the cost increase would not be economically feasible. The use of settling ponds imposed a disproportionately higher cost on smaller farms. Boyd and Queiroz (2001) found that settling basins would not be feasible on many Alabama catfish farms due to lack of suitable land space.

### *Effect on Production Capacity*

Better management practices may have an effect on production capacity. Several studies have demonstrated that BMPs, particularly those that require construction of new facilities, can reduce the production capacity of the business. This may occur from the lack of additional land space (Boyd and Queiroz 2001), the lack of access to sufficient credit (Engle et al. 2005), or the need to convert existing production facilities to treatment facilities (Engle and Valderrama 2003).

In Maine the use of individual identification tags on cultured fish was examined as a method of assessing the efficacy of containment on salmon farms. Although the direct cost of tagging is significant ($0.10 to $0.12/fish) (Hammer and Blankenship 2001), the indirect cost of reduced production capacity is much higher. Production capacity is reduced by reduced growth from handling stress and inefficient use of tank volumes from a need to keep tagged lots separate. Current estimates suggest that production capacity may be reduced by as much as 30% and that the total costs to Maine salmon farmers may exceed $40 million (Pietrak et al. 2003).

### *Financial Risk*

Components of BMPs that require construction of new infrastructure that entails new investment capital may increase financial risk. It should be noted, however, that BMPs that increase the efficiency of input use may reduce operating capital requirements and reduce financial risk.

On trout farms, the primary factor affecting the economic and financial feasibility of effluent treatment options is the capacity to borrow operating and investment capital (Engle et al. 2005). Typically, borrowing capacity is based on a firm's balance sheet, although specific banks may define borrowing capacity in different ways. Collateral used for loans frequently includes the values of land, raceways, and sometimes swimming inventory. Farms would need to take tanks out of production to add treatment technologies. This reduces operating capital borrowing capacity and increases the need for investment capital. Purchasing adjoining land segments is not an option in many trout-producing areas due to the high (and increasing) land values in many of those regions.

Trout farms that had previously incorporated treatment options likely did so when adjoining land prices were low or because sunk costs on older farms did not generate cash expenses. However, sunk costs in capital goods will eventually need to be replaced.

Trout farming entails relatively high levels of financial risk (Engle et al. 2005). Additional investment capital to treat effluent further increased financial risk. Although some fish farmers successfully manage around relatively high levels of financial risk, at some point the risk becomes greater than the operator's ability or willingness to accept and the farm shuts down.

Limits to borrowing capacity forced farms to take tanks out of production (Engle et al. 2005). Larger farms could manage the expense of treating effluents better than smaller farms, but imposing these regulations forces farms to reduce production due to limited capacity to borrow additional funds. Such regulations create a paradox for farmers in that the increased investment capital required for compliance increases economies of scale and incentives to expand farm size. However, because the additional investment is not generating additional production, it uses up borrowing capacity and causes farmers to reduce production potential. Thus, farms are forced to operate at inefficient levels.

### *Monitoring, Reporting, and Inspection Costs of BMPs*

The effectiveness of direct pollution control strategies depends upon the ability of regulators to enforce regulations (Brennan 2002). For individual farms, monitoring and reporting activities required by regulators increases management and labor costs.

In Australia, effluent discharges are monitored with monthly sampling and analysis of effluent concentrations and water volumes. The program is very costly and may not be cost-effective. Spot sampling of effluents is highly inaccurate due to the variability of nutrient concentrations in effluent (Preston et al. 2000). However, more continuous monitoring would be cost prohibitive.

The Engle et al. (2005) analysis of BMP costs on trout farms estimated costs for specific types of BMP plans. This analysis provided estimates of the added costs of each of a series of BMP components proposed for trout flow-through systems, measured as the decrease in net returns resulting from their adoption. The BMP plan for drugs and chemicals reduced net returns by $7,613/year (22%), caused by the increased variable costs of interest on operating capital and increased hours of part-time labor hired. The solids control BMP plan reduced net returns by $6,714 (20%). It is clear that BMP components can have substantial effects in decreasing net returns.

## Summary

Better management practices are one of a number of policy tools used in environmental management. In contrast to many other policy alternatives, BMPs were developed to balance environmental concerns with policies that affect the profitability of agriculture. The most rapid adoption will occur where management practices enhance environmental management and increase profits. Proper siting and efficient use of feed and fertilizer are common examples of practices that also result in higher profits. Profit-enhancing BMPs frequently are those that result in more efficient input use, are adopted quickly by farmers, and become standard operating practices.

Proposed new BMPs often require additional investment capital for construction of new farm infrastructure, thereby increasing financial risk. Careful economic analysis of proposed new management practices is essential. Enterprise budgeting, partial budgeting, investment analysis, and whole-farm modeling can be used to evaluate the relative costs and benefits of individual, or sets of, BMPs.

Several empirical studies of the costs associated with implementing BMPs in field crop farming, urban stormwater control, swine production, and aquaculture indicate that the feasibility of adopting or complying with specific policy tools depends upon the costs of implementation and the technical and operating feasibility. Costs associated with BMPs include the investment capital needed to install new structures required to implement BMPs; operating and maintenance costs of managing the farm with BMPs; and monitoring, reporting, and inspection costs. Excessive costs will cause the BMP to be unfeasible and will result in either business closures, if mandated by regulation, or lack of adoption, if voluntary.

Noneconomic factors can also affect the adoption of BMPs. Farmers may perceive the BMP as too complex, too expensive, too risky, or not compatible with their farming system. Thus, it is important to evaluate prospective BMPs carefully, beginning with the technical and operating feasibility, analysis of all investment and operating costs and how these affect the overall farm operation, and the perceptions of farmers and the likelihood of adoption. With careful ex ante economic analysis, BMPs often can be developed that simultaneously improve environmental performance and farm profitability.

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## Appendix 1

# A Suggested Protocol for Developing a Management System to Prevent Escapes from Net-Pen Aquaculture Facilities (adapted from Maine Aquaculture Association 2002)

The containment management system (CMS) for prevention of escapes from net-pen aquaculture systems consists of two parts: a facility prerequisite program (FPP) and a facility containment program (FCP).

## Facility Prerequisite Program

The facility prerequisite program (FPP) should minimally include the following components. All categories of the FPP should be audited for compliance by an external, third-party auditor.

### *Site Plan*

Provide a site plan or schematic drawing of the facility that includes supporting documentation identifying key structural and material specifications for all farm components. The site plan should be verified and signed by the farm manager before inclusion in the CMS document. The site plan should clearly describe methods and equipment used to establish effective physical containment barriers that are appropriate to the size of fish in the facility. These containment barriers must be kept in place and maintained at all times.

### *Inventory-Control Procedures*

Describe methods used to count fish prior to stocking on the farm. This count should include an estimate of reasonable variance based on random-sample spot-checks designed to verify reported shipping numbers. The counting methodology and verification protocol should be clearly outlined in the mandatory prerequisite program. Inventory numbers with their associated predetermined variances will be used for inventory purposes in the CMS program. Inventory methods and records associated with numbers of fish contained within the farm should be made available to external auditors.

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### *Integrated Predator Deterrence (IPD) Program*

Develop a procedure for predator control if it is determined that predators can affect the site. This plan and any attendant records must be available during an audit. The IPD program will conform to all relevant state and federal regulations, and prioritize non-lethal deterrence methods.

### *Clear, Pre-established Response Procedures*

Develop a protocol that demonstrates the farm's capability to take immediate corrective actions or make repairs to the site in the event of a CMS breakdown or confirmed or suspected compromises to containment barriers. Stabilization of the situation is the highest priority. Notification of appropriate authorities, if required by law or for timely management response, is an important component of an effective plan. List contact numbers in the plan and train employees in response procedures.

### *Unique Event Management Plan*

Develop a unique event management plan that includes an assessment of the potential for escapement due to unusual occurrences, such as ship/cage collisions, sinking of the transport boat, or collisions with large floating objects. The unique event management plan should include response procedures and standard operating procedures that are pre-planned for specific types of unique events. The unique event management plan should also include pre-established situation thresholds that trigger requests for assistance from appropriate agencies or external contractors. A hazard analysis should be completed prior to undertaking any unusual activity—such as towing a cage with fish—for which a prior hazard analysis has not been conducted.

### *Severe Weather Preparation Plan*

Develop a severe weather preparation plan if it is determined that there is potential for severe weather at the farm site and that weather may compromise the containment system. The severe weather preparation plan should consist of a standard set of procedures to be implemented to prepare for severe weather. These procedures should include, but are not limited to, systematic checking of all mooring system components, replacement of any worn mooring system components, installation of additional storm moorings at locations appropriate for the expected wind direction, systematic checking of all net/cage connections, and tie down of all loose equipment. The severe weather preparation plan should also include a documentation component that the farm manager must sign after implementing the plan before a storm.

### *Training*

Develop a plan for training all employees with a direct role in any aspect of the CMS. The plan should describe the nature of training, who is responsible for providing training, and documentation that training has occurred. The purpose of training is to familiarize each employee with control measures and their attendant monitoring, corrective actions, verification procedures, and record-keeping procedures. Additional training may be required for personnel with special responsibilities for oversight of any of the procedures, event management, and preparations described in this system.

### *Escape Log*

Develop and maintain an escape log that provides information on the number, life stage, and size of any fish that escape. Large escape events involving compromised containment barriers that could possibly lead to fish escapement into the wild will require immediate corrective action including, but not limited to, stabilizing the situation, installing secondary containment barriers, moving the remaining fish to a more secure location, and notifying appropriate resource management agencies. Escapes should be classified as less than 25, greater than 50, or greater than 100 fish escaping from the system. Describe regular monitoring and documentation conducted on all nets, mooring components, and cage collars to ensure their integrity. A corrective action report will be filled out for every escape recorded. The corrective action report should minimally include the date, number of escapes, reason for the escape, corrective action taken to prevent further escapes, and who took that action.

## Facility Containment Program

The facility containment program (FCP) should minimally include the following components. Compliance with these components will be determined through the audit process.

### *Organizational Chart and Narrative*

Provide a diagram identifying all company personnel, by job description. Identify who has responsibility for the CMS development, implementation, and maintenance. Provide a short narrative to describe each position and its relationship to the organizational chart.

### *Process Flowchart*

Provide a process flow diagram that illustrates the operational steps that fish follow through the farm. The diagram should start when juvenile fish are stocked into the farm, and continue until the fish are removed by harvest and sent to a processing plant. The flowchart should clearly identify when ownership of the fish changes and responsibility is transferred. The process flowchart shall identify the location of the critical control points (CCPs), and the hazard to be controlled at that location. This process flowchart may be used as a site plan as described above.

### *Hazard Analysis*

Conduct a hazard analysis for the site to determine which of the operational control steps illustrated on the process flowchart are CCPs. The site-specific risk analysis can form the basis of the hazard analysis. The hazard analysis should be included as part of the individual site plan. Critical control points are determined based on the following criteria: the likelihood that an escape will happen at that process step, the probability of the escape being significant (>100 fish) if an escape occurs, the ability to identify a mechanism to control the hazard at that CCP, the ability to establish verifiable critical limits that, if exceeded, will likely correspond to an escape, and the ability to monitor those critical limits before an escape occurs. For each step that is determined to be a CCP, the following components should be developed and described: a control mechanism that manages events at the CCP, a measurable critical limit that is linked to the control mechanism and will be exceeded before an escape happens, and any corrective actions that will be used in an event that exceeds the critical limit or in an escape.

Include in the hazard analysis a comprehensive assessment of the potential for predator attacks at the farm site. Predators will occasionally attempt to attack farm animals on net-pen farms. Predator attacks may cause mortalities, sub-lethal stress, or damage farm structures. If predator attacks are likely, include a comprehensive integrated predator deterrence (IPD) plan.

### *Record-Keeping Procedures*

Describe the system used to complete, store, and verify the monitoring procedures required in either the FPP or FCP. This description should include blank forms of all records kept as part of the CMS. Procedures should be in place to ensure that records are filled out and signed at the time of the monitoring. Records should be available for review during an audit. Documentation of personnel trained in the design, management, and implementation of the containment system shall be included.

### *Verification Procedures*

Develop verification procedures documenting critical limits, monitoring procedures, and corrective actions at each CCP. Two types of verification will be included: the routine and annual audit. Routine verification involves normal record keeping that is part of the CMS and demonstrates that the appropriate critical limits are being monitored, and, if exceeded, corrective action has been implemented. Annual verification involves an external auditor reviewing all the CMS documents, inspecting the farm, and interviewing staff to evaluate the overall effectiveness of the CMS. Audit data should be reviewed to determine if trends indicate system failure. A record of the results of the annual verification audit should be maintained.

## Reference

Maine Aquaculture Association. 2002. *Maine Aquaculture Association Generic Containment Management System*. Hallowell, Maine: Maine Aquaculture Association.

# Appendix 2

# Selected Excerpts from the Food and Agriculture Organization (FAO) of the United Nations Code of Conduct for Responsible Fisheries

## Article 6—General Principles

6.1. States and users of living aquatic resources should conserve aquatic ecosystems.

6.7. The harvesting, handling, processing, and distribution of fish and fishery products should be carried out in a manner which will maintain the nutritional value, quality, and safety of the products; reduce waste; and minimize negative impacts on the environment.

6.8. All critical fisheries habitats in marine and fresh water ecosystems, such as wetlands, mangroves, reefs, lagoons, nursery and spawning areas, should be protected and rehabilitated as far as possible and where necessary. Particular effort should be made to protect such habitats from destruction, degradation, pollution, and other significant impacts resulting from human activities that threaten the health and viability of the fishery resources.

6.13. States should, to the extent permitted by national laws and regulations, ensure that decision making processes are transparent and achieve timely solutions to urgent matters. States, in accordance with appropriate procedures, should facilitate consultation and the effective participation of industry, fish-workers, environmental, and other interested organizations in decision making with respect to the development of laws and policies related to fisheries management, development, international lending, and aid.

6.14. International trade in fish and fishery products should be conducted in accordance with the principles, rights, and obligations established in the World Trade Organization (WTO) Agreement and other relevant international agreements. States should ensure that their policies, programs, and practices related to trade in fish and fishery products do not result in obstacles to this trade, environmental degradation, or negative social, including nutritional, impacts.

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6.16. States, recognizing the paramount importance to fishers and fish-farmers of understanding the conservation and management of the fishery resources on which they depend, should promote awareness of responsible fisheries through education and training. They should ensure that fishers and fish-farmers are involved in the policy formulation and implementation process, also with a view to facilitating the implementation of the Code.

6.19. States should consider aquaculture, including culture-based fisheries, as a means to promote diversification of income and diet. In so doing, States should ensure that resources are used responsibly and adverse impacts on the environment and on local communities are minimized.

## Article 9—Aquaculture Development

9.1.1. States should establish, maintain, and develop an appropriate legal and administrative framework which facilitates the development of responsible aquaculture.

9.1.2. States should promote responsible development and management of aquaculture, including an advance evaluation of the effects of aquaculture development on genetic diversity and ecosystem integrity, based on the best available scientific information.

9.1.3. States should produce and regularly update aquaculture development strategies and plans, as required, to ensure that aquaculture development is ecologically sustainable and to allow the rational use of resources shared by aquaculture and other activities.

9.1.4. States should ensure that the livelihoods of local communities, and their access to fishing grounds, are not negatively affected by aquaculture developments.

9.1.5. States should establish effective procedures specific to aquaculture to undertake appropriate environmental assessment and monitoring with the aim of minimizing adverse ecological changes and related economic and social consequences resulting from water extraction, land use, discharge of effluents, use of drugs and chemicals, and other aquaculture activities.

9.2.1. States should protect transboundary aquatic ecosystems by supporting responsible aquaculture practices within their national jurisdiction and by cooperation in the promotion of sustainable aquaculture practices.

9.2.2. States should, with due respect to their neighboring States, and in accordance with international law, ensure responsible choice of species, siting, and management of aquaculture activities which could affect transboundary aquatic ecosystems.

9.2.3. States should consult with their neighboring States, as appropriate, before introducing non-indigenous species into transboundary aquatic ecosystems.

9.2.4. States should establish appropriate mechanisms, such as databases and information networks to collect, share, and disseminate data related to their aquaculture activities to facilitate cooperation on planning for aquaculture development at the national, subregional, regional, and global level.

9.2.5. States should cooperate in the development of appropriate mechanisms, when required, to monitor the impacts of inputs used in aquaculture.

9.3.1. States should conserve genetic diversity and maintain integrity of aquatic communities and ecosystems by appropriate management. In particular, efforts should be undertaken to minimize the harmful effects of introducing non-native species or genetically altered stocks used for aquaculture, including culture-based fisheries into waters, especially where there is a significant potential for the spread of such non-native species or genetically altered stocks into waters under the jurisdiction of other States as well as waters under the jurisdiction of the State of origin. States should, whenever possible, promote steps to minimize adverse genetic, disease, and other effects of escaped farmed fish on wild stocks.

9.3.2. States should cooperate in the elaboration, adoption, and implementation of international codes of practice and procedures for introductions and transfers of aquatic organisms.

9.3.3. States should, in order to minimize risks of disease transfer and other adverse effects on wild and cultured stocks, encourage adoption of appropriate practices in the genetic improvement of broodstocks, the introduction of non-native species, and in the production, sale, and transport of eggs, larvae or fry, broodstock, or other live materials. States should facilitate the preparation and implementation of appropriate national codes of practice and procedures to this effect.

9.3.4. States should promote the use of appropriate procedures for the selection of broodstock and the production of eggs, larvae, and fry.

9.3.5. States should, where appropriate, promote research and, when feasible, the development of culture techniques for endangered species to protect, rehabilitate, and enhance their stocks, taking into account the critical need to conserve genetic diversity of endangered species.

9.4.1. States should promote responsible aquaculture practices in support of rural communities, producer organizations, and fish-farmers.

9.4.2. States should promote active participation of fish-farmers and their communities in the development of responsible aquaculture management practices.

9.4.3. States should promote efforts which improve selection and use of appropriate feeds, feed additives, and fertilizers, including manures.

9.4.4. States should promote effective farm and fish health management practices favoring hygienic measures and vaccines. Safe, effective, and minimal use of therapeutants, hormones and drugs, antibiotics, and other disease control chemicals should be ensured.

9.4.5. States should regulate the use of chemical inputs in aquaculture which are hazardous to human health and the environment.

9.4.6. States should require that the disposal of wastes such as offal, sludge, dead or diseased fish, excess veterinary drugs, and other hazardous chemical inputs does not constitute a hazard to human health and the environment.

9.4.7. States should ensure the food safety of aquaculture products and promote efforts which maintain product quality and improve their value through particular care before and during harvesting and on-site processing and in storage and transport of the products.

## Reference

FAO (Food and Agriculture Organization of the United Nations). 2000. *Code of Conduct for Responsible Fisheries*. Rome: FAO Department of Fisheries. Available at ftp://ftp.fao.org/docrep/fao/005/v9878e/v9878e00.pdf

## Appendix 3

# Core Guiding Principles for the Development of Integrated Coastal Management that Includes Aquaculture (adapted from GESAMP 2001)

1) Adhere to the Rio principles: sustainable development (inter-generational equity), the precautionary approach, and the polluter pays principle.
2) Integrate or co-ordinate with other sector activities or plans and with integrated coastal management where such initiatives exist.
3) Involve all potential stakeholders in planning and decision-making.
4) Assess costs and benefits (financial, economic, social, environmental) of aquaculture in a specific area (e.g., estuarine or lagoon system) and comparatively assess costs and benefits of aquaculture relative to other resource uses, including risk assessment.
5) Estimate environmental capacity.
6) Use incentives rather than regulation where possible.
7) Control effects, rather than the scale of activity.
8) Evaluate, iterate, and adapt for refinement and improvement.
9) Analyze the effectiveness of institutions and representative organizations.

## Reference

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 2001. *Planning and Management for Sustainable Coastal Aquaculture Development*. GESAMP Reports and Studies 68. Rome: Food and Agriculture Organization (FAO) Fisheries Department.

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## Appendix 4

# Aquaculture-Specific Guidelines for Ecological Monitoring (adapted from GESAMP 1996)

When formulating programs or requirements for environmental assessments and monitoring, due consideration should be given to the diversity of aquaculture practices (including, in particular, the species used and the culture methods applied) and their environmental settings.

Any environmental assessment and monitoring effort should be related to the scale of perceived impact of a given aquaculture operation.

In many cases, particular emphasis will need to be given to simplicity, flexibility and affordability of environmental assessments and monitoring, in order to facilitate the acceptance and enforcement of such measures. Consultation and participation of interested and affected parties in the formulation of requirements for environmental assessment and monitoring should be encouraged. A detailed evaluation of financial, manpower, and time requirements for any such effort should precede their implementation to demonstrate their cost-effectiveness and feasibility.

The ecological component of an environmental impact assessment should be designed such that all significant impacts of wastes are identified and an appropriate monitoring program constructed.

Monitoring should preferably be undertaken within a framework of established Environmental Quality Objectives and Standards.

Monitoring for ecological protection should be regarded as an integral part of managing aquaculture operations. In particular, the results derived from monitoring should be used to evaluate the ecological effects of the operation, the suitability of relevant Environmental Quality Standards, and the utility of the monitoring program itself.

## Reference

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 1996. *Monitoring the Ecological Effects of Coastal Aquaculture Wastes*. GESAMP Reports and Studies 57. Rome: Food and Agriculture Organization (FAO) Fisheries Department.

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## Appendix 5

# Selected Excerpts from the International Council for the Exploration of the Sea (ICES) Code of Practice on the Introductions and Transfers of Marine Organisms 2004

II. Recommended procedure for all species prior to reaching a decision regarding new introductions
   a) Member Countries contemplating any new introduction are expected to submit to the Council well in advance a detailed prospectus on the proposed new introduction(s) for evaluation and comment.
   b) The prospectus should include the purpose and objectives of the introduction, the stage(s) in the life cycle proposed for introduction, the native range, the donor location, and the target area(s) of release. The prospectus should also include a review of the biology and ecology of the species as these pertain to the introduction (such as the physical, chemical, and biological requirements for reproduction and growth, and natural and human-mediated dispersal mechanisms) and information on the receiving environment.
   c) The prospectus should also provide a detailed analysis of the potential impacts on the aquatic ecosystem of the proposed introduction. This should include, wherever possible, assessments from previous introductions. This analysis should include a thorough review of:
      i) the ecological, genetic, and disease impacts and relationships of the proposed introduction in its natural range and donor location;
      ii) the expected ecological, genetic, and disease impacts and relationships of the introduction in the proposed release site and projected range, as well as vectors for further distribution;
      iii) an economic assessment, where appropriate.
   d) The prospectus should conclude with an overall assessment of the issues, problems, and benefits associated with the proposed introduction. An evaluation of risks should be included.

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  - e) Upon review of the prospectus, the ICES Council will provide comments and recommendations on the proposed introduction.

III. If the decision is taken to proceed with the introduction

  - a) Using internationally recognized protocols, such as the Office International des Épizooties (OIE), or any other appropriate protocols available at the time, review the health records of the donor location and surrounding area of the organisms to be introduced.
  - b) The introduced organisms should be used to establish a broodstock for the production of progeny. The organisms should be transferred into a quarantine facility. This facility should be in the recipient country or other location agreed to by the recipient country.
  - c) The imported consignment(s) is not to be released to the wild, and should be separated from subsequent progeny.
  - d) Only progeny of the introduced species may be transplanted into the natural environment, provided that:
    - i) a risk assessment indicates that the likelihood of negative genetic and environmental impacts is minimal,
    - ii) no disease agents, parasites, or other non-target species become evident in the progeny to be transplanted, and
    - iii) no unacceptable economic impact is to be expected.
  - e) During the pilot phase, the progeny, or other suitable life stages, should be placed on a limited scale into open waters to assess ecological interactions with native species, and especially to test risk assessment assumptions. Contingency plans, including the removal of the introduced species from the environment, should be ready for immediate implementation.
  - f) A monitoring program addressing specific issues of the introduced species in its new environment should be undertaken, and annual progress reports should be submitted to ICES for review at meetings of the Working Group on Introductions and Transfers of Marine Organisms until the review process is considered complete.

## Reference

ICES 2004. *Code of Practice on the Introductions and Transfers of Marine Organisms*. Available at www.ices.dk/reports/general/2004/ICESCOP2004.pdf

## Appendix 6

# Review and Decision Model for Evaluating Proposed Introductions of Aquatic Organisms

Using the flow diagram on the next page, each member of an evaluation board or panel of experts selects the number corresponding to their judgment about the probability for the occurrence of the event as indicated by the questions listed in decision boxes: no (1), unlikely (2), possibly (3), probably (4), yes (5). If information is unavailable, or if uncertainty is too great, then "Don't know" is marked. Average opinionnaire values are used at each decision point (Kohler and Stanley 1984).

## Reference

Kohler, C.C. and J.G. Stanley. 1984. A suggested protocol for evaluating proposed exotic fish introductions in the United States. Pages 387–406 in *Distribution, Biology and Management of Exotic Fishes*, edited by W.R. Courtenay, Jr., and J.R. Stauffer, Jr. Baltimore: Johns Hopkins University Press.

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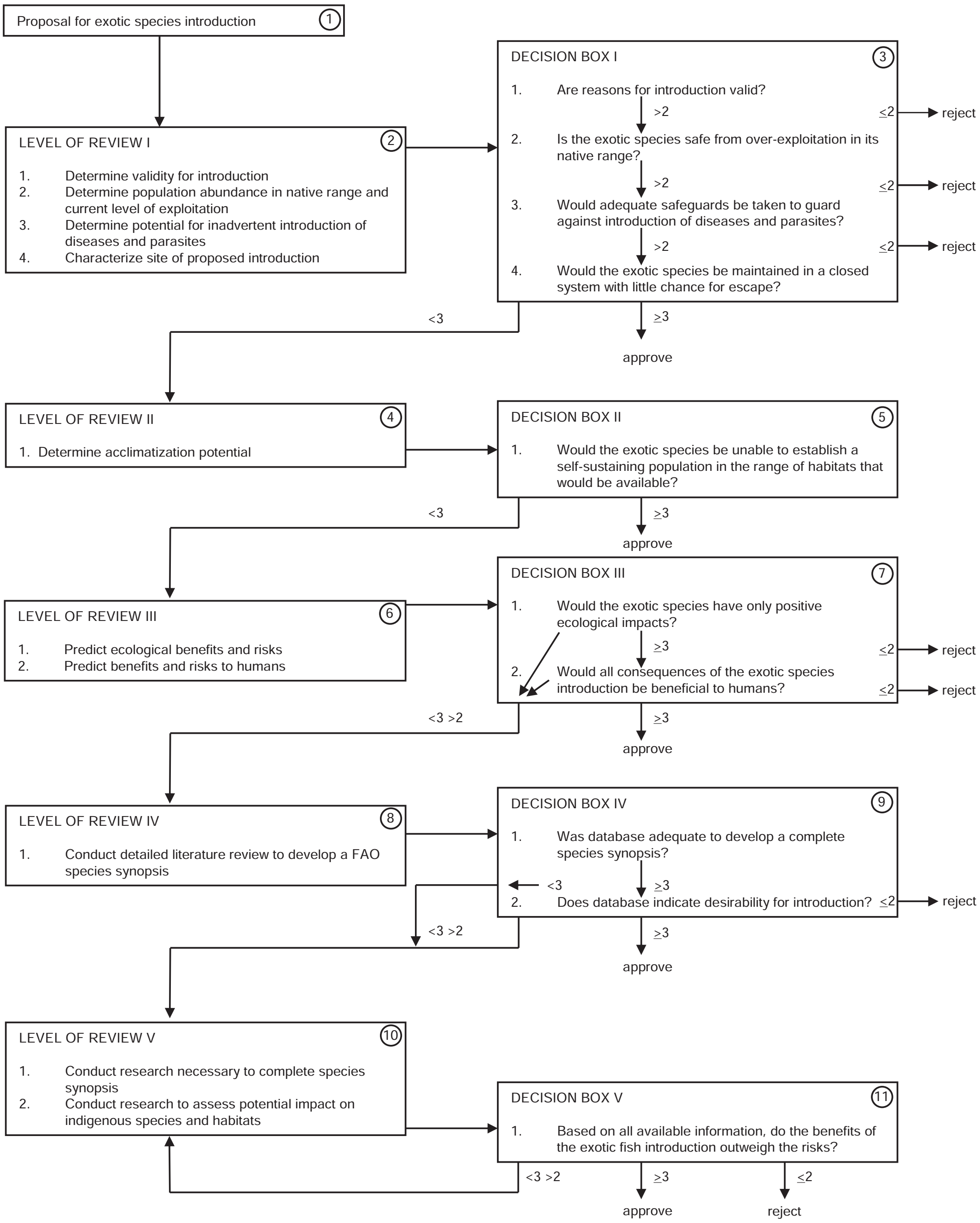
Proposal for exotic species introduction ①
LEVEL OF REVIEW I ②
1. Determine validity for introduction
2. Determine population abundance in native range and current level of exploitation
3. Determine potential for inadvertent introduction of diseases and parasites
4. Characterize site of proposed introduction
DECISION BOX I ③
1. Are reasons for introduction valid?
>2
≤2
reject
2. Is the exotic species safe from over-exploitation in its native range?
>2
≤2
reject
3. Would adequate safeguards be taken to guard against introduction of diseases and parasites?
>2
≤2
reject
4. Would the exotic species be maintained in a closed system with little chance for escape?
<3
≥3
approve
LEVEL OF REVIEW II ④
1. Determine acclimatization potential
DECISION BOX II ⑤
1. Would the exotic species be unable to establish a self-sustaining population in the range of habitats that would be available?
<3
≥3
approve
DECISION BOX III ⑦
LEVEL OF REVIEW III ⑥
1. Predict ecological benefits and risks
2. Predict benefits and risks to humans
1. Would the exotic species have only positive ecological impacts?
≥3
≤2
reject
2. Would all consequences of the exotic species introduction be beneficial to humans?
≤2
reject
<3 >2
≥3
approve
LEVEL OF REVIEW IV ⑧
1. Conduct detailed literature review to develop a FAO species synopsis
DECISION BOX IV ⑨
1. Was database adequate to develop a complete species synopsis?
<3
≥3
2. Does database indicate desirability for introduction?
≤2
reject
<3 >2
≥3
approve
LEVEL OF REVIEW V ⑩
1. Conduct research necessary to complete species synopsis
2. Conduct research to assess potential impact on indigenous species and habitats
DECISION BOX V ⑪
1. Based on all available information, do the benefits of the exotic fish introduction outweigh the risks?
<3 >2
≥3
≤2
approve
reject

## Appendix 7

# Recommendations on the Safe and Effective Use of Chemicals in Coastal Aquaculture (adapted from GESAMP 1997)

1) Chemotherapeutants should not be the first option when combating disease but used only as a last resort after environmental conditions, nutrition, and hygiene have been optimized.
2) Prophylactic treatment should be avoided since the selective pressure for development of antibacterial resistance poses a threat to the long-term efficacy of a drug.
3) When multiple chemical alternatives are available, producers should select drugs not only on the basis of efficacy data but also on available information regarding environmental persistence, potential effects on non-target organisms, propensity to stimulate microbial resistance, and rate of residue elimination.
4) Producers should utilize antibacterials having as narrow a spectrum of activity as possible but without loss of efficacy, so as to minimize selective pressure for resistance in other micro-organisms.
5) In order to document cost-effectiveness and guide future treatment, producers should maintain records of chemical use including agents used, amounts, reasons for use, methods of application, dates of use, amount/number and size of stock treated, success/failure of treatments, and times of harvest of treated stock.
6) Producers should not discharge to natural water bodies any effluent containing chemical residues at concentrations likely to cause adverse biological effects and should first reduce concentrations, preferably by residue removal or increased residence time, and/or by dilution with other effluent waste streams within the farm.
7) Farms in close physical proximity should collaborate in minimizing the risk of contaminating of their water supplies and those of neighboring facilities with chemical residues and drug resistant bacteria.

## Reference

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution). 1997. *Towards safe and effective use of chemicals in coastal aquaculture*. Reports and Studies 65. Rome: Food and Agriculture Organization (FAO) Fisheries Department.

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## Appendix 8

# A Code of Practice for the Use of Inhibitory Compounds in Aquaculture

1) Medically important inhibitory compounds should be banned from use in aquaculture. However, some medically important compounds may need to be used in exceptional circumstances for certain specified diseases.
2) The availability of inhibitory compounds should be restricted to qualified individuals, such as veterinarians.
3) Access to inhibitory compounds should be denied to all laymen and inexperienced personnel.
4) The storage of inhibitory compounds should be in the manner recommended by manufacturers/suppliers.
5) The use of inhibitory compounds should be strictly in accordance with the written instructions from the manufacturer/supplier.
6) The use of pharmaceutical compounds should be by rotation. Thus, the repeated use of single compounds should be avoided.
7) The use of suitable withdrawal periods, after the use of pharmaceutical compounds, is necessary before animals are removed from the aquacultural facility.
8) The deliberate or accidental release of inhibitory compounds into the aquatic environment must be avoided.
9) Unused inhibitory compounds must be disposed of safely.
10) A surveillance program must be adopted to ensure that the code of practice is carried out.

## Reference

GESAMP (IMO/FAO/Unesco/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution). 1991. *Reducing Environmental Impacts of Coastal Aquaculture*. Reports and Studies 47. Rome: Food and Agriculture Organization.

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## Appendix 9

# Principles of the Hazard Analysis and Critical Control Point System Adapted for Minimizing the Environmental Impacts of Aquaculture (adapted from Gunderson and Kinnunen 2004)

1) Conduct a hazard analysis. Identify the significant environmental hazards of aquaculture. Consider the likelihood of occurrence and the severity of each hazard (i.e., risk analysis). Prepare a list of steps in the process where significant hazards occur and describe measures to prevent or control hazards at each step.
2) For each hazard, identify one, or more, critical control point (CCP) in the production process where the hazard can be controlled. Critical control points are those where control is best achieved. One CCP can be used to control multiple hazards.
3) Define and establish control limits for each CCP identified. For each control measure, define a criterion (or critical limit) to indicate successful control. Establish an operating limit, which is a threshold set to avoid violation of the critical limit, where corrective action is initiated.
4) Establish monitoring to verify that each CCP is operating within critical limits. Identify what will be monitored, how control limits will be monitored, monitoring frequency, and individuals responsible for monitoring. Establish procedures for using monitoring results to adjust the process and maintain control.
5) Establish corrective actions to be taken when monitoring indicates a deviation from an established critical limit at a CCP. Corrective actions should address the immediate problem and establish measures to minimize the potential for future recurrence.
6) Establish procedures to verify that the HACCP system is in compliance with the HACCP plan. Validation is the collection of information from monitoring and testing to ensure that implementation of the plan can effectively control environmental hazards.
7) Establish effective record-keeping procedures. Required records include the HACCP plan and associated support documents, monitoring records, corrective action records,

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and verification records. Timely review of records can indicate the effectiveness of control methods and suggest the need for adjustments to the HACCP plan.

## Reference

Gunderson, J.L. and R.E. Kinnunen, editors. 2004. *Aquatic Invasive Species–Hazard Analysis and Critical Control Point Training Curriculum, Second Edition*. Duluth, Minnesota: Minnesota Sea Grant. Available at www.seagrant.umn.edu or www.deq.state.mi.us/documents/deq-ogl-AIS-HACCP_manual.pdf

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