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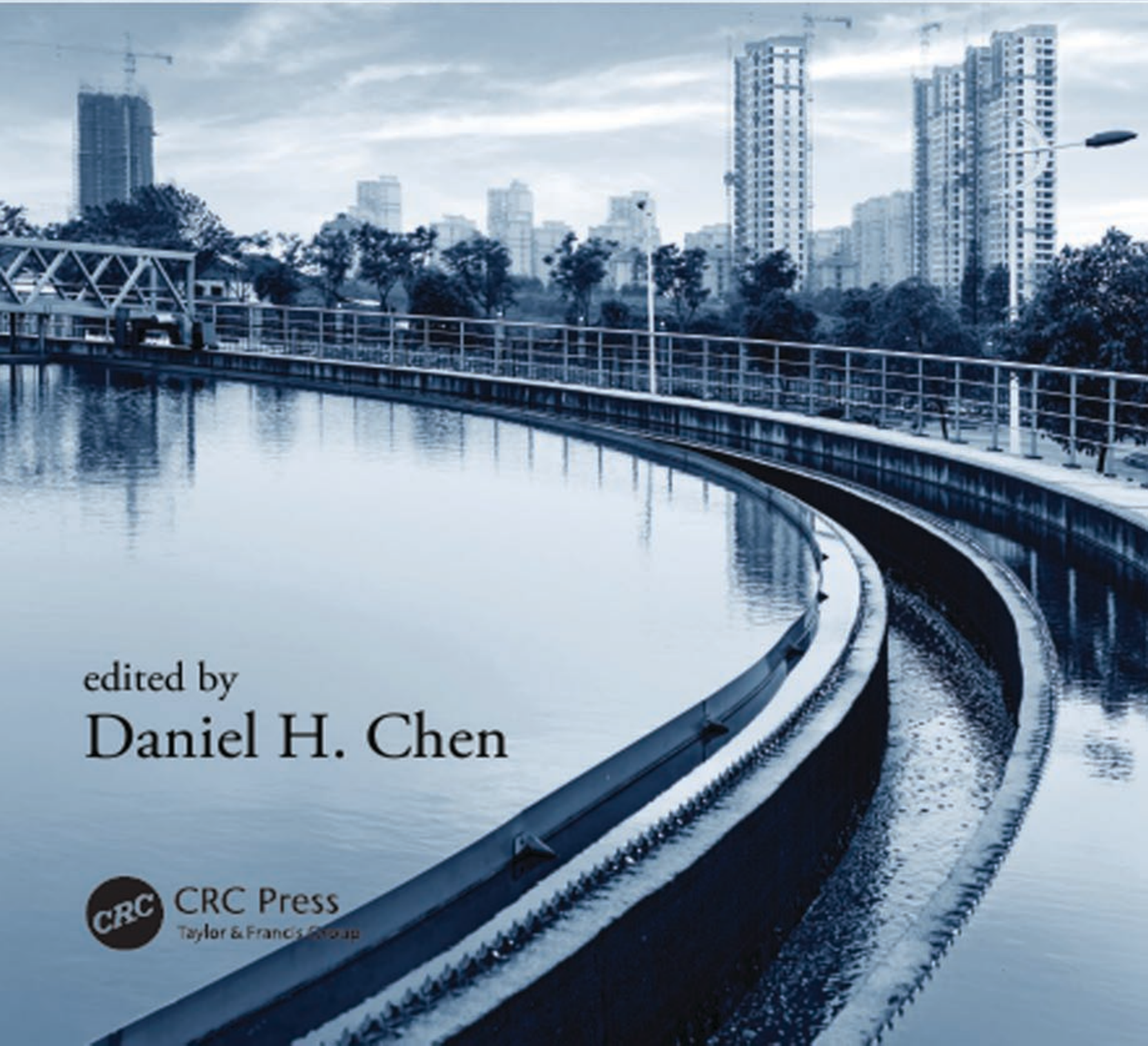
SUSTAINABLE WATER MANAGEMENT AND TECHNOLOGIES

SUSTAINABLE WATER MANAGEMENT

VOLUME I



edited by

Daniel H. Chen

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SUSTAINABLE WATER MANAGEMENT AND TECHNOLOGIES

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VOLUME I

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Preface

Water is the fundamental building block for human civilization, economic development, and the well-being of all living species. While the world population and the economy continue to grow, the availability of water and other natural resources remain nearly constant. Water shortages inevitably lead to conflicts between competing interests (irrigation, municipal, industrial, energy, environmental), regions (arid vs. wet), and nations (water scarce vs. water rich, developed vs. developing). Facing a looming water crisis, society not only needs to make significant scientific/engineering efforts to advance cost-effective water monitoring/treatment/reuse/integration technologies but also needs to tackle strategy/management issues such as water resources planning/governance, water infrastructure planning/adaption, proper regulations, and water scarcity/inequality as an integrated part of the solution or approach toward water sustainability. For this reason, the *CRC Sustainable Water Management and Technologies* addresses both cornerstone areas: management and technology. This book set presents the best practices as a foundation and proceeds to stress emerging technologies and strategies that facilitate water sustainability for future generations. Timely water topics like unconventional oil and gas development, global warming with changing precipitation patterns, integration of water and energy sustainability, and green manufacturing are discussed. The book is intended for a global audience that has a concern and interest about water quality, supply, resources conservation, and sustainable use.

Water, energy, and climate interactions are the most pressing issues for the 21st century. Water is currently treated as if in infinite supply, yet this is far from the case and use is drastically up worldwide owing to population growth and the pursuit of higher living standards. Water consumption in the production of everyday products such as coffee, beef, and plastics will eventually be priced in. The shale gas revolution is a welcome change in the energy front because of its low greenhouse emissions and relative cleanness for power generation. But the impact of hydraulic fracturing (fracking) on surface water and groundwater quality is of concern. This handbook provides expert assessments on this subject.

The handbook covers the basic principles, best practices, and latest advances in sustainable water management/technology with emphases on the following:

1. Emerging nanotechnology, biotechnology, geographical information system/global position system (GIS/GPS), and membrane technology applications
2. Sustainable processes/products to protect the environment/human health, to save water, energy, and materials
3. Best management practices for water resource allocation, groundwater protection, and water quality assurance, especially for rural, arid, and underdeveloped regions of the world
4. Timely issues such as the impact of shale oil/gas development, adapting water infrastructure to climate change, energy–water nexus, and interaction among water, energy, and ecosystems

This handbook is composed of two books: one is *Sustainable Water Management* and the other is *Sustainable Water Technologies*, the latter devoted to technologies for water resources monitoring, water efficiency (conservation, treatment, reclamation, recycle, reuse, and integration), and water quality (safe for drinking, landscaping, groundwater recharging, and industrial purposes).

This handbook is intended as a technical reference for environmental/civil/chemical engineers, water scientists/risk managers/regulators, academics, and advocacy groups that have responsibilities or interests in water resources, quality, and sustainability. It is also my hope that this handbook will facilitate young science, engineering, and social science students to learn the basics of water technology and management and then to develop the aspiration and skill set to contribute to the solution of this water sustainability issue facing mankind in the 21st century.

The information contained herewithin is the result of professional experience, literature review, and skillful analysis by the leading experts of the field (in alphabetical order): Frank R. Anscombe, Daniel Attoh, John Anthony Byrne, Ramesh C. Chawla, Daniel H. Chen (Editor), Liwen Chen, Hyeok Choi, Tapas K. Das, Dionysios D. Dionsiou, Rachel Fagan, Polycarpos Falaras, Pilar Fernández-Ibáñez, Lucas Gregory, Changseok Han, Leslie D. Hartman, Jude O. Ighere, Natalie Johnson, Carey W. King, Teik Thye Lim, Hebin Lin, Cindy Loeffler, Helen H. Lou, Willy Giron Matute, Declan E. McCormack, Mark L. McFarland, Mohamed K. Mostafa, Dorina Murgulet, John W. Nielsen-Gammon, Jerry Lin, Kevin O'Shea, Robert W. Peters, Jennifer L. Peterson, Suresh C. Pillai, Qin Qian, Walter Rast, Larry A. Redmon, Kelly T. Sanders, Preetam Kumar Sharma, Virender K. Sharma, Saqib Shirazi, Richard Stumpf, Jeffrey A. Thornton, Ross Tomson, Yen Wah Tong, Michael Twardowski, Kevin Urbanczyk, Kevin Wagner, Judy Westrick, Ralph A. Wurbs, Y. Jeffrey Yang, and Hesam Zamankhan. I sincerely appreciate their dedication and contributions.

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Daniel H. Chen, PhD

Editor

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1 Water Quality Management

Kevin Wagner, Lucas Gregory, and Allen Berthold

CONTENTS

1.1 WATER QUALITY AND ITS MANAGEMENT IN THE UNITED STATES

The *National Water Quality Inventory Report to Congress* (referred to as the *305(b) report*) is the primary means for informing Congress and the public about water quality conditions in the United States. This report describes the level to which each waterbody is attaining established water quality standards.

1.1.1 Water Quality in the United States

According to the *305(b) report*, the majority of waterbodies in the United States do not meet established water quality standards. More than half (51%) of river miles, two-thirds (67%) of lake acres, and almost three-quarters (72%) of the bay and estuary areas assessed were impaired in 2010. More than 42,700 waterbodies were impaired in the United States in 2010, with Alaska having the fewest (35) and Pennsylvania having the most (6957).

Pathogens (in rivers and streams) and mercury (in lakes, reservoirs, bays, and estuaries) are the leading causes of water quality impairment (Table 1.1). Organic enrichment/oxygen depletion and polychlorinated biphenyls (PCBs) are common causes of impairment in all waterbody types as well. These impairments have affected the use of these waters for aquatic life harvesting; fish, shellfish, and wildlife protection and propagation; and recreation.

In many US waters, the source of the impairment is unknown. Where sources have been identified, atmospheric deposition, agriculture, and municipal discharges (Table 1.2) are the most common cause of impairment. With the exception of municipal

TABLE 1.1
Top Causes of Impairment in Rivers/Streams, Lakes/Reservoirs, and Bays/Estuaries in the United States and Percentage of Assessed Miles or Area Impaired in Parentheses

Rank	Rivers/Streams	Lakes/Reservoirs	Bays/Estuaries
1	Pathogens (16%)	Mercury (43%)	Mercury (33%)
2	Sediment (12%)	Nutrients (18%)	PCBs (23%)
3	Nutrients (10%)	PCBs (16%)	Pathogens (21%)
4	Organic enrichment/oxygen depletion (9%)	Turbidity (8%)	Organic enrichment/oxygen depletion (17%)
5	PCBs (8%)	Organic enrichment/oxygen depletion (8%)	Dioxins (14%)

Source: EPA, 2014a, National summary of state information, Watershed Assessment, Tracking & Environmental Results. http://ofmpub.epa.gov/waters10/attains_nation_cy.control (accessed August 18, 2014).

TABLE 1.2
Top Sources of Impairment in Rivers/Streams, Lakes/Reservoirs, and Bays/Estuaries in the United States and Percentage of Assessed Miles or Area Impaired by Source in Parentheses

Rank	Rivers/Streams	Lakes/Reservoirs	Bays/Estuaries
1	Agriculture (13%)	Atmospheric deposition (27%)	Atmospheric deposition (25%)
2	Unknown (10%)	Unknown (18%)	Unknown (18%)
3	Atmospheric deposition (10%)	Agriculture (5%)	Municipal discharges (17%)

Source: EPA, 2014a, National summary of state information, Watershed Assessment, Tracking & Environmental Results. http://ofmpub.epa.gov/waters10/attains_nation_cy.control (accessed August 18, 2014).

discharges, the top sources of pollutants are nonpoint sources (NPSs), which present significant challenges in waterbody restoration.

1.1.2 OVERVIEW OF WATER QUALITY MANAGEMENT

To address water quality impairments and ensure the aquatic integrity of the nation's waters, the US Congress enacted the Federal Clean Water Act (CWA) to be administered under the US Environmental Protection Agency (EPA). The water quality management framework established by the CWA is based on the establishment and implementation of water quality standards (Figure 1.1). Water quality standards serve as the basis for administering permits, evaluating compliance, and assessing waterbody conditions.

Standards are established by each state, reviewed and approved by the EPA, and normally updated every 3 years. Water quality standards consist of three key elements:

1. *Designated uses*, which describe the waterbody's uses
    a. Examples: recreation, domestic water supply, aquatic life, fish consumption
2. *Water quality criteria*, which are scientifically based numeric or narrative criteria designed to protect designated uses
    a. Example: The geometric mean criterion to protect primary contact recreation in fresh water is 126 colony-forming units (cfu) of *Escherichia coli* per 100 ml of water.
3. *Antidegradation policies*, which are designed to keep clean waters clean

Because water quality standards serve as the basis for water quality management, appropriate standards must be applied to each waterbody. Applying incorrect designated uses and water quality criteria can result in wasted time, taxpayer money, and effort; take away resources from waters that truly require it; and, in the process, degrade stakeholder confidence in and support for restoration efforts. For example, when water quality standards were established in Texas, all classified segments, except those with significant ship or barge traffic, were designated as being used for primary contact recreation (i.e., swimming). No site assessments were completed to determine whether waterbodies were actually used for primary contact recreation or if they could physically support recreation (i.e., possessed

FIGURE 1.1 General water quality management framework in the United States. (Adapted from Parrish, G. 2006. Tribal WQS Training Academy—Introduction to assessment and attainment of water quality standards. First National Forum on Tribal Environmental Science. September 27, 2006, Ocean Shores, WA. http://www.epa.gov/osp/tribes/NatForum06/4_25a.pdf.)

needed width, depth, or accessibility). Over time, this resulted in hundreds of rivers and streams being identified as not supporting contact recreation (i.e., impaired). Subsequently, significant funding was, and continues to be, dedicated to develop and implement strategies to address these "impairments." This was partially corrected in the 2010 Texas Surface Water Quality Standards, and efforts are now underway to conduct the individual site assessments needed to accurately identify the true use of each river and stream.

Once water quality standards are established, each state monitors and evaluates water quality data collected to assess its compliance with applicable water quality standards. Waterbodies not complying with established standards must undergo remedial efforts to bring them into compliance. For those waters meeting standards, antidegradation policies are applied to ensure that they stay in compliance and their designated uses are maintained and protected.

1.2 SURFACE WATER QUALITY ASSESSMENT

Routine monitoring is conducted to assess overall water quality, evaluate changes over time, document pollutant loading identify areas needing protection, and assess the effectiveness of programs designed to restore and protect water quality. Monitoring assists in setting water quality standards, developing restoration strategies for waterbodies not meeting standards, and evaluating wastewater permits (Texas Commission on Environmental Quality [TCEQ] 2013). The CWA gives states the primary responsibility for monitoring and assessing the nation's waters and reporting on their quality. However, the EPA maintains oversight of state monitoring programs via CWA §106, which requires the EPA to determine if states have monitoring programs that meet CWA requirements.

1.2.1 Water Quality Monitoring

In the United States, only 29% of river and stream miles, 43% of lake and reservoir acres, and 38% of bay and estuary area have been assessed (EPA 2014a). Because of financial and logistic limitations, states have made trade-offs between the number of sites sampled and the frequency with which they sample. Monitoring is typically planned to maximize available resources so that data collected are (1) reasonably representative of the monitored waterbody both spatially and temporally, (2) acceptable for the planned uses of the data, and (3) focused on priority waters.

In Texas, sampling is generally carried out quarterly, allowing representation of the range of seasonal temperatures and flows (TCEQ 2013). Because of the general adoption of this monitoring frequency, Texas was able to evaluate 1214 waterbodies for its 2012 Integrated Report (TCEQ 2012b). Although this level of monitoring (quarterly) is suitable for providing baseline data when carried out over a long period, in many cases, it is not sufficient for characterizing watershed conditions and loadings, particularly for parameters with high variability (i.e., bacteria). As a result, waterbodies identified as impaired must routinely undergo verification monitoring to confirm the impairment and provide sufficient data for loading calculations.

1.2.2 Surface Water Quality Assessment Approaches

In compliance with CWA §305(b) and §303(d), states must routinely assess and report the current conditions of the states' waters and identify those not meeting water quality standards. EPA guidance requires states to document and submit this assessment biennially, in even-numbered years (TCEQ 2012a). Water quality is evaluated according to assessment guidance developed by each state. Based on the evaluation, waterbodies are placed in one of five categories: those attaining all standards (Category 1), those attaining some standards but data are insufficient to assess all uses (Category 2), those with insufficient data to make an assessment (Category 3), those where standards are not supported but no total maximum daily load (TMDL) is required (Category 4), and those where standards are not supported (Category 5).

Water quality criteria and screening levels generally apply to perennially flowing streams when flow exceeds critical, low flow conditions. Low flow measurements are excluded from waterbody assessments to help prevent inappropriate impairment designations resulting from these extreme hydrologic events (TCEQ 2012b). Similar exemptions are not made for extreme high flows in Texas (i.e., those exceeding the 90th percentile historical flow), although they were proposed in 2010 but disapproved by the EPA. However, high flow exemptions should be reconsidered as recreation is generally limited and best management practices (BMPs) are ineffective during these conditions.

Texas guidance requires a minimum of 10 samples (20 for bacteria), collected over the most recent 7-year period, to assess water quality standard attainment. The state established this minimum sample requirement to provide an acceptable balance between providing certainty in the assessment and using limited monitoring resources. However, in some cases, erroneous impairment designations occurred from using such limited data sets, which ultimately led to excessive expenditure of funds to identify and treat unsubstantiated problems.

1.2.3 Alternative/Complementary Approaches to Current Surface Water Quality Assessment Methods

To address identified issues from using minimal monitoring and data to assess water quality, a variety of approaches should be explored. This includes using risk-based approaches, increasing monitoring and data requirements for use attainment determinations, and increasing data frequency using surrogate relationships.

1.2.3.1 Risk-Based Approach

A risk-based approach is proposed to complement current water quality assessment methods, particularly as bacteria criteria are applied to protect recreational use. This method is postulated to better factor in both observed pollutant concentrations and exposure than the current application of numeric water quality criteria (i.e., 126 cfu *E. coli*/100 ml for primary body contact recreation). In 1986, the EPA promulgated this criterion based on an illness rate of 0.8% for swimmers in freshwater (EPA 2002a). The regression used to calculate the geometric mean density associated with this illness rate is

$$\text{Log } (E.\ coli \text{ geometric mean}) = 0.1064 \times \text{illness rate per 1000 swimmers} + 1.249.$$

This equation can be restated to evaluate the illness rate on the basis of observed concentrations:

$$\text{Illness rate per 1000 swimmers} = [\text{Log } (E.\ coli \text{ geometric mean}) - 1.249]/0.1064.$$

Thus, a waterbody with a geometric mean of 191 cfu/100 ml would be expected to have an illness rate of 9.7 per 1000 swimmers. If less than 100 people recreate in this waterbody annually as is the case in many rural waterbodies, then the expected number of illnesses observed would be approximately 1 annually. If less than 10 people recreate in this waterbody annually, then less than 0.1 illness would be expected annually or essentially 1 illness every 10 years. This approach strongly suggests that the level of recreation should be taken into account when evaluating impairments. If less than 10 people recreated in the example waterbody annually, the threat to public health is minimal because of limited exposure despite an exceedance of the water quality standard. Further research is needed to evaluate the application of such an approach; however, regulatory agencies should consider such risk-based approaches to ensure that resources are targeted to those waterbodies where public health is most threatened.

In 2010, Texas strove to better integrate exposure into application of the bacteria criteria in its water quality standards by establishing two additional beneficial uses, secondary contact recreation 1 and 2, for waterbodies where recreation activities do not involve significant risk of ingestion and where recreational activities are limited. The recreational use attainability analysis process, established to assign these new standards to specific waterbodies, could benefit from the risk-based approach outlined as well.

1.2.3.2 Increased Monitoring and Requirements for Impaired Status

Planning remedial actions such as TMDLs and other watershed-based plans (WBPs) is extremely costly. An assessment by EPA (1996b) found that, on average, development costs for TMDLs in watersheds with both point sources and NPSs averaged \$468,260 (in 1995 dollars). With inflation, that equates to \$732,326 in 2014 dollars. At this cost, increasing monitoring or requirements for impaired status designation is prudent to ensure wise use of public funds.

One strategy to reduce erroneous impairment designations and protect against unneeded expenditures resulting from using limited data sets is to increase the minimum number of samples required for assessing use attainment. If quarterly sampling is the generally accepted sampling frequency and the most recent 7-year period is used for assessing use attainment (as is the case in Texas), a rational approach would require a minimum of 28 samples for assessment purposes (instead of 10). This approach could be implemented with minimal cost.

Another possible strategy to reduce erroneous impairment designation is to collect 1 or 2 years of intensive (monthly or twice monthly) data before listing. Studies clearly demonstrate that uncertainty decreases with increased monitoring frequency (Spackman Jones et al. 2011). If the impairment is confirmed, an improved data set is then available for planning remedial actions. This approach is particularly applicable to marginally impaired waters. In 2012, the TCEQ initiated a similar approach to increase confidence that new bacteria listings are based on criteria exceedances rather than data variability. *E. coli* and *Enterococcus* data variability is considered using a two-tiered approach where (1) all waterbodies having more than 10 samples are initially screened to determine exceedance of the geomean, followed by (2) identification of impairments where sample size exceeds 20 and statistical confidence is sufficient to make this determination. For waterbodies with more than 20 samples, a confidence interval (CI) is calculated (at the 80% confidence level) to determine use attainment. If the lower boundary of the CI is below the state water quality criterion (i.e., 126 for *E. coli* or 33 for *Enterococci*), then the waterbody is not listed as impaired but instead identified as a concern and targeted for additional monitoring. Waterbodies are listed as impaired, however, if the lower boundary is above the criterion. This statistically based approach allows recreational attainment to be effectively assessed without requiring an extraordinarily high number of samples (TCEQ 2012a).

1.2.3.3 Use of Surrogate Variables to Increase Data Frequency

Using correlations between variables requiring laboratory analysis (i.e., nutrients, bacteria, suspended sediment) and those that can be measured frequently (or continuously) using in situ sensors (i.e., turbidity, electrical conductivity) can considerably increase data availability and the accuracy of waterbody characterizations and loading estimates. Surrogate relationships using turbidity, for example, have been found to provide high-frequency estimates of total phosphorus and total suspended solids (Spackman Jones et al. 2011) and reasonably predict *E. coli* concentrations (Brady et al. 2009; Collins 2003; Huey and Meyer 2010). Loads derived from high-frequency or continuous concentration records are considerably more accurate than loads calculated from routine sampling, which often poorly represents or totally misses storm and other runoff events (Spackman Jones et al. 2011). States are increasingly using continuous monitoring stations. Texas, for instance, continuously monitors almost 100 sites, measuring a variety of parameters (depending on the site) such as flow, water temperature, specific conductance, turbidity, total dissolved solids, dissolved oxygen, pH, ammonia, nitrate, and total reactive phosphorus. Increased use of continuous stations and employment of surrogate relationships will improve waterbody characterization whether for evaluating attainment or developing remedial strategies.

1.3 METHODS TO ADDRESS WATER QUALITY IMPAIRMENTS

When a waterbody is listed as impaired, states may use a variety of methods to address the impairment, including evaluating the appropriateness of existing water quality standards, collecting more data, or developing restoration plans (TCEQ 2010).

1.3.1 Water Quality Standards Review

If there is evidence that one or more of the assigned standards are inappropriate because of local conditions, waterbodies may be slated for a review of their standards via use attainability analysis (UAA). These analyses are assessments of physical, chemical, biological, and economic factors that affect attainment of individual waterbody uses. UAAs focusing on recreational waterbody uses are termed recreational use attainability analyses (RUAAs) and focus on quantifying the actual recreational uses of an assessed waterbody and its physical features that do or do not make recreation conducive. In most cases, RUAAs are carried out to determine if a designated recreational use other than primary contact recreation (e.g., swimming, wading by children) such as secondary contact (boating, fishing) is appropriate (TCEQ 2012c). Depending on UAA results, uses or associated criteria may be revised to be more or less stringent. Standards revisions are reviewed by the public, adopted by the delegated state agency, and approved by the EPA. When a review and resulting standards revisions are completed, the waterbody may be recategorized or removed from the *303(d) List* of impaired waters (TCEQ 2010).

1.3.2 Verification Monitoring

As noted earlier, use of limited data sets has caused erroneous impairment designations. Previously recommended improvements to the monitoring and assessment process can minimize verification monitoring needs; however, in some cases, verification monitoring will still be needed. Currently, when there is insufficient information to determine the best course of action to restore an impaired waterbody, additional monitoring data and information is collected to determine the degree and geographic extent of nonsupport, if a standards review is needed, or if a restoration plan is required. Depending on the results, waterbodies may be recategorized as unimpaired or placed in queue for a UAA or restoration plan development (TCEQ 2010).

1.3.3 Assessment of Recovery Potential

For waterbodies requiring watershed planning, prioritizing water quality restoration efforts is essential to efficiently allocate available resources and achieve timely restoration results. EPA developed the Recovery Potential Screening (RPS) tool to help prioritize waterbody restoration efforts (Norton et al. 2009) by determining which waterbodies have the highest likelihood of successful water quality restoration on the basis of characteristics of the local watershed (EPA 2014b).

RPS compares the relative ability of waterbodies or watersheds to recover from impairment by measuring a series of ecological, stressor, and social indicators associated with the likelihood of achieving restorative success. Ecological indicators evaluate features such as corridor and shoreline stability and biotic community integrity while stressor indicators assess characteristics such as hydrologic alteration and severity of pollutant loading. Additionally, social indicators examine elements such as local leadership, restoration costs, and other socioeconomic considerations. Users select indicators from a list of almost 200, based on what is appropriate for the waterbodies being screened, the availability and quality of data, and the goals of the planned restoration project. RPS calculates a Recovery Potential Integrated score by combining the weight of the selected indicators to establish an overall score. This score, in turn, ranks the comparative restorability of screened watersheds based on information provided (EPA 2014b).

In Texas, RPS has been applied to the Matagorda Bay watershed and various impaired segments in the Trinity River Basin. In its application in the Matagorda Bay watershed, Gregory et al. (2014) found that applying the RPS tool at refined scales to be problematic if only existing data are used. Data availability generally decreased with watershed size, thus diminishing its use at smaller scales. Gregory et al. (2014) concluded that the RPS tool is best suited to large-scale assessments such as those occurring at river basin (four-digit HUC) or statewide scales. Likewise, Lambert et al. (2013) found that the primary limiting factor in the application of the tool in the Trinity watershed was the availability of data. Further, Lambert et al. (2013) similarly concluded RPS to be most useful if applied, at least initially, on a larger scale (i.e., river basin scale) before application at more refined regional sub-basin levels or local project levels.

1.3.4 WATERSHED PLANNING

For waterbodies requiring restoration, TMDLs/TMDL Implementation Plans (I-Plans) or other WBPs must be developed, describing the means by which these waterbodies will be restored.

1.3.4.1 TMDLs and TMDL I-Plans

TMDLs are required by CWA §303(d) to address impaired waters and must be submitted to EPA for review and approval. Generally, a TMDL should be completed within 13 years of the initial listing of a waterbody (TCEQ 2010). TMDLs serve three primary purposes: (1) they determine the maximum amount (load) of a particular pollutant that a segment can receive each day and still meet water quality standards; (2) they identify predominant sources contributing pollutant loading; and (3) they allocate the allowable load and determine the necessary pollutant source reductions required. TMDLs also describe seasonal variations, address future growth, and include margins of safety to cover uncertainties.

Accompanying the TMDL is the TMDL I-Plan, which describes regulatory and voluntary activities necessary to achieve pollutant reductions identified in the TMDL (TCEQ 2010). I-Plans, developed by watershed stakeholders, specify regulatory limits for point source dischargers and recommend voluntary BMP implementation for NPS to address the pollutant of concern. I-Plans describe the management measures and control actions needed, the schedule for implementing them, and the legal authority for the regulatory control actions. They also provide reasonable assurances that voluntary practices will be undertaken. For instance, the plan may identify grant funds secured to implement voluntary actions. The plan also includes measurable results expected to be achieved through the plan, along with an effectiveness monitoring plan to determine its success. The ultimate goal is attainment of water quality standards, but additional, interim results may be included to assess progress toward that goal (TCEQ 2010).

1.3.4.2 Watershed-Based Plans

WBPs help to holistically address water quality problems by fully assessing potential contributing causes and sources of pollution and then prioritizing restoration and protection strategies to address these problems in a defined geographic area (EPA 2013a). They may be developed to protect high-quality waters, address threatened waters before they become impaired, or restore waterbodies for which TMDLs have been developed or are not practical (TCEQ 2010). These plans are developed locally, giving the decision-making authority to those most vested in the plan's goals. WBPs provide a coordinated framework for implementing prioritized and integrated water quality protection and restoration strategies driven by specific environmental objectives. Through the watershed planning process, stakeholders are encouraged to address *all* sources and causes of impairment and threats to surface water and groundwater resources within a watershed. WBPs are best developed and implemented through diverse, well-integrated partnerships to assure the long-term health of the watershed. Adaptive management is used to modify WBPs based on new knowledge gained through monitoring and evaluation of implementation strategies (TSSWCB 2014). WBPs can take many forms; however, most plans are developed consistent with EPA guidelines promulgated in 2003 and outlined in the *Handbook for Developing Watershed Plans to Restore and Protect Our Waters* (EPA 2008).

1.3.5 Comparison of Methods

Water quality standards review, verification monitoring, and watershed planning all aid in addressing water quality impairments; however, these methods are often haphazardly applied. Over time, though, an optimized approach to sequencing these methods has emerged. The process generally begins with characterizing the impaired watershed using existing data while simultaneously initiating general water quality awareness programs, preliminary surveys of waterbody use, and evaluation of the need for a UAA and additional monitoring. Subsequently, monitoring is conducted to fill data gaps or confirm impairments while water quality awareness programs continue and UAAs are completed where needed. Based on the watershed characterization, verification monitoring, and UAA results, the waterbody in question may be delisted (i.e., removed from the *303(d) List*) or advanced for watershed plan (TMDL or WBP) development. If watershed planning is required, then needed data and stakeholder awareness are in place to allow TMDL/WBP development and concurrent stakeholder processes to proceed most efficiently and successfully. Greater use of this approach will ensure efficient use of resources. Ideally, recovery potential assessments should be applied statewide or at the river basin scale before this process to best target resources where success is most likely.

1.4 WATERSHED PLANNING APPROACHES

Planning is important for achieving successful water quality restoration as it helps offset uncertainty, focus attention on objectives, gain economical operation, and facilitate control. Uncertainty in natural resource management is considerable, and as it increases, so does the need for planning. Since plans are developed to achieve specific objectives, they ensure that efforts are targeted and goal oriented. Effective planning minimizes costs by examining alternatives and costs projections before implementation. Well-developed plans also provide mechanisms for measuring progress and detecting deviations from goals.

1.4.1 HISTORY AND EVOLUTION OF WATERSHED PLANNING

Watershed planning is not a new concept. As far back as the *River Basin Study (308 Act) of 1925*, Congress authorized the US Army Corps of Engineers to complete comprehensive river basin studies (Kauffman 2002). The *Watershed Protection and Flood Prevention Act of 1954* (P.L. 83-566) authorized the USDA Natural Resources Conservation Service (NRCS) to help plan and implement watershed projects to prevent erosion, flooding, and sedimentation; further conservation and development of water resources; and further resource conservation in authorized watersheds (i.e., those up to 250,000 acres). Today, there are more than 1300 active or completed PL-566 watershed projects nationwide.

Since the enactment of the *Federal Water Pollution Control Act Amendments of 1972*, the development of TMDLs has been a recognized approach for restoring water quality. Further, EPA programs such as the Clean Lakes Program Phase I Diagnostic/Feasibility Studies used a watershed approach to determine the causes of pollution in a specific lake, evaluate potential controls, and recommend the most feasible and cost-effective restoration methods. Between 1976 and 1994, 352 Phase I Studies were conducted across the United States (EPA 2012).

Outside of these efforts, most early water quality work focused on point source permitting with little emphasis on NPS and watershed scale planning. Passage of the *Water Quality Act of 1987* prompted the first serious efforts to control NPS, thus necessitating greater emphasis on watershed-level management. Subsequently, a *Watershed Protection Approach Framework* was endorsed by senior EPA managers in 1991. Watershed-level planning to address water quality issues did not begin in earnest until a series of 39 lawsuits regarding the pace of TMDL development were filed against EPA in 35 states, mostly between 1997 and 2002.

Since that time, TMDL and NPS programs have evolved and accelerated watershed plan development to address water quality impairments. The *Nonpoint Source Program and Grants Guidance for Fiscal Year 1997 and Future Years* issued by the EPA (1996a) first outlined elements of a well-designed watershed plan. These elements are strikingly similar to those used today. In 1998, the EPA received a significant increase in funding to develop and implement Watershed Restoration Action Strategies (WRAS) under the CWA §319 NPS Grant Program, which further accelerated watershed planning nationwide (EPA 1998). The focus on WRAS development continued into 2001 when funding began shifting to TMDL development and implementation (EPA 2000). In 2001, NPS Program support continued for development of TMDLs, and the key elements of a well-designed watershed implementation plan, first outlined in 1996, were refined (EPA 2001). In 2002, the NPS Program Guidance explicitly outlined the nine key elements of a WBP that remain in use today (EPA 2002b). It was not until 2008 that EPA released its *Handbook for*

Developing Watershed Plans to Restore and Protect Our Waters, thus providing specific guidelines and expectations for developing and implementing WBPs. Although work continues on developing WBPs that meet EPA's 2008 guidelines, emphasis has now shifted to the implementation of these plans (EPA 2013b). Developing and implementing WBPs and TMDL I-Plans has been and will continue to be critical to the restoration of the more than 42,000 impaired waterbodies nationwide.

1.4.2 TMDLs and I-Plans

TMDLs are used nationally to improve water quality. As of 2013, more than 45,000 TMDLs had been completed with approximately 4000 new TMDLs developed annually (EPA 2013c). TMDLs and I-Plans vary from state to state; however, law requires all TMDLs to include the following:

- Numeric water quality target required to attain water quality standards
- Loading capacity of the waterbody
- Load and waste load allocations (i.e., allowable point source and NPS loading)
- Margin of safety
- Consideration of seasonal variation (EPA 2013d)

Additional elements typically contained within TMDL documents include the following:

- Identification of waterbody, pollutant of concern, pollutant sources, and priority ranking
- Reasonable assurance for point sources and NPSs
- Monitoring plan to track TMDL effectiveness
- Implementation plan
- Public participation (EPA 2013d)

All states except Texas combine TMDLs and corresponding implementation plans into one document submitted to and approved by EPA. Because submission of implementation plans is not required by law, the Texas I-Plan is a stand-alone document, separate from the TMDL, which is only approved at the state level (i.e., not submitted to EPA). In Texas, only the TMDL is approved by the EPA. Texas I-Plans generally include the following:

- Watershed overview
- Summary of TMDLs
- Implementation strategy
- Management measures and control actions
- Sustainability
- Water quality indicators
- Implementation milestones
- Communication strategy

TMDLs and I-Plans are traditionally waterbody and pollutant specific, but several states have recently developed statewide TMDLs to address a variety of pollutants. Connecticut, Vermont, and Rhode Island completed statewide bacteria TMDLs in 2010 and 2011, respectively. Minnesota and North Carolina completed statewide mercury TMDLs in 2007 and 2012, respectively. Michigan completed a statewide PCB TMDL in 2013. Given that the source of the mercury and PCBs addressed by these TMDLs is atmospheric deposition, development of statewide TMDLs to address these pollutants is plausible.

The prudence of developing statewide bacteria TMDLs is less obvious as bacteria sources and needed management measures can vary considerably between and within watersheds. Statewide bacteria TMDLs generally consist of a core document outlining applicable water quality standards, types of pollution sources, impaired waters addressed, TMDL allocation process, implementation process, funding sources available, and waterbody-specific reductions needed. Summaries of available data and information, reductions needed, and watershed maps for each impaired waterbody are included as appendices. Statewide bacteria TMDLs are followed by the development of WBPs meeting the EPA's nine key elements (CT and VT) or TMDL I-Plans (RI). Development of statewide bacteria TMDLs certainly expedites the delisting of waterbodies from the *303(d) List*; however, the advantages of this approach are unclear. Local stakeholder involvement appears more limited with statewide TMDL development. Also, public comments received regarding these TMDLs identify a number of limitations resulting from the limited data used and the lack of watershed-specific source identification and loading information provided. Public comments indicated that stakeholder ability to identify, prioritize, and target implementation measures is greatly compromised as a result. Although it can be argued that bacteria sources and remediation measures are similar statewide, these statewide approaches do not appear to be noticeably more efficient than developing waterbody-specific TMDLs or WBPs. Since individual WBPs (or TMDL I-Plans) are developed in response to the statewide TMDLs and require additional resources, significant financial gain is unlikely.

Some states have used TMDL and TMDL I-Plan templates to expedite the development process. This may provide a feasible alternative to statewide TMDLs, providing an expedited process for development while still allowing individual watershed characterization and targeting of BMPs.

1.4.3 WATERSHED-BASED PLANS

WBPs are less common than TMDLs but have been increasingly employed to address water quality issues over the last decade. The EPA provided extensive guidance on developing (EPA 2008) and reviewing WBPs (EPA 2010) to ensure that the WBPs adequately address the nine key elements critical for achieving improved water quality. The EPA's nine key elements are as follows:

a. Identification of causes and sources of impairment
b. Expected load reductions from management measures
c. Proposed management measures
d. Technical and financial assistance needs

e. Information, education, and public participation
f. Schedule for implementing management measures
g. Interim milestones for progress in implementation
h. Criteria for determining pollutant load reductions and water quality improvement
i. Load reduction and water quality monitoring

WBPs are generally voluntary, locally driven efforts designed to address all sources and causes of watershed impairments and threats. While EPA (2008) recommends WBPs address watersheds that are 250,000 acres or smaller (i.e., 10- or 12-digit HUCs), WBPs addressing much larger watersheds—Arroyo Colorado (451,840 acres), Lampasas River (839,800 acres), Pecos River (12,434,468 acres)—are common. WBPs can be developed as stand-alone documents or can implement completed TMDLs (EPA 2008) as well as integrate a variety of programs including those addressing water quantity, source water assessment and protection, urban development, and wetland and habitat protection and restoration or others as appropriate.

A major benefit of developing WBPs is that once accepted by the EPA, implementation funding is then available via the CWA §319 program. This has incentivized stakeholders and states to increasingly develop and implement WBPs.

1.4.4 COMPARISON OF TMDLs AND WBPs

TMDL I-Plans and WBPs are similar in that they use similar data sets and analysis tools, have the goal of improving water quality, define loading reductions and actions needed to achieve water quality restoration, are developed in cooperation with regional and local stakeholders (TCEQ 2010), and implement NPS management measures using a voluntary approach. Both must be approved or accepted by the EPA, although in Texas, I-Plans are only approved by the state.

Several notable differences in these watershed planning approaches should be considered when selecting the best approach for a particular waterbody impairment, including the following:

- TMDLs result in automatic removal of waterbodies from the *303(d) List* while WBPs must undergo an arduous process to result in removal.
- TMDLs focus on a singular pollutant in most cases while WBPs can focus on multiple pollutants and issues.
- TMDL point source controls are compulsory while similar WBP measures are voluntary.
- TMDL I-Plans are remedial actions for impaired waters while WBPs may be either remedial or preventive.
- I-Plans are based on TMDLs while WBPs can be based on TMDLs or use other environmental measures to design goals for water quality (TCEQ 2010).
- EPA-accepted WBPs are eligible for NPS grant funds while TMDL I-Plans are not.

In most states, both methods are used to address the large numbers of impairments. In Texas, WBPs are targeted to threatened or recently listed waterbodies (listed in the *303(d) List* in the preceding 6 years) with the goal of achieving water quality standards before a TMDL must be established. Alternatively, TMDLs are targeted to waterbodies on the *303(d) List* for more than 6 years to ensure that measures are in place within 13 years of their listing (TSSWCB 1996).

When deciding how best to restore an impaired waterbody, the merits of each approach and applicability to the particular watershed should be considered. Certainly, it is advantageous that TMDL development results in automatic removal of the waterbody from the *303(d) List*; however, the EPA's acceptance of a WBP qualifying the watershed for NPS grant funding is of great benefit as well. Based solely on these two considerations, it would seem reasonable to develop TMDLs for all impaired waterbodies and subsequently develop WBPs for watersheds where NPS is a dominant source to qualify them for grant funding to assist with implementation. For those impaired only by point sources, TMDL I-Plans are likely most suitable.

1.5 THE WATERSHED PLAN DEVELOPMENT PROCESS

The *Handbook for Developing Watershed Plans to Restore and Protect Our Waters* (EPA 2008) outlines a detailed planning process based on six major steps in watershed planning:

1. Build partnerships.
2. Characterize the watershed.
3. Finalize goals and identify solutions.
4. Design an implementation program.
5. Implement watershed plan.
6. Measure progress and make adjustments.

Despite the excellent guidance provided by the EPA, watershed planners frequently struggle with sequencing their efforts to best integrate the scientific and stakeholder processes required to develop and implement a plan.

1.5.1 Linking Process and Plan

At the outset, it is advisable to have face-to-face meetings with key stakeholders before the first stakeholder meeting and maintain close communication with them throughout the process. This allows the planner to directly respond to individual stakeholder questions that might not come out in a public setting, alleviate concerns, and provide needed assurances in a private setting. Initial face-to-face meetings allow the planner to begin gathering preliminary input regarding water resource issues of concern, water quality goals, and ongoing activities or those previously undertaken or planned in the watershed that will affect water quality. Discussions at initial stakeholder meetings can be based on this preliminary input. Throughout the watershed planning and implementation process, it is important to continuously conduct public outreach to increase public awareness of local water resources and issues influencing them, efforts to improve local water resources, and opportunities for local involvement.

Watershed characterization is initiated and conducted just before or concurrent with initial outreach efforts and partnership building. This can proceed rapidly unless additional monitoring is required. The first step in watershed characterization is to compile existing data on water quality and potential pollution sources. EPA guidance (2008) provides an extensive listing of reports and data useful for watershed characterization. Initial data analysis should include statistical summaries and preliminary pollutant loading assessments. Load duration curves can accomplish this and allow development of initial loading reduction estimates and suggest the prominence of point source or NPS pollutant loading in the watershed. Preliminary characterizations should provide significant insight into current pollutant loadings, reductions needed, potential causes and sources of pollution, and the presence of data gaps that must be filled before proceeding with planning. Characterization results should be presented to key stakeholders early on to gather input regarding results. This input should aid in filling identified data gaps and drafting initial sections of the WBP (causes and sources of pollution and load reduction needed) or TMDL (numeric water quality target and loading capacity).

Once the identified data gaps are addressed, work with stakeholders to finalize goals and objectives, as well as the load reductions needed to meet these goals, can proceed. It may be advisable to establish work groups to address major source categories (i.e., agriculture, wastewater), identify management measures to achieve goals, and identify critical areas for implementation. An iterative process is required to develop management measures required to achieve goals. Either literature values or a watershed model is needed to assess the level of recommended management measure implementation necessary to meet water quality goals. Finalizing development of management measures to achieve goals typically requires several iterations of discussion with stakeholders to reach a consensus on the level of implementation needed for each management measure.

After a consensus is reached, completing the design of the WBP or I-Plan can proceed rapidly. Based on the recommended management measures, implementation cost estimates and funding sources can be identified. This evaluation will determine how quickly implementation will proceed and guide development of the implementation schedule. This schedule serves as the basis for developing interim milestones that will act as checks regarding the rate of implementation. Additionally, with the implementation schedule and literature values or watershed model used for evaluation of management measures, estimates of water quality status at various points during implementation can be determined. A monitoring plan is established to measure progress in meeting these water quality estimates. Finally, an education and outreach plan is developed to guide these efforts throughout the implementation process. From here, efforts shift to implementing the watershed plan, measuring progress, and making adjustments (adaptive management), as needed.

1.5.2 Time Frames for Development, Tools Required, and Costs

In Texas, EPA-accepted WBPs have required at least 2 years and on average 3 1/2 years each to develop. Extended planning time frames such as this have resulted in disengaged or frustrated stakeholders. It has been suggested that an intensive 6- to 12-month time frame is feasible and appropriate for gaining stakeholder input, keeping them engaged throughout the process, and completing the plan more quickly. A well-designed and organized stakeholder meeting schedule, integrated with timely modeling, data analysis, and writing, makes this time frame achievable. Before beginning this intensive stakeholder process, 6 to 12 months should be invested in characterizing the watershed and identifying/informing key stakeholders. It may be advisable to hold a kick-off meeting to inform local leaders and communities about the effort and time frame. This approach can reduce the time needed to 1 to 2 years, thus expediting the move to implementation.

Complex watershed models and direct loading estimates from monitoring data and literature values are commonly used to develop WBPs and TMDLs (EPA 2008). Costs, available funds, data availability, stakeholder needs, and planner capabilities must be considered when selecting the approach. Generally, the simplest approach that yields the required information and satisfies stakeholder needs is recommended. In some cases, more complex and costly hydrologic models may be needed or desired to evaluate implementation alternatives. However, they should be used sparingly and only as warranted because of their expense. Using simple techniques for initial plan development is recommended because watershed planning is an iterative process employing adaptive management, where more complex models can be used in later stages as needed.

Watershed planning is currently very costly. As previously discussed, development costs for TMDLs addressing both NPSs and point sources averaged $468,260 in 1995 ($732,326 in 2014 dollars). Similarly, median development costs for 13 WBPs in Texas were $830,703, with $498,422 provided by CWA §319 funds and $332,281 provided by local partners. A streamlined development process using simplistic, scientifically based methods is needed to reduce development costs, expedite planning, and quickly move watersheds to implementation. This could include development of (1) WBP and TMDL templates; (2) standard practices for calculating loads and load reductions, writing plans, and conducting stakeholder processes; and (3) mentoring programs allowing experienced planners to assist new watershed planners.

1.5.3 Stakeholder Involvement: A Look at Various Approaches for Engagement and Effective Approaches

Watershed planning and implementation success is ultimately determined by the level of local buy-in. A scientifically based plan developed using the most advanced tools will not restore water quality if local support is lacking. This fact makes building strong watershed partnerships a critical first step and cornerstone for developing effective watershed plans. No single stakeholder process will work across all watersheds; various types of stakeholder groups can be formed and function well using a variety of processes. Importantly, the group must be representative, consist of key stakeholders, and able to work together within established guidelines. Koontz and Johnson (2004) found that the larger the number of interest areas represented and greater mix of stakeholder types (in terms of sector—public and private) involved, the greater the likelihood of successfully developing a plan, prioritizing issues, and reporting accomplishments.

Although it is important to ensure that the public is aware of efforts and has the opportunity to provide input and comment, key stakeholders must be identified, actively involved, and buy in to the plan. Key stakeholders are those who have the ability to make the measures ultimately described in the plan happen (i.e., fund them) either through direct authority or influence. In watersheds addressing agricultural NPS, it is critical to involve local soil and conservation districts and NRCS field offices, which are responsible for funding implementation of agricultural practices at the local level. It is also critical to involve county Extension agents as they are responsible for education and outreach at the county level and provide direct linkages to county commissioners' courts and other local leaders. City officials or staff responsible for managing wastewater and storm water infrastructure and county officials responsible for septic system inspection should also be engaged early. These groups should be the first contacted in any watershed; however, other leaders should be sought out including industry and local thought leaders. During individual discussions with this initial group, gathering recommendations on other local leaders to involve is important. Multiple recommendations to include a particular individual provide a clear indication that they should be included.

Barriers to stakeholder involvement during both the development of a watershed plan and its implementation exist. Getting stakeholders to attend meetings is commonly problematic because of lack of awareness of meetings, interest in the subject, time available to attend, purpose of meetings, regard for the resource discussed, or understandability of technical information presented at prior meetings. These barriers should be identified and addressed early if possible. Stakeholders must see value in the resource and in their participation. Thus, highlighting the value of the water resource and having efficient meetings with clear purpose and result in action being taken are critical needs for maintaining stakeholder support.

1.6 KEY PRACTICES AND PROGRAMS INCLUDED IN WATERSHED PLANS

Every watershed plan is different; however, there are key practices and programs frequently recommended to address the major source categories and others that should be considered.

1.6.1 Common Practices and Programs

1.6.1.1 Agricultural NPS BMPs

Agricultural BMPs are commonly found in WBPs and TMDLs. These practices are implemented voluntarily by producers, oftentimes with (1) technical and financial assistance provided by local soil and water conservation districts, state conservation agencies, or NRCS, and (2) education programs and BMP demonstrations provided by Extension. The Texas NRCS *Field Office Technical Guide* contains more than 100 practices to address agricultural natural resource concerns (NRCS 2002).

Recommended BMPs depend on land use, soil type, topography, producer goals, resource concern addressed (i.e., nutrients, bacteria, sediment), and other site-specific factors. NRCS has identified essential practices for each land use including conservation crop rotation and residue management for cropland, and prescribed grazing and watering facilities for pasture and range land. NRCS also recommends nutrient management where fertilizer is applied, pest management where pesticides are used, animal waste management systems for animal feeding operations, and irrigation water management for irrigated cropland. These practices, along with erosion control measures needed to bring soil loss to acceptable levels, form the core of a resource management system and address an array of water resource issues (NRCS 2005).

Reducing or eliminating tillage to improve surface residue, using soil tests to determine nutrient application rates, scouting for weeds and insects to target pesticide applications, and installing buffers along water courses to filter runoff and increase infiltration are considered the “Core 4 Practices” for cropland. These BMPs improve soil and water quality and increase farmer profits (CTIC 2014). For range and pasture land, proper grazing management, or prescribed grazing, is the core practice with complementary practices such as cross fencing and installing alternative water sources commonly prescribed as well. For operations with flowing streams, particular attention must be paid to managing grazing within riparian areas to ensure that streambanks are not destabilized and vegetation is not overgrazed. Rotational grazing of these “creek pastures” is a particularly effective practice to help safeguard these sensitive areas and protect water quality.

1.6.1.2 Urban NPS BMPs

Urban storm water is primarily managed via municipal separate storm sewer system (MS4) permits and local ordinances. These programs, along with education programs, ultimately lead to physical practice installation. Urban NPS BMPs rely on infiltration, filtration, detention, and retention to treat runoff. Infiltration trenches and basins, porous pavement, and filtration basins reduce urban runoff volumes by encouraging storm water absorption. Filter strips, riparian buffers, and grassed swales treat runoff using vegetation to filter and settle pollutants. Detention and wet ponds temporarily impound runoff to control runoff rates and allow settling and retention of suspended solids and associated pollutants.

1.6.1.3 Wastewater Management

Wastewater is managed via a variety of federal, state, and local laws. Individual onsite sewage facilities (OSSFs) are regulated by states and local governments. Because 20% of all homes in the United States rely on them and an estimated 10%–20% of all OSSFs malfunction each year (EPA 2014c), WBPs and TMDLs frequently include OSSF inspection, repair, replacement, or decommissioning and connection to a wastewater treatment facility (WWTF).

The remaining wastewater is collected and transported via sanitary or combined sewer systems and treated by WWTFs to the level required to meet specific standards outlined by state or federal permits. Combined sewer systems collect runoff and wastewater in the same system while sanitary sewer systems only collect sewage. TMDLs and WBPs commonly address WWTF permitting and compliance issues, as well as unauthorized discharges resulting from sanitary and combined sewer overflows. Addressing WWTF permits, noncompliance, and overflows can be costly owing to associated infrastructure expenses; however, they result in direct water quality improvements.

1.6.1.4 Educational Programs

Education programs are critical for implementing TMDL I-Plans and WBPs; however, they are generally designed to increase awareness of local water resources. Targeting the program messages (i.e., about issues with local resources, specifics of what can be done to mitigate issues, and importance of addressing them) and audiences (i.e., agricultural producers, OSSF owners, etc.) is important to increase the adoption of voluntary measures. Additionally, education on specific measures to groups such as elected officials can be vital when expensive infrastructure improvements are required. Various programs have been developed to address specific issues among target audiences (i.e., *Lone Star Healthy Streams*, which informs livestock owners in Texas on bacteria issues and BMPs), and these programs have been successfully implemented in watersheds where WBPs and TMDLs are being implemented. Without such education programs, the goals outlined in TMDLs and WBPs would not be achieved because of a lack of awareness by local stakeholders of water quality issues/concerns and the measures to address them.

1.6.1.5 Implementation Monitoring

Monitoring implementation progress is also critical to the success of WBPs and TMDLs. As the old adage states, “You can’t manage what you don’t measure.” It demonstrates progress, or lack thereof; helps identify when course corrections are needed; keeps stakeholders engaged; and ultimately documents restoration. Unfortunately, sufficient resources are not typically dedicated to implementation monitoring, and many plans rely on existing routine monitoring to evaluate success. Much more monitoring is generally needed to show progress and document success.

1.6.2 DIVERGENCES

Management measures and control actions included in WBPs and TMDLs vary depending on the causes and sources addressed. Aside from these two variables, divergences from commonly used practices are limited. Success is generally most dependent on appropriate targeting, local buy-in, dedication of required resources, and sufficient monitoring.

1.6.3 EMERGING PRACTICES FOR SUSTAINABLE MANAGEMENT

Significant opportunities to enhance water management, improve efficiency, and sustain water resources through increased technology use and greater integration of watershed planning, green infrastructure and smart growth programs, environmental flows programs, and water supply planning exist. Each of these program types can have considerable benefits to water quality and quantity along with other environmental benefits when properly integrated and implemented.

Green infrastructure encompasses an array of practices ranging from low impact development practices such as rain gardens, permeable pavements, green roofs, tree planting, and rainwater harvesting to large-scale preservation and restoration of forests, floodplains, and wetlands. Regardless of size, the premise behind green infrastructure is to mimic nature and ultimately keep rain where it falls when possible, thus reducing downstream water quality issues and storing more water on-site (American Rivers 2014). New technologies are increasingly available to improve water management, increase system efficiencies, and benefit water quality. For example, new irrigation technology (i.e., soil moisture, rain, and plant stress sensors; ET-based controllers) is increasingly being used to improve water use efficiency, conserve water, and reduce runoff from irrigated cropland, lawns, and landscapes. Improved sensors are also allowing continuous monitoring of a greater number of constituents, improving data availability and water management. Other technologies, such as supervisory control and data acquisition (SCADA), are helping to improve drinking water treatment and distribution as well as wastewater collection and treatment.

Decentralized wastewater treatment systems are a valuable watershed protection tool to cost-effectively and sustainably target problem areas. Many communities are considering them because of the economic and environmental advantages they offer. When properly maintained and operated, decentralized treatment can provide the safety and reliability of conventional large-scale WWTFs, while avoiding large capital costs associated with collection systems, reducing operation and maintenance costs, minimizing solids handling, and enhancing opportunities for reuse of wastewater.

Wastewater reuse has increased in recent years, particularly in arid regions. As a conservation tool, treated wastewater is being reused to irrigate public parks, fracture oil and gas wells, and supply drinking water, or stored in aquifers for later use. Reuse can benefit water quality as it lowers freshwater withdrawals while reducing point source discharges and associated pollutant loadings to surface waters. Alternatively, reuse may negatively affect those waterbodies where WWTF discharges are of good quality and form the majority of base flows. Site-specific evaluation of reuse is needed to ensure that multiple benefits of increased water supplies and improved water quality are achieved. Water conservation is increasingly encouraged to improve in-home, lawn and landscape, and agricultural irrigation water use efficiency. Conservation reduces water use (leaving more in lakes, rivers, and aquifers), wastewater generation and discharges, urban runoff, and agricultural irrigation return flows (reducing pollutant discharges). Increased integration of these efforts into WBPs and TMDLs will ultimately improve implementation, success, and sustainability of the plan and the watershed.

1.6.4 Recommendations for Improving Watershed Plans

Continued inclusion of traditional practices in WBPs and TMDL I-Plans remains an effective strategy for restoring water quality; however, improvements can be made.

Outreach and education should be expanded to encourage implementation, better targeting of BMPs is needed to achieve water quality improvements, and enhanced monitoring is needed to document success. Increased use of new technologies can greatly enhance water management and should be included where possible.

It is also imperative that other water programs be taken into account and integrated into WBPs and TMDL I-Plans to achieve common goals where possible. Wetland restoration, wildlife habitat improvement, environmental flows protection, water conservation, water resource development, and other natural resource planning/implementation efforts all affect water quality. Likewise, water quality restoration efforts and practices affect these efforts. These programs should be integrated where possible to increase efficiency and effectiveness, expand support (monetarily and otherwise) for implementation programs, increase likelihood of implementation, and increase the probability of success.

1.7 IMPLEMENTATION OF WATERSHED PLANS

Once watershed plans are completed and accepted/approved, the roles and focus of watershed coordinators and stakeholders change substantially as focus shifts from plan development to implementation. This presents numerous challenges, particularly with regard to maintaining momentum and sustaining implementation over many years. Effectively transitioning from development to implementation is critical because even the best plan will fail to restore water quality if it is not effectively implemented.

1.7.1 Transitioning from Planning to Implementation

In order to successfully implement a watershed plan, (1) a sustainable organizational structure must be created, (2) funds must be secured (and well-managed) to implement the management measures and control actions recommended in the plan, (3) monitoring must be initiated to track implementation progress and water quality changes, and (4) education and outreach must be conducted to encourage implementation and keep stakeholders informed of efforts and results.

To facilitate this transition, the focus of the watershed coordinator shifts to that of a fund raiser/grant writer, project/program manager, implementation tracker, educator, and communicator. Securing implementation funds for measures outlined in the WBP or I-Plan is paramount. The watershed plan serves as the foundation for preparing proposals by providing the need statement for recommended measures, implementation goals, expected outcomes, monetary needs, and implementation timelines and targets. Concurrently, it is important to initiate monitoring and assessment of water quality and implementation to track progress as compared to milestones/targets and provide feedback into the program regarding needed course corrections. Throughout implementation, continuous communication of implementation status and results, particularly with local leaders, elected officials, and others involved, is essential to build credibility, garner support for implementation, strengthen accountability among partners, and stimulate further stakeholder involvement.

Maintaining stakeholder involvement can be challenging during the transition between planning and implementation. This phase, however, provides a good opportunity to evaluate the stakeholder group makeup, organizational structure, and other factors and assess needed changes to ensure sustainability. Stakeholders who developed the plan should be surveyed regarding their continued interest in participating. Additionally, it is imperative that those responsible for implementing various aspects of the plan be actively involved. Meeting frequency should be discussed as implementation efforts generally require less frequent (i.e., quarterly, semiannual, or annual) meetings than plan development.

Various financial and social barriers often prevent full implementation of watershed plans (Reimer et al. 2011). Implementation costs commonly exceed a waterbody's perceived value to the community and are viewed as excessive when a waterbody is rarely used. Further, stakeholders often believe others are responsible for the impairment and thus decline taking action. Education and awareness, social considerations (i.e., beliefs about practice effectiveness), and infrastructure (physical attributes of what practices should be applied to) are the most common implementation barriers (Rodriguez et al. 2008). These should be mitigated before implementation by reducing the complexity of planned implementation, effectively conveying practice benefits and compatibility, demonstrating practices so that stakeholders can physically observe a practice before adoption, providing educational resources regarding practices, and routinely reporting implementation impacts (Rogers 2003).

1.7.2 Maintaining Momentum

Maintaining stakeholder momentum is a difficult task. Bureaucratic red tape can slow progress and impede momentum. It often takes years to secure needed funding and implement certain measures (i.e., infrastructure improvements) and the level of funds needed may seem impossible to generate. Water quality response to implementation oftentimes takes even longer. Watershed coordinators must work diligently to continuously show progress, demonstrate that local efforts have been worthwhile, and continue promoting additional implementation efforts.

Creating volunteer opportunities is a great way to engage stakeholders and demonstrate local value. Volunteers can provide a wide array of support for administration, outreach, and monitoring. Events such as stream and lake cleanups can increase program visibility and provide opportunities for involvement. Volunteer monitoring can also greatly assist in maintaining momentum by engaging the public in water quality assessments, informing them of water quality, providing more data (increased monitoring frequency and number and distribution of sites), and allowing better targeting of restoration measures and tracking of success all at a low cost. If watershed managers effectively engage stakeholders, successfully secure funds, and routinely report progress and results, momentum will be maintained.

1.7.3 Sustainability

Long-term, successful implementation requires a local presence that is supported by sustainable funding and organization, in pursuit of a significant cause. Most TMDL I-Plans and WBPs are written with 5- to 10-year implementation time frames, but many require much longer. State and federal funds for WBP or TMDL

I-Plan implementation are limited, particularly for the extended time frames usually required to achieve water quality improvement. Securing sufficient local funding to implement plans should be the ultimate goal for achieving sustainable implementation as it fosters better local stewardship, bestows more local control, and is a good investment for local governments and businesses.

From an organization perspective, experience has shown that one size does not fit all when it comes to structure, coordination, or funding. Multiple organizational models have been successful in sustaining implementation, including the following:

- Governmental organizations
- Quasi-governmental organizations
- Cooperative extension programs/universities
- Nongovernmental organizations (NGOs)
- Fee-based systems
- Hybrid models

Stakeholders should evaluate local conditions and assess opportunities for joining efforts with existing organizations or determine if a new organization should be established. If a new organization is established, the advantages and limitations of each should be considered. Local, state, and federal governments sometimes allocate permanent funding for local or regional resource protection (i.e., National Estuary Programs); however, this is uncommon. Establishment of quasi-governmental organizations (i.e., river authorities) to support watershed efforts has been successful in some cases but does require legislative action for creation. Frequently, NGOs, such as foundations and trusts, are created. These tax-exempt organizations are recognized for their ability to create and sustain grassroots stewardship using donations, grants, and fund-raising events. Fee-based systems (i.e., regional partnerships and task forces) have been established to provide services to participating local or regional governments in addition to fostering stewardship. These systems, which are often administered by academic or other tax-exempt organizations, require interlocal or intergovernmental agreements to establish and fund. Hybrid models, such as those partnering NGOs with permanent support from local, state, or federal agencies (e.g., Coastal Bend Bays Estuary Program), have also been successful. Each organizational structure has its advantages and disadvantages, and should be evaluated to determine the best fit for local conditions.

1.8 ANALYSIS OF WATERSHED PLAN IMPACTS

To assess the characteristics of successful watershed plans, 52 of the 295 CWA §319 NPS Success Stories (EPA 2014d) were evaluated representing every state in the United States except Oregon, New Jersey, New Hampshire, Florida, and Colorado. Approximately 23% of those evaluated addressed dissolved oxygen and biotic integrity, 23% addressed nutrients, 35% addressed bacteria/pathogens, and 19% addressed sediment/turbidity. For each success story, the parameter addressed, percent reduction achieved, segment size or watershed size, duration of implementation, implementation costs, and key practices implemented were documented where possible (not all success stories provided these variables). This analysis provides insight into the characteristics of successful watershed plans, but analysis of all success stories and more consistent reporting of key elements are recommended for future success stories and evaluations.

1.8.1 CHARACTERISTICS OF SUCCESSFUL WATERSHED PLANS

On the basis of median values observed, the typical successful watershed plan addressed a 12-mile waterbody segment, required 8 years to implement, and cost $1 million; however, these varied significantly. Segment lengths addressed ranged from less than 1 mile to more than 100 miles, implementation required from 2 to 35 years, and costs ranged from $3000 to more than $49 million. Considering all data, no significant correlations were observed between miles restored and cost (Figure 1.2) or duration (Figure 1.3) of implementation.

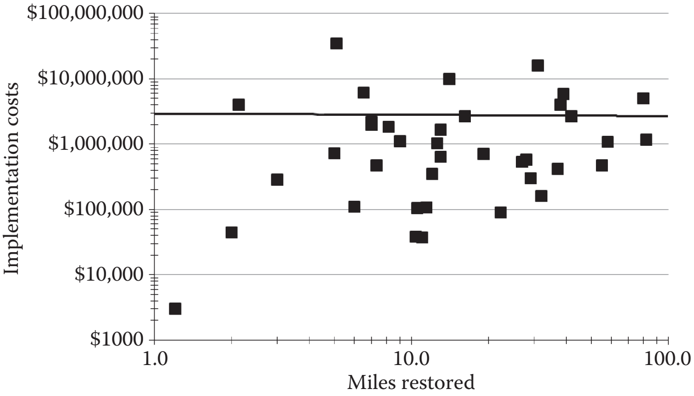

FIGURE 1.2 Comparison of implementation costs to miles restored.

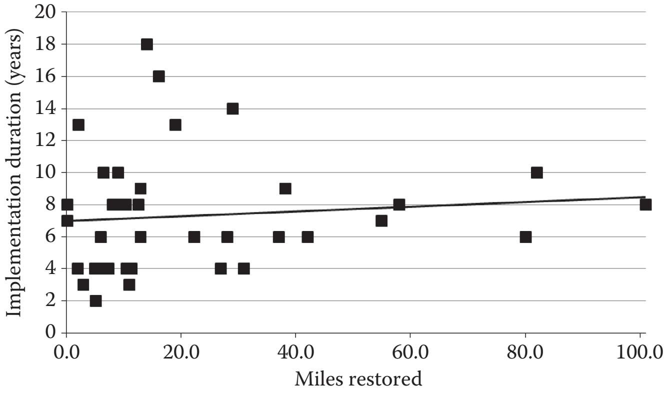

FIGURE 1.3 Comparison of implementation duration to miles restored.

Cost per mile restored varied considerably with cause of impairment (Figure 1.4). Overall, addressing sediment was most expensive while addressing pathogens was least. The median cost per mile restored was more than $90,000 for sediment impairments, almost $65,000 for dissolved oxygen, more than $45,000 for nutrients, and exceeded $20,000 for pathogens. Because of the high variability in costs, there were no significant differences between costs regardless of cause of impairment.

Considerable reductions were achieved with these watershed plans. Of the nine success stories reporting the percent reductions achieved, 31% to 99% reductions were observed with a median reduction of 80%. Of the 17 reporting watershed size, 5 were less than 40,000 acres (12-digit HUCs), 8 were 40,000–250,000 acres (10-digit HUCs), and 4 were 250,000 acres (8-digit HUCs) or larger.

The following were the practices most commonly implemented in these successful watershed plans:

- Fencing including livestock exclusion and riparian fencing
- Animal waste management
- Alternative water
- Riparian protection and restoration
- Education
- Grazing management
- Nutrient management
- Heavy use area protection
- OSSF repair and replacement

Interestingly, WWTF upgrades were listed as a key practice in only one success story reviewed, but this is likely because NPS Success Stories were the source of these data. Surprisingly though, few urban BMPs were listed as key practices.

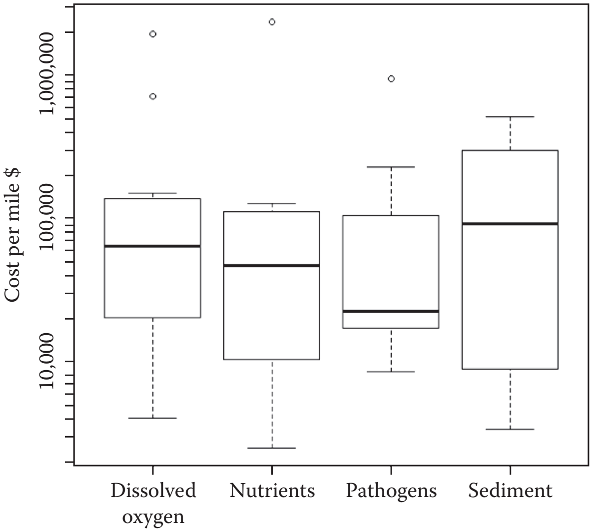

FIGURE 1.4 Cost per mile restored by cause of impairment.

Essential agricultural BMPs (as identified by NRCS), education, and OSSF repair and replacement, along with riparian and heavy use area protection and fencing, were the practices most commonly identified as resulting in water quality restoration and implementation success.

1.8.2 Recommendations for Improving Watershed Plan Impacts

Despite the EPA's recommendation to target WBPs to 12-digit HUCs, success is commonly achieved at larger scales. Plans should be developed on scales that are logical for the watershed and current issues. Conversely, the EPA's recommendation to utilize a 5- to 10-year implementation time frame appears to be an appropriate recommendation. Only 17% of the waterbodies required longer than 10 years to restore. Although there are no "silver bullets" for improving water quality, implementation of essential agricultural BMPs in conjunction with education programs, OSSF repair and replacement, and practices to protect riparian and heavy use areas have been successful in restoring water quality and should be a component of most watershed plans. Regardless of the parameter addressed, implementing watershed plans can be costly; thus, raising stakeholders awareness and involvement and securing adequate funding to support needed implementation are critical.

1.9 IMPACT OF TRAINING/SUPPORT PROGRAMS FOR WATERSHED PROFESSIONALS ON SUCCESS OF WATERSHED PLANNING AND IMPLEMENTATION EFFORTS

In 2002, the EPA instituted new guidelines for the development of WBPs and subsequently hosted just two courses entitled "Watershed Partnerships: Collaboration for Environmental Decision Making" in 2003 and 2004 to help participants from across the United States with plan development. Impacts of discontinuing this course surfaced in a 2006 assessment of watershed plans from across the United States, which identified severe deficiencies in the watershed plans developed to that point (Scozzafava 2006). In response, Texas assembled a multiagency team to develop a training and support program to improve watershed plan development in the state.

1.9.1 Professional Development Courses and Trainings

In 2007, Texas tailored the discontinued EPA course to develop a training program for delivery in Texas. Between 2008 and 2013, seven *Texas Watershed Planning Short Courses* were held. This short course is the only watershed planning course of its kind in the nation, and as such approximately 15% of attendees are from out of state. This course provides instruction on stakeholder coordination, education, and outreach; meeting the EPA's nine key elements of a watershed plan; data collection and analysis methods; and tools available for plan development. Since the initiation of the course, WBPs and the stakeholder-driven watershed planning process instilled through the course have become the foundation for water quality improvement efforts in Texas. Practitioners developing both WBPs and TMDL I-Plans have participated in the course and are now using the techniques learned to address water quality issues. Approximately 30 watershed planning efforts and almost a dozen more TMDL I-Plans have benefited from the training. Of the more than 228 short course participants, the majority are currently involved in watershed planning efforts in Texas and elsewhere across the United States (Dictson and Wagner 2013). Additionally, this short course has now been adapted into a graduate-level course at Texas A&M University and was used to train 16 graduate students in proper techniques for developing WBPs during the 2013 academic year.

Ultimately, the program's success is measured by water quality improvement in the state. Such improvements are being observed in watersheds across Texas by those participating in the course (i.e., restoration of Buck Creek), and more are expected. Success is also measured in the knowledge gained by participants. Pre- and post-examinations given to Short Course participants have shown increases in knowledge ranging from 53% to 98% and averaging 76%, demonstrating the course's success. Participants leave the course extremely satisfied with their experience (95% satisfaction rating), ready to implement what they have learned (Dictson and Wagner 2013).

1.9.2 Watershed Coordinator Forums

In 2009, Texas began hosting semiannual *Texas Watershed Coordinator Roundtables*. These roundtables, attended by 75 watershed managers on average, serve as forums for maintaining dialog among watershed coordinators, facilitating interactive solutions to common watershed issues faced, and adding to the fundamental knowledge conveyed at the short courses. Topics addressed include the following:

- Sustainable organizational structure for long-term WPP implementation
- Strategies and expectations for demonstrating successful implementation
- Financing watershed plans
- Stakeholder involvement and facilitation
- Bacteria dynamics, assessment methods, and BMPs
- Watershed management trends and tools
- Partner programs for watershed planning
- Catalyzing success
- Urban BMPs and low-impact development
- Watershed planning resources

As with the short course, participants leave the roundtables extremely satisfied with their experience (94.3% satisfaction rating), ready to implement what they have learned.

1.10 OPPORTUNITIES TO ENHANCE THE SUCCESS OF WATERSHED PLANNING AND IMPLEMENTATION PROGRAMS

With a majority of waterbodies in the United States not meeting water quality standards, improvements to all aspects of water quality management are needed to achieve the national goal that all waters of the United States be “fishable and swimmable.” First and foremost, appropriate, site-specific standards should be applied to each waterbody. This, combined with increased monitoring, use of risk-based approaches, and increased data requirements for use attainment determinations, is needed to improve waterbody assessments and ensure wise use of public funds.

Once waterbodies are identified as impaired, an optimized approach to sequencing water quality standards review, verification monitoring, and TMDL and WBP development should be used to expedite restoration and removal from the *303(d) List* and enhance funding for implementation efforts. Further, a streamlined process using simplistic, scientifically based methods and a compressed stakeholder process should be employed to accelerate planning efforts, reduce development costs, and quickly move watersheds to implementation. To support this process, (1) WBP and TMDL templates; (2) standard practices for calculating loads and load reductions, writing plans, and conducting stakeholder processes; (3) mentoring of new watershed planners; and (4) continued professional development of coordinators (i.e., short course and roundtables) are needed.

Successful implementation is highly dependent on effective targeting of implementation efforts, strong local support, acquisition of required resources, and sufficient monitoring. Combining this with continued implementation of traditional practices, expanded outreach and education, increased use of new technologies, and better integration with other water programs will lead to greater water quality improvement and water sustainability.

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2 Water Monitoring and Diagnosis

Kevin Urbanczyk

CONTENTS

2.1 WATER MONITORING

2.1.1 INTRODUCTION

Water monitoring is essential for sustainable water management. In order to plan for the future, one must know about water quality and quantity. *Monitoring* is the activity of observing conditions in a system. It is defined as "to watch, keep track of, or check usually for a special purpose" (Merriam-Webster 2015). In the case of monitoring natural waters, our "special purpose" is to track the movement of water over and within the surface of the earth in terms of both water quality and quantity. It is analogous to a physician checking the pulse of a patient. A good water monitoring program tracks the "pulse" of a natural system.

2.1.2 WHY MONITOR?

Water exists on the earth as part of the hydrologic cycle (Figure 2.1 and Table 2.1). This water is meteoric, meaning that it is directly involved in the overall process of evaporation of water from the oceans, movement onto the continents, followed by precipitation in the form of rain or snow and subsequent return to the ocean basins. Other forms of water that are not part of this cycle exist as connate water trapped in rock and sediment and as juvenile water trapped in the earth's interior (Fetter 2001). The meteoric water is the portion of this overall system that is of importance for water management even though recent advances in geophysics and chemistry are now assessing the limited abundances of juvenile water in the earth's mantle and even possible contributions to the meteoric water system (Schmandt et al. 2014; Wolaver et al. 2012). The movement of water in the hydrologic cycle is driven by energy from the sun and is essentially a system that transfers water from the ocean basins onto the earth's continents. The return of this water back to the ocean basins is via gravity flow in the form of surface and groundwater. Our ability to monitor this dynamic system is essential for sustainable water management. Anthropogenic activities irrevocably modify the natural system and we must be able to understand the impact of these activities in order to plan for a future with adequate freshwater supplies. Not only do we need to be monitoring current water-related trends, we must make use of historic water data (preferably to include predevelopment data) as well, in order to understand the inevitable declining trends in water quantity and quality that come with water development for uses

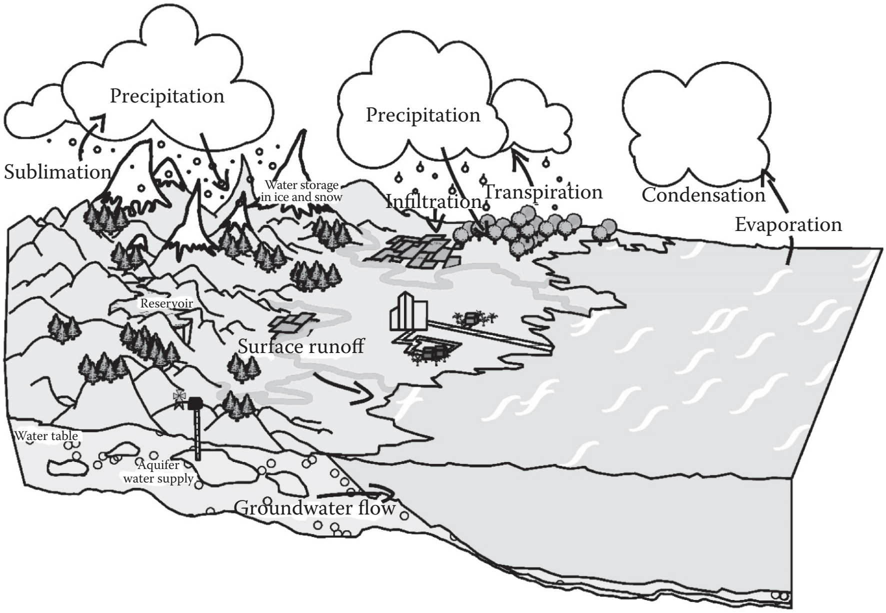


FIGURE 2.1 The hydrologic cycle.

TABLE 2.1
Estimate of the Distribution of Global Water

Water Source	Water Volume, in Cubic Miles	Water Volume, in Cubic Kilometers	Percent of Freshwater	Percent of Total Water
Oceans, seas, and bays	321,000,000	1,338,000,000	–	96.54
Ice caps, glaciers, and permanent snow	5,773,000	24,064,000	68.7	1.74
Groundwater	5,614,000	23,400,000	–	1.69
Fresh	2,526,000	10,530,000	30.1	0.76
Saline	3,088,000	12,870,000	–	0.93
Soil moisture	3959	16,500	0.05	0.001
Ground ice and permafrost	71,970	300,000	0.86	0.022
Lakes	42,320	176,400	–	0.013
Fresh	21,830	91,000	0.26	0.007
Saline	20,490	85,400	–	0.006
Atmosphere	3095	12,900	0.04	0.001
Swamp water	2752	11,470	0.03	0.0008
Rivers	509	2120	0.006	0.0002
Biological water	269	1120	0.003	0.0001

Source: USGS, 2014a, How much water is there on, in, and above the Earth?: https://water.usgs.gov/edu/earthhowmuch.html (accessed May 4, 2015); Gleick, P.H., ed., 1993, *Water in Crisis: A Guide to the World's Fresh Water Resources*, Oxford University Press, New York.

such as for industrial or municipal purposes. Historic water data are also necessary to calibrate predictive models for future water supply. An understanding of a variable climate is also necessary for predictive models for future water supplies.

2.1.3 TYPES OF FEATURES THAT CAN BE MONITORED

This chapter focuses on basic types of freshwater monitoring and diagnosis. It focuses on site-specific field monitoring activities. The types are divided into the following categories:

- Water Quality and Quantity
  - Surface water
  - Groundwater
  - Precipitation
- Biology
  - Aquatic habitat
  - Indices of biologic integrity
  - Invasive species
- Geomorphology
  - Sediment
  - Impact of invasive species

2.1.3.1 Water Quality and Quantity

Two primary objectives in water monitoring are to understand water quality and water quantity. These can often be monitored at the same time and with the same equipment, or may also be monitored separately. Water quality monitoring typically includes some type of assessment of basic chemistry, including pH, specific conductivity (SC), dissolved oxygen (DO), and temperature (Bartram and Balance 1996; USEPA 2012). Various types of field-deployable probes can measure many other parameters (nitrogen compounds, phosphorus compounds, total alkalinity, chlorine, iron, etc.). Field or laboratory analysis can determine other aspects such as biologic and chemical oxygen demand (related to quality of aquatic habitat), fecal coliform bacteria, fluoride, lead, chromium, arsenic, pesticides, pharmaceuticals, and many other parameters. Water quantity is a physical parameter and is assessed in the form of measurements such as stream discharge, groundwater level, or lake/reservoir level.

Table 2.1 indicates that non-marine surface water makes up only ~0.036% (lakes, swamps, and rivers) of the water in the hydrologic cycle, yet this category is an important source for water supply. The United States Geological Survey (USGS) estimates that 80% of the freshwater used in the United States is from surface water sources (Maupin et al. 2014). Alternatively, the state of Texas estimates that surface water accounted for approximately 40% of all water used in 2008 (Texas Water Development Board [TWDB] 2012). The dependency on surface water or groundwater is partly a function of climate—much of Texas is arid and therefore groundwater is the dominant source of water in the western part of the state. Surface water sources are located in both rivers and lakes. An important point to make is that most surface water is in direct contact with the groundwater in the area. “Base flow” in the hydrogeologic sense is that portion of the flow in a river that is contributed from groundwater. In many cases, it can be clearly demonstrated that flow in a river is directly the result of base flow, yet, in many locations, the two are managed as if they were separate water reservoirs (Sansom 2008). Surface water in Texas is the property of the people and is appropriated for various uses.

Table 2.1 indicates that groundwater comprises 1.69% of the global hydrologic cycle. Approximately 20% of all freshwater use in the United States is from groundwater sources (Maupin et al. 2014). Meteoric water gets into the groundwater system via various processes of infiltration and recharge to an aquifer. Groundwater flow is considerably slower than overland surface flow and has been historically misunderstood. An early 20th-century Texas Supreme Court decision considered groundwater too “mysterious and occult” to understand and, thus, regulate (Mace et al. 2004; Sansom 2008). Groundwater in the state of Texas falls under the rule of “right of capture,” which means that landowners above groundwater reservoirs can pump unlimited water for any purpose (Sansom 2008).

Coastal water includes water in bays and estuaries in coastal regions. These represent an important area of mixing of fresh surface water and groundwater with marine water. Precipitation is that part of the hydrologic cycle where water is transferred from the atmosphere as water vapor to the lithosphere.

2.1.3.2 Biology

The biology of an aquatic system is intimately connected to the water quality and quantity of the system. Monitoring the condition of the biologic system, therefore, is another technique to track the "pulse" of the water system. There are numerous techniques for monitoring a biological system. One is to develop an Index of Biological Integrity (IBI; Danielson 1998). The development of the IBI involves four steps. For a wetland, an assemblage of plants, amphibians, birds, algae, or macroinvertebrates of interest are selected. Second, "metrics" are developed for the biologic system. A metric is a component of the biologic system that has a measurable change in value as a result of human disturbance. The metrics are then combined into an IBI that essentially is a "score" for a system's biological integrity.

Another technique for assessing the biology of a river system is to complete aquatic habitat suitability studies that relate habitat suitability to stream flow (Hardy 1998). This approach requires site-specific field monitoring of pools, runs, and riffles in a river system. In each of these hydrologic components, variables such as velocity, depth, and substrate are determined, and these are matched to know optimal conditions for an aquatic species of interest. An example is the work of Trungale (2012; Figure 2.2). Field measurements are made in each of the flow components and the conditions are summarized with biological information regarding the affinity of a particular species for the physical parameters (velocity, depth, and substrate). The information is summarized into a Weighted Usable Area (WUA), percent flow habitat, and composite suitability. This technique requires that field data be acquired at multiple river stages and that adequate biological information is available for calibration of the WUA estimates. Figure 2.3 is a summary graph for the Devils River minnow showing individual Habitat Suitability Indices for each of the physical parameters (depth, velocity, and substrate). The Composite Suitability Index indicates the positions along the stream profile where the habitat conditions are ideal for the minnow.

2.1.3.3 Geomorphology

Water in rivers is almost always in contact with rock or soil. The amount of sediment carried by a river is not the same at all times and areas (Leopold et al. 1974). Sediment load in a river consists of larger particles that stay on or near the bottom of the river (bed load) and smaller particles that stay indefinitely suspended above the bottom of the river (suspended load). The particle size boundary between these two is a function of energy in the river. In any one location, this boundary can change with changes in discharge and particles that had been bed load will become suspended load with increasing discharge. Dams placed on rivers can have a detrimental impact on the river in terms of excessive erosion of sediment pore water below the dam (Collier et al. 1996), or, as is the case in some rivers, the ability of a river to move sediment declines as discharge declines over time (Dean and Schmidt 2011; Everitt 1993; Schmidt et al. 2003). Sediment abundances can change over time with changes in land management adjacent to a river and its tributaries. Monitoring the shape of the river channel and adjacent sand and gravel bars can provide information about temporal changes in the sediment budget.

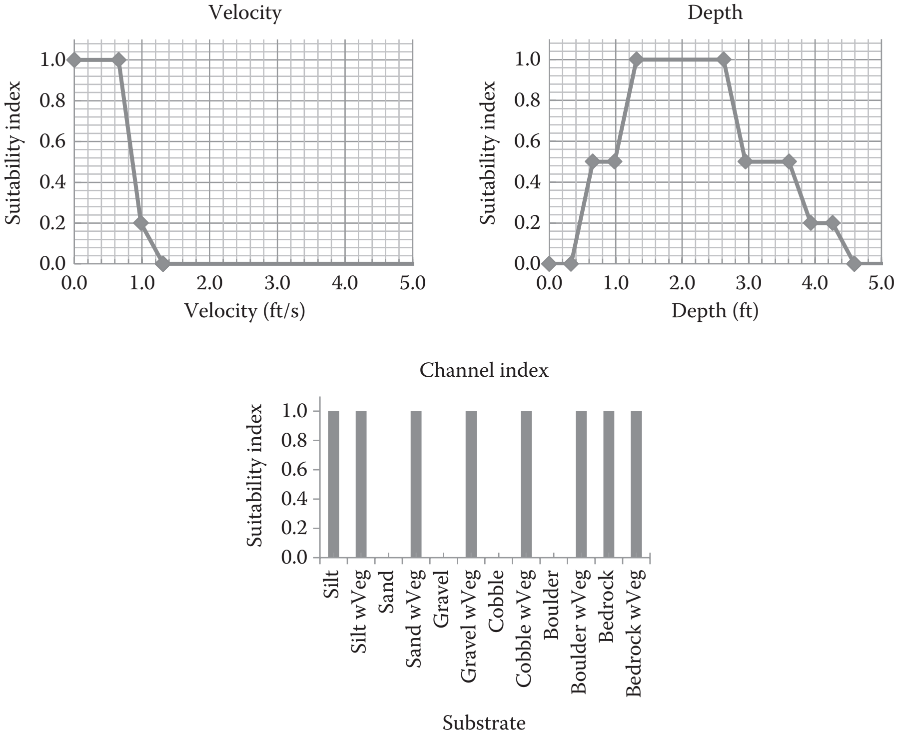


FIGURE 2.2 Habitat suitability indices for the Devils River minnow (*Diondadiabolic*). (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015); and Trungale, J.F. 2012. Instream Flow-Habitat Relationships in the Upper Rio Grande River Basin, Appendix 3.4, Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

2.1.4 PARAMETERS FOR MONITORING

2.1.4.1 Water Quality

Field parameters for water quality monitoring include the basic set of parameters: temperature (*T*, in degrees Celsius), pH (standard pH units), SC (in microsiemens per centimeter), DO (in milligrams per liter or percent saturation), and turbidity. These basic water quality observations can be made with the help of everyday citizens (Arroyoseco 2015; Meadowscenter 2015) or as part of an organized scientific data collection effort. The USGS considers these as “direct field measurements” (Wilde, variously dated). The SC is the measured conductivity adjusted to 25°C. Acid

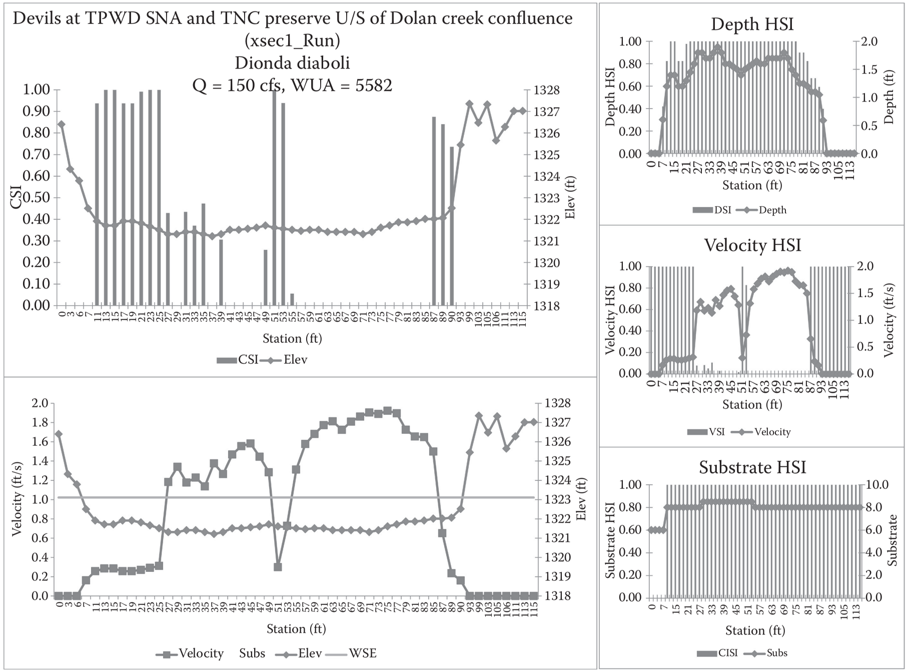


FIGURE 2.3 Devils River minnow habitat at 150 cfs in a "run" hydrologic component. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015); and Trungale, J.F. 2012. Instream Flow-Habitat Relationships in the Upper Rio Grande River Basin, Appendix 3.4, Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

neutralization capacity can be measured in the field by titration and is referred to as "alkalinity." Assuming that there are no other compounds in the water capable of neutralizing the added acid, this can be converted to mg/L HCO_3.

The list of laboratory parameters possible for water quality studies is quite large. A comprehensive list will not be included here, but many of the commonly analyzed parameters are discussed. Laboratory analysis usually starts with the same four basic parameters discussed above (T, pH, SC, and DO). A titration for alkalinity is often completed even though this is best measured directly at the source to avoid equilibration of the dissolved carbon with the atmosphere (especially important for groundwater samples). Cations and anions are also commonly determined (K^+, Na^+, Ca^{+2}, Mg^{+2}; Cl^-, SO_4^-, NO_x^- [various forms], and HCO_3^-). Other laboratory parameters include stable isotopes of O and H, C14 for age dating, tritium, additional metals, organic complexes, various forms of bacteria (coliform), herbicides, pesticides, and pharmaceuticals.

Provided that a full suite of cations and anions are available in an analysis, a test of the quality of the analysis involves evaluating the electroneutrality of the analysis. This is a comparison of the sum of the cations and the anions in terms of milliequivalents per liter. Since a water should be charge balanced, the ratio of the sums should be equal to one (Dominico and Schwartz 1990).

2.1.4.2 Water Quantity

Water quantity in a stream or river is measured as volume of water per unit time. It is typically reported as cubic meters or cubic feet per second. In lakes and reservoirs, it is reported as stage levels that are related to a water volume with units such as cubic meters or acre-feet.

2.1.5 TECHNOLOGY

2.1.5.1 Multiprobes for Water Quality

This discussion will focus on the technology for field water quality data collection.

For the five basic direct measurement parameters, standard probes are readily available from various manufacturers. Temperature, pH, SC, and DO can be measured with individual dedicated probes, or multiprobes can be purchased, which will measure all of them at the same time. Various protocols are employed for maintenance, calibration, and operation of these probes (Texas Commission on Environmental Quality [TCEQ] 2012a; USGS, variously dated). Many field probes are capable of storing data ("data logging"). These can be deployed and instructed to take measurements on a repetitive cycle in order to create high-resolution time series data.

2.1.5.2 Water Quantity

A basic measure for water quantity is water level. Water surface elevation (stage) of a stream can be measured at monitoring sites relative to a permanent land surface datum such as a benchmark (Beck et al. 2006). Stage information from these sites can be used to determine changes over time. Discharge in cubic meters per second can be obtained for these sites provided a rating curve has been developed for that location.

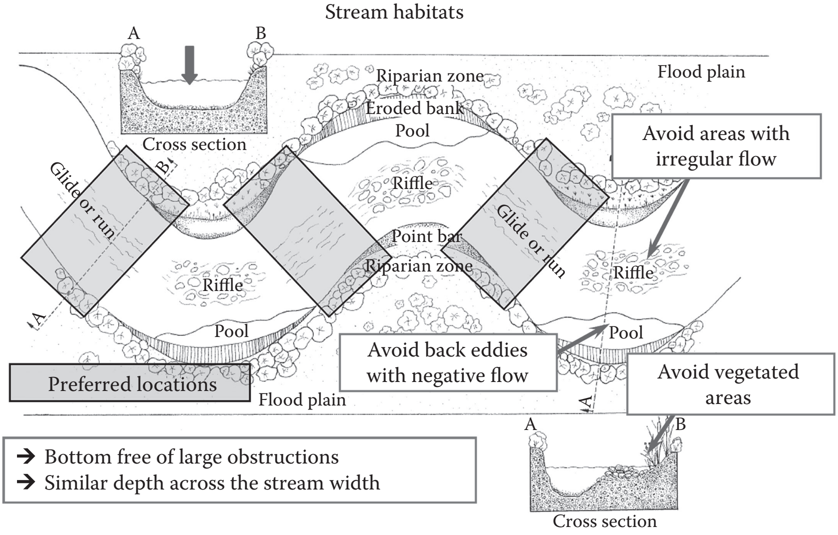
A quantitative estimate of discharge at a site requires measurement of depth and velocity at multiple stations at a carefully selected location on a river. A site is selected with the following considerations (Figure 2.4 and TCEQ 2012a):

- A straight reach with laminar flow that extends bank to bank
- A uniform stream bed devoid of large rocks and vegetation or anything that creates a disturbance
- An area devoid of back eddies and turbulence

Once an appropriate site has been selected, the discharge measurement is made by determining the depth and velocity at multiple stations across the stream or river. For smaller streams, this can be done by wading across the stream and taking measurements at multiple locations. For larger streams, this must be done from a bridge or from a boat, or by using a meter such as an acoustic Doppler current profiler (ADCP) that can measure the depth and velocity from a floating platform that can be towed across the river surface.

Velocity can be estimated in the following ways:

- Float method—Measure the velocity of a floating stick by determining the amount of time it takes it to float a premeasured distance (Weight and Sonderegger 2000).
- Current meters for smaller streams—These are attached to a top set rod so that the vertical position of the meter can be adjusted:



Avoid areas with irregular flow

Avoid back eddies with negative flow

Avoid vegetated areas

Preferred locations

→ Bottom free of large obstructions
→ Similar depth across the stream width

FIGURE 2.4 Stream habitats for consideration for selecting discharge measurement sites. (From TCEQ. 2012a. *Surface Water Quality Monitoring Procedures, Volume 1: Physical and Chemical Monitoring Methods*, Texas Commission on Environmental Quality, RG-415.)

    - Price or pygmy meters are analog devices that have cups attached to a wheel that spins proportionally to the current. The operator counts audible “clicks” that occur with every revolution over a specific period. The number of clicks per minute can then be converted to a velocity. This has historically been a standard procedure for the USGS.
    - Electromagnetic velocity sensors (e.g., Marsh–McBirney FlowMate)
    - Acoustic Doppler velocity sensors (e.g., SonTek FlowTracker)
- ADCPs can be used for small or large streams. These are either mounted on a small flotation device or attached to a boat. They are capable of measuring total depth and velocities at multiple “cells” in a vertical profile under the instrument. These can be integrated into a cumulative discharge if the instrument is moved laterally across the river in an appropriate location.

Since velocity is not constant in a vertical stream profile, a depth at each station (excluding the ADCP technology) must be selected for the velocity measurement. For a shallow stream, the average velocity for a vertical profile is located at the 0.6 position down from the water surface. For deeper streams, the average velocity is best measured by making two velocity measurements, one at the 0.2 position and the second at the 0.8 position. The two velocities are then averaged for the overall average velocity. The TCEQ SWQM stipulates the depth of 2.5 ft to be the boundary between these two techniques. See Figure 2.5 for an example of a discharge measurement.

The total discharge of a stream at a monitoring site can be measured with these techniques. The discharge is calculated at each station as the depth × width × velocity. The sum of the discharge from each station is the total discharge at the site. It is standard practice to try to keep each station width such that no station exceeds 5% of the total discharge. In practice, this is not always the case owing to site conditions and the time required to make this many measurements. The TCEQ protocol (TCEQ 2012a) is to set velocity measurement to average for at least 40 s per measurement. Add to this the amount of time required to move from station to station, measure the depth and key in the data, and then multiply by at least 20 for the 5% requirement; a single discharge measurement typically takes 45 min to an hour to complete. This is in addition to the time required to select an appropriate site, set up a tag line across the river to follow, and set up the instrument. Some protocols require two measurements be made at the site. If the difference between the two measurements is less than 5% of the average of the two measurements, the measurements are considered good. Otherwise, they must be repeated.

Another way to measure the discharge of a stream is to engineer the channel in the form of a weir or a flume. A weir is a barrier across the channel. Depending on its shape, the depth of flowing water over the weir can be related to the discharge. A flume is a manmade channel through which the water flows. Similar to the weir, the depth of the water in the flume can be related to the total discharge.

A **rating curve** is a mathematical relationship between stage (a function of the depth of the water) and the discharge. The actual discharge must be measured at a site at multiple stages in order to properly develop a rating curve. Weirs and flumes are often constructed in a way where this relationship is known. Figure 2.6 shows a

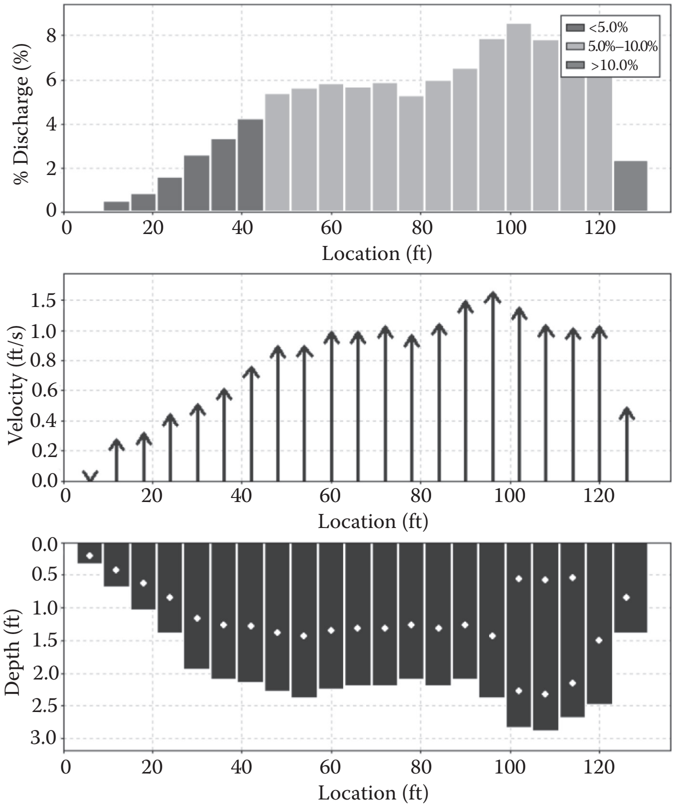


FIGURE 2.5 Example from a Sontek Flowtracker discharge report for the Rio Grande in the Lower Canyons reach, Rio Grande Wild and Scenic River. Note that for all depths greater than 2.5 feet, two velocity measurements were made: one at the 0.2 position and one at the 0.8 position. All other stations were at positions where the stage was less then 2.5 feet, and therefore velocity was measured only at the 0.6 position.

rating curve for Seneca Creek at Dawsonville, Maryland (Leopold et al. 1964). See also the USGS Water Science School resource (USGS 2014b). Once a rating curve is established, the "stage–discharge" relationship is known. If the stage can be measured, then the discharge can be calculated. This can be accomplished visually if a staff gage is present. A staff gage is a graduated rod that is permanently placed in the channel at the location of the rating curve. The stage can also be measured adjacent to the river in a stilling well that is in contact with the water in the river. The water level in the stilling well can be measured with a float attached to a recorder. Changes in water elevation are recorded with this device in digital or analog fashion. An alternative is to use a pressure transducer, which is a device that converts changes in pressure related to water level changes into a digital signal that can be recorded to track water level changes over time. The device must be inserted into the water at a known vertical position relative to a local datum in order to measure water level changes and relate these to changes in discharge using a rating curve. One additional technology

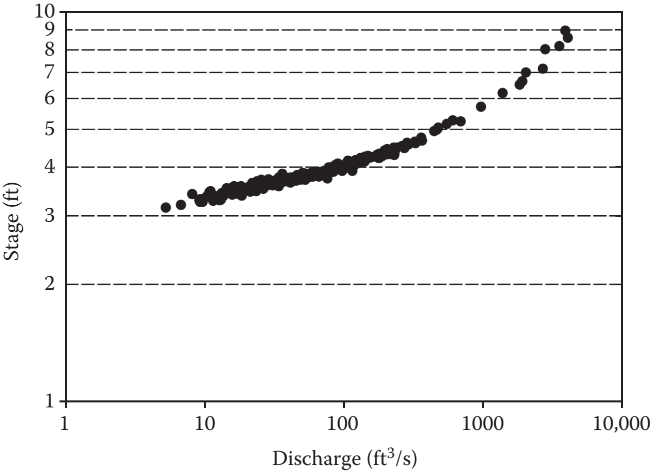


FIGURE 2.6 A rating curve for the Blanco River at Wimberley, TX, plotted on a log–log scale.

for measuring water surface elevation is ultrasonic distance measuring technology. This type of device has the benefit that it does not have to be in contact with the water. It measures sonic waves in the air space above the water in order to determine the water surface elevation relative to a local datum. A "sounder" is a device that is attached to a tape measure and can be manually lowered into a well until it hits the water surface at which point an audible sound is emitted and the depth from the top of the well to the water surface is determined from the tape measure position.

2.2 DIAGNOSIS

2.2.1 ANALYSIS OF TIME SERIES DATA

Time series data are data that are collected in successive order. They are usually collected at uniform intervals of time. Time series data in sustainable water management can include any or all of the types of data described in this chapter. Large data sets are common from projects that continue for multiple years, decades, or even centuries. Modern data collection techniques also allow for high temporal resolution, which contributes to the size of the data sets. Careful statistical analysis of time series data is important.

Hirsch et al. (1982) discuss methods for identifying and quantifying changes in water quality via analysis of time series data. McLeod et al. (1991) and Hipel and McLeod (1994) discuss trend analysis methodology for water quality time series data from rivers and streams. Their focus was to consider real data series with less than perfect conditions such as nonnormal, positively skewed populations; irregularly spaced instantaneous observations; season periodicities; and covariable dependence. The proposed procedure attempted to eliminate seasonal effects and quantitatively test for trends in the data. Machiwal and Jha (2006) provide a summary of time series analysis for hydrologic data. They include a discussion of tools and of case studies. Theirs is a thorough discussion of statistical methods that includes applications in climatology, surface water hydrology, groundwater hydrology and irrigation, and soil moisture.

2.2.2 EXAMPLES

2.2.2.1 Federal and State Programs

The United States Environmental Protection Agency (EPA) implements Section 303(d) of the Clean Water Act to identify impaired waters. These impaired waters are included in the "303(d) list" (EPA 2015). The EPA requires individual states to provide the list of the impaired waters in the states. The states must utilize all available information in order to develop the list. This includes water that the states monitor and date from outside organizations. Each state is required to report every 2 years on the health of all of its waters (305(b)). Much of the information for the 303(d) list comes from this report.

The most recent 303(d) list for waters in the state of Texas is found in the 2012 Texas Integrated Report of Surface Water Quality for Clean Water Act Sections *305(b)* and *303(d)* for 2012 (TCEQ 2012b). An example listing is included in Table 2.2. The listings on this table are for individual segments of the Rio Grande above Amistad Reservoir (2306_01 to 2306_08).

TABLE 2.2
Example of a 303(d) Impaired Water Listing for the Parameter Chloride

2012 Texas Integrated Report - Texas 303(d) List (Category 5)

SegID: 2306	Rio Grande above Amistad Reservoir From a point 1.8 km (1.1 miles) downstream of the confluence of Ramsey Canyon in Val Verde County to the confluence of the Rio Conchos (Mexico) in Presidio Country	
Parameter(s)	*Category*	*Year Segments First Listed*
chloride	5c	2010
2306_01	From the lower segment boundary at Ramsey Canyon upstream to the confluence of Pandier Gulch	
2306_02	From the confluence of Panther Gulch upstream to FM 2627	
2306_03	From FM 2627 upstream to Boquillas Canyon	
2306_04	From Boquillas Canyon upstream to Mariscal Canyon	
2306_05	From Mariscal Canyon to a point upstream of the IBWC gage at Johnson Ranch	
2306_06	From a point upstream of the IBWC gage at Johnson Ranch to the mouth of Santa Elena Canyon at the Terlingua Creek confluence	
2306_07	From the mouth of Santa Elena Canyon at the Terlingua Creek confluence upstream to the Alamito Creek confluence	
2306_08	From Alamito Creek confluence upstream to the Rio Conchos confluence	

Source: TCEQ, 2012a. *Surface Water Quality Monitoring Procedures, Volume 1: Physical and Chemical Monitoring Methods*, Texas Commission on Environmental Quality, RG-415.

Note: The Category 5c indicates that the additional data or information will be collected and/or evaluated for the parameter before a management strategy is selected.

The National Water-Quality Assessment Program (USGS 2014c) provides a national assessment of water quality conditions and changes, and how the changing conditions are affected by human activities. The program focuses on five national priority topics: fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public supply wells.

The USGS National Streamflow Information Program (USGS 2014d) is designed to provide stream flow data for local, state, and national needs. A primary goal is to provide a core stream gage network for the country. These include a series of strategically placed gages that are continuously operated and the data are made available via the Internet. Specific activities include the development and maintenance of a stable stream gaging network and the collection of intensive data during major floods and droughts. Regional and national assessments are made for protecting endangered species that are dependent on flow conditions and delineating flood-hazard zones. The data include water quality and quantity, most of which is collected real-time. High temporal resolution data (15-min interval data) are available for some locations.

The Texas Clean Rivers Program (TCEQ 2015) is a partnership with regional water authorities to coordinate and conduct water quality monitoring and assessment within each river basin in Texas. It is similar to the federal programs listed above. It provides water quality data, evaluates water quality issues, assists with watershed planning and management strategies, and provides information for multiple stakeholders.

The International Boundary and Water Commission (IBWC) also maintains a water quality and quantity monitoring program. The IBWC implements the Texas Clean Rivers Program for the Rio Grande Basin in addition to maintaining numerous stream flow gages designed to assist with the application of the water treaties between the United States and Mexico (IBWC 2015).

2.2.2.2 Application—Environmental Flows Recommendations

Environmental flows are the amounts of water necessary to sustain aquatic life in the rivers and bays and the estuaries into which they empty (Sansom 2008). The 2007 Texas Legislature identified the Rio Grande among other rivers in the state of Texas as a priority system for the purpose of developing environmental flow regime recommendations and adopting environmental flow standards (TCEQ 2009). The process included the interaction of an Environmental Flows Advisory Group (which included senators, representatives, commissioners, and board members of key state agencies), a Science Advisory Committee (SAC, which included nine technical experts in diverse areas relevant to the evaluation of environmental flows), a Basin and Bay Area Stakeholder Committee (BBASC, selected from interest groups within the basin), and the Basin and Bay Expert Science team (BBEST, six members with technical expertise to complete the report, selected by the BBASC). This summary refers to the Upper Rio Grande (URG) BBEST report (Upper Rio Grande Basin and Bay Expert Science Team 2012).

The URGBBEST team was first required to determine if the target reach of the river (that part of the Rio Grande below the confluence with the Rio Conchos and above Amistad Reservoir; Figure 2.7) was ecologically sound. This required the definition of a Sound Ecological Environment (SEE) specific for the reach of interest. The definition chosen by the group is one that

- Sustains the full complement of the current suite of native species in perpetuity, or at least support the reintroduction of extirpated species
- Sustains key habitat features required by these species
- Retains key features of the natural flow regime required by these species to complete their life cycles
- Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations

The team then used four basic types of data to make the SEE determination and to make environmental flow recommendations for the URG reach. These included a hydrology-based overlay, a geomorphology-based overlay, a biology-based overlay, and a water quality–based overlay. They relied heavily on existing monitored data such as flow and water quality from sources described above. The URG is located in far West Texas (Figure 2.7).

The study area included the Rio Grande from the confluence of the Rio Conchos and all subbasins in the Texas portion. The area is located in the Chihuahuan Desert and Southern Texas Plains ecoregions (Griffith et al. 2007) and is composed of three unique drainage basins: the Rio Grande comprising the southern border of Big Bend

FIGURE 2.7 Location map for the Upper Rio Grande BBEST environmental flows study. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

National Park, the Pecos River basin downstream from the park boundary, and the Devils River basin upstream from Amistad Reservoir (Figure 2.7). The Rio Grande and Pecos portions are in the Chihuahuan Desert while the Devils River is in the Semiarid Edwards Plateau component of the Southern Texas Plains ecoregion.

The Chihuahuan Desert ecoregion is composed of mountains (limestone and volcanic) and alluvial basins. This ecoregion includes the Chihuahuan Basin and playas (1200 to 4500 ft in elevation, 8 to 14 inches annual precipitation, and 67°F to 97°F average low/high temperature); Chihuahuan Desert grasslands (2000 to 6000 ft in elevation, 10 to 18 inches annual precipitation, and 62°F to 90°F average low/high temperature); Low Mountains and Bajada (2000 to 6000 ft in elevation, 9 to 17 inches annual precipitation, and 65°F to 92°F average low/high temperature); and Chihuahuan Mountain Woodlands (4800 to 8378 ft in elevation, 18 to 26 inches annual precipitation, and 58°F to 90°F average low/high temperature). The Semiarid Edwards Plateau ranges in elevation from 880 to 1780 ft and receives 19 to 22 inches of precipitation annually and experience average temperatures ranging from 74°F to 96°F (Griffith et al. 2007; URGBBEST 2012).

Regional aquifers in the URGBBEST study area play an important role in environmental flows. The most important of these is the Edwards–Trinity (Plateau) aquifer (ETPA; Figure 2.8). It is a major aquifer (as defined by the TWDB) and is the hydrogeologic centerpiece of the aquifers of the area. Five minor aquifers interact directly or indirectly with the Rio Grande. These include the West Texas Bolsons

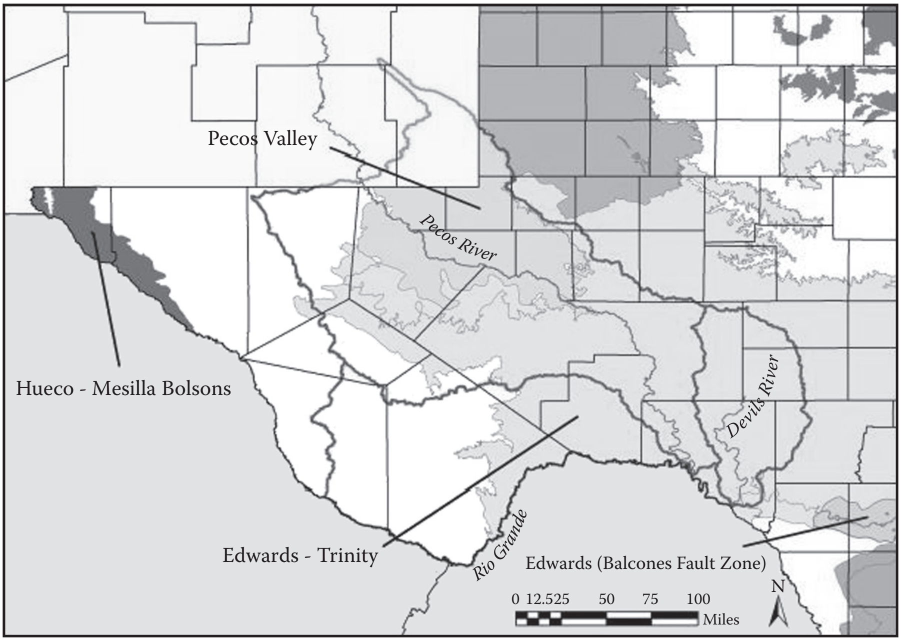


FIGURE 2.8 Major aquifers in the Upper Rio Grande BBEST study area. (Modified from George, P.G., R.E. Mace, and N. Petrossian. 2011. *Aquifers of Texas*, Texas Water Development Board Report 380.)

(Wade et al. 2011), Igneous Aquifer, Capitan Reef Complex, Rustler Aquifer, and the Marathon Aquifer (George et al. 2011).

The ETPA extends across much of the southwestern part of Texas and is composed of limestone, dolomites, and sands of the Edwards and Trinity Groups. Water quality ranges from fresh to slightly saline. Total dissolved solids (TDS) range from 100 to 3000 mg/L.

The URGBBEST team chose to define the Rio Grande (this discussion focuses only on the main stem of the river) study area into two specific reaches: the *Parks Reach* that extends from the confluence with the Rio Conchos down to La Linda and the *Lower Canyons Reach* that extends from La Linda to the headwaters of Amistad Reservoir. The hydrology of the Parks Reach is highly dependent on dam releases (mostly from the Rio Conchos stem). This results in a more regulated hydrograph. The Lower Canyons Reach has stable base flows provided by groundwater inputs and increased flood pulses owing to larger watershed inputs.

Understanding the geomorphology of the Parks Reach was an important part of the SEE consideration.

The Rio Grande in the early 20th century was a wide, meandering, multithreaded stream (Dean and Schmidt 2011; Everitt 1993; Mueller 1975; Stotz 2000). A highly variable flow regime consisting of intense flooding followed by extreme low flows and large sediment loads from the surrounding desert landscape contributed to this condition. High flows occurred for approximately 5 months per year, starting in early May with snowmelt from the Rio Grande upstream from the confluence with the Rio Conchos and followed by water from monsoon rains flowing to the Rio Grande and Rio Conchos drainage basins. Water development in the Rio Grande and Rio Conchos basins that started in the early 1900s caused drastic reductions in stream flow by the 1950s (Dean and Schmidt 2011; Everitt 1993; Schmidt et al. 2003). Today, up to 90% of the flow in the Rio Grande below the confluence with the Rio Conchos is from the Rio Conchos, and this flow has also significantly declined (Dean and Schmidt 2011; Schmidt et al. 2003). A negative impact of the decline in stream flow has been channel narrowing that has occurred over the last 60 years. The channel narrowing problem is compounded by the influx of nonnative vegetation (tamarisk and giant river cane). Periodic large flood events "reset" the channel by scouring sediment and vegetation, and temporarily widen the channel. Figure 2.9 shows a model of channel changes since 1900. The figure relies on careful observation of historic aerial photographs and analysis of stream gage data. Evident on the figure is the general decline in channel width as stream flow has declined and vegetation (mostly nonnative) density has increased. This records an overall decline in ecological soundness. This evidence combined with the gradual decline in water quality culminating with the listing of the reach on the 303(d) list (Table 2.2) led the BBEST group to define the Parks Reach as not ecologically sound.

The BBEST study included a thorough assessment of the historic flows on the Rio Grande, which included the observation of increasingly low flows and the impact of groundwater on flows in the Rio Grande.

As described above, the Parks Reach of the study area has historically been characterized by large flood events and extreme low flows. Its current hydrology is highly dependent on dam releases along the Rio Conchos. The Lower Canyons Reach has more stable base flows because of the ETPA. This groundwater input is of better

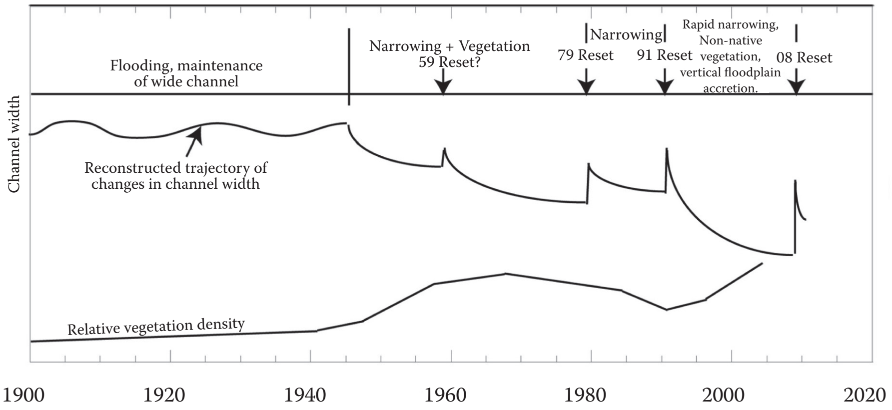


FIGURE 2.9 Reconstructed model of changes in channel width and vegetation density since 1900. (From Dean, D.J. and Schmidt J.C., *Geomorphology*, 126, 333–349, 2011. With permission.)

quality than the surface water that it contributes flow to. Stream gage data from the IBWC were used to quantify this base flow increase. The gages of interest include the following (see Figure 2.10 for gage locations):

- Below the Rio Conchos IBWC #08-3742.00—This gage is located at the upper end of the study area, below the confluence of the Rio Conchos from Mexico and the Rio Grande.
- Johnson Ranch IBWC #08-3750.00—This gage is located in Big Bend National Park in the Parks Reach.
- Fosters Weir IBWC #08-3772.00—This gage is located in the Lower Canyons Reach and is near the lower end of the study area.

One component of the analysis was to select periods with base flow conditions and compare the upstream to the downstream gages. These times are typically in the winter when there are no monsoon-driven patterns in the hydrograph. Figure 2.11 shows four selected times during which base flow conditions exist. The influence of the ETPA is clearly evident in this figure. In each period, the two upstream locations (below the Rio Conchos and Johnson Ranch) experience base flow conditions of 150 cubic feet per second (CFS) or less, while the downstream gage shows much higher flows (196, 225, 215, and 266 cfs higher, respectively, for the four periods selected). It is important to note that there are no perennial tributaries between the gages; therefore, the increase is most importantly the result of increased base flow provided by the ETPA aquifer. The Rio Grande flows into the area of the ETPA aquifer between the Johnson Ranch gage and the Foster's Weir gage (see Figures 2.8 and 2.10).

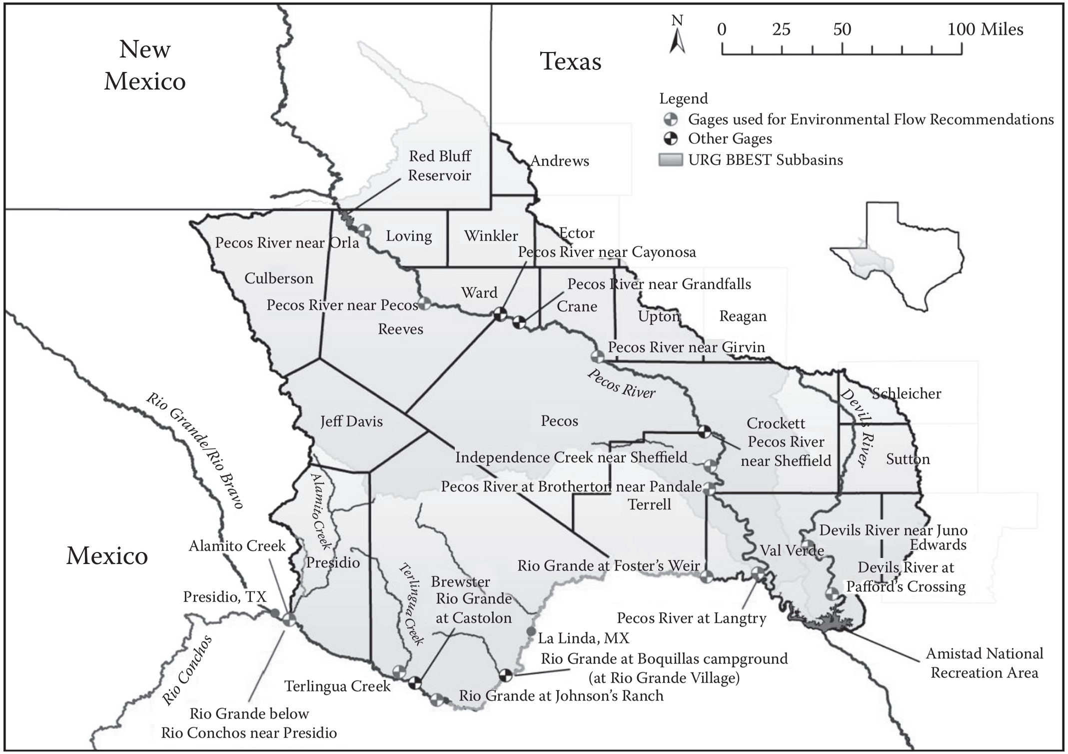


FIGURE 2.10 Gaging station for the Rio Grande, Pecos, and Devils Rivers in the Upper Rio Grande BBEST subbasin. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

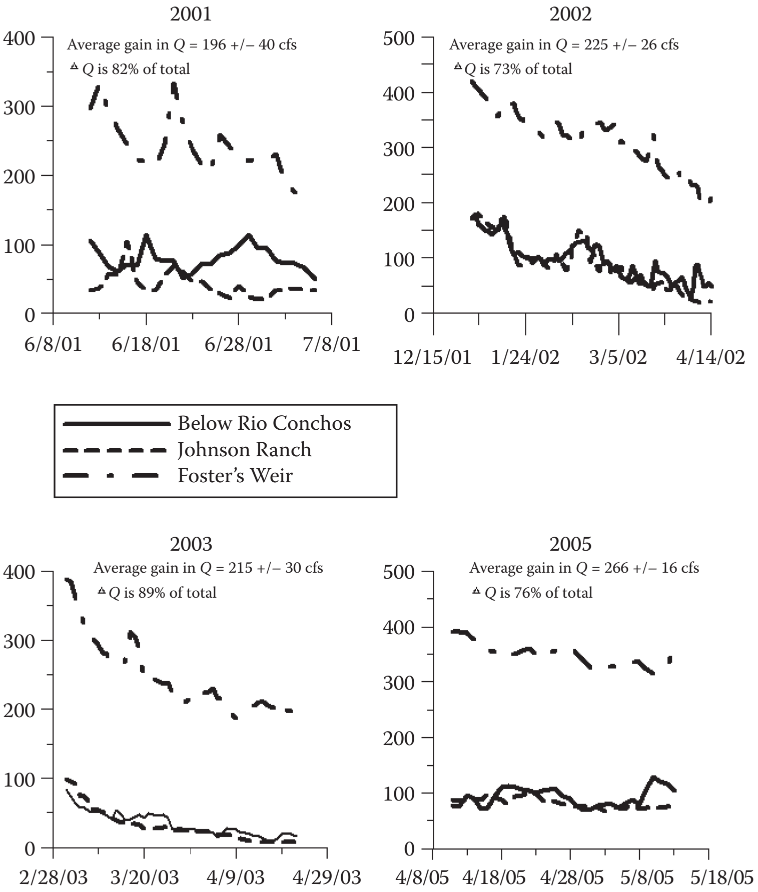


FIGURE 2.11 Average gain in discharge through the Parks and Lower Canyons Reaches as observed during low flow conditions. (From Bennett, J., K.M. Urbanczyk, B. Brauch, B. Schwartz and W.C.P. Shanks. 2009. The Influence of Springs on Discharge and River Water Chemistry in the Lower Canyons, Rio Grande Wild and Scenic River, Texas. Portland GSA Annual Meeting (October 18–21, 2009); and Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

Figure 2.12 shows the influence of the freshwater from the ETPA on the water quality in the Rio Grande. The graph shows the results of two separate seepage runs, one in 2006 and the other in 2011 (Bennett et al. 2012). The river miles that are plotted on the *x* axis span the full Lower Canyons Reach (the Parks Reach shows little synoptic change). The increase in discharge in the Lower Canyons Reach can be seen in the upper left graph and the influence of the dilute ETPA water can be seen in the

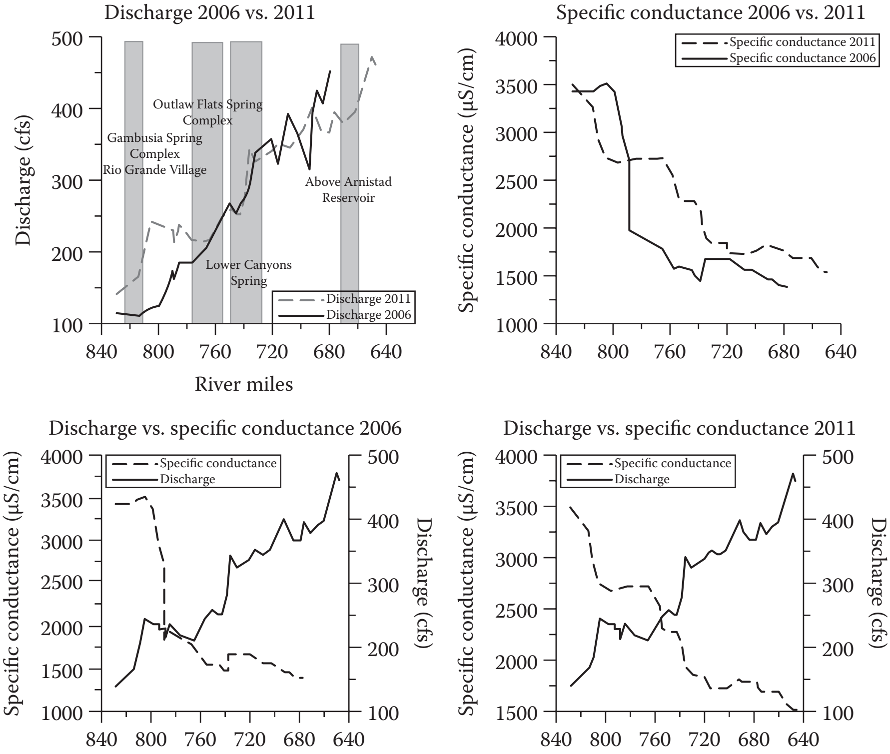


FIGURE 2.12 Longitudinal trends in discharge and specific conductance for years 2006 and 2011. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

decline of the specific conductance from up to down river. This is clearly a gaining reach with a related increase in water quality.

For the Instream Environmental flow analysis, the URGBBEST considered the concept of the Natural Flow Regime, which stresses the importance of the dynamic processes that occur over a range of flows that help maintain the physical, biological, chemical, and ecological integrity of river systems (Poff et al. 1997). This paradigm incorporates five critical components of flow that regulate ecological processes in river ecosystems: magnitude, frequency, duration, timing, and the rate of change in flow (Poff and Ward 1989; Richter et al. 1996; Walker et al. 1995). The Hydrology-based Environmental Flow Regime (HEFR) methodology was used for characterization of flow regimes (SAC 2011). The tool employs statistical calculations based on historic mean daily discharges in order to quantify attributes of four portions of the flow regime: subsistence flows, base flows, high flow pulses, and overbank flows.

TABLE 2.3
General Flow Components for the Stream Segments of the Study Area

Component	Hydrology	Geomorphology	Biology	Water Quality
No-flow periods	Flow ceases between perennial pools	Encroachment of vegetation	Generally stressful for fish communities	Temperatures rise and oxygen levels decrease. These conditions sometimes cause fish kills
Subsistence flows	Infrequent low flows	Increased deposition of fine and organic particles, encroachment of vegetation	Provide restricted aquatic habitat limit connectivity	Elevate temperature and constituent concentrations; maintain adequate levels of dissolved oxygen
Base flows	Average flow condition, including variability	Maintain soil moisture and ground water table; maintain a diversity of habitats; exports or transport sediment?	Provide suitable aquatic habitat; provide connectivity along channel corridor	Provide suitable in-channel water quality
High flow pulses	In channel short duration, high flows	Deposit sediment, development of inset flood plains; prevent encroachment of riparian vegetation	Serve as recruitment events for organisms; provide connectivity to near-channel water bodies	Restore in-channel water quality after prolonged low flow periods; episodic in nature and associated with fish kills (anecdotal, no real investigation of this yet)
Overbank flows	Infrequent high flows that exceed the channel	Provide lateral channel movement and floodplain maintenance; recharge floodplain water table; form new habitats; flush organic material into channel; deposit nutrients in floodplain	Provide new life phase cues for organisms; maintain diversity of riparian vegetation; provide conditions for seedling development; provide connectivity to floodplain	Restore water quality in floodplain water bodies
Channel maintenance	For most streams, channel maintenance occurs mostly during pulse and overbank flows	Long-term maintenance of existing channel morphology	Maintains foundation for physical habitat features instream	Water quality condition like those during pulse overbank flows

Source: Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).

Table 2.3 summarizes the ecological functions of various flow components for the URGBBEST study. The study incorporated hydrology, geomorphology, biology, and water quality overlays in order to determine if the different reaches were ecologically sound and to make environmental flow recommendations. A discussion of the specific methods employed follows.

The general approach for hydrologic assessment was to assign each day of the hydrologic record to a specific flow component. This type of hydrologic separation uses a time series record of stream flow to derive a base flow signature. The method used was to parse the individual flow components using the Indicators of Hydrologic Alteration (IHA) method (TNC 2015) in conjunction with the HEFR (SAC 2011). The IHA method separates the flow data into five fundamental characteristics of hydrologic regimes: the magnitude, timing, frequency, duration, and rate of change in flow conditions. The flow components in the IHA results include the following:

- Subsistence Flows—These are infrequent low flows that result in deposition, encroachment of vegetation, restricted aquatic habitat, elevated temperatures, and constituent concentrations, and maintain adequate levels of DO.
- Base Flows—These are the average flow conditions for the river. They maintain groundwater levels and provide soil moisture, flow variability, diversity of habitats, suitable aquatic habitats, connectivity along channel corridors, and suitable in-channel water quality.
- High Flow Pulses—High flow pulses in HEFR were divided into frequencies. This approach defines the high flow pulse episodic events by evaluating the duration (days), volume (acre-feet), and peak flow (cubic feet per second). The URGBBEST decided on five sets of frequencies for high flow pulses: one per 2 years, one per year, one per two seasons, one per season, and two per season.
- Overbank Flows—A subset of high flow pulses—were created for infrequent elevated flows that exceed the channel capacity. They provide lateral channel movement, floodplain maintenance, recharge of floodplain water tables, formation of new habitats, distribution of organic material into the channel, deposition of nutrients in the floodplain, new life phase cues for organisms, diversity of riparian vegetation, conditions for seedling development, connectivity to floodplain, and restoration of water quality to floodplain waters. Overbank flow frequencies are set at one per 5 years for all HEFR analyses. The multipeaks multiplier was also set at 2.

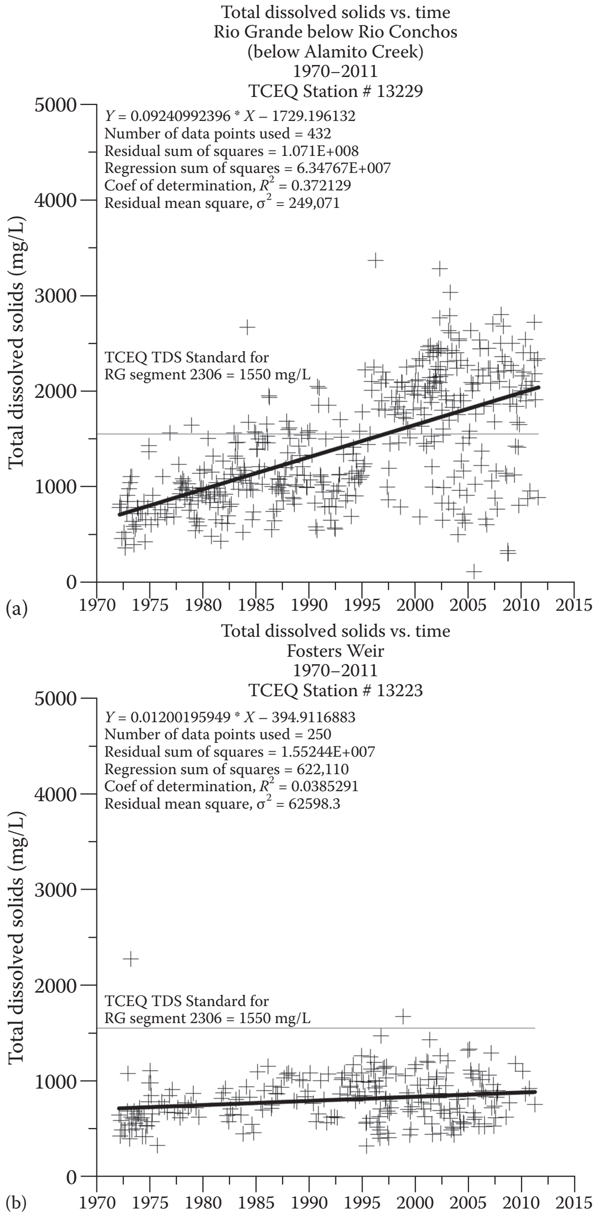
The analysis of water quality utilized high temporal resolution data from the Clean Rivers Program (TCEQ 2015). The data for each station include water quality and discharge measured at the same place at the same time. Figure 2.13 shows the TDS over time for two stations representing the Parks Reach and the Lower Canyons Reach of the study area.

The URGBBEST recognized the importance of the dependencies of instream, riparian, and floodplain biological communities to subsistence, base, high flow pulses, and overbank flows. They summarized the relationship of the biological communities and the relationship of hydrology and geomorphology to the various habitats. They looked at benthic macroinvertebrates, ichthyofauna, and basic riparian biology and related these to the flow components in order to assist with the instream flow recommendations.

The geomorphology method relied on observations of channel narrowing described above, on multiple cross sections collected over several years, and on data from sediment gaging stations located in the Parks Reach. Figure 2.14 shows suspended sediment dynamics during a typical flash flood in the Parks Reach. A primary goal was to determine the magnitude of flow that would limit the channel narrowing process. This was accomplished using one-dimensional hydraulic modeling and resulted in an estimate of 10,500 cfs for a typical channel filling flow.

Sediment transport was also modeled in the form of a digital elevation model (DEM) of Difference (DOD; Wheaton et al. 2010). This technique requires three-dimensional models of the river channel and adjacent floodplain for two different periods, one before and one after a flood event. The models can be constructed from aerial LIDAR, ground-based LIDAR, RTK, or Total Station data. A considerable amount of time is required to create the models, but they are useful for demonstrating changes associated with sediment transport. Figure 2.15 includes a DOD and an associated DEM. The colors are symbolized such that if a change occurred, it is colored increasingly red for deposition and blue for scouring. The example illustrates the sediment load problem in the Parks Reach of the study area.

Tables 2.4 and 2.5 are examples of the type of quantitative summary information that was required for the URGBBEST report. Daily stream flow measurements from the stream gages formed the core of the analysis. The IHA software parsed the data into the flow components and the HEFR technique was used to make the initial recommendations. The results were then modified using the water quality, biology, and geomorphology information. The final recommendations were then published in the report and are now part of the state record for environmental flows.



Total dissolved solids vs. time
Rio Grande below Rio Conchos
(below Alamito Creek)
1970–2011
TCEQ Station # 13229

$Y = 0.09240992396 * X - 1729.196132$
Number of data points used = 432
Residual sum of squares = 1.071E+008
Regression sum of squares = 6.34767E+007
Coef of determination, $R^2 = 0.372129$
Residual mean square, $\sigma^2 = 249{,}071$

TCEQ TDS Standard for
RG segment 2306 = 1550 mg/L

Total dissolved solids vs. time
Fosters Weir
1970–2011
TCEQ Station # 13223

$Y = 0.01200195949 * X - 394.9116883$
Number of data points used = 250
Residual sum of squares = 1.55244E+007
Regression sum of squares = 622,110
Coef of determination, $R^2 = 0.0385291$
Residual mean square, $\sigma^2 = 62598.3$

TCEQ TDS Standard for
RG segment 2306 = 1550 mg/L

FIGURE 2.13 Total dissolved solids plotted through time illustrating the use of long-term water quality data to show a gradual decline in water quality in the Parks reach (a) and the overall improved water quality for the Lower Canyons reach (b) of the study area. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

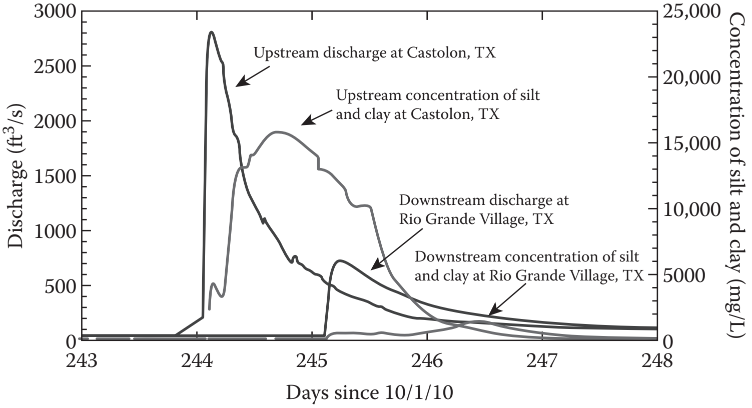


FIGURE 2.14 Suspended sediment dynamics at sediment gage stations in the Parks reach of the study area during a flash flood in 2010. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

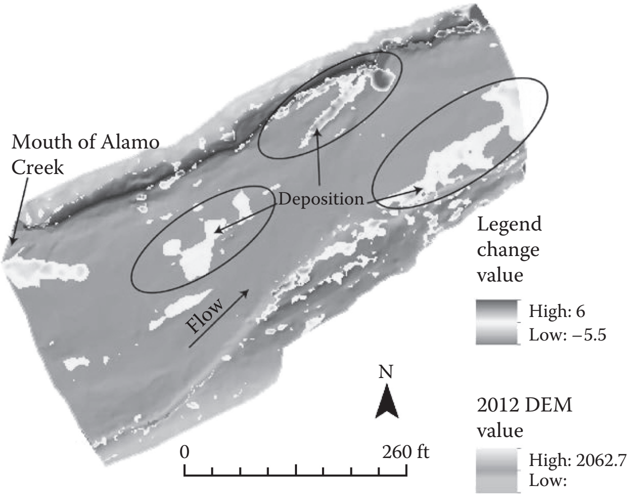


FIGURE 2.15 DEM and DOD showing deposition in the Parks reach during the 2011 to 2012 time period. (From Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).)

TABLE 2.4
Environmental Flow Regime Recommendation, Rio Grande at Johnson's Ranch (Parks Reach)

Channel resetting flows	Qp: Greater than 35,000 ft³/s with Average Frequency of 1 per 10 years		
Overbank flows	No flow recommendations		
High flow pulses	Qp: 10,500 ft³/s with Average Frequency 1 per year Volume is 273,397 Duration is 5		
Base flows (ft³/s)	788 (43.4%) 509 (62.8%) 339 (81.3%)	469 (33.8%) 258 (54.7%) 168 (71.1%)	643 (61.8%) 406 (74.6%) 228 (85.8%)
Subsistence flows (ft³/s)	N/A	40 (91.3%)	40 (97.5%)
	Nov Dec Jan Feb	Mar Apr May Jun	Jul Aug Sep Oct
	Winter	Spring	Monsoon
	High (75th %ile)		
	Medium (50th %ile)		
Flow levels	Low (25th %ile)		
	Subsistence		

Source: Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).

Note: Period of record: 1/1/1936 to 12/31/1967; Subsistence and base flows calculated using non-zero flows only.

TABLE 2.5
Environmental Flow Regime Recommendation, Rio Grande at Foster's Weir (Lower Canyons Reach)

Overbank flows	Qp: 24,190 ft^3/s with Average Frequency 1 per 5 years Volume is 514,209 Duration is 28		
High flow pulses	Qp: 12,710 ft^3/s with Average Frequency 1 per 2 years Volume is 255,443 Duration is 17		
	Qp: 9394 ft^3/s with Average Frequency 1 per year Volume is 3,180,801 Duration is 14		
High flow pulses		Qp: 6145 ft^3/s with Average Frequency 1 per 2 seasons Volume is 100,385 Duration is 9	Qp: ll,650 ft^3/s with Average Frequency 1 per 2 seasons Volume is 258,289 Duration is 16
		Qp: 4344 ft^3/s with Average Frequency 1 per season Volume is 69,770 Duration is 7	Qp: 7451 ft^3/s with Average Frequency 1 per seasons Volume is 146,598 Duration is 11
Base flows (ft^3/s)	883 (34.1%)	823 (39.9%)	975 (58,7%)
	682 (55.6%)	599 (54.5%)	735 (71.3%)
	540 (76.3%)	449 (68.4%)	530 (82.8%)
Subsistence flows (ft^3/s)	331 (98.3%)	301 (90.1%)	290 (96.4%)
	Nov Dec	Jan Feb Mar Apr May	Jun Jul Aug Sep Oct
	Winter	Spring	Monsoon
Flow levels	High (75th %ile) Medium (50th %ile) Low (25th %ile) Subsistence		

Source: Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Rio Grande Basin and Bay Area Stakeholders Committee and Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rio-grande-rio-grande-estuary-and-lower-laguna-madre (accessed May 4, 2015).

Note: Period of record: 1/1/1962 to 12/31/2009; Subsistence and base flows calculated using non-zero flows only.

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3 Sustainable Monitoring of Algal Blooms

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CONTENTS

3.1 INTRODUCTION TO ALGAL BLOOMS

Harmful algal blooms (HABs) have been reported in various types of freshwater and saltwater bodies worldwide (Chorus and Bartram 1999). In particular, HABs associated with cyanobacteria (i.e., blue green algae) have been of great interest because of their significant environmental and health impact. The formation of cyanobacterial HABs is manipulated by anthropogenic, environmental, and climatic factors. Nutrient enrichment of water bodies has been a primary factor in the proliferation of cyanobacterial HABs. Cyanobacterial HABs also cause negative impacts to other organisms by creating hypoxic zones, losing habitat, imposing mechanical damage, synthesizing toxic metabolites, and especially producing cyanotoxins. The subsequent risk of cyanobacterial HAB formation to environmental and human health is an increasingly relevant and timely topic.

From a worldwide freshwater concern, five classes of cyanotoxins have remained primary focus: microcystin (MC), nodularin, saxitoxin, cylindrospermopsin, and anatoxin-a. Among them, MCs are the most widespread and have been found in North and South America, Africa, Europe, Asia, Australia, and Antarctica. Several strains from the cyanobacteria genera such as *Microcystis*, *Anabaena*, *Oscillatoria*, *Anabaenopsis*, *Planktothrix*, and *Nostoc* have been reported to produce MCs (Chorus and Bartram 1999). MCs are water-soluble and stable molecules, which allow them to persist in the environment even after a bloom dissipates (Chorus and Bartram 1999). Synthesis of MCs is influenced by environmental conditions and genetic composition. The gene cluster mcyA–J was identified as the origin of biosynthesis (Kaebernick and Neilan 2001). The nonribosomal assemblage of MCs is accomplished using a multienzyme complex including peptide synthetase and polyketide synthase (Dittman and Wiegand 2006; Kaebernick and Neilan 2001). MCs are cyclic hepatotoxins with the principal amino acid sequence, cyclo-(D-Ala^1-L-X^2-D-MeAsp^3-L-Z^4-Adda^5-D-Glu^6-MDha^7). The D-MeAsp is D-erythro-*b*-methylaspartic acid and the MDha is *N*-methyldehydroalanine. The X and Z represent a variation of L-amino acids. For example, one of the commonly reported MCs is MC-LR, where X is leucine (L) and Z is arginine (R). The conversed Adda [(2*S*, 3*S*, 8*S*, 9*S*)-3-amino-9-methoxy-2,6,8-trimethyl-10-phenyldeca-4,6-dienoic acid] is the primary region that causes inhibition of protein phosphatase 1 and 2A. This inhibition results in severe tissue and organ damage, especially liver damage where the toxin is concentrated (Chorus and Bartram 1999). MCs have been reported to promote liver tumors and have genotoxic potentials.

MCs have been found to be the causative agent in numerous wildlife and domestic animal and human poisonings (Codd et al. 2005a; Drobac et al. 2013; Stewart et al. 2008). The primary human exposure routes to MCs are drinking water, fish consumption, and recreational waters. Although it would be rare to be exposed to a natural toxin such as MCs intravenously, such an exposure through hemodialysis was reported in Brazil (Jochimsen et al. 1998). Symptoms included vomiting, visual disturbance, gastroenteritis, liver damage, tinnitus, and nausea. A 1996 incident in Caruaru in northeast Brazil caused the death of 60 patients (Pouria et al. 1998). A study by Chen et al. (2009) analyzed serum samples from Lake Chaohu fishermen. These fishermen's primary water and food supplies were derived from Lake Chaohu, which has seasonal cyanobacterial blooms. Their statistical analysis supported a positive relationship between serum MCs and liver function enzymes (alanine aminotransferase and aspartate aminotransferase). These data suggest a risk of health from chronic exposure to MCs. Potentially, the 1999 World Health Organization's recommended no observable adverse health effect level of MC-LR at 40 μg/kg/day and drinking water equivalent concentration of MC-LR at 1 μg/L may need further investigation (Chorus and Bartram 1999).

3.2 CONCERNING AREA AND ECONOMIC IMPACTS

Cyanobacterial HABs have recently become spatially and temporally more prevalent in the United States and worldwide (Stewart and Falconer 2008). Cyanobacterial HABs have been found in 7 of the 15 largest continental lakes: Lake Victoria in

Africa (Miles et al. 2013); Lakes Erie, Huron, Ontario, and Michigan in North America (De Stasio and Richman 1998; Hotto et al. 2007; Vanderploeg et al. 2001; Wilhelm 2008); Lake Winnipeg in North America (Schindler et al. 2012); and Lake Ladoga in Asia (Gromov et al. 1996). Other large bodies of water that have been affected by cyanobacterial HABs include Lake Taihu in China (Paerl et al. 2011), Lake Kasumigaura in Japan (Islam et al. 2013), the St. Lucie Estuary in Florida, USA (Lapointe et al. 2012), and the Baltic Sea in Northern Europe (Funkey et al. 2014). These toxic blooms have affected several important river systems such as the Nile River in Africa (Zakaria et al. 2006), River Murray in Australia (Bormans et al. 1997), St. Johns River in North America (Burns 2008), and La Plata River in South America (Nagy et al. 2002). Regional surveys focusing on smaller rivers and lakes within urban settings and agricultural beltways suggest that cyanobacterial HABs occur in temporal, subtropical, and tropical climates. In 2010, 23 lakes with cyanobacterial blooms in the Midwestern United States were sampled and analyzed for 13 cyanotoxins, and MCs occurred in all blooms (Graham et al. 2010).

In addition to cyanobacterial HABs' negative ecological, biochemical, and health impacts, they create economic losses to local surrounding communities and water treatment facilities because of unpleasant odor and taste, de-oxygenation during decomposition of dead fish, machinery clogging in filters and pumps, and increased costs of operating water treatment plants. Only a few studies have been conducted to reflect and estimate the economic impact of cyanobacterial HABs (Atech Group 2000; Dodds 2009; Steffensen 2008). Steffensen (2008) highlighted a few case studies and the important factors that must be considered to derive an economic cost evaluation, including human health, recreational activities, agriculture, monitoring and testing, and migration. The Atech Group (2000) reported the overall cost related to algal blooms in Australia, which was estimated to be $200 million per year. The study performed by Dodds (2009) focused on eutrophication of US freshwater (instead of specifically cyanobacterial HABs) and estimated an annual loss of more than $2 billion in the United States from recreation and angling cost, lake property values, biodiversity loss, and drinking water treatment cost.

3.3 GREAT LAKES SYSTEM

Genera of cyanobacteria that form unpleasant and potentially hazardous surface blooms include *Microcystis*, *Anabaena*, and *Aphanizomenon*. In southwest Lake Erie, during the 1970s, the main scum-forming cyanobacterium was *Aphanizomenon flos-aquae*, whereas during recent years, *Microcystis aeruginosa* dominates visible scum within these shallow, nutrient-enriched, stagnant, and intermittently oxygen-deficient waters. The time frame for *Microcystis* blooms in the Great Lakes region is July to October. *Anabaena* blooms also appear in Lake Erie. Since 2006, bottom-hugging mats of the cyanobacterium *Lyngbya wollei* have also been recognized to contribute to the degradation of Maumee Bay.

A confluence of factors makes southwest Lake Erie vulnerable to surface scums. During spring, the Maumee River episodically surges, delivering suspended soil particles and nutrients obtained by water runoff from economically important farmlands within its large watershed after snowmelt or rain. Variable loads of suspended soil particles conveyed via the Maumee River range from 275,000 to 1,940,000 tons annually (Myers et al. 2000). Rain-swelled river surges also convey essential agricultural nutrients, phosphorus, and nitrogen. Tenfold rises in phosphorus levels in western Erie are associated with Maumee River surges. Related loads of nutrients and suspended soil particles produce effects that favor cyanobacteria. Abundant nutrients promote blooms of green algae during May and June, reducing light availability within the water column, which is already curtailed by suspended soil particles. The combination of phytoplankton abundance and low light favors subsequent emergence of a surface scum of cyanobacteria. *Microcystis* cells acquire sufficient phosphorus to divide two to four times, representing a 4- to 16-fold potential increase in biomass (Mur et al. 1999). Over the long term, addition of soil particles gradually makes southwest Lake Erie even shallower. As any water body becomes shallower, its temperature will slightly rise if other factors remain the same. Modest warming owing to silting could extend the duration of blooms.

Microcystis colonies are supported by the ecological factor of anoxic bottom waters (Sejnohova and Marsalek 2012). *Microcystis* cells winter on the bottom. Aeration of bottom waters provides a control method because aeration reduces benthic colonies and reduces resuspension of nutrients out of sediments. Because many studies have indicated that high oxygen saturation inhibits *Microcystis* blooms, abundant blooms in southwest Lake Erie inferentially suggest low dissolved oxygen levels. Low dissolved oxygen has traditionally not been much analyzed in Lake Erie's southwestern waters but was indeed confirmed during one July survey (Bridgeman et al. 2006).

Long water retention times also sustain a bloom. Approximately 90% of water supplied to Lake Erie arrives via the steady, gravity-propelled flow of the Detroit River, bringing water from Lake Huron. In comparison, the variable flow of the Maumee River contributes only 5% of source water to Lake Erie. Accordingly, flow within Erie's western basin is dominated by the Detroit River. Southwest Lake Erie is naturally isolated with weak egress, near-stagnant conditions, which favor blooms of *Microcystis*, as shown in Figure 3.1 (Sayers et al. 2014).

Microcystis scums likewise appear in shallow, near-shore waters of Saginaw Bay, an embayment of Lake Huron. In this circumstance, the Saginaw River conveys suspended soil particles and nutrients to promote blooms within shallow, slow-moving waters of the bay. Another fecund water body is Green Bay in Wisconsin. In Green Bay, *Microcystis* scums seasonally appear near the Fox River's entrance into the bay. Surface blooms also appear in near-shore waters of Erie's west-central basin, suggesting bacterial replication zones within shallow waters (scums above deeper water may be attributed to conveyance by currents from shallow origins).

An embayment to Lake Erie suffers chronic blooms of vertically dispersed and filamentous *Planktothrix agardhii* (Saxton 2008). A century ago, Sandusky Bay reportedly averaged 12 ft in depth (Landacre 1908). The bay's depth has later been estimated at 8.5 ft (Richards and Baker 1985), suggestive of silting across decades. Estimated loads of suspended soil particles via the Sandusky River range from 197 to 350 tons per year (Myers et al. 2000). Mur et al. (1999) point out "Blooms of this type often lead to virtual monocultures which can prevail year-round for many years…. By causing high turbidity, these cyanobacterial populations effectively suppress the

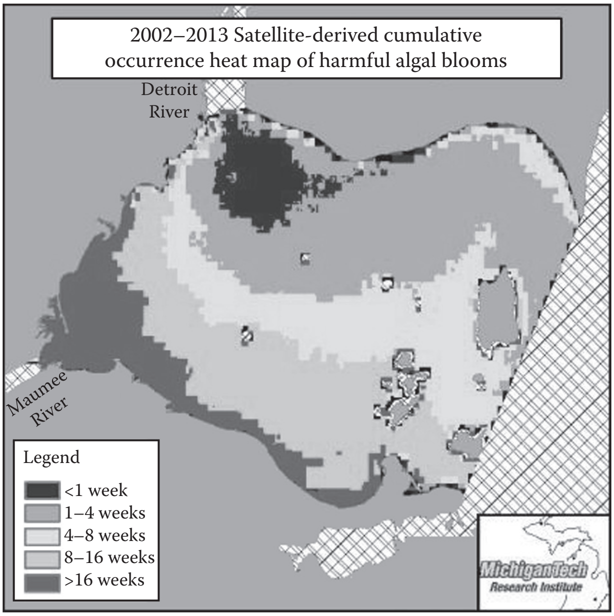


FIGURE 3.1 Satellite-derived cumulative occurrence heat map of HABs. Based on 12 years of satellite images, the map illustrates that *Microcystis* blooms occur most frequently in shallow near-shore Ohio and Michigan waters of southwest Lake Erie during July to October. Blooms can be borne by eastward currents, thru islands, into Erie's central basin. The Maumee River enters the heart of the bloom area, visually indicating the importance of nutrients and suspended soil particles conveyed by this river into shallow lake waters. In contrast, the much larger Detroit River contributes water with low nutrients and soil particles, inhibiting blooms (dark gray area) (note: this map does not include Sandusky Bay and the central basin of Erie).

growth of other phytoplankton species." Sandusky Bay also experiences seasonal *Microcystis* scums, which surmount its year-round burden of *Planktothrix*.

Other waters of the Great Lakes are not vulnerable to problematic cyanobacteria because of deeper depths, cooler temperatures, or lower nutrients. Indeed, Lake Erie as a whole offers a very interesting contrast between blooms that form in its shallow, stagnant, nutrient-rich southwest basin versus the eastern basin of the same lake, which is free of surface scum. The eastern basin is much deeper. Though the lake as a whole receives suspended soil particles and nutrients, no surface blooms of cyanobacteria appear in the deep eastern basin. This is not surprising because on a larger geographic scale, this is consistent with location of planktonic blooms in oceans, all around the planet. Oceanic blooms occur near shore, where nutrient loadings from land enter relatively shallow water, such as the fecund Georges Bank or Chesapeake Bay. As unique freshwater seas, the Great Lakes are vast enough to encompass both deep and shallow waters with blooms of surface scum cyanobacteria confined by nature.

It would be welcome if more historical data were available about the abundance, duration, and extent of surface blooms of cyanobacteria across many decades to inform opinions whether recent blooms around the Great Lakes constitute worsening or variable normality. Some intrinsic hindrances deserve acknowledgement. *Microcystis* submerges when wind speeds rise, complicating estimates of areal extent. Some historic measurements assessed total phytoplankton (rather than specific varieties of cyanobacteria), hindering comparisons across decades. Between 1920 and 1964, phytoplankton abundance within Lake Erie is reported to have increased nearly sixfold, with diatoms being somewhat displaced by cyanobacteria (Davis 1964). During the first half of the 20th century, surveys reported *Anabaena* and *Microcystis* in Lake Erie (Steffen et al. 2014). During the 1950s, other surveys reported *Anabaena*, *Lyngbya*, *Planktothrix*, and *Microcystis*, with *Aphanizomenon* being most abundant. Another survey during 1956–1957 reported *Microcystis* being more abundant than *Aphanizomenon flos-aquae* and *Planktothrix*. It is hard to obtain a reliable understanding of plankton community changes through time, from these reports.

By the 1960s, more and more Americans expressed concern about surface water quality around the country. Lake Erie's conditions drew much attention. A tributary through Cleveland experienced notorious fires, owing to combustible floating detritus and oil. Chemical factories in Canada, Michigan, and Ohio were found to discharge tons of mercury, triggering fishing bans within Lake Erie during 1970. Surface blooms of cyanobacteria were still another perceived degradation of Lake Erie at the time. Awareness of such problems helped inspire the Clean Water Act of 1970. During the ensuing decade, the United States invested $5 billion in upgrades to municipal wastewater treatment plants discharging to Lake Erie, while detergents containing phosphorus were banned by state governments. In a welcome biological response, by the mid-1980s, improvements became evident within Lake Erie, including reduced blooms of nuisance cyanobacteria and a more desirable mix of phytoplankton species (Makarewicz and Bertram 1991). Since the mid-1990s, however, a reversal has been taking place. Surface blooms have worsened, although nutrient loads are not known to have increased commensurately. Worsening blooms may partly be attributed to new factors such as introduction of *Dreissenid* mussels, which may increase availability of nutrients (Steffen et al. 2014).

Unwelcome consequences of nuisance blooms are worthy of mention. Drinking water supplies for human use may require added purification steps. Another cost is suspension of drinking water service. During August 2014, the City of Toledo halted consumption of drinking water by hundreds of thousands of customers for several days owing to contamination with a molecule associated with *Microcystis*. Blooms can also cause skin rashes among swimmers and boaters and merit closure of beaches. Customer demand for water-based businesses, such as marinas and hotels, is dampened by the repulsive smell and appearance of blooms. Poisonings of birds and wildlife can be attributed to cyanobacteria, though cases from the Great Lakes were not provided in one overview (Stewart et al. 2008). For illustration of potential, deaths of thousands of birds (gulls, ducks, coots, pheasants, hawks, and songbirds) occurred at Storm Lake, Iowa, during 1952, associated with *Anabaena flos-aquae*. Documented mammal deaths from this bloom included 50 squirrels, 18 muskrats, 15 dogs, 4 cats, 2 hogs, 1 skunk, and 1 mink. Blooms are prudently regarded as potential hazards. Blooms can be made up of an enormous number of organisms. This enormous number is relevant to perspectives about risk. Toxicity is dose-dependent a fundamental principle of pharmacology. A vast dose of any molecule associated with a bloom could be harmful.

Though *Microcystis* blooms have been worsening on Lake Erie, there are plausible reasons for guarded optimism; these can be countervailed in the future. First, in recent years, scientists are readily obtaining satellite images of large water bodies such as the Great Lakes, enhancing understanding of where near-surface blooms occur and enabling measurement of areal extent. Second, there is potential for development of in-lake continuous sensors for rapid analysis of chemical and biological aspects of blooms. Also, there is emerging availability of technologies to capture or divert suspended soil particles within rivers, offering promise of in-river installations to curb soil-associated nutrients from reaching vulnerable lake waters. Likewise, environmentally gentle technologies, such as pumps that circulate oxygen-rich water (Hudnell 2010; Nakano et al. 2001), can be targeted at shallow, stagnant, turbid, oxygen-poor waters such as Maumee Bay where *Microcystis* populations thrive.

3.4 IMPORTANCE OF SUSTAINABLE MONITORING OF ALGAL BLOOMS

The global water supply crisis is pandemic, requiring a definite commitment toward sustainable water management and quality monitoring from all stakeholders (Nfodzo et al. 2013). Identifying environmental factors to develop pertinent water management strategies, including early warning systems, treatment of source waters, and best land management practices, is paramount to protect and sustain freshwater and brackish water resources. Cyanobacteria and their toxins are currently in the Drinking Water Contaminant Candidate List of the US Environmental Protection Agency (EPA 2012a). Methodologies for early detection or in situ and remote sensing of HAB outbreaks would provide a major mechanism for reducing or preventing exposures to the toxins released by HABs. Scientists are now challenged to monitor, assess, and even forecast the presence, severity, and toxicity of HAB events in an effort to minimize their impacts (Seltenrich 2014). Development of precise, accurate, and sustainable monitoring capabilities toward HABs and their toxins is necessary to establish early warning systems and design better fate and transport models.

If possible, monitoring activities should be time responsive, while not being labor intensive or ecosystem disruptive. Collected data on HAB activity and toxin release would be a great addition to the federal effort to improve human safety, enhance the economy, and protect our environment (Tyson et al. 2004). Developing sustainable HAB monitoring systems has been one of the highest priorities of the National Oceanic and Atmospheric Administration (NOAA), EPA, the National Science Foundation (NSF), and the National Institutes of Health (NIH), which are responsible for investigating the source, transport, fate, and toxicity of HABs (Hudnell 2010). Distributing HAB information has tremendous impacts to many end users and general public, including (i) water and wastewater treatment authorities and industries to adjust treatment level and thus to modify overall treatment protocol,

(ii) agricultural and manufacturing industries to reconsider water intake location and effluent discharge, (iii) fishing industries to be aware of the temporal and spatial level of HABs and toxins, (iv) public health authorities to advise public about drinking water safety and park and recreation activities, and (v) many other associated parties (e.g., sportsfishing community, power industry, marina operators, and ocean and ecosystem researchers).

3.5 MONITORING APPROACHES AND OBSERVING PROGRAMS

Strategies and targets for monitoring algal blooms are various, as summarized in Table 3.1. Algae species (e.g., living organisms) or biological toxins (e.g., chemical compounds) are monitored to determine detrimental impacts of algal blooms. Usually, algae and toxins themselves are directly quantified while measuring easy-to-detect surrogate parameters for them (so-called proxies) is an alternative to indirectly estimate algal blooms. On-site, in situ, or remote observing approaches can be selected for monitoring, depending on the size of concerned areas, frequency of observing needs, and technical difficulty level of measuring the parameters. Some approaches deliver general characteristics of algal blooms (e.g., macroscale observation) while others exactly qualify and quantify species by species (e.g., microscale observation). Current monitoring strategies include (i) manual on-site sampling followed by in-lab analysis (current norm); (ii) in situ sensing of proxy parameters such as phycocyanin, chlorophyll, or biomass; (iii) automated on-site sampling followed by in situ analysis; and (iv) remote sensing based on satellite image analysis.

3.5.1 Manual On-Site Sampling Followed by In-Lab Analysis

Manual sampling followed by lab analysis is commonly used and is the simplest method to monitor HAB activity and toxin release. Once algal blooms are anticipated, visiting a site and taking water samples is the first step. Sites of interest can be determined based on the history of HAB events. Satellite images can also be used to guide sampling locations (see Section 3.5.4). Some areas such as shoreline and downstream of reservoirs or rivers tend to exhibit higher toxin concentrations.

TABLE 3.1
Strategies and Targets for Monitoring Algal Blooms

Measuring target	Algal species (living organisms) Biological toxins (chemical compounds) Total toxicity (bioassays)
Measurement directness	Direct measurement Indirect measurement (proxy)
Observing approach	On-site (or in situ) measurement Remote sensing
Information scale	Macroscale information Microscale information

Highest concentrations of cyanobacterial toxins are usually observed in scums (just below dead materials at the surface of a water body) and within dense cyanobacterial blooms. Sampling occurs on a case-by-case basis depending on current water conditions, but it is focused on the peak recreational season (between Memorial Day and Labor Day in the United States) (Codd et al. 2005b). Sampling protocol varies. Surface scum–forming cyanobacteria such as *Anabaena flos-aquae* have gas-filled cavities that allow them to float to the surface of water; hence, surface sampling is recommended. *Planktothrix agardhii* is more uniformly distributed within a water column and thus depth sampling is required. Ideally, samples should be preserved at the time of collection and analyzed within 36 h after collection (Westrick et al. 2010).

Samples are shipped and subject to qualitative and quantitative analysis of algae species or chemical toxin species. The analysis is target specific. There are several screening methods to measure algal blooms. Algae are generally microscopic organisms. The main groups of algae found in freshwater are blue green algae, green algae, diatoms, and euglenoids while some minor groups include golden brown algae, brown algae, crytomonads, dinoflagellates, glaucophyta, haptophytes, red algae, and yellow green algae. Identifying algae species can be done manually based on microscopic observation of their size and shape. For example, many species even within blue green algae are identifiable, including *Microcystis*, *Anabaena*, *Nodularia*, and *Oscillatoria*. Measuring chlorophyll, a central pigment in a plant's photosystem, is also proposed to indirectly estimate the level of algal bloom (Addy and Green 1996). However, since the ratio of chlorophyll to algal biomass varies among algal groups, this approach cannot quantify algae concentration accurately.

Measuring biological toxins in water can be an alternative to measuring algae species in order to monitor HAB activity. Cyanobacteria generate and release many cyanotoxins in water, including microcytins, anatoxin-a, cylindrospermopsin, and saxitoxins (Hawkins et al. 2005). Screening methods for detecting those toxins are divided into two general categories: biological assays and chromatographic methods. As one of the most powerful biological assays, neurochemical and enzyme-linked immunosorbent assay (ELISA) utilizes antigen–antibody interaction to detect MCs. Color changes initiated by the interaction are detected by a screening kit. This method has a high detection limit of up to 0.2 μg/L, but it has limitation in specificity (Jianwu et al. 2007). Anatoxin-a and MC variants are found intracellularly during around 95% of algal bloom period. However, some chemical species such as cylindrospermopsin are released to water by living cyanobacterial cells (Codd et al. 2005b). Typically, biological assays cannot measure these extracellular toxins. Since antibodies used in ELISA have cross-reactivity with other types of MCs, total concentrations of MCs are measured.

If such a screening test is positive, samples are sent to a laboratory for further analysis to qualify and quantify specific toxin species by using more accurate chromatographic techniques such as high-performance liquid chromatography (HPLC). More than 80 different MC species can be identified by HPLC (Pyo et al. 2005). Traditionally, MCs have been analyzed by HPLC with an ultraviolet detector. However, analytical methods are shifting toward HPLC with more sophisticated mass spectrometry (MS/MS) with high accuracy and responsiveness despite its high

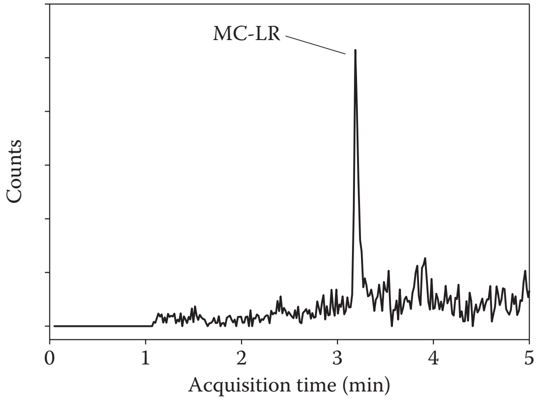


FIGURE 3.2 Chromatogram of *Microcystin*-LR scanned by high-performance liquid chromatography coupled with electrospray tandem mass spectrometry. This method is capable of qualifying and quantifying toxin species with high accuracy and responsiveness.

cost (Tomoyasu and Keiji 1996). Figure 3.2 shows a chromatogram of MC-LR measured by HPLC coupled with electrospray tandem MS/MS. With proper pretreatment of samples, the analytical method can achieve a detection limit of much less than 0.1 μg/L (EPA 2012b). As an alternative to the measurement of algae or toxins, the total toxicity of water samples can also be measured by mouse bioassay and protein phosphate inhibition assay (Hawkins et al. 2005; Jianwu et al. 2007).

Many local health and water authorities follow this simple monitoring approach to analyze water samples in their areas periodically and thus to release HAB information to the public. There are also federal-level efforts. A HAB monitoring project by NOAA has regularly sampled Bear Lake, Muskegon Lake, Western Lake Erie, and Saginaw Bay around Great Lakes. Satellite images are used to find areas of interest, which are suspicious of HABs and thus need to be monitored (also see Section 3.5.4). Table 3.2 shows the variation of MC concentration in water taken

TABLE 3.2
***Microcystin* Concentration in Western Lake Erie (Location: N 41°42.454, E 83°23.000) during August and September of 2013**

Sampling Date	*Microcystin* Concentration (μg/L or ppb)
August 19, 2013	56.4
August 26, 2013	43.2
September 3, 2013	20.8
September 10, 2013	8.78

Source: NOAA (National Oceanic and Atmospheric Administration). 2013. Center of excellence for great lakes and human health, western Lake Erie MCs sample. http://www.glerl.noaa.gov/res/Centers/HABS/western_lake_erie.html.

from one of the Western Lake Erie sampling stations. In addition to MCs, other water quality parameters and cell counts are monitored weekly. Samples are taken at the surface because they best represent the portion of the water column that most likely comes into contact with many users. Total intracellular concentrations of MCs are quantified by the ELISA technique. Considering that most MCs are retained in the cells until cell death, the reported MC concentration is very close to total water MC concentration for new and peak blooms.

3.5.2 In Situ Autonomous Observing Approaches

The recent increase in toxic cyanobacteria blooms in western Lake Erie during the past decade affects millions of people through drinking water processing plant shutdowns, beach and fisheries closures, and direct adverse health effects from unintended toxin exposures (Dyble et al. 2008; Millie et al. 2008, 2009). For these reasons, local governments and water quality managers are dependent on effective monitoring programs. However, most established programs are labor intensive and consequently have limited spatial–temporal coverage of their sampling (e.g., no more than weekly sampling at a few sites). These sampling limitations can significantly limit the timely detection of HABs and ultimately our understanding of the environmental factors that control HAB dynamics. For example, weekly sampling may miss critical episodic events occurring on time scales of hours to days, such as strong rain runoff or wind resuspension events from intense storms, which, in turn, could increase nutrient fluxes into an ecosystem and stimulate HAB formation (Bridgeman et al. 2012; Michalak et al. 2013).

3.5.2.1 Platforms

Because of the ecological complexity and transient nature of HABs, developing sustainable detection and monitoring programs requires deployment platforms that can operate autonomously at the appropriate spatial (meters to kilometers) and temporal (hours to weeks) scales. A number of autonomous buoy platforms that particularly address the temporal measurement needs are now available. Static moored buoy systems such as YSI's Harbor buoys and Satlantic's Land Ocean Biogeochemical Observatory (LOBO) provide integrated and automated water quality measurements with real-time telemetry of results. In particular, the LOBO system is composed of a floating platform and instrument frame, power and wireless telemetry system, integrated sensor suite, automated processing, and web-based data visualization software (e.g., http://algae.loboviz.com/loboviz/). Autonomous buoy measurements can be continuously conducted on short time scales (e.g., every 30 min to 1 h) over long deployment times (several months) to provide excellent temporal sampling of HABs and associated critical ecological parameters. LOBO data from a recent deployment in Western Lake Erie demonstrate the power of these high temporal scale measurements when compared to typical weekly monitoring programs (Figure 3.3).

Since the buoy systems described above are generally deployed as surface floats and make their measurements in the upper meter of the water column, this deployment scheme may not be adequate in deeper and continuously stratified ecosystems where HABs can occur with little or no surface manifestation (McManus et al. 2008;

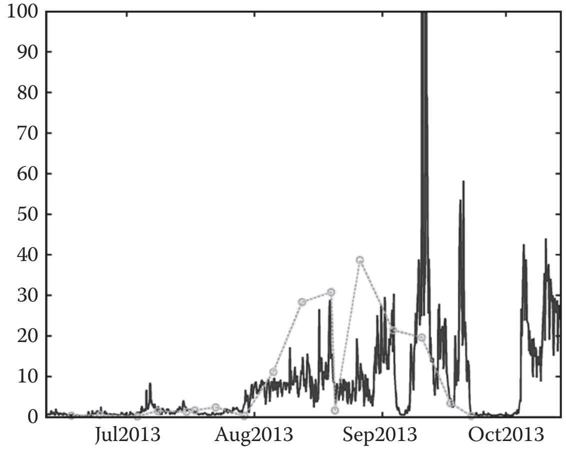


FIGURE 3.3 Phycocyanin (in micrograms per liter) measured by the LOBO (dark line) at hourly intervals in western Lake Erie from June through October 2013. Discrete NOAA GLERL phycocyanin measurements (bright circles) at the LOBO location for the same period measured on a weekly basis.

Sullivan et al. 2010; Twardowski et al. 2005). Under these conditions, Autonomous Moored Profiler (AMP) systems provide additional resolving capability with respect to depth. The WET Labs AMP (Donaghay 2004; Sullivan et al. 2002, 2005, 2010) is a totally self-contained autonomous vertical profiling system consisting of an underwater winch with an associated wire attached to a bottom anchor, a data logger and profiler controller with integrated wireless telemetry (spread spectrum radio or iridium), battery packs, and an instrument frame with syntactic foam floats to provide positive buoyancy. The AMP profiler collects data from the bottom-up by slowly reeling out the winch wire with user-defined ascent rates until it reaches the surface. Once at the surface, it transmits data and returns to the bottom by rapidly reeling in the winch wire.

The AMP can (1) accommodate a large, comprehensive suite of user-definable, high-quality instrumentation for significant deployment periods (e.g., hourly profiles for months); (2) profile fine-scale structure at user-programmable ascent rates as slow as 1 cm/s; (3) profile from the very near bottom up to (and through) the air–sea interface; (4) allow near–real-time wireless data download and remote operational programming from anywhere in the world; and (5) be easily deployed from a small boat, allowing simple system repositioning if required and recovery for normal maintenance (cleaning, battery swapping). Most moored buoy systems can carry a fairly large and extensive instrument payload and provide high temporal scale sampling, while the AMP systems can also provide high spatial sampling throughout the vertical water column. Furthermore, moored buoy systems can continue operations during storm events that have dramatic impacts on the physical and biogeochemical properties of water column (Babin et al. 2004; Chang and Dickey 2001; Glenn et al. 2008) while measurements from other platforms (e.g., REMUS autonomous vehicles or boat sampling operations) may not be possible. Such characteristics make moored profiling platforms ideal for HAB monitoring.

However, unless arrays of profiling moorings are deployed, high spatial sampling resolution in the horizontal plane is not achieved. Autonomous underwater vehicle (AUV) platforms (e.g., gliders) can provide this coupled vertical and horizontal resolving capability. A number of these platforms are commercially available, including the Webb Research Slocum glider and Bluefin Robotics Spray glider. While these gliders use different methodologies to propel the vehicle (variable buoyancy, wave, and solar power), they share the common trait of being able to travel long distances with controlled navigation for over long periods (several weeks) with little servicing. These gliders vertically profile the water column as they transit horizontally and transmit their data to shore when surfacing. One drawback to these long-term deployment AUV systems is a somewhat limited payload in both the size and design of the acceptable instruments and the total amount of power available to the instrument suite. Glider AUVs also may not be able to maintain waypoint navigation in significant currents induced by strong winds, tides, or river outflows (Glenn et al. 2008).

3.5.2.2 Instruments

While buoy and glider platforms primarily act as a “bus” for instruments, their ultimate usefulness in HAB detection and monitoring is dependent on the suite of instruments they can support. Continued advances in instrument technology have produced a number of compact, energy-efficient sensors suitable for most autonomous platforms and HAB monitoring work. These include an array of small, power-efficient fluorometers for detecting chlorophyll, phycocyanin, phycoerythrin, and fluorescent dissolved organic matter, where many of the measurements can sometimes be made simultaneously by a single integrated sensor (e.g., Turner Designs C3 fluorometer or the WET Labs ECO triplet). Similarly, a number of compact optical backscattering sensors are currently available to measure turbidity or the volume scattering function in both single and multiple wavelengths and angles (e.g., WET Labs ECO-BB3 and ECO-VSF or the Turner Designs Cyclops). Most of these sensors include integrated wipers or shutters on their measurement faces to mitigate biofouling on long deployments. Although these instruments do not directly quantify HAB species or abundance, their measurements can be used in developing optical proxies for HAB detection and monitoring. Larger instruments that can be integrated onto autonomous sampling platforms include multispectral and hyperspectral absorption and attenuation sensors (Turner Designs ICAM and WET Labs ac9 and acs), which may be useful in detecting absorption and scattering optical signatures of HABs, and in situ nutrient analyzers for monitoring nitrogen (NO_2, NO_3, NH_4) and phosphorus (PO_4) loading (e.g., Satlantic ISUS/SUNA and WET Labs Cycle sensors). In addition to the instruments described above, most autonomous platforms include standard instruments to make measurements of core hydrographic parameters such as pressure, temperature, and salinity. A number of improvements in stability and drift have recently occurred with in situ oxygen and pH sensors, making these instruments more valuable to long-term monitoring, and CO_2 sensors are also now becoming commercially available.

3.5.3 AUTOMATED ON-SITE SAMPLING FOLLOWED BY IN SITU ANALYSIS

As discussed previously in Section 3.5.1, prerequisites for identifying algal species and chemical toxins are to collect samples on-site and to return them to a laboratory for target-specific analyses. As a result, there have been efforts to both take and analyze samples automatically in situ by introducing the most elaborate observing devices. Such a device can provide collection and analysis of water samples on-site, as mentioned in Section 3.5.2. It is composed of many electromechanical and mechanistic fluidic systems to collect water samples, pretreat them (e.g., filtering and concentrating), and apply molecular probes to identify algae and their products. Collected data are then available for remote authorities in real time. A device can hold many detecting units that target specific water quality parameters. As a result, it has a modular design composed of a core processor, a sampling unit, many analytical modules, and a data transmission unit. It can be deployed at various depths and also store water samples for further analyses (Mikulski et al. 2008).

One of the well-known devices is the environmental sample processor (ESP), which is an advanced biological sensing system that automatically collects and analyzes water samples on-site (Monterey Bay Aquarium Research Institute [MBARI] 2014). Using DNA probe technology, it can detect algae and pathogens and send results in real time via radio, satellite, or cellular modem. Development of the first generation of an ESP prototype was initiated by MBARI in 1999, and it was deployed in the Gulf of Maine in 2001 and in Monterey Bay, California, in 2002. The second generation of ESP developed in 2006 has a new feature of modular core system that can be reconfigured and modified to suit a wide variety of deployment and analysis requirements. It is more compact, robust, and user-friendly and has lower power requirements. Many analytical procedures that are adopted in lab analyses are miniaturized, automated, and integrated into an analytical module. ESP uses different real-time chemistries for detection including sandwich hybridization assay (SHA) and ELISA (MBARI 2014). As an example for SHA, ESP collects water sample, concentrates organisms, and creates a nucleic acid extract that is delivered to a probe component. If a target rRNA is present in the extract, it sticks to the capture probe while the rest of the extract is washed away. The probe is specific and thus precise discrimination can be achieved. The next solution contains another probe that attaches to a different region of the target molecule. A signal probe generates a light signal that is directly proportional to the amount of the target (Preston et al. 2009). ESP is also capable of detecting a variety of other general water quality parameters in situ simultaneously including temperature, salinity, light transmission, and chlorophyll concentration. Having the data at the same time can help investigate the correlation between the water quality parameters and HAB activities.

Once a new analytical module for a target of interest (even a chemical compound such as biological toxin) is developed, the module can be installed into the device. The ESP may replace existing monitoring programs with discrete sampling, by eliminating the labor-intensive and time-consuming protocol associated with site visiting and sampling and delivering and analyzing samples (Doucette et al. 2009). NOAA is currently developing an integrated early warning system that uses the ESP approach. For example, ESP helps the NOAA Northwest Fisheries Science Center support the conservation and management of living marine resources and their habitats in the Northeast Pacific Ocean (NWFSC 2014).

3.5.4 REMOTE SENSING BASED ON SATELLITE IMAGE ANALYSIS

The demonstration of remote sensing of cyanobacterial blooms goes back four decades. Wrigley and Horne (1974) showed the potential of remote sensing with aerial infrared photography of a bloom of *Aphanizomenon flos-aquae* in Clear Lake, California. Strong (1974) found that data from Landsat (launched in July 1972) could detect evidence of the dense cyanobacterial blooms that plagued Lake Erie. Öström (1976) made perhaps the first ecological study with remote sensing, using Landsat data to examine the scope and causes of *Nodularia* blooms in the Baltic Sea. It took until the recent decade, however, for data to be available in a sufficiently timely way to allow routine monitoring.

Several factors (Table 3.3) have to be considered in using remote sensing to monitor cyanobacterial (or other harmful) algal blooms. The most obvious is the spatial resolution. Satellite data are obtained as “pixels” that cover an area on the ground. The pixel at the shoreline typically contains both land and water retrievals so that any water body must be more than 3 pixels wide to obtain even 1 pixel that might be useful. Ocean color sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) have pixels that cover approximately 1 km and thus a water body must be at least 3 km wide to provide a useful pixel. Landsat, with 30-m pixels, can resolve much smaller water bodies.

Unfortunately, high spatial resolution comes at the expense of frequency (i.e., temporal resolution). Clouds obscure approximately half of the summer days for a typical midlatitude lake in the United States and Europe. Practically, the two Landsat satellites 7 and 8, each with a 16-day revisit, return usable information every several weeks, making them useful for general assessment of the trophic state of lakes (Olmanson et al. 2008; Sass et al. 2007) but not for routine monitoring of algal blooms. Additional moderate resolution sensors are being planned and implemented. With the launch of the Sentinel-2 satellite in 2015 with a 10-day repeat,

TABLE 3.3
Sensor Resolution Suitability for Monitoring Cyanobacterial Blooms

Satellite	Spatial (Pixel Size)	Temporal (Revisit)	Spectral Red/NIR Bands
MERIS and OLCI (2015)	300 m	2 days	6
MODIS high resolution	250/500 m	1–2 days	2
MODIS low resolution	1 km	1–2	4
Landsat	30 m	8	2
Sentinel-2 (2015)	20–30 m	10	3

Note: MERIS, medium-resolution imaging spectroradiometer; MODIS, moderate-resolution imaging spectroradiometer; OLCI, ocean and land color instrument on Sentinel-3.

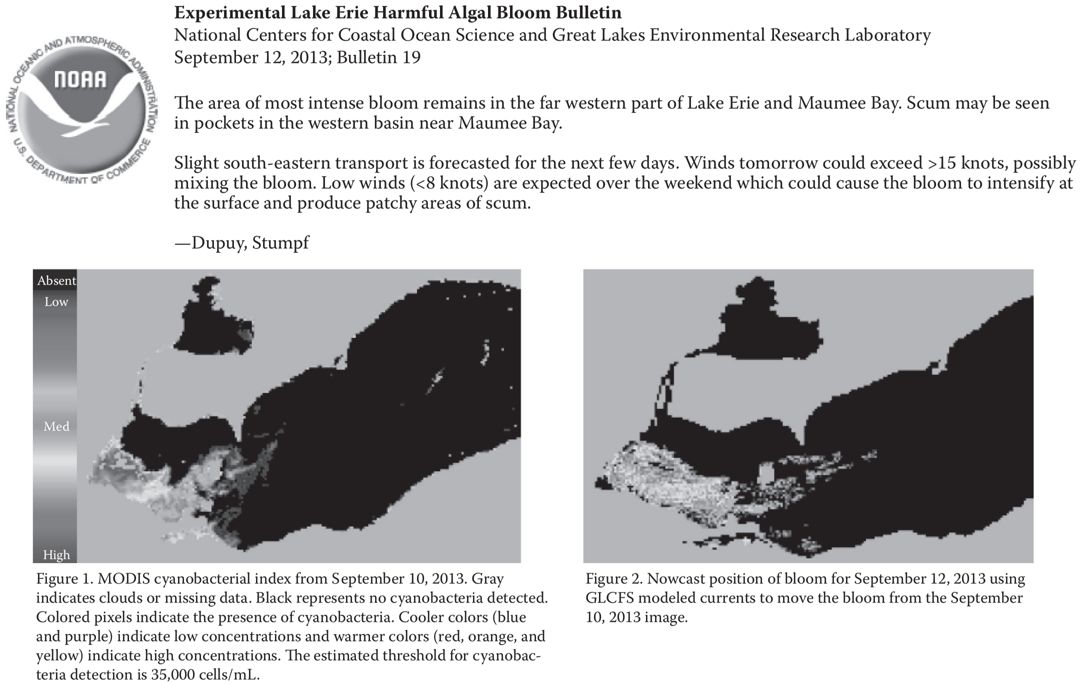
followed in 2 years by Sentinel-2B, the combination of satellites may provide sufficient frequency to begin monitoring the trophic state of smaller lakes at higher spatial resolution.

Detecting blooms depends on identifying and implementing suitable algorithms, which is a problem of spectral resolution. Extensive discussion of algorithms to detect cyanobacteria is presented by Kutser (2009). In short, water bodies with little turbidity other than that caused by algae may be reliably monitored by relatively simple measures of water brightness (Kahru et al. 2007; Öström 1976). This type of approach has been successfully applied to several routine monitoring programs of the Baltic Sea (Stumpf et al. 2010). However, more spectral bands are needed to identify pigments. Total pigment concentration may be estimated using two spectral bands. While this is more informative than water brightness, interpreting the data still requires caution. Ratios of visible bands (blue, green, and red) are effective in water containing only algae. These algorithms do not adequately discriminate between chlorophyll, dissolved pigments, and other pigmented compounds such as iron.

Red (600–700 nm) and near-infrared (NIR) bands (700–800 nm) are far more effective for bloom discrimination in inland and coastal turbid waters. Chlorophyll-a absorbs strongly around 680 nm while other water pigments have slight and spectrally uniform absorption in the red and NIR. Algorithms based on band ratios of water reflectance between 680 and 709 nm have been demonstrated to estimate chlorophyll in eutrophic water (Gilerson et al. 2010) and cyanobacterial blooms (Simis et al. 2005). Phycocyanin as an indicator pigment for cyanobacteria absorbs in wavelengths from 620 to 650 nm. The MERIS sensor has a band in this range, also making it potentially well suited for identifying blooms with phycocyanin (Hunter et al. 2009; Simis et al. 2005).

The red–NIR ratio methods can produce excellent estimates of chlorophyll because the water reflectance is accurately determined. A significant problem with satellite (or aerial) imagery is that the ratios involve relatively small numbers and yet most of the signal received comes from the atmosphere or is surface reflectance (glint). Slight errors in the correction for atmosphere then lead to large errors in the calculated water reflectance and the derived estimated pigment. Wynne et al. (2010) estimated that standard atmospheric corrections for MERIS led to physically impossible negative reflectances for approximately 20% of the time in bloom regions of Western Lake Erie, rendering the band ratio algorithms ineffective for routine application.

Spectral curvature algorithms, which use three or more bands, can detect and quantify blooms and circumvent the problem of atmospheric correction. The spectral curvature, which is essentially the second derivative, is essentially insensitive to atmospheric correction (Gower et al. 2005). Two frequently used algorithms are the maximum chlorophyll index (MCI) (Gower et al. 2005) and the cyanobacterial index (CI) (Wynne et al. 2008). Both indices correspond to the amount of biomass (Binding et al. 2013; Matthews et al. 2012; Wynne et al. 2010) and can be applied routinely for monitoring (e.g., Wynne et al. 2013). These algorithms have been reliably applied to data that have not been atmospherically corrected (Gower et al. 2005; Wynne et al. 2008). NOAA has monitored Lake Erie every summer for 5 years, creating bulletins and forecasts that are consistent from image to image (Wynne et al. 2013), as shown in Figure 3.4 as an example.



Experimental Lake Erie Harmful Algal Bloom Bulletin
National Centers for Coastal Ocean Science and Great Lakes Environmental Research Laboratory
September 12, 2013; Bulletin 19

The area of most intense bloom remains in the far western part of Lake Erie and Maumee Bay. Scum may be seen in pockets in the western basin near Maumee Bay.

Slight south-eastern transport is forecasted for the next few days. Winds tomorrow could exceed >15 knots, possibly mixing the bloom. Low winds (<8 knots) are expected over the weekend which could cause the bloom to intensify at the surface and produce patchy areas of scum.

—Dupuy, Stumpf

Figure 1. MODIS cyanobacterial index from September 10, 2013. Gray indicates clouds or missing data. Black represents no cyanobacteria detected. Colored pixels indicate the presence of cyanobacteria. Cooler colors (blue and purple) indicate low concentrations and warmer colors (red, orange, and yellow) indicate high concentrations. The estimated threshold for cyanobacteria detection is 35,000 cells/mL.

Figure 2. Nowcast position of bloom for September 12, 2013 using GLCFS modeled currents to move the bloom from the September 10, 2013 image.

FIGURE 3.4 Example of part of the NOAA Lake Erie Harmful Algal Bloom Bulletin (NOAA 2014). The left image was created with MODIS 1-km data approximating the MERIS algorithm. The right image is a distribution expected on the day of the bulletin using a transport model. The bulletin was originally published in color. In this grayscale, darker areas indicate cooler colors (blue and purple) for low concentrations and brighter areas indicate warmer colors (red, orange, and yellow) for high concentrations. Black is water background. (From Wynne, T. T., R. P. Stumpf, M. C. Tomlinson et al. 2013. Evolution of a cyanobacterial bloom forecast system in western Lake Erie: Development and initial evaluation. *Journal of Great Lakes Research* 39:90–99.)

Binding et al. (2011) demonstrated reproducibility of the MCI for time series studies of Lake of the Woods in Canada. Although these algorithms are not sensitive to chlorophyll below approximately 10–15 μg/L (Matthews et al. 2012), their sensitivity is enough to detect concentrations of concern in most practical cases (WHO 2000). Between the two algorithms, the MCI shows sensitivity to sediment turbidity at the low end of its chlorophyll concentration (Binding et al. 2013) while the CI has not shown such sensitivity. With the MERIS 620-nm band, a curvature algorithm can also show the presence of phycocyanin (Matthews et al. 2012). Thus, one algorithm can provide biomass from chlorophyll and the other identifies the bloom as cyanobacteria. The advantage of combining the two is apparent, as shown in Figure 3.5.

While MERIS failed in 2012, the European Space Agency is planning the launch of its replacement, the Ocean and Land Color Instrument (OLCI), on Sentinel-3 in 2015. The OLCI has the MERIS bands, assuring continuity of monitoring into the future. The existing 10 years of MERIS data (comprehensive at 1 km, and somewhat more irregular at 300 m before 2009) allows for evaluation of recent trends in blooms. For example, Stumpf et al. (2012) used the data set to determine the nutrient loading factors driving interannual variations in the Lake Erie cyanobacterial blooms. For higher resolution, Sentinel-2 will have not only Landsat bands but also an additional NIR band that should improve separation of algal blooms from other pigments in water. Between these and future hyperspectral satellite sensors, comprehensive routine monitoring will be possible into the future.

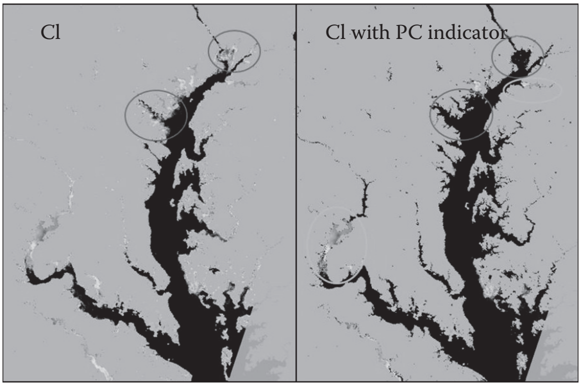


FIGURE 3.5 Images of CI. The left image is the CI for upper Chesapeake Bay and the Potomac River on August 23, 2010, from the European Space Agency's MERIS sensor. The CI is sensitive not only to cyanobacteria blooms but also to other blooms that scatter light. The right image is the CI only where phycocyanin (PC) is indicated. The two dark circles in the left image show areas where other algae were excluded and the two bright circles added into the right image show known cyanobacterial blooms (*Microcystic* spp).

3.5.5 COMPARISON OF THE MONITORING APPROACHES TOWARD SUSTAINABILITY

The field observation and sampling followed by laboratory analysis is simply used to identify algal species and to assay biological toxins species by species (i.e., direct microscale observation). Despite its high accuracy and reliability, this approach is neither sustainable nor practical to meet the vast spatial and temporal measuring need. In situ sensing is a recent monitoring approach. The in situ autonomous observing approach optically senses easy-to-detect surrogate parameters such as phycocyanin as an accessory pigment to chlorophyll often associated with HABs (i.e., as a proxy to HABs). However, such a color product is not specific to HABs. High level of chlorophyll may or may not be associated with toxic blooms. Even not all algal blooms are associated with the release of biological toxins. As a result, the in situ sensing system is useful for monitoring general algal blooms. Going beyond monitoring standard color products, it would be highly desirable for the in situ sensing approach to determine the toxic or nontoxic nature of algal blooms and, if technically possible, to identify species of toxins present in water. This is also needed because the toxicity level varies species by species. As one of the most sophisticated approaches, the automated sampling followed by in situ analysis provides both on-site collection of water samples and their direct analysis simultaneously to identify various organisms and toxins. Despite its capability of collecting microscale information with high accuracy in situ and in real time, the high cost for fabricating and operating such a sensing processor (in addition to limited analytical capability) is a hurdle in deploying it widely. Nevertheless, these in situ real-time monitoring approaches benefit immediate decision-making and timely response, which are crucial elements for developing an early warning system as a sustainable environmental infrastructure. Alternatively or concurrently, remote monitoring relies on spectral images taken from satellites and aircrafts to provide the large spatial scale and high frequency of observations required to assess bloom locations and movements. The remote sensing approaches are useful for monitoring general algal bloom activities (i.e., indirect macro-observation) similar to the in situ sensing of proxy parameters. While no single platform system can likely satisfy all space–time monitoring, detection, and science needs, by combining data from multiple platforms and sources, it will be possible to develop a deep understanding into the behavior and functioning of HABs within their aquatic ecosystems.

3.6 CHALLENGES AND PROSPECTS

Continued advances in technology and increased focus on HABs have increased our knowledge of their distributions and ecology (Berdalet et al. 2013). The new technologies have resulted in greatly improved detection and monitoring and the generation of continuous records of important ecological indicators in aquatic systems at the required spatial and temporal scales. There is also a solid interest among federal agencies in the United States (including NOAA, USEPA, NSF, and NIH) in monitoring algal blooms and toxin release in order to provide linkages between oceans and the Great Lakes and human health and to understand aquatic processes and systems (Tyson et al. 2004). A comprehensive research environment should be built to support collaboration among researchers in diverse disciplines, including biochemistry, oceanography, pharmacology, and environmental scientists with the ultimate goal of monitoring, assessing, and predicting algal blooms and toxin release. Monitoring general algal bloom activities gives an idea on potential hazard while monitoring actual biological toxins gives an insight on imminent hazard.

Integrating the current HAB monitoring systems and observing programs would be helpful for reliably monitoring HAB activities with high accuracy because they are complementary to each other considering each monitoring system has its own advantages and limitations as discussed (Zamankhan et al. 2014). They measure and use different water quality parameters to estimate HABs. Correlation among the observing targets might exist because the monitoring systems were developed to represent the same phenomenon, HABs. Comparing biological toxin level with either phycocyanin concentration or CI might result in correlation between observed toxin release and estimated algal activity. This practice can be a mechanistic tool to determine whether monitoring of general algal bloom activities is helpful for predicting actual toxin release and whether measuring phycocyanin as a surrogate chemical to HABs is a valid approach for monitoring HABs. Information on environmental conditions that affect monitoring results and data interpretation, including nutrient level, water temperature, wind speed, and precipitate, should be incorporated into the integrated system.

There is also a research need to directly detect biological toxins in situ such as MCs. Real-time monitoring of the level of MCs in situ using an innovative sensor and development of a wireless MC sensing network are of high interest at this moment (Choi et al. 2014). Because of the lack of knowledge regarding assays of MCs on a microscale sensor suitable for real field applications, there have been few attempts to implement the in situ MC sensing idea. This approach will have huge impacts on the design and development of sustainable environmental monitoring networks. In addition, the sensing network, which is deployed to monitor HAB toxins in an area suspicious of HAB activities based on remote sensing analysis or in situ phycocyanin detection, makes it possible for us to obtain insights on the close relationship between general algal bloom activity and actual toxin release.

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4 Groundwater Management (Aquifer Storage and Recovery, Overdraft)

Dorina Murgulet

CONTENTS

4.1 INTRODUCTION

Groundwater is an essential source of freshwater in the United States and in many parts of the world. In many areas, it is the only source of water supply for drinking, agricultural, and industrial purposes. As a freshwater resource, groundwater has many advantages over surface water: It is more uniformly distributed over larger areas, better protected from surface contamination (i.e., chemical and bacterial), and less vulnerable to seasonal and perennial quality changes than surface water [1]. As surface water resources are already developed or fully appropriated to different uses, groundwater has become increasingly targeted as a new and more available resource. Recent studies indicate that in the United States, groundwater supplies 33% of the entire water supply, 98% of the water supply for domestic use, and 42% of the water supply for irrigation use [2]. Furthermore, Siebert et al. [3] show that 37% of the agricultural lands around the world are irrigated using groundwater and 43% of the total consumptive irrigation water is supplied from groundwater. However, the rate at which groundwater has been used in the past few decades raises serious concerns related to the depletion or overdraft of this resource. In addition, agricultural land application of fertilizers, pesticides, and herbicides may have adversely affected the quality of groundwater. Poor wastewater management practices have led to contamination of shallow aquifers and water quality degradation and have rendered the resource for human consumption. Effective groundwater management from both quality and quantity perspectives is utterly important for a healthy economy, environment, and quality of life. This chapter offers an overview of groundwater availability (i.e., groundwater reservoirs, storage, and depletion) and best recovery management practices (i.e., artificial aquifer recharge).

4.2 GROUNDWATER

Land areas where aquifers are exposed to the surface and where precipitation is absorbed and percolates downward to the underground water-bearing units are called aquifer recharge areas. This infiltration process is part of the hydrologic cycle and is referred to as natural aquifer recharge. Natural replenishment of groundwater occurs from both regional and diffuse recharge and from direct infiltration of precipitation and focused recharge from surface water bodies such as ephemeral streams, wetlands, and lakes [4]. Natural recharge is directly influenced by precipitation, infiltration, and evapotranspiration (ET) rates, which are subject to dramatic fluctuations especially during severe drought periods (i.e., climate change and global warming). Global modeling estimates indicate that diffuse recharge range from 13,000 to 15,000 cubic kilometers per year (km^3 $year^{-1}$), which is equivalent to approximately 30% of the world's renewable freshwater resource [5–7]. This corresponds to a mean capita groundwater recharge of 2100 to 2500 cubic meters per year (cm^3 $year^{-1}$) [4]. These estimates reflect recharge fluxes based on global distribution of precipitation and water surpluses rather than field observations and do not include focused recharge, which can be significant in semiarid environments [8,9]. Nevertheless, wet conditions do not necessarily result in increased recharge rates.

For instance, greater winter precipitation rates in the southwest United States during the El Niño/Southern Oscillation years were accompanied by enhanced evaporation rates from desert blooms that consumed the excess water [10].

4.2.1 THE GROUNDWATER RESERVOIRS: STORAGE

Groundwater is stored in and moves slow through stratigraphic formations located at varying depths with different hydrogeologic characteristics (i.e., permeabilities). An aquifer is defined as a geologic unit that can yield water to a well. These water-bearing formations are called aquifers and can be open to direct recharge from the surface (i.e., unconfined aquifers) and completely or partially isolated from surface recharge (i.e., confined or semiconfined aquifers). An aquifer may be composed of one or multiple layers of unconsolidated silt, sand and gravel, sandstone or cavernous limestone, fractured granite, or basalt with sizable openings or rubbly lava flows [11]. In terms of water storage, groundwater is the largest single resource of freshwater available for human consumption worldwide. United States Geological Survey (USGS) estimates that 1 million cubic miles of the world's groundwater is stored in just within one-half mile of the land surface and that this storage is more than 30 times greater than the approximately 125,045 and 1250 km^3 volume of freshwater in lakes and streams, respectively, worldwide at any given time (Figure 4.1). However, practically no more than a small fraction of this resource can be developed and made available through wells and springs for use [12].

Groundwater fills the void spaces and cracks in consolidated and unconsolidated rock formations. If all the water is removed from a saturated portion of aquifer material (through drying in the laboratory), the volume removed represents the *total porosity* of the material, which is the fraction of voids within the total volume of solids (Figure 4.2). Some rocks or stratigraphic units can have porosities up to 50%, but only a small part of this may be well connected to allow water to move through (i.e., clay formations which generally act as barriers to flow).

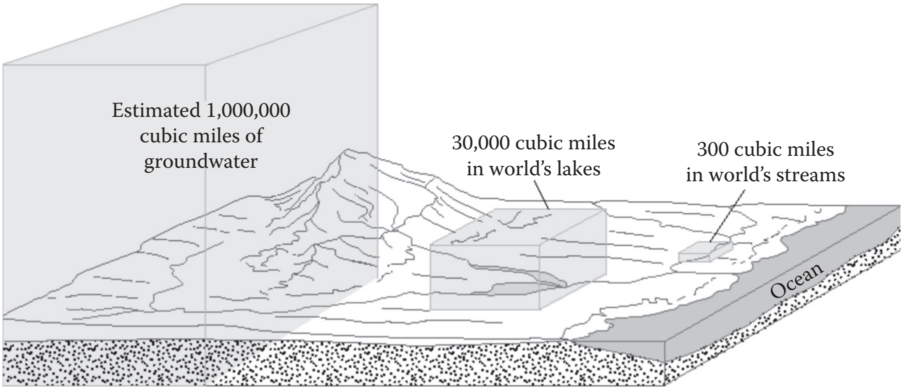

FIGURE 4.1 Comparison of the amount of freshwater in storage in different reservoirs. (From USGS, *General Interest Publication "Ground Water"* United States Geological Survey; [cited on 2014 July 25], Available from http://pubs.usgs.gov/gip/gw/gw_a.html.)

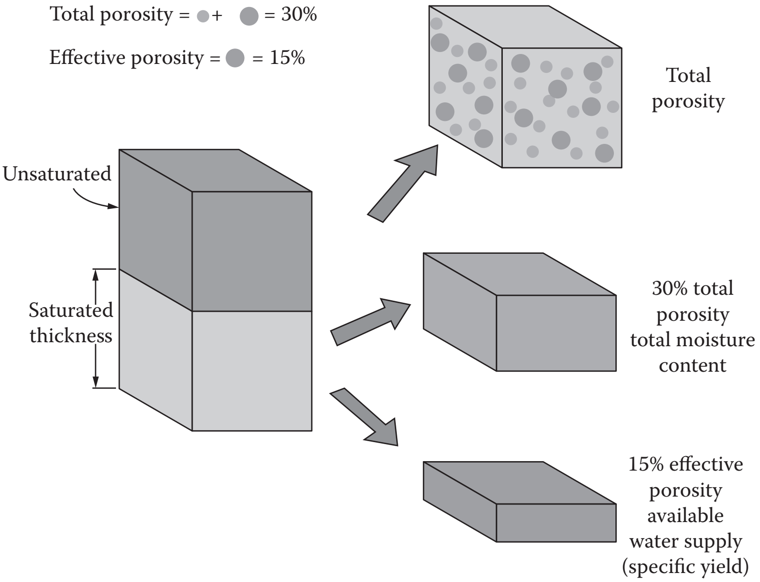

FIGURE 4.2 A schematic illustration of an aquifer sample of known volume with a saturated porosity of 30% from which only half is released under gravity drainage from large pore spaces, and the other half is tightly held in small pores or mineral associations. The former fraction can be pumped out, and is defined as the effective porosity or specific yield. This schematic view also shows how the water available for extraction compares with the total water and aquifer volumes. Illustration not to scale. (From Buddemeier R. W. and Schloss J. A., *Groundwater Storage and Flow*, 2000. [Accessed on 2014 August 22]. Available from http://www.kgs.ku.edu/HighPlains/atlas/apgengw.htm.)

4.2.2 Storage in Unconfined and Confined Aquifers

Groundwater storage is directly related to the total *effective porosity* of an aquifer, which is the amount of void spaces in a unit volume of rock where water can be stored and extracted. Good aquifers may have up to 30% effective porosity, but values higher than this have been observed. The volume of water that can be extracted from aquifers is dependent on the amount of effective porosity. A characteristic closely related to this is the *specific yield* (Sy) of the aquifer, which represents the volume of water per unit volume of aquifer that can be extracted by pumping [11]. Effective porosity and specific yield are most often considered to be equivalent. The specific yield is an extremely important aquifer characteristic that is used to estimate the total volume of available groundwater from the saturated thickness (ST):

$$\text{Volume} = \text{Area} \times \text{ST} \times \text{Sy} \tag{4.1}$$

At any given location, the saturated thickness of an aquifer may vary depending on recharge and extraction rates. This affects the volume of water in storage. Also, the average local porosity and the specific yield vary with changes in saturated thickness, which is given by the water table elevation for unconfined aquifers. These variations

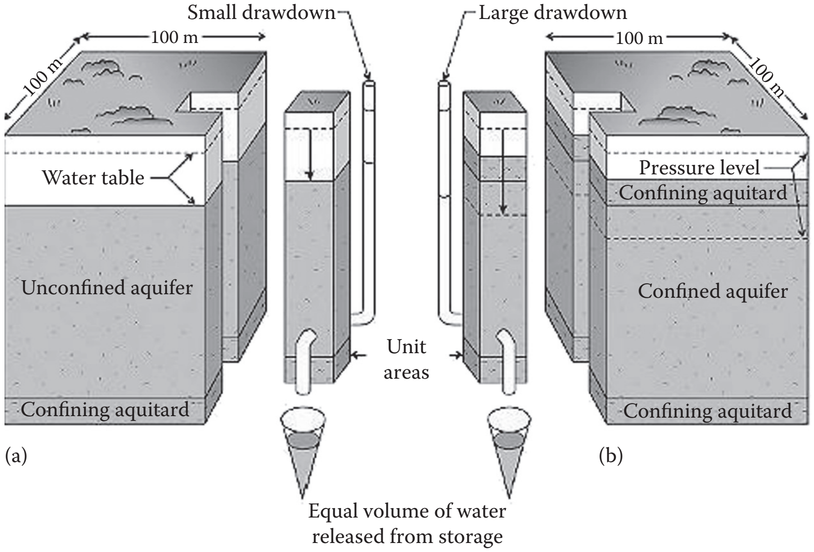

FIGURE 4.3 Pumping in an idealized confined aquifer causes dewatering in cone of depression (saturated thickness of aquifer decreases) (a). Confined aquifers remain completely saturated during pumping (saturated thickness of aquifer remains unchanged) (b). (From UNSW Australia, Groundwater levels and aquifer storage, The University of New South Wales. *Fact sheets*. [Accessed on 2014 August 22]. Available from http://www.connectedwaters.unsw.edu.au/schools-resources/fact-sheets/groundwater-levels-and-aquifer-storage.)

are, in general, difficult to predict or measure with detailed accuracy owing to local variations in the aquifer structure. This is true especially for confined aquifers where the saturated thickness varies with aquifer thickness. The noticeably different responses of unconfined and confined aquifers to injection/recharge and pumping dictate how the storage is affected in general. For instance, when groundwater is extracted from an unconfined aquifer, the saturated thickness is reduced by dewatering of aquifer solids as seen in Figure 4.3 [13]. The opposite is true for recharge or injection: the saturated thickness of the aquifer is increasing though watering of aquifer grains. Therefore, the storage changes with water level (i.e., water table elevation) fluctuations. Aquifers with true confined conditions expand and compress in response to water injection or extraction, respectively. Particularly, interbedded clay layers and aquitards compress more when compared to sands and gravels or consolidated materials of the aquifer [14]. Excessive compression of aquifer materials by overpumping is, in some cases, irreversible [15]. Dewatering of confined hydraulic systems can lead to compression and subsidence. Therefore, sustainable pumping in a confined aquifer causes the potentiometric water level to decline but the saturated thickness remains constant (Figure 4.3).

4.2.2.1 Facts of Groundwater Storage in Aquifers

- Storage in confined and unconfined aquifers is not the same.
    - In unconfined aquifers, water is removed from void spaces; the water table is lowered, causing dewatering of aquifer matrix.

  - In confined aquifers, water stems from decompression of matrix sediments and the water in storage; the aquifer hydraulic pressure is lowered while aquifer thickness remains the same (except when aquifer resources are mined and the potentiometric surface drops below the top of the aquifer).
  - For the same drop in water level, more water is extracted from an unconfined aquifer than from a confined aquifer.
- Aquifer storage: yield per unit area and unit change in hydraulic head.
  - The storage coefficient in unconfined aquifers is high, slightly smaller than the porosity: the water volume produced per unit area of an unconfined aquifer for a 1-m drop in the water table is defined as *specific yield* (Sy) (Figure 4.3).
  - The storage coefficient in confined aquifers is much smaller (~10^{-6}): the volume of water produced per unit aquifer area for a 1-m decline in the potentiometric surface is defined as storativity (S). The aquifer matrix remains saturated while water is removed from storage (Figure 4.3).
  - Water in confined aquifers is being stored through compressibility of water and grains and change in aquifer structure; water expands as the aquifer is depressurized (pumped).
  - Overpumping can lead to land subsidence.

4.2.3 The Status of Groundwater Storage

As discussed in Section 4.1, because surface water resources are extremely limited or absent in many areas around the world because of development and surface water overappropriation, groundwater commonly offers the only reliable source of freshwater in many areas worldwide. However, pumping of groundwater has resulted in significant declines in storage as aquifers are developed at a faster rate than they are replenished. Many of the world's aquifers are currently being mined (i.e., prolonged and progressive decrease in the amount of water in an aquifer) at a relative fast rate, significantly decreasing the available storage [4]. In response to extended periods of drought in Australia (i.e., the multiannual Millennium Drought), substantial and continuous groundwater storage declines of approximately 100 ± 35 km^3 were observed in the Murray–Darling basin from 2000 to 2007 [16]. On the other hand, in the second half of the 20th century, during the multidecadal droughts in the West African Sahel, groundwater recharge and storage increased rather than lessened. Coincidently, this was the effect of land use change from savannah to cropland, which increased soil crusting and enhanced surface runoff, resulting in focused recharge via ephemeral ponds [17]. In parts of the California Central Valley, prolonged surface water irrigation increased groundwater recharge and water levels by a factor of 7 and 100 m, respectively, replenishing aquifers that were previously depleted [18]. In South Asia, intensive groundwater extraction has induced greater recharge rates in areas with permeable soils as a result of dry-season irrigation and, consequently, increased available groundwater storage during the subsequent monsoon [19].

Global-scale modeling [20] reveals areas of recent (1998 to 2002) increased groundwater storage from return surface water-fed irrigation in Egypt (the Nile basin),

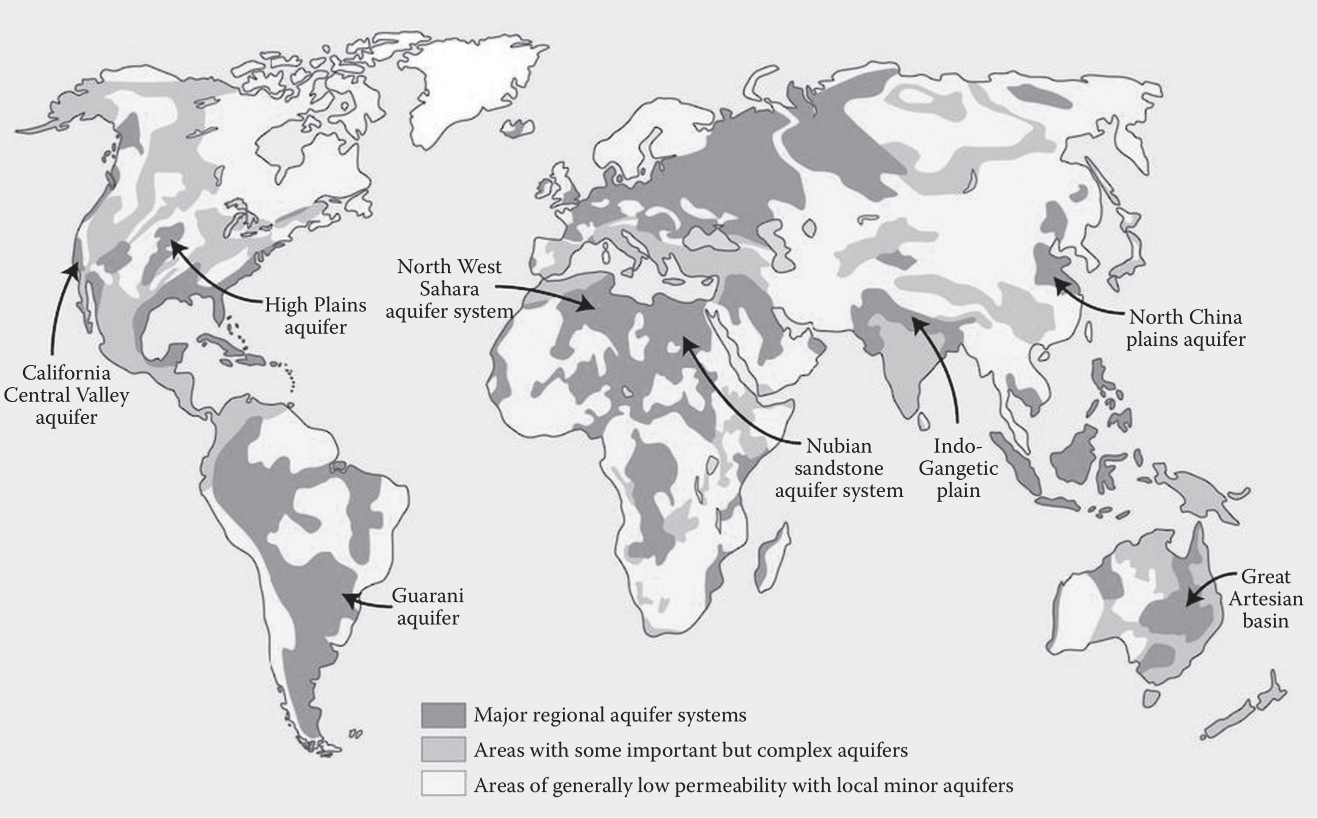

FIGURE 4.4 Location of regional aquifer systems and global groundwater resources map. (From Taylor R. G. et al., Ground water and climate change. *Nature Climate Change*, 2012; DOI: 10.1038/nclimate1744.)

Iraq (the Tigris–Euphrates basin), Syria and Turkey, Pakistan (the lower Indus basin), and southeastern China (Figure 4.4). In contrast, in several semiarid, arid, and humid environments including the North China Plain, northwest India, the US High Plains, Brazil, and Bangladesh, groundwater-fed irrigation areas and the associated intense extraction have depleted aquifer storage (Figure 4.4) [21–26]. In general, large-scale groundwater depletion has been observed to occur when sources of irrigation are shifted from surface water to predominantly groundwater in response to intense drought conditions and limited availability of surface water. This was the case for the California Central Valley during the 2006 to 2009 drought (Figure 4.4). Gravity Recovery and Climate Experiment (GRACE) satellite data along with ground-based observations indicate a decline in groundwater storage between 24 and 31 km^3. This volume is equivalent to the storage capacity of the largest surface reservoir in the United States, Lake Mead [27,28]. However, more ground observation data are necessary to better understand localized groundwater storage changes and to constrain the GRACE satellite observations at larger scales (≥150,000 km^2) [4]. Furthermore, there is a great lack of information regarding the quantity of groundwater storage in most aquifers that may be accurately used. Managed aquifer recharge (MAR) presents the best promise to recover depleted aquifers and supplement groundwater storage.

4.3 DEPLETION THREAT TO AQUIFERS

4.3.1 Trends in Groundwater Depletion

For many years, groundwater resources were not in danger of being depleted because of smaller population, lower industrial and agricultural development, and practical limitations that prevent the extraction of large quantities of water especially from deeper aquifers. The early groundwater use was limited to the shallow aquifers primarily through dug wells, springs, and mountainside galleries [29]. In the late 19th and the early 20th centuries, the introduction of new and easily affordable mechanical drilling technologies such as the hydraulic rotary drilling made the extraction of groundwater from deeper aquifers possible. The deep aquifer exploitation in combination with improvements in deep-well pumps led to a significant increase in groundwater use. Worldwide, groundwater use increased by an order of magnitude in the second half of the 20th century [30] with predictions to increase even further. The three categories of water use with the greatest demand are agriculture, power plant cooling, and domestic use. The 2000 USGS water availability study shows that groundwater withdrawals have been steadily increasing between 1950 and 1980 (at approximately 0.7 billion gallons per day) and remained almost constant until 2005 [31]. California, Texas, Nebraska, and Arkansas accounted for nearly one-half of all groundwater withdrawals for 2000, with the largest extractions for irrigation.

Another recent study estimates that, assuming current conditions, total water demand is projected to increase by as much as 12.3% between 2000 and 2050, especially because of population growth and the need for new thermoelectric plants [32]. The study does not offer specific details about projected groundwater use rates but indicates that, on the basis of current groundwater extraction rates, the ratio of withdrawal to available precipitation is greater than 25%. This may be indicative of unsustainable use of

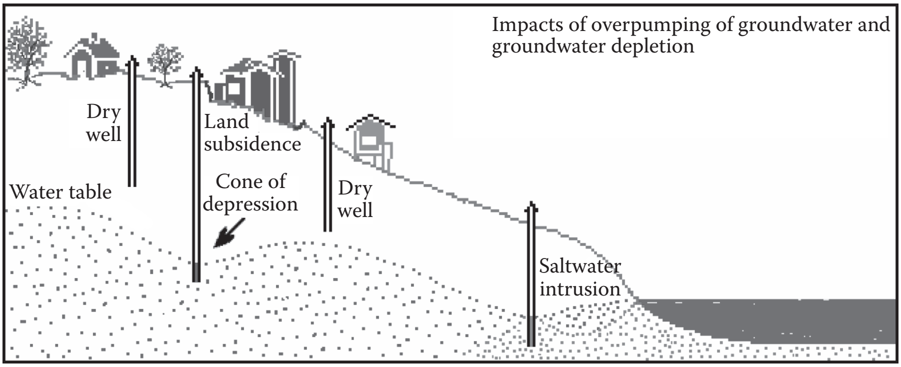

FIGURE 4.5 Effects of groundwater depletion in this example include saltwater intrusion, drying up of wells, and deterioration of water quality (i.e., increased salt contents). (From USGS, *The water and science school: Groundwater depletion*. [Accessed on 2014 August 22]; Available from http://water.usgs.gov/edu/gwdepletion.html.)

aquifers. As demand exceeds supply, many states such as Arizona, Arkansas, California, Colorado, Florida, Idaho, Kansas, Mississippi, Montana, Nebraska, Nevada, New Mexico, Oklahoma, and Texas have an extreme or high risk to water sustainability and are likely to experience limitations on water availability. For instance, areas at extreme risk of water sustainability are the Great Plains and Southwest United States [32].

Given the increasing current and predicted water supply demands and the limited availability of surface water, it is not surprising that groundwater resources have been overexploited worldwide. Aquifers continue to deplete at various rates around the world, and the related consequences vary regionally; some of the most common impacts of aquifer overdevelopment are land subsidence, aquifer depletion as a result of overpumping, surface water resource depletion attributed to the interaction with groundwater, and saltwater intrusion in coastal areas [33] (Figure 4.5, [34]). Declining groundwater levels at rates between 1 and 3 m per year are reported by many countries. Furthermore, regions in North Africa, the Arabian Peninsula, and many areas in the United States (i.e., groundwater age in the confined section of the Carrizo–Wilcox aquifer is dated at 23,000 years) are mining the “fossil” waters stored in the deeper aquifers (Figure 4.6) [35]; these resources will never be replenished unless feasible artificial recharge methods are applied. Multiple studies indicate that agricultural irrigation is by far one of the greatest water consumers compared to any other sector, causing major aquifer depletions [33,36]. However, in many areas, a shift from irrigation to urban water use to accommodate increased population demands seems to be the main cause of groundwater depletion lately (i.e., Texas, coastal area of Alabama).

4.3.2 GROUNDWATER DEPLETION AND LAND PRACTICES

There is now increasing recognition of the potential adverse impacts of different land use practices on water availability. For instance, it is of particular concern how aquifer recharge characteristics are affected by different land practices as water balances assume a certain level of quality and quantity of recharge to maintain a safe yield

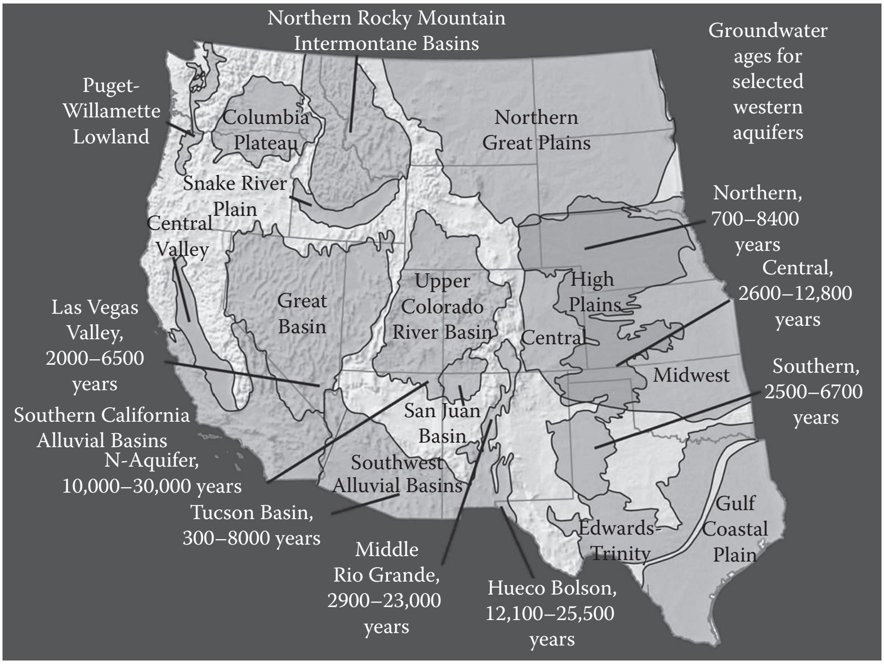

FIGURE 4.6 Map showing groundwater ages in areas with significant water supplies in the western United States. (From Artiola J., and Uhlman K., *Arizona Well Owner's Guide to Water Supply*. 2009. p. 76. [cited on 2014 August 20]; Available from http://cals.arizona.edu/pubs/water/az1485.)

(i.e., groundwater production rates that do not produce negative effects on aquifer resources; ensure sustainable groundwater use). Land use practices are important factors that influence water quality and quantity; therefore, although they are difficult to accurately determine at a large scale, their impact should be closely monitored. Landscape patterns are influenced by both natural processes and those related to human activity (anthropogenic). However, in recent decades, human-generated processes have been the dominant force in shaping landscape patterns in the United States. As a region's population and rate of development increases, landscape usage is altered to accommodate growing needs. Inappropriate distribution and placement of industrial, commercial, agricultural, high-intensity residential, and other human developments can adversely affect the regional environment. Specifically, these land practices not only are major sources of contamination to the environment but also represent an extreme threat to groundwater recharge. Polluted effluents resulting from developed areas can degrade surface water and (indirectly) groundwater quality wherever there is a connection between the two entities. Sustainable groundwater development is imperative to urban planning, particularly in communities that utilize groundwater for drinking water. Development and implementation of measures intended for management and protection of natural resources require land use/land cover analysis.

In areas where surface water resource is negligible or overallocated, groundwater has been "mined." This is mainly in response to dramatic increases in land irrigated areas such as in Western Kansas where the Ogallala aquifer is being pumped at faster rates than recharge [36,37]. The Ogallala aquifer, one of the world's largest underground freshwater sources, consists of sand, gravel, clay, and silt. The local confining conditions of this aquifer along with minimal rainfall, high evaporation, and low infiltration of surface water in the recharge area results in extremely low recharge (less than an inch annually), making it essentially a nonrenewable resource [38–40]. In general, in most regions where groundwater is available and easily accessible, land use adjusted toward water-intensive crops and drought sensitivity increased, whereas in water-scarce zones, farmers maintain drought-resistant practices to mitigate drought impacts and reduce water use [41–43]. Studies indicate that there is a direct relationship between agricultural land use change and the rate of groundwater depletion [44]. In states like Texas, which is one of the top four water-consuming states in the United States, water demand is expected to shift from agriculture (irrigation use is expected to shrink from 57% to 43% by 2050) to urban use as population is expected to almost double by 2050 [43]. It is expected that groundwater use will increase in Texas because surface water supplies are extremely limited [44,45]. In areas such as this, although an extreme increase in water use is not projected, the combination of very low recharge with an increase in groundwater withdrawals (already allocated surface water resources will cause a shift from surface water to groundwater use) will adversely affect the groundwater resource [43].

Recent research has shown that land use impacts on groundwater resources could be indirectly linked to climate change and global warming. The relationship between climate and groundwater is complicated by shifts in agricultural irrigation sources such as rain-fed versus irrigated. In many arid, semiarid, and humid areas worldwide (i.e., North China Plain, India, the US High Plains, Brazil, and Bangladesh), irrigation has depleted groundwater storage because of high rates of extraction. In the California Center Valley, this is particularly the result of a shift from surface water–fed irrigation to predominately groundwater [4]. Nevertheless, in some parts of the California Center Valley, surface water irrigation since the 1960s has increased aquifer water levels by up to 100 m, significantly increasing the groundwater storage. Therefore, the indirect effects of climate on groundwater through changes in land practices (i.e., changes in agricultural practices and irrigation sources and demand) may have greater impacts than the direct impacts of climate change [4].

4.3.3 GROUNDWATER AND CLIMATE CHANGE

Natural replenishment of groundwater occurs from both rain-fed regional and focused recharge (i.e., leakage from surface waters such as streams, wetlands, and lakes). However, the rate of recharge is highly dependent on the current climatic conditions, land use/land cover, and underlying geology [4]. As shown in this chapter, groundwater availability at a sustainable quality and quantity is threatened by many factors such as land practices, industry and population growth, lack of best management practices, and climate change. Out of all factors, climate change plays a leading role as it affects precipitation rates, aquifer replenishment, land practices, and water demands. Mounting evidence shows that we are in a climate change period caused by increasing atmospheric concentrations of greenhouse gases [46]. This phenomenon can have profound effects on the hydrologic cycle through precipitation, soil moisture, increasing temperatures, and ET. General Circulation Models fail to accurately predict changes on mean precipitation but an agreement exists on extreme changes of temperature and precipitation as a result of an intensification of the hydrologic system [47]. Although more rain and ET is expected, the extra precipitation will not be equally distributed around the globe. Some parts of the world may experience significant flooding while others may see significant decreases in precipitation and season changes (i.e., timing alteration for the wet and dry seasons). Consequently, it is imperative to understand the impact of climate change on hydrological processes and water resources. The most updated 100-year warming trend (1906–2005) as reported by the Intergovernmental Panel on Climate Change is 0.74°C ± 0.18°C [46]. Research has shown that the mean sea level has been increasing at a rate of 3.2 mm $year^{-1}$ over the past 20 years. This is important because as seawater migrates farther inland, it can cause destructive erosion, flooding of wetlands, and contamination of aquifers and agricultural soils, and can have disturbing effects on coastal habitats [48].

Although the most noticeable impacts of climate change are related to surface water, concerns are directed toward the groundwater resource. Climate change can affect groundwater resources directly through recharge and indirectly through changes in groundwater use [4]. Since aquifers recharge mainly through infiltration of precipitation and through interaction with surface water bodies, climate change impacts on precipitation, ET, soil humidity, and surface water levels ultimately affect groundwater systems (Figure 4.7). This is a great concern for water managers and government as groundwater is the main source of freshwater available for human consumption and irrigation of agriculture worldwide. To understand the climatic or nonclimatic impacts on groundwater resources, an understanding of recharge and runoff alteration is necessary.

The long-term response of groundwater to climate forcing has been observed from paleohydrological patterns in major aquifers in arid and semiarid zones around the world. The observed responses, independent of human activities, indicate that groundwater in large sedimentary aquifers such as those in the Central United States (i.e., High Plains aquifer), southern and northern Africa (Kalahari sand and Nubian sandstones aquifers), and Australia (Great Artesian basin) originated from precipitation thousands of years ago [8,49,50]. Chloride accumulations in the unsaturated profiles of recharge basins indicate that little (≤5 mm $year^{-1}$) to no recharge has occurred since [8]. Therefore, in these aquifers, recharge represents a very small fraction of the total storage, indicating that these "fossil aquifers" are rather storage dominated than recharge flux dominated [51]. As precipitation rates are decreasing and groundwater use is increasing, withdrawals from these nonrenewable resources are "mined." Therefore, overdraft of groundwater that is mainly attributed to irrigation is depleting the world's ancient Pleistocene-age, ice sheet–fed aquifers.

Changes in the spatial and temporal distribution of snow and ice at high latitudes have been shown to reduce the magnitude and seasonal duration of recharge. Recent research shows that there are shifts on groundwater level picks primarily caused by earlier spring melting and longer and lower base flow periods (e.g., surface water flow is sustained by groundwater) [52]. Under these conditions, surface water levels are low during the summer and stream flow becomes insufficient to sustain ecological health and agricultural needs [52]. Warming of surface temperatures may

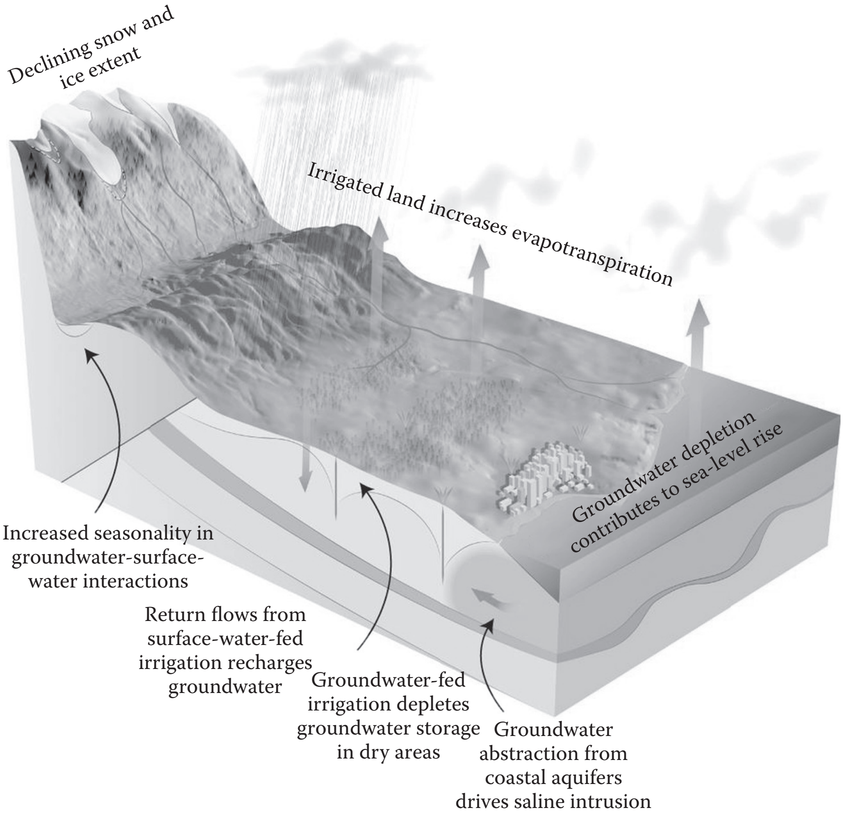

FIGURE 4.7 Conceptual representation of key interactions between groundwater and climate (From Taylor R. G. et al., Ground water and climate change. *Nature Climate Change*, 2012; DOI: 10.1038/nclimate1744.)

particularly enhance the interaction between surface water and groundwater such as in the permafrost areas for example. In fact, some factors may act to enhance aquifer recharge. For instance, in areas with seasonal and perennial ground frost, aquifer recharge is expected to increase although the volume of snow decreases [53]. Furthermore, in some parts of the California Central Valley, aquifer recharge has increased approximately seven times since the 1960s because of surface water irrigation. In this area, groundwater levels increased by up to 100 m [19]. However, persistent droughts projected for the California Central Valley for the second half of the 20th century will likely lead to a shift from the surface water–sustained irrigation to a predominantly groundwater supply [54].

Many coastal aquifers that are important sources of freshwater for many countries worldwide (more than 1 billion people living in coastal regions) have experienced salinity intrusion, which renders the freshwater supply. It is expected that the global sea level rise (SLR) of 1.8 mm year^{-1} may have contributed to migration of the freshwater–seawater interface inland [55]. Seawater intrusion is a function of multiple factors such as reduction of groundwater recharge and lowering of seaward hydraulic gradients, coastal topography, and groundwater withdrawals from coastal aquifers [56,57]. Analytical models suggest that the seawater intrusion effect on coastal aquifers as a result of SLR and climatic forcing is negligible compared to the effects of decreased recharge and groundwater overdraft [57,58]. Most seawater intrusion problems have been observed predominately in areas with unsustainable groundwater withdrawals in response to fast increases in population rates (i.e., areas such as Bangkok, Jakarta, Bangladesh, Gaza, the United States, the Coastal Plain aquifer system, and the Central and West Coast basins) [58–61]. While SLR will theoretically affect the low-lying coastal areas, it is expected that shallow aquifers in these zones will be more severely affected by saltwater contamination from surface infiltration owing to increasing intensity of storm surges and flooding [57,58].

The impact of warmer temperatures will intensify the hydrologic cycle through changes in rates of precipitation and ET and an increased likelihood of severe weather patterns, higher flooding events, and more droughts, indirectly affecting the flux and storage of water in surface and subsurface reservoirs [4,62]. Current sea level predictions do not account for the rise in sea level (i.e., 0.5 cm year^{-1}) attributed by recent studies to groundwater exploration and recycling into the ocean through precipitation. Recent research shows that depletion of aquifers is contributing to SLR as groundwater from deep aquifers is brought up for surface activities where part of it evaporates into the atmosphere and, as part of the hydrologic cycle, falls into the oceans as precipitation. The relationship between climate and groundwater in any given area is complicated by land practices and, more precisely, by shifts in rain-fed and irrigated agriculture. The impacts of climate change on groundwater resources are likely to be less than the indirect effects of climate on groundwater through changes in land practices (i.e., changes in agricultural practices and irrigation sources and demand) [4].

4.4 GROUNDWATER RECHARGE

4.4.1 Artificial Recharge

In light of the latest observed declines in natural recharge, climate change, and growing population, water management tools such as groundwater banking are designed and implemented to increase water supply reliability and sustainability. Dewatered or high-storage aquifers are generally used to store excess water during wet years (years with abundant rainfall and surplus water available); water is then pumped and used during dry years (years with little rainfall, no surplus water, and increased water demands). Groundwater banking is accomplished two ways: through in lieu or storing water by substituting surface water for pumping groundwater, and direct recharge accomplished through storing of water in the groundwater basin through engineered systems (i.e., designed to allow water to percolate or directly recharge the aquifers).

4.4.1.1 Direct Recharge

Artificial recharge is increasingly used for short- or long-term underground storage of water to prevent unsustainable aquifer development and meet water demands in dry periods [63]. The traditional engineered method to store water has been with dams, but difficulties encountered with permitting and land acquisition processes are limiting factors in finding good location sites. In addition, dams have several disadvantages including evaporation losses (approximately 2 m $year^{-1}$ in warm and dry climates), sediment accumulation, potential for failure and amplified environmental disasters, increased contamination and human diseases, high cost, and public opposition, among others [64–66]. Some forms of artificial recharge of groundwater or MAR are accomplished by storing surface water or storm water into basins, ditches, recharge ponds, and other structures to facilitate infiltration into the soil and transport to recharge deeper aquifers [63]. Additional purposes of artificial recharge are to mitigate seawater intrusion and land subsidence and to improve the quality of surface water recharged to aquifers through soil-aquifer filtration and into groundwater in places where groundwater is the main source of freshwater [63]. Some other forms to increase recharge are oriented toward ground vegetation such as, for instance, replacement of deep-rooted vegetation with low-rooted vegetation or bare soil or replacement with plants that intercept the least precipitation with their foliage. These methods have been shown to increase the amount of water that reaches the soil [63,67]. Induced recharge is also achieved by placing pumping wells in the close vicinity of rivers or lakes to prefilter the surface water through the bottom river/lake sediments before it is transported for conventional drinking water treatments (Figure 4.8). This “bank filtration” method is predominantly used because, typically, groundwater is preferred for drinking purposes given that it has consistent water quality that does not vary seasonally like surface water. Also, surface water is already allocated and not accessible for new use [63,68].

More recently, a new water storage recovery technology that is gaining acceptance by water resource planners and scientists worldwide is the aquifer storage and recovery or retrieval (ASR), which involves storage of available water (i.e., excess surface water or water extracted from underdeveloped aquifers) through injection wells into aquifers for use during dry or high water demand periods [63,69]. Surface water storage methods encounter problems especially related to evaporation, contamination, and increased human diseases. Underground storage and artificial recharge have the advantage of essentially nonexistent evaporation from aquifers and favorable economic aspects. Direct recharge to the aquifers through injection wells is mainly used where soil permeabilities are low and surface area available for infiltration is not available. Most of the water injected in the aquifers in the United States is treated to meet drinking water quality standards to minimize well clogging and to protect the quality of ambient aquifer water. In Australia, ASR operations have been successfully implemented since 1993 and water of lower quality is also injected in the aquifers. For instance, deep wells are used to inject treated municipal wastewater effluent and storm runoff in brackish aquifers in order to increase water availability for irrigation. The same wells are used to extract the water. Low-cost water treatment and well redevelopment are used to ease clogging and to protect groundwater quality for different purposes [70,71].

4.4.1.2 In Lieu Recharge

In lieu recharge, another form of groundwater banking and aquifer recharge, is accomplished by using surface water in lieu of pumping groundwater. For instance,

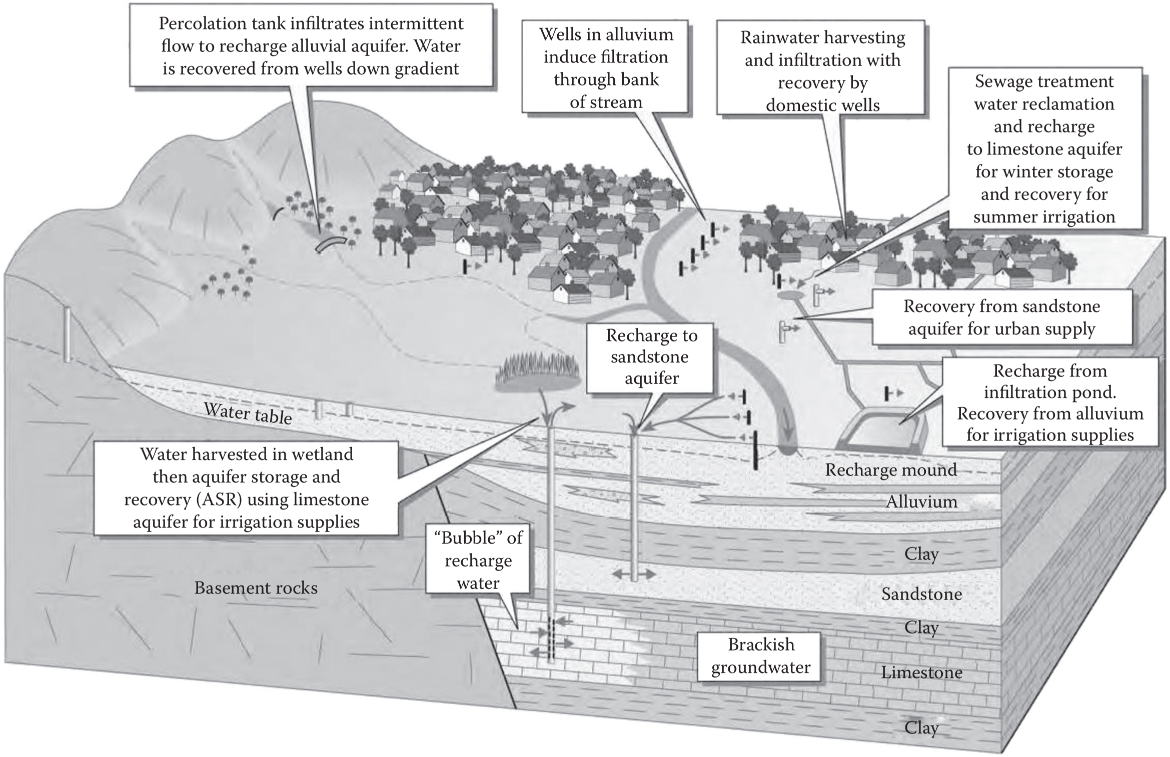

FIGURE 4.8 Schematic showing a variety of recharge methods, water sources, and several different aquifers used for storage and treatment with recovery for a variety of uses. Recharge in this case occurs via wells, percolation tanks, and infiltration basins. (From Dillon P., Pavelic P., Page D., Beringen H., and Ward J., 2009. *Managed aquifer recharge: An introduction*, Waterlines report series No. 13, Australian Government National Water Commission, 2009. Available from http://www.nwc.gov.au.)

groundwater users are paid to not pump and to allow their fields to lay fallow or farmers are offered surface water for irrigation use in lieu (instead) of pumping groundwater. This is the case in California, where surplus water during wet years is stored in the groundwater basin.

4.4.2 GROUNDWATER MANAGEMENT AND RECOVERY

4.4.2.1 Managed Aquifer Recharge

Long-term storage is becoming increasingly necessary as the adverse impact of climatic forcing on groundwater resources is more evident and as the probability of weather extremes, such as more frequent droughts and flooding, will render the surface water resource or bring in excess water (i.e., storm water). Climate change, along with increasing populations, intensifies the need for underground storage of excess water during wet periods to prevent unsustainable aquifer development and meet water demands during dry periods. Underground storage and artificial recharge, also referred to as MAR, has the advantage of essentially nonexistent evaporation from aquifers and favorable economic aspects. Consequently, this practice is rapidly gaining acceptance in many parts of the world. Direct recharge to the aquifers through injection wells is mainly used where soil permeabilities are low and surface area for infiltration is limited. Furthermore, the vadose zones are not suitable for shallow wells and trenches, and most importantly, aquifers are deep and confined [63].

MAR is generally applied in areas where, during times of high precipitation rates or low water demand (both surface water and groundwater), available excess resources from surface water, groundwater, storm water, desalinated water, and treated wastewater are stored in depleted aquifers or aquifers with available storage to supplement groundwater resources for use during droughts. For instance, in areas with increased groundwater recharge during winter, capture of projected increased groundwater storage may help sustain foreseen increases in summer demand. Of the multitude of MAR types (Figures 4.8 and 4.9) [72], injection of excess water into deep aquifers and their use as natural storage reservoirs offers many advantages: it avoids evaporative losses, ecosystem impacts are associated with large, constructed surface water reservoirs, and improved water quality, among others. However, identification of recharge methods and options available for technical feasibility of MAR projects is usually governed by the type of aquifer, topography, land use, and intended uses of the recovered water. Most commonly, recharge occurs via injection wells, percolation tanks, and infiltration/recharge ponds/basins. Figure 4.8 depicts a variety of water sources and artificial recharge methods for different aquifers (i.e., unconfined vs. confined; limestone vs. sandstone) for storage, treatment, and recovery for a variety of uses [73].

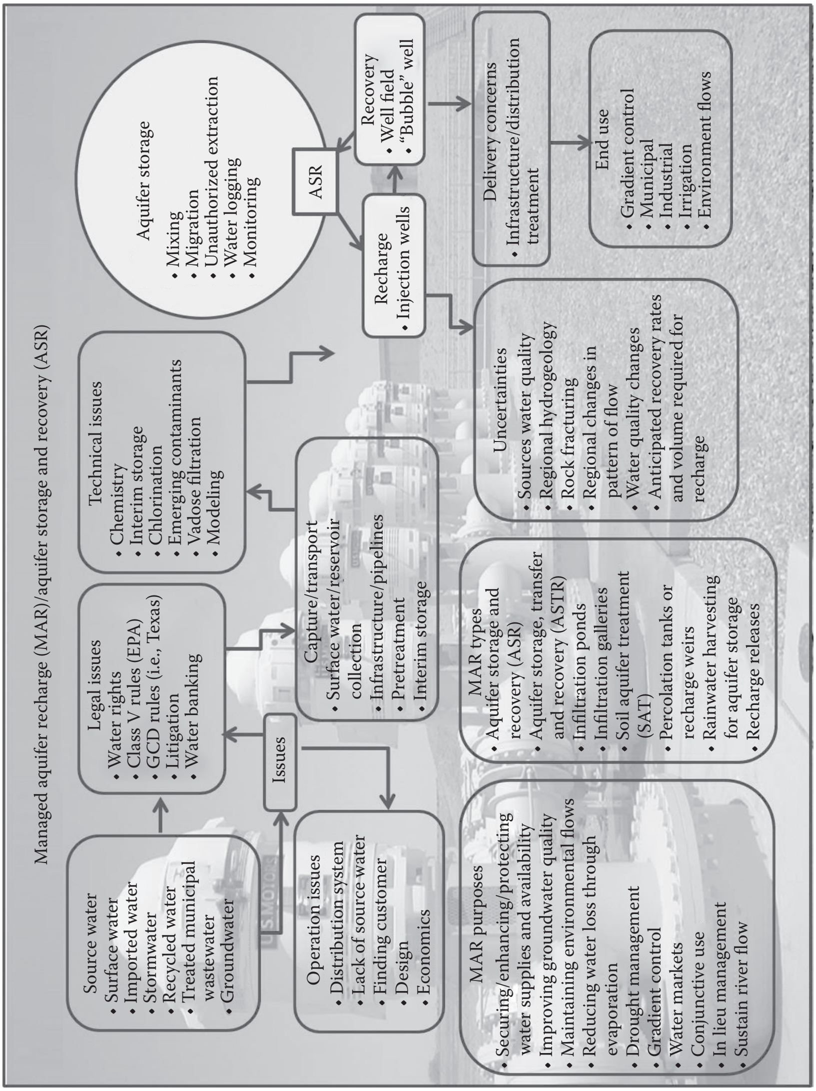

FIGURE 4.9 Schematic explanation of MAR components including purposes, issues, types, and uncertainties. Aquifer storage is exemplified as one the practices of choice for the current discussion. (From Uhlman K., Personal communication, Bureau of Economic Geology, University of Texas at Austin, 2014.)

4.4.2.2 Aquifer Storage and Recovery

Aquifer storage and recovery represents the process of recharge through injection wells in aquifers from which recovery of the stored water is accomplished using the same wells ("bubble wells" from the freshwater bubble) or different wells when stored water is allowed to travel downgradient (aquifer storage, transfer, and recovery [ASTR]). The latter provides additional water treatment. Both recovery types are applied and acceptable as long as accurate plans for monitoring and water banking (i.e., legal transfer and market exchange of water) are implemented. For the purpose of this discussion, ASR is the process of recharge through injection into an aquifer for later withdrawal by pumping [74].

ASR is a relatively new and rapidly spreading artificial recharge practice, which uses a combination of recharge and pumped wells. ASR wells are used to inject/recharge available surplus water (typically during wet seasons) for pumping during times when it is needed. Injected water displaces native water in the aquifer to form "freshwater bubbles" (e.g., stored water, see Figure 4.10), which may have highly irregular shapes depending on the aquifer system's physical properties (e.g., variable permeability and conductivities, fractures, conduits, etc.). Other components of ASR include the "buffer zone" and "native groundwater" (Figure 4.10). This system is typically used for seasonal storage of surface water, groundwater, storm water, and treated municipal wastewater in areas where water demands are much greater in one season versus another (e.g., in summer versus winter, or vice versa) and where surface storage of water is not possible or economically not feasible. The seasonal surplus water is injected and stored in deep, confined aquifers with ASR wells, which are pumped in the demand season to supplement production from water treatment plants [74,75].

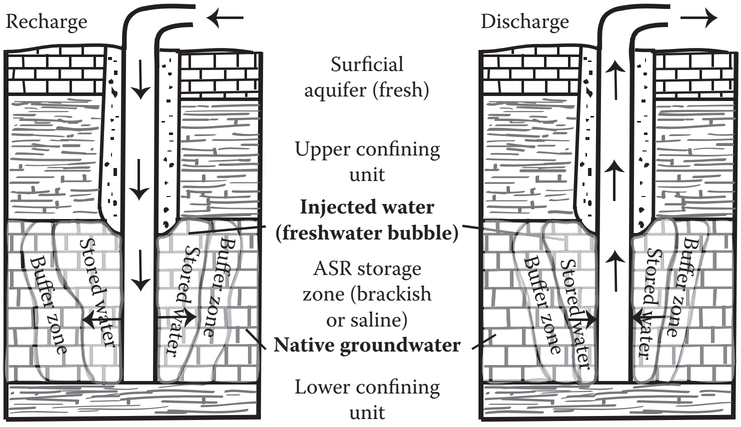

FIGURE 4.10 Cross section of an ASR well used for both injection and recovery. The injected water is separated from the ambient groundwater by a buffer water zone. The target stored volume (TSV) includes the stored water and the buffer zone volume. A buffer zone is not required/present if the chemistry of the injected and native/ambient waters is similar. Approximately one-third of the ASR wells inject water in saline or brackish aquifers and many projects store water in aquifers that have at least one chemical constituent that makes that water not suitable for potable consumption.

The use of ASR systems allows managers to design and operate water treatment plans to meet daily demands. Meeting seasonal peak demands by implementation of ASR systems is often cheaper than the use of surface reservoirs or treatment plants with limited capacities for peak demands. Besides limiting loss of water through evaporation (which can be relatively large especially in semiarid and arid areas), groundwater storage offers the advantage of providing good-quality raw water supplies to the water treatment plants that most of the time requires only chlorination. In addition, ASR offers the option of long-term storage of large volumes of water for use at later times during severe, multiyear droughts to augment deficient surface water supplies for the human and natural system. This capability is of special importance for many countries under the current climate change conditions. For instance, in many countries around the world that have experienced long-term declines in water levels because of heavy pumping to meet increases in urban and agricultural needs, aquifer storage must be replenished in the winter when there is more precipitation, less water consumption, and more stream flow. Other advantages of ASR over surface water systems include limited or no environmental impacts by reducing or eliminating the need of construction of dams and large surface reservoirs and by diversion of flood flows. A schematic representation of an aquifer storage and recovery system component is presented in Figure 4.10.

4.5 AQUIFER GEOCHEMISTRY

4.5.1 Hydrogeochemistry of Native Waters

Groundwater replenishes from a variety of sources including precipitation, surface water, and human activities (i.e., irrigation or artificial recharge). The proportion and concentration of dissolved constituents in these different recharge waters may vary considerably. Naturally, there is a large range of dissolved elements in groundwater as a result of the interaction with the atmosphere, the surficial environment, host rock, and residence times. The chief dissolved chemical components in groundwater are anions (bicarbonate, sulfate, and chloride) and cations (potassium, sodium, calcium, and magnesium) [76]. These constituents typically exist in concentrations ranging from a few to hundreds of milligrams per liter. Trace elements such as arsenic, fluoride, and manganese, although generally present in very low concentrations (i.e., a few micrograms per liter), may pose serious contamination problems in groundwater [77].

Varying degrees of water–rock interaction arise while water moves through aquifer matrixes, which are characterized by different mineralogical compositions and permeabilities; it is the chemical exchange between the rock/minerals and water that gives water its geochemical characteristics. Nevertheless, the intensity of these interactions and the resulting chemical composition are dependent on (1) the mineralogical composition of the aquifer, (2) the time the water has been in contact with rock, and (3) the chemical state of groundwater. For instance, minerals such as silica, which are common in most rocks, do not react readily with most groundwaters. On the other hand, carbonate minerals such as calcite or dolomite or carbonate rocks such as limestone and dolostone do react quite readily with water; carbonate dissolution plays an important role in the evolution of many groundwaters. Where carbonate minerals are predominant in rock composition (i.e., most sedimentary rocks and some igneous and metamorphic rocks contain carbonates), groundwater evolution can be evaluated using carbonate chemistry; relatively high calcium and bicarbonate contents are found in groundwaters that are primarily controlled by carbonate reactions. Relatively high magnesium levels are also present if the rock includes some dolomite. Another reaction to consider in groundwater is the ionic exchange, which can be an important process for trace elements such as those that behave as cations. For instance, heavy-metal cations will be naturally absorbed from contaminated waters by rocks and sediments rich in clay minerals. In general, the content of dissolved constituents is more elevated in groundwater than in surface water, which is attributed to the longer contact and reaction time of groundwater with rock. Furthermore, deep groundwater, which is generally characterized by longer residence times and has been in contact with rock for a long time, tends to be more enriched in dissolved constituent concentrations than shallow and young waters (i.e., low residence times). Changes in the composition of groundwater are also common as a result of natural variations within the aquifer. Temperature, pH, and oxidation–reduction potential dictate the chemical state of groundwater and chemical reactions. For instance, seasonal changes in temperature as a result of water table fluctuations or variation in recharge rates and sources will result in changes of the chemical state and, as a result, alteration of the groundwater composition [78].

4.5.2 Hydrogeochemistry of ASR Water-Related Sites

Generally, water injected in ASR wells comes from a variety of sources such as treated potable drinking water (i.e., municipal water), untreated groundwater and surface water (i.e., storm water, imported water), and recycled water (treated municipal wastewater). To prevent degradation of ambient groundwater quality, many state regulatory agencies require that water injected into ASR wells meets or is treated to meet primary drinking water. The type of geology and the quality of the injected water potentially may increase the potential for contamination of the underground source of drinking water (USDW) [74].

In 1999, the Class V Underground Injection Control Study showed that although changes in the dissolved constituent concentrations of the aquifer after recharge with ASR wells were observed, no circumstances of contamination of underground or drinking sources by ASR practices were reported [79]. The ASR practice is a viable option for water resources but careful consideration should be given to aquifer water quality changes as a result of water–rock interaction. Recent studies show that injected water can enhance the dissolution of metals such as (As), manganese (Mn), and iron (Fe) from the host formations. Many studies document As mobility during artificial recharge of aquifers [80–82]. Furthermore, analyses of a deep recharge system report oxidation of pyrite, which enhances mobilization of As, cobalt (Co), and nickel (Ni) [80]. Coprecipitation or adsorption of Ni and Co onto Fe hydroxides further away from the injection well was also observed by Stuyfzand. Furthermore, in heterogeneous aquifers such as the Floridan aquifer, responses to artificial aquifer recharge evaluated using cycle tests from wells located within a few hundred meters from each other are demonstrated not only by carbonate geochemical data but also by the variable geochemical reactions. Time-series analyses of water quality responses during several ASR cycles are used for comparison of water chemistry changes during injection, storage, and recovery. Mixing and mobilization between "end-member" waters are clearly defined by time-series graphs; where the concentration of an element is significantly different between the injected and native waters (i.e., low in injectate and high in the native water, or vice versa), mixing between the two components will be observed during withdrawal as exemplified by a mixing curve between injected and native groundwater. On the other hand, very low concentrations of a metal in both end-member waters and an increase in concentration during recovery hint at dissolution from the host rock [83].

Other potential issues are as follows [76]:

- Introduction of pathogens into aquifers of nondisinfected injectate. This is particularly the case in states that allow injection of raw water and treated effluent under state regulations; the fate of microorganisms after injection is chiefly important as their growth within the aquifer could lead to decreased water recovery that could be related to clogging of well screens or contamination of the aquifer and risks to public health.
- Disinfection by-products (DBPs) can form in the aquifer if water is disinfected before injection; failure to remove soluble organic carbon from the injectate before disinfection can result in formation of compounds such as trihalomethanes and haloacetic acids as the chlorinated disinfectant may react with the carbon. The presence of DBPs in USDWs attributed to ASR activities has been noticed, but per EPA, as of 2007, concentrations do not exceed applicable primary drinking water standards.
- Differences in the chemical state of the injectate and receiving aquifer may be large enough to cause problems within the recharged aquifer. For instance, if the oxidation–reduction (redox) potential of the two end-member waters is largely different, leaching of As and radionuclides may occur and, dependent on their abundance on the geologic matrix, may increase public health risk. Furthermore, if the pH of the injectate is not acidic enough, carbonate precipitation within the aquifer may occur and may cause clogging of the well screen. In most cases, however, when water is injected in a brackish or poor-quality aquifer, the quality of the native water is improved.
- Drinking water standards are often revisited. For instance, EPA lowered the As drinking water standard since 1999 when the Class V study was published to 0.01 mg or 10 μg As/L. It was observed that some ASR test wells and operations have had As concentrations exceeding the maximum contaminant; recovered waters in some ASR operations had also Mn and Fe concentrations exceeding the National Secondary Drinking Water Regulations.

4.5.2.1 Aquifer Storage and Residence Time

As mentioned in Section 4.5.2, mobilization of As, Fe, Mn, U, and other metals from aquifer matrixes are observed during ASR activities. The major variables affecting this mobility include the following: (1) the chemistry of the native and injected water (i.e., dissolved oxygen and redox potential, pH), (2) chemistry and mineralogy of the aquifer matrix, (3) residence time or contact time of input water, (4) number of cycle tests (i.e., injection and extraction), and (5) the hydrogeology and geochemistry of the site. Most of these variables were discussed earlier in the chapter. The residence time or transfer and storage time represent the average duration the injected water reacts with the ambient water and rock. The residence time determines the time available for water–rock interactions and biogeochemical reactions and, therefore, the concentration in which the dissolved constituent will be present in the recovered water. Knowledge of residence times is important in selecting and designing the ASR system to ensure efficient recovery [84]. Where additional treatment of the injectate is the goal as with ASTR practices, the residence time in the aquifer is extended beyond that of a single well or aquifer storage and recovery using bubble wells [85]. Systems need to allow sufficient residence time for the injected water to transit between injection and recovery wells to meet drinking standards at recovery. This passive treatment of water is particularly important when the injected water needs further treatment such as pretreated sewage effluent. Increased residence time of recharged water in aquifers enhances processes such as attenuation of pathogen and biodegradation of organic contaminants within an attenuation zone. The size of the attenuation zone and the required residence time are dependent on the aquifer conditions (i.e., temperature, dissolved oxygen, nitrate, organic carbon, and other nutrients and minerals), source water type, and prior exposure to hazards [85]. In most aquifers, if proper pretreatment of the injected water was accomplished, the attenuation zone is small and generally ranges in size between 20 and 200 m (Figure 4.11).

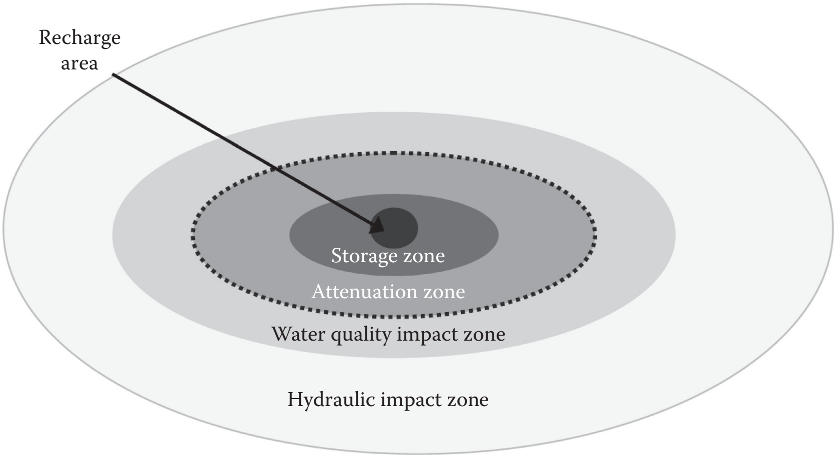

FIGURE 4.11 Schematic showing zones of influence of a MAR operation. (From Dillon P., Fernandez E.E. and Tuinhof A. *Management of aquifer recharge and discharge processes and aquifer storage equilibrium.* IAH contribution to GEF-FAO Groundwater Governance Thematic Paper 4, 2012. 49 pp. [cited on 2014 August 25]; Available from http://www.groundwatergovernance.org/resources/thematic-papers/en/.)

4.6 ESSENTIAL CONTRIBUTORS TO SUCCESSFUL MANAGEMENT OF GROUNDWATER STORAGE

4.6.1 Artificial Recharge

Application of any of the artificial recharge methods requires a thorough investigation of the site. A multitude of aspects such as geology, geochemistry, hydrology, biology, and engineering should be included in designing the artificial recharge systems and formulating management strategies. For instance, soil and hydrogeologic surveys are generally conducted to locate potentially suitable sites for artificial recharge of groundwater with surface infiltration systems. For surface infiltration systems to be productive, soils and vadose zones must be permeable to transmit water downward into the ground and to the aquifer. Also, these systems need to overlie unconfined and sufficiently transmissive aquifers that allow lateral flow away from the infiltration zone to avoid excessive groundwater mounding. Thus, soil maps and hydrogeologic investigations are used to do the first screening and to select promising sites. Pilot testing of these systems should be conducted to ensure satisfactory performance and establish best management strategies before considerable amounts of money are invested into building large systems. This is particularly important for large systems, where large-scale effects are expected to be significant and large amounts of money are generally spent. Even though MAR has been in use for many years, there are still several issues that need to be resolved, such as the following: (1) policy and regulation (economics and pricing, quality, codes of practice, areal extent and location, attenuation zones, ownership, adapting to new knowledge, institutions), (2) technical (clogging in unconsolidated media, preferential flow, fate, sustainability, storage capacity and target storage volume, capture strategies), and (3) education (community responsibilities, local government, regulators, accreditation at operative levels).

Although considerable knowledge of ASR has been gained over the last few decades, there are still several uncertainties related to the feasibility and optimal design of regional ASR systems. Several issues have been identified: (1) source water quality: laws and regulations require that injected water meets the drinking water standards; (2) uncertainties about regional hydrogeology: vertical and lateral extents of the aquifer system, presence of confining layers and the potential for cross-aquifer migration of water; rock fracturing (fracturing caused by increased pressure buildup caused by simultaneous injection of several wells) and conduit flow; (3) changes in regional flow paths (increased aquifer pressure may alter regional and local flow path; implications on recovery and monitoring); (4) water quality changes (chemical interaction between the injected water and both the native groundwater and the aquifer system matrix, i.e., rocks); and (5) anticipated recovery rates and volume required for recharge (well clogging and porosity plugging attributed to particular matter and chemical reactions may affect the recharge and recovery rates) [74,83].

Major areas that need to be addressed when considering the use of ASR technologies at large scales include regional science issues, water quality issues, and local performance/feasibility issues. Pilot projects are valuable means for acquiring detailed information on ASR performance. However, successful local-scale operations do not demonstrate/prove the feasibility of ASR implementation regionally. Construction of regional flow and transport models is a vital and indispensable tool to assess the practicality of ASR at large scales. Furthermore, periodic evaluations are necessary to ensure viable operation of ASR technologies as practical water conservation alternatives. Because of concerns related to maximum contaminant levels, the design and construction of ASR systems as well as its operation should consider the possibility of water–rock interaction and mobilization of metals in the recovered water. To monitor the geochemical status of water, the design and operation of ASRs should also include the placement of monitoring wells with a well-designed monitoring schedule. Other considerations should include the hydrogeological characteristics of the targeted aquifer. For instance, unconsolidated aquifers are generally composed of relatively coarse textured soils (sands and gravels) and are saturated; when compared to the finer-textured, unsaturated soils below the vadose zone and soil horizons, these materials do not give the same quality improvement of the recharge water [74,83]. A list of concerns and limitations related to the use of MARs is presented in Figure 4.9. For MAR strategies to be successful, a series of factors should be satisfied: the temporary availability of surface water or groundwater supplies, favorable hydrogeology, a well-established regulatory framework, and institutional innovation (i.e., creation of water banking authorities such as the Arizona Water Banking Authority) [86].

4.6.1.1 In Lieu and Conjunctive Water Use

In lieu conjunctive water management relies upon balancing historical groundwater pumping with surface water deliveries from project contributors (i.e., water districts) during times of increased precipitation and excess surface water supply. Project participants can reclaim the stored water during times of surface water shortfalls. This technique is an alternative to direct aquifer recharge of surface water either during years of surplus or as part of the reservoir reoperation [87]. Hydrologic modeling exercises focusing on enhancing the storage capacity available to manage surface water should also contemplate the context of in lieu conjunctive water management. Management efforts should include an inventory of the magnitude of the likelihood for historic groundwater users for irrigation/agricultural purposes to use any available surface water supplies. The willingness of historic groundwater users to participate in a program such as this can play a major role in the implementation of the in lieu conjunctive use in a particular area; local considerations related to cost and assurances may arise. An incentive such as paying off the farmers not to pump or supplying the surface water in lieu of groundwater pumping is generally necessary. On the other hand, certain physical characteristics can make a particular area attractive for in lieu conjunctive use. According to the Natural Heritage Institute [88], several evaluation criteria should be considered in evaluating the viability of this water management strategy for a particular area:

- The relative contribution of surface water versus groundwater to irrigation in an area of interest; in lieu groundwater banking should ideally be implemented in areas where substantial groundwater pumping for irrigation takes place and significant amounts of surface water are available to offset groundwater pumping.

- The proximity of surface water suppliers to agricultural lands irrigated solely with groundwater; if economically feasible and depending on institutional and accounting arrangements, water districts that own the surface water distribution network, for instance, would deliver surface water in lieu of groundwater pumping.
- The amount of aquifer storage space available to accommodate the “stored” groundwater otherwise used to irrigate agricultural fields.

The delivery of surface water to offset groundwater pumping does not necessarily require water delivery outside of the jurisdiction of the original surface water rights holder. Furthermore, any historic groundwater user, such as municipal or agricultural, could take advantage of the in lieu water management. For instance, the Sacramento Region north of the American River is a good example of urban in lieu conjunctive use; several municipal water districts in this region have formed a joint powers authority to manage the use of their individual river surface water rights and groundwater pumping from their common local aquifer. Developing viable in lieu conjunctive water management projects is likely to occur as part of standard internal water district planning as most draw upon both groundwater and surface water to meet irrigation needs [88].

4.7 INVESTIGATIONS

MAR can be used to complement overall water supply and enhance drought resilience. Aquifer storage and recovery have been extensively applied for water resources management and conservation in water-short regions around the world. In concept, ASR represents the storage of drinking water, treated surface water, reclaimed wastewater, imported water, or groundwater from other aquifers in suitable aquifers through wells. Water is recovered when needed from the same wells (ASR) or from other wells situated at a distance downstream, using a slight modification of ASR technology called “aquifer storage, transfer, and recovery” or ASTR. ASR is particularly applicable in areas where surface recharge of aquifers through surface basins and infiltration galleries is not viable such as in most parts of Texas where evaporation rates are extremely high. A significant benefit of aquifer storage is the elimination of evaporation; during the drought of 2011, an estimated 192,404 AF of surface water evaporated from the six Highland Lakes of the Lower Colorado River Authority, while 168,334 AF of water was delivered to the City of Austin for municipal use. In the United States, not only did ASR prove to be an efficient and economically feasible water management practice; it has minimum environmental impact when compared to traditional surface reservoir storage or infiltration systems as well. According to the Texas Water Development Board, in 2011, approximately 95 ASR well fields, in which the same well is used for injection and recovery, were operating in the United States (Figure 4.12): at least 13 operating projects and approximately 30 additional ones from various stages of permitting, construction, or testing were in Florida; at least 12 ASR projects were operating in New Jersey and the northeast; and 11 projects at the minimum were operational in California [75].

FIGURE 4.12 Geographic distribution of operational ASR well fields and recharge ponds in the United States in 2009. (From TWDB, *An Assessment of Aquifer Storage and Recovery in Texas*; 2011, Texas Water Development Board Report # 0904830940.)

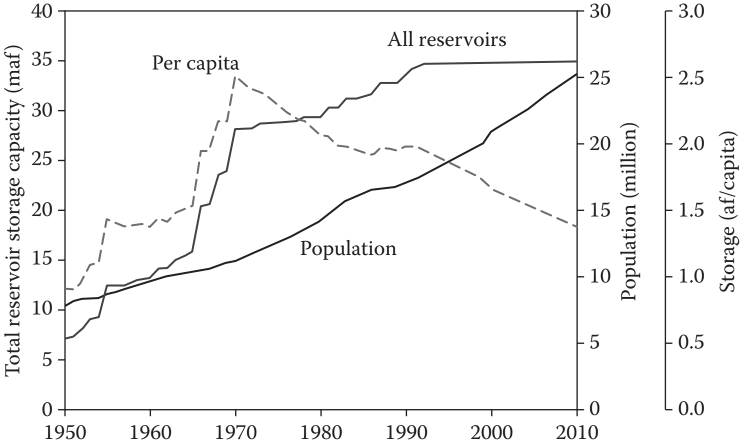

FIGURE 4.13 Texas per-capita reservoir storage capacity, population increase, and total reservoir storage from 1950 to 2010. (From Scanlon B. R., Duncan I., and Reedy R.C., Drought and the water–energy nexus in Texas, *Environ. Res. Lett.*, 2013. 8, 045033, doi:10.1088/1748-9326/8/4/045033.)

For the purpose of this discussion, we will exemplify the Texas MAR systems. In Texas, per-capita traditional reservoir storage has decreased 40% since the 1970s because of population increase and limited new reservoir construction (Figure 4.13) [72,89]. This reduction in storage capacity increases our vulnerability to drought. As in other areas, in Texas, MAR can be used to complement overall water supply and enhance drought resilience.

4.7.1 TEXAS MAR SYSTEMS

Currently, there are three water utilities in Texas that complement their supply with MAR to manage drought and to meet peak water demands; in addition, El Paso water utility also implements MAR to restore groundwater levels in order to reduce water quality degradation and land subsidence risks. Table 4.1 lists the source water, aquifer storage, well capacities, and other characteristics of the three ASR systems. These systems have been successfully running and are good examples for other communities in Texas and other states to gain confidence in using ASR technologies for multiple needs. The 2012 Texas Water Plan includes MAR technology as part of the plan to meet future water needs, and it reports that an additional 50,650 AF of water will be added to storage by the year 2060, in existing and planned new MAR systems [72].

4.7.2 SOURCES, RESERVOIRS, AND WATER CUSTOMERS OF MAR

The three active MAR/ASR facilities in Texas utilize different sources of water for injection, spanning from reclaimed water, surface water, to groundwater [75]. An estimated 916,000 AF of treated municipal wastewater is estimated to be available for reuse (both direct and indirect) by the year 2060 [72]. ASR reservoirs include depleted aquifers, such as the Trinity Aquifer near Dallas/Fort Worth and the Gulf Coast Aquifers and confined aquifers, such as the Carrizo–Wilcox. As mentioned earlier, aquifer recharge via infiltration ponds or galleries is not feasible in Texas because of high evaporation rates. Furthermore, shallow water table aquifers may

TABLE 4.1
Texas Facilities (2014)

Location	Date	Source Water	Capacity (mg/day)	In Storage (acre-ft)	Aquifer
El Paso Water Utility	1985	Treated Municipal Wastewater	10	>1500	Hueco Bolson
City of Kerrville	1995	Treated River Water	2.65	>2100	Lower Trinity
San Antonio Water System	2004	Edwards Aquifer	60	>70,000	Carrizo (confined)

Source: Uhlman K., Personal communication, Bureau of Economic Geology, University of Texas at Austin, 2014.

not be suitable if the addition of stored water would waterlog the soils. Primary customers would include municipal utilities and coastal areas, making the urban high water demand regions and areas with depleted surface water resources (i.e., coastal areas such as Corpus Christi, Texas) of the state ideal for siting ASR facilities.

4.7.2.1 Impediments to MAR in Texas

Regulatory guidelines and protections are necessary to allow MAR to succeed in Texas. In the absence of clarification of groundwater ownership and protection, stored groundwater is at risk of unauthorized extraction under the existing "Rule of Capture." Technological tools are readily available to assure efficient design and tracking of recharged water, but the regulatory framework is insufficient to protect the investment. At a minimum, there is a need for uniformity across the Groundwater Conservation Districts in groundwater classification and statutory definition of aquifer storage and recovery [72]. Texas' current regulations and statutes, both statewide and local, do not readily facilitate the maximum beneficial use of either groundwater or surface water for MAR [90].

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5 Reservoir System Management

Ralph A. Wurbs

CONTENTS

5.1 INSTITUTIONAL SETTING FOR RESERVOIR MANAGEMENT

Sustainable river/reservoir system management involves the development, conservation, control, regulation, protection, allocation, and beneficial use of water in streams, rivers, lakes, and reservoirs. Reservoir storage is necessary to use the extremely variable water resources of a river basin for beneficial purposes such as municipal and industrial water supply, irrigation, hydroelectric power generation, and navigation. Dams and appurtenant structures also regulate rivers to reduce damages caused by floods. Public recreation, water quality, erosion and sedimentation, and protection and enhancement of fish, wildlife, and other environmental resources are important considerations in managing reservoir/river systems.

Water resources development and management is accomplished within an institutional framework of organizations, traditions, programs, policies, and political processes. Funding and financial arrangements are key considerations in constructing reservoir projects and establishing operating strategies. Water is a publicly owned resource, and its allocation and use are governed by state water rights systems. Treaties and interstate compacts allocate river flows between neighboring countries and states. River basin management must be consistent with federal and state environmental laws and policies.

5.1.1 WATER ALLOCATION SYSTEMS

Stream flow and reservoir storage capacity in major river basins are typically shared by many water users who use the water for a variety of purposes. Water right systems provide a basis to (1) allocate resources among users, (2) protect existing users from having their supplies diminished by new users, and (3) govern the sharing of limited stream flow and stored water during droughts when supplies are inadequate to meet all needs. The institutional framework for river basin management involves a hierarchy of water allocation systems. The water resources of international rivers are allocated between nations by treaties and other agreements. In the United States, water is allocated among states through river basin compacts and other means. Within individual states, water is shared by river authorities, municipal water districts, cities, irrigation districts, individual farmers, industries, and private citizens through water rights systems. A water district or river authority distributes water to its customers in accordance with contractual commitments.

States in the western and eastern halves of the United States have generally adopted different approaches to water rights attributed largely to the western states having much drier climates (Wurbs 2013). Water allocation and accounting systems tend to be more rigorous in regions where demands approach or exceed supplies. Each state has developed its own set of rules and practices governing water rights. These water allocation systems have evolved historically and continue to change. State water rights systems generally have the following components or features:

- State-negotiated compacts approved by the federal government allocate waters of interstate river basins between states. Some states are also affected by federal agreements with Canada or Mexico for sharing international waters or by rights reserved for Indian reservations, military installations, and other federal lands.

- A legally established priority system based generally on variations of the riparian or prior appropriation concepts guides the allocation of the waters within a state among numerous water management entities and water users.
- An administrative system is needed to grant, limit, and modify water rights and to enforce the allocation of water resources, particularly during droughts and times of insufficient supply. These systems may or may not include formal issuance of written permits to water right holders.

5.1.2 ENVIRONMENTAL POLICY

A myriad of federal and state environmental policies and programs, including the several examples noted here, guide river basin management. The Fish and Wildlife Conservation Act of 1958 (PL 85-624) established the policy that fish and wildlife conservation be coordinated with other project purposes and receive equal consideration. The National Environmental Policy Act of 1970 (PL 91-190) articulated the policy of protecting the environment and established requirements for evaluating the environmental impacts of federal actions. Section 404 of the Water Pollution Control Act Amendments of 1972 (PL 92-500), as further amended by the Clean Water Act of 1977 (PL 95-217), established the dredge and fill permit program administered by the US Army Corps of Engineers (USACE).

Requirements for conservation of endangered species, pursuant to the 1973 Endangered Species Act (PL 93-205) as amended by the Endangered Species Act Amendments of 1978 and 1979 (PL 95-632 and PL 96-159) and other legislation, are administered by the Fish and Wildlife Service in coordination with other agencies. Endangered species are officially identified, and they and their habitat are protected from actions that could cause their destruction. Endangered species have significantly affected river/reservoir system management nationwide including operations of several major reservoir systems in the Columbia, Missouri, and other river systems.

5.1.3 RESERVOIR OWNERS AND OPERATORS

A number of organizations are directly responsible for developing and managing reservoir projects. Numerous other public agencies, project beneficiaries, and interest groups play significant roles in determining operating policies. Most reservoirs in the United States are owned and operated by private electrical and water utilities, cities, water districts, and other local entities. However, the majority of the storage capacity is contained in federal reservoirs. Most, though certainly not all, of the very large reservoir systems in the United States are operated by the federal water agencies. The much more numerous nonfederal reservoirs tend to be much smaller in size than the federal projects (Wurbs and James 2002).

Billington et al. (2005) describe the history of developing large federal reservoir projects in the United States. The USACE is the largest reservoir management agency in the nation, with more than 500 reservoirs in operation. The USACE is unique in having nationwide responsibilities for construction and operation of large-scale multiple-purpose reservoir projects. The US Bureau of Reclamation (USBR) operates approximately 130 reservoirs in the 17 western states and has constructed numerous other projects that have been turned over to local interests for operation. The Tennessee Valley Authority (TVA) operates a system of approximately 50 reservoirs in the seven-state Tennessee River Basin. The Natural Resource Conservation Service, Forest Service, and National Park Service are among the various other federal agencies responsible for reservoirs.

The responsibilities of the various organizations involved in operating reservoir systems are based on project purposes. The USACE has played a clearly dominant role nationwide in constructing and operating major reservoir systems for navigation and flood control. The USBR water resources development program was founded upon facilitating development of the arid West by constructing irrigation projects. The TVA reservoir system is operated in accordance with operating priorities mandated by the 1933 Congressional act that created the TVA. This act specified that the TVA system be used to regulate stream flow primarily for the purposes of promoting navigation and controlling floods and, so far as may be consistent with such purposes, for generation of electric energy.

The activities of the federal water resources development agencies have evolved over time to emphasize comprehensive multiple-purpose water resources management. Hydroelectric power, recreation, and fish and wildlife are major purposes of USACE, USBR, and TVA projects. Municipal and industrial water supplies have been primarily a nonfederal responsibility though significant municipal and industrial storage capacity has been included in federal reservoirs for the use of nonfederal project sponsors. Numerous cities, municipal water districts, and other local agencies operate their own reservoir projects. Private companies as well as governmental entities play key roles in hydroelectric power generation, thermal-electric cooling water projects, and industrial water supply.

Contractual arrangements and other institutional aspects of reservoir operations vary greatly between purposes. For example, flood control operations for a USACE reservoir are simpler institutionally than water supply and hydroelectric power operations owing to the USACE being directly responsible for flood control operations. The USACE is responsible for flood control operations at projects constructed by the USBR as well as its own projects.

Nonfederal sponsors contract with the USACE and USBR for municipal and industrial water supply storage capacity. All costs, including construction and maintenance, allocated to municipal and industrial water supply are reimbursed by nonfederal sponsors in accordance with the Water Supply Act of 1958, as amended by the Water Resources Development Act of 1986 and other legislation (Wurbs 1994). Construction costs are reimbursed with interest through annual payments over a period not to exceed 50 years. Nonfederal sponsors for federal projects are often regional water authorities who sell water to municipalities, industries, and other water users, under various contractual arrangements. Of the 117 USACE reservoirs nationwide that contain municipal and industrial water supply, approximately 75% of the water supply storage is in reservoirs in the Southwestern Division, mainly in Oklahoma and Texas (Institute for Water Resources 2003).

The Reclamation Acts of 1902 and 1939 and other legislation dictate the policy that costs allocated to irrigation in federal projects be reimbursed by the project beneficiaries. The details of repayment requirements for irrigation projects have varied over the years with changes in reclamation law. Congressional acts authorizing specific USBR projects have often included repayment provisions tailored to the circumstances of the individual project. Thus, local sponsor repayment contracts for water supply for irrigation vary between projects.

Water supply operations are controlled by agency responsibilities, contractual commitments, and legal systems for allocating and administering water rights. Water allocation and use are regulated by state water rights systems and permit programs. Many of the major reservoir systems in the United States are on interstate rivers, and several are on rivers shared with either Mexico or Canada. Operations of some reservoir systems are strictly controlled by agreements between states and nations that were negotiated over many years.

Hydroelectric power generated at USACE and USBR reservoirs is marketed to electric utilities by the five regional power administrations of the Department of Energy. The power administrations are required by law to market energy in such a manner as to encourage the most widespread use at the lowest possible rates to customers consistent with sound business principles. The power administrations operate through contracts and agreements with the electric cooperatives, municipalities, and utility companies that buy and distribute the power. Reservoirs are operated in accordance with the agreements. The TVA is directly responsible for marketing, dispatching, and transmission of power generated at its plants. Many private and public electrical power companies operate their own reservoirs and hydropower plants. Several large hydroelectric power systems are composed of multiple storage and generating components owned and operated by federal, state, local, and private entities. Hydroelectric facilities are typically components of systems that rely primarily on thermal plants for the base load, with hydropower supplying peak loads.

5.1.4 Transition from Development to Management Focus

Numerous major reservoir projects located throughout the United States are operated by the USACE, USBR, TVA, other federal agencies, river authorities, water districts, cities, and private industry. Most of these projects were constructed during the period from the 1920s through the 1970s, which has been called the construction era of water resources development. Though other countries are also building dams and other large-scale water projects, most dam construction worldwide since 1970 has been in China. Although additional new reservoir projects are needed and continue to be developed in the United States, most of the major reservoir systems required to manage our rivers are in place. Economic, environmental, and institutional considerations constrain construction of water resources development projects (Nusser 2014; Scheumann and Hensengerth 2014). Since the 1970s, water resources management policy and practice have shifted to a greater reliance on managing floodplain land use, improving water use efficiency, and optimizing the operation of existing facilities.

Public needs and objectives and numerous factors affecting reservoir management change over time. Population and economic growth in various regions of the nation are accompanied by increased needs for flood control, water supply, energy, recreation, and the other services provided by water resources development. Depleting groundwater reserves are resulting in an increased reliance on surface water in many areas such as Texas. With increasing demands on limited water resources, water right systems for allocating water resources among numerous water users have grown in importance. Concerns continue to grow regarding maintenance of instream flows for preservation of riverine habitat and species, wetlands, and freshwater inflows to bays and estuaries. Environmental restoration has become a major concern. With an aging inventory of numerous dams and reservoirs being operated in an environment of change and intensifying demands on limited resources, operational improvements are being considered increasingly more frequently.

Storage reallocations and other operational modifications are a key strategy for responding to changing water management needs and objectives. Storage capacity may be reallocated between flood control and conservation pools. Operational modifications may involve reallocation of conservation storage between users and types of use, conjunctive surface water/groundwater management, schemes to operate water supply reservoirs to better deal with floods, multiple-reservoir system operations, and various other refinements in operating practices.

The purposes to be served by a federal reservoir project are established with Congressional authorization of project construction. Later, additional purposes may be added or the original purposes may be modified by subsequent congressional action. When the original purposes are not seriously affected and structural or operational changes are not major, modifications in operating policies can be made at the discretion of the agency without congressional action. Johnson et al. (1990), Institute for Water Resources (2003), and McMahon and Farmer (2004) explore issues to be addressed in reallocating storage capacity and otherwise modifying operations of federal reservoir projects.

5.2 RIVER/RESERVOIR SYSTEMS

The terms *lake* and *reservoir* are used interchangeably in this chapter to refer to an impoundment of stream flow. Reservoir projects include dams, spillways, outlet works, hydropower plants, and other auxiliary water control structures. Although many natural lakes are formed without constructed dams, most large freshwater impoundments are man-made.

The history of dam building dates back several thousand years (Jackson 1997). The USBR (1987), Gosschalk (2002), Tancev (2005), Hewlett (2006), Siddiqui (2009), and Lewis (2014) address the planning, design, construction, and maintenance of dams and appurtenant structures. Votruba and Broza (1989), Berga et al. (2006), Haynes and Barnes (2009), and Boes (2011) cover a variety of engineering, environmental, and institutional issues associated with reservoir projects. Wurbs (1996, 2011) reviews capabilities for computer modeling of river system management.

5.2.1 Stream Flow Variability

Reservoirs are essential for regulating river flow fluctuations to develop reliable water supplies and mitigate flood risks. Flow conditions at a particular site may vary from a dry streambed to major floods. Both seasonal within-year variations and multiple-year droughts are important. Mean daily flows in cubic feet per second from January 1900 through August 2014 at US Geological Survey gages on the Mississippi River at St. Louis, Missouri, and the Brazos River at Waco, Texas, are plotted in Figures 5.1 and 5.2 to illustrate the great variability of river flows that is fundamental to river basin development and management. The gage sites on the Mississippi and Brazos Rivers have watershed areas of 1,810,000 and 76,900 km^2, respectively. Although a

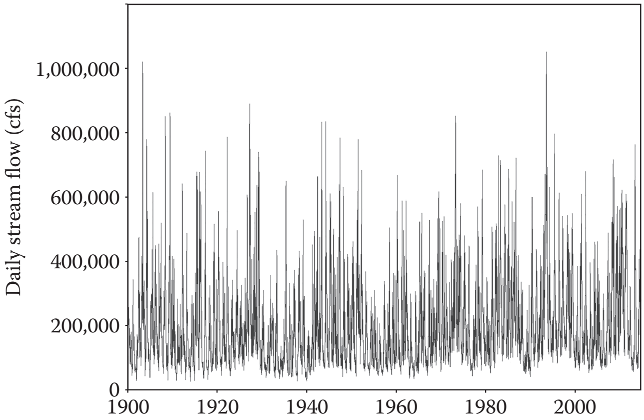


FIGURE 5.1 Observed mean daily flow of the Mississippi River at St. Louis, Missouri, illustrates the great variability characteristic of most rivers.

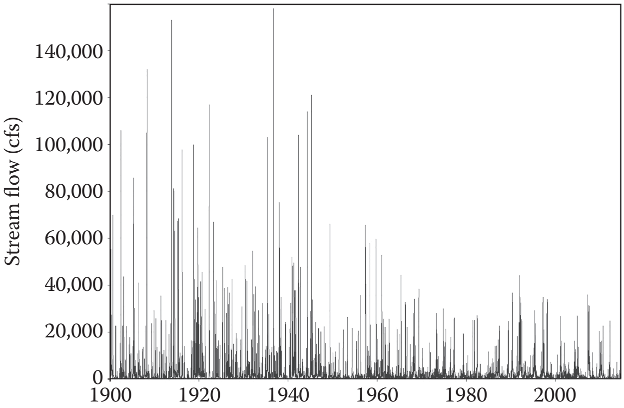


FIGURE 5.2 Effects of constructing several reservoirs during 1950–1965 above the gage on the Brazos River at Waco, Texas, are evident in this plot of daily flows.

number of major reservoir projects were constructed during 1940–1970 upstream of both sites, the effects on flows are most evident at the Brazos River gage, which is located relatively close to upstream dams.

Spatial variations in climate and economic development are also key considerations in water resources development and management. Water resources and water needs often do not coincide geographically. The California Central Valley and State Water Projects reflect the fact that the majority of the precipitation in California occurs in the northern third of the state, but most of the water use occurs in the southern half of the state. Farmers and municipalities in eastern Colorado are supplied water diverted through the Big Thompson Project from the Colorado River on the opposite side of the continental divide through the Rocky Mountains.

5.2.2 Inventory of Major Reservoirs

Although reservoirs play important roles in water management throughout the world, China has by far the greatest number of large dams of any nation. Most of the dams in China were constructed during the past 50 years. The United States has the second largest number of major reservoir projects, with most being constructed during the 1930s through 1970s. This chapter focuses on operation of large reservoirs on major rivers in the United States.

There are many thousands of reservoirs in the United States, but most of the storage capacity is contained in a few hundred of the largest reservoirs. The five largest reservoirs in the United States are Lakes Mead (Hoover Dam) and Powell (Glen Canyon Dam) on the Colorado River and Lakes Sakakawea, Oahe, and Fort Peck on the Missouri River, which have total storage capacities of 37.7, 33.3, 29.5, 28.8, and 23.3 billion m^3, respectively. Lakes Mead and Powell are owned and operated by the USBR. Lakes Sakakawea, Oahe, and Fort Peck are owned and operated by the USACE.

An inventory of reservoirs in Texas compiled by Wurbs and Zhang (2014) illustrates size variability. The Texas Commission on Environmental Quality administers a water right permit system with approximately 6000 active permits that include 3440 reservoirs with a total conservation storage capacity of 50.2 billion m^3. Permits are required for all reservoirs with conservation storage capacities exceeding 246,800 m^3 (200 acre-ft) and other smaller reservoirs with significant water supply diversions. Water right permits are not required for flood control storage. The 209 major reservoirs with conservation storage capacities exceeding 246,800 m^3 contain 97.8% of the total storage capacity of the 3440 reservoirs. The 62 reservoirs with capacities exceeding 1.234 million m^3 (100,000 acre-ft) account for 89.5% of the total storage. Eight Texas reservoirs with conservation capacities exceeding 1.234 billion m^3 (1,000,000 acre-ft) contain 47.6% of the total capacity of the 3440 reservoirs.

In addition to the conservation storage capacity cited in the preceding paragraph, two single-purpose flood control and 26 multiple-purpose reservoirs in Texas owned and operated by the USACE contain flood control pools with storage capacities totaling 17.2 billion m^3. Two reservoirs on the Rio Grande owned and operated by the International Boundary and Water Commission contain 3.28 billion m^3 of flood control capacity as well as 6.94 billion m^3 of conservation capacity. Two multiple-purpose reservoirs constructed by the USBR but operated by nonfederal sponsors include flood control pool capacity of 1.2 billion m^3. The flood control pools of these federal reservoirs are controlled by people operating gated outlet structures. The Natural Resource Conservation Service has constructed approximately 2000 smaller flood retarding dams with ungated outlets in rural watersheds of Texas. Numerous small ungated flood detention basins are constructed and maintained by local entities in cities throughout the state.

Lake Texoma on the Red River between Texas and Oklahoma, operated by the USACE, with conservation and flood control capacities of 3.01 and 3.28 billion m^3 is the largest reservoir in Texas. Toledo Bend Lake on the Sabine River owned and operated jointly by the Sabine River Authorities of Texas and Louisiana, with a conservation storage capacity of 5.59 billion m^3, has the largest conservation storage capacity in Texas.

5.2.3 EROSION AND SEDIMENTATION

Natural stream erosion and deposition processes are significantly altered by the construction and operation of reservoir projects (Morris and Fan 1998; USACE 1995). The impacts of individual projects vary significantly, depending on the stream flow and sediment characteristics of the parent stream, and the specific operating rules of a given project. Interruption of the natural sediment processes of a stream generally results in deposition of sediment in the upstream reservoir area and corresponding erosion and degradation of the streambed and banks immediately downstream from the project. The location of deposits in the reservoir is a function of the size of the reservoir, the amount and gradation of the sediments being transported, and the pool level at the time of significant inflow. The amount of bank and shoreline erosion is closely related to the rate and magnitude of the pool level fluctuations.

Large reservoir projects frequently trap and retain essentially all of the suspended sediment and bed material load within the upstream pool, thus releasing sediment-free water. These releases are capable of eroding the bed and banks of the river downstream of the outlet structure. The extent of this erosion is related to the composition of the bed and bank material, the volume of water released on an annual or seasonal basis, release rates and flow velocities, and the manner in which the flow is released. Fluctuating releases often result in an initial loss of the banks. This loss is closely related to the magnitude of the stage fluctuation. The recession of banks as a result of fluctuating releases usually stabilizes in the first few years of operation, as the underwater slope reaches a quasi state of equilibrium. Once this equilibrium slope has been achieved, the bank erosion process behaves as in the natural channel. Periodic wetting and drying of the banks through fluctuating releases accelerates this process. Reservoir releases also result in lowering the streambed, with the maximum amount of lowering occurring immediately downstream from the outlet structures, and decreasing in the downstream direction. This degradation process continues until the slope is reduced to its equilibrium value and the bed becomes naturally armored by removal of the fines, which exposes the coarser, nonerodible bed materials. After the bed becomes naturally armored, future lowering of the streambed is usually insignificant (USACE 1995).

Channels downstream from small- and medium-size reservoir projects often exhibit characteristics that are entirely different from what were described above for large reservoirs. Channel capacity below the smaller reservoirs tends to be lost over time. Reservoir projects that make only limited releases may result in extensive deposition and subsequent vegetative encroachment in the downstream channel. With construction of a reservoir, the preconstruction periodic flushing flows, which are capable of removing deposits near the mouth of tributaries, are often replaced by low, nonerosive reservoir releases. This contributes to the loss of channel capacity and reservoir operating flexibility.

Reservoir shorelines are subject to a number of forces contributing to their instability and frequently undergo major changes during the life of a project. Fluctuating pool levels saturate previously unsaturated material, resulting in massive slides when the pool is drawn down to lower levels. This material accumulates at the base of the slope and often forms an underwater bench, leaving steep unstable slopes above the water line. Reservoir banks are also subject to attacks by both wind and waves, which tend to remove this material and undercut the banks.

Sediment deposits in the reservoir pool are an important consideration, since storage capacity and many reservoir management activities are adversely affected. Sediment deposits occur throughout a reservoir but particularly in the upper reaches where inflow velocities are reduced by the impoundment.

Much of the erosion and deposition process is beyond the control of reservoir managers. However, the following precautions can significantly minimize problems (USACE 1987):

- Minimize the rate of reservoir pool drawdown.
- Avoid sudden increases in reservoir releases and subsequent downstream stage fluctuations.
- Keep reservoir pool levels as low as possible during known periods of high sediment inflow, thus encouraging sediment to deposit in the lower zones of the reservoir.
- Periodically raise pool levels high enough to inundate existing sediment deposits, thus precluding the establishment of permanent vegetation and subsequent increased sediment deposits in the backwater reaches entering the pool.
- Schedule periodic releases through the outlet works to preclude sediment accumulations in and near the intake structure and in the downstream channel.
- Be aware of conditions that may affect the erosion/deposition process, such as the potential for ice jams, tributary inflow, shifting channels, and local constraints, and adjust regulation criteria to minimize adverse impacts.

5.3 RESERVOIR SYSTEM OPERATIONS

An operating plan or release policy is a set of guidelines for determining the quantities of water to be stored and to release or withdraw from a reservoir or system of several reservoirs under various conditions. The terms *operating* (or *release* or *regulation* or *water control*) *procedures*, *rules*, *schedule*, *policy*, or *plan* are used here interchangeably. Operating decisions involve allocation of storage capacity and water releases between multiple reservoirs, between project purposes, between water users, and between periods. Typically, a regulation plan includes a set of quantitative criteria within which significant flexibility exists for qualitative judgment. Operating plans provide guidance to reservoir management personnel. Reservoir system operations can be categorized as follows:

- Operations during normal hydrologic conditions from the perspective of optimizing the present day-to-day, seasonal, or year-to-year use of the reservoir system
- Operations during normal hydrologic conditions from the perspective of maintaining capabilities for responding to infrequent floods and droughts expected to occur at unknown times in the future
- Operations during flood events
- Operations during low flow or drought conditions

A wide variety of operating policies are presently in use at reservoir projects throughout the United States and the world. For many water supply reservoirs, operations are based simply on making withdrawals or releases as necessary to meet water demands. Flood flows pass through uncontrolled spillways, and no predeveloped plans are in place for responding to supply depletion during infrequent severe droughts. On the other hand, complex regulation plans guide operations of many reservoirs including major federal multiple-purpose, multiple-reservoir systems. Typically, an operating plan involves a framework of quantitative rules within which significant flexibility exists for operator judgment. Day-to-day operating decisions may be influenced by a complex array of factors and often are based largely on judgment and experience. Operating procedures may change over time with experience and changing conditions.

5.3.1 OUTLET STRUCTURES

Reservoir projects include dams and appurtenant outlet structures, pumping plants, pipelines, canals, channel improvements, hydroelectric power plants and transmission facilities, navigation locks, fish ladders, recreation facilities, and various other structures. Reservoir releases to the river below a dam are made through spillways and outlet works. Spillways provide the capability to release high flow rates during major floods without damage to the dam and appurtenant structures. Spillways are required to allow flood inflows to safely flow over or through the dam, regardless of whether the reservoir contains flood control storage capacity. Spillways may be gated or uncontrolled. A controlled spillway is provided with crest gates or other facilities that allow the outflow rate to be adjusted. For an uncontrolled spillway, the outflow rate is a function of the head or height of the water surface above the spillway crest. Since spillway flows involve extremely high velocities, stilling basins or other types of energy dissipation structures are required to prevent catastrophic erosion damage to the downstream river channel and dam. For many reservoir projects, a full range of outflow rates are discharged through a single spillway. Some reservoirs have more than one spillway. A service spillway conveys smaller, more frequently occurring release rates, and an emergency spillway is used only rarely during extreme floods.

The major portion of the storage volume in most reservoirs is located below the spillway crest. Flows over the spillway can occur only when the storage level is above the spillway crest. Outlet works are used for releases from storage both below and above the spillway crest. Discharge capacities for outlet works are typically much smaller than that for spillways.

Outlet works are used to release water for downstream water supply diversions, maintenance of instream flows, and other beneficial uses. Flood control releases may also be made through outlet works. An outlet works typically consists of an intake structure in the reservoir, one or more conduits or sluices through the dam, gates located either in the intake structure or conduits, and a stilling basin or other energy dissipation structure at the downstream end.

Water supply diversions may be either lakeside or downstream. Lakeside withdrawals require intake structures, pumps, and pipeline or canal conveyance facilities. Downstream releases through an outlet works may be diverted from the river at locations that are great distances below the dam. Downstream releases may be made through hydroelectric power penstocks, navigation locks, or other structures, as well as outlet works and spillways.

Release requirements specified in operating plans are expressed in terms of flow rates or discharges. Rating curves are used by reservoir operators to relate release rates to storage levels and gate openings. The rating curves are developed by hydraulic analyses of the outlet structures, typically in conjunction with preconstruction design of the project.

5.3.2 RESERVOIR POOLS

Reservoir operating policies typically involve dividing the total storage capacity into designated pools. A typical reservoir consists of one or more of the vertical zones, or pools, illustrated in Figure 5.3. The allocation of storage capacity between pools may be permanent or may vary with seasons of the year or other factors.

Water is not withdrawn from the inactive pool, except through the natural processes of evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest outlet or, in the case of hydroelectric power, by conditions

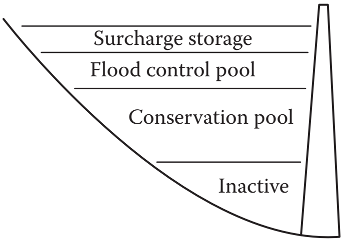


FIGURE 5.3 Reservoir storage capacity is divided into vertical zones called pools.

of operating efficiency for the turbines. An inactive pool also may be contractually set to facilitate withdrawals from outlet structures that are significantly higher than the invert of the lowest outlet structure at the project. The inactive pool is sometimes called dead storage. It may provide a portion of the sediment reserve, head for hydroelectric power, and water for recreation and fish habitat.

Conservation storage purposes, such as municipal and industrial water supply, irrigation, navigation, hydroelectric power, and instream flow maintenance, involve storing water during periods of high stream flow and low demand for later beneficial use as needed. Conservation storage also provides opportunities for recreation. The reservoir water surface is maintained at or as near the designated top of conservation pool elevation as stream flows and water demands allow. Drawdowns are made as required to meet the various needs for water.

The flood control pool remains empty except during and immediately after a flood event. The top of flood control elevation is often set by the crest of an uncontrolled emergency spillway, with releases being made through other outlet structures. Gated spillways allow the top of flood control pool elevation to exceed the spillway crest elevation.

The surcharge pool is essentially uncontrolled storage capacity above the flood control pool (or conservation pool if there is no designated flood control storage capacity) and below the maximum design water surface. Major flood events exceeding the capacity of the flood control pool encroach into surcharge storage. The maximum design water surface profile, or top of the surcharge storage, is established during project design from the perspective of dam safety. Reservoir design and operation are based on assuring that the reservoir water surface will never exceed the designated maximum design water surface elevation under any conditions. For most dams, particularly earthfill embankments, the top of dam elevation includes a freeboard allowance above the top of surcharge pool to account for wave action and provide an additional safety factor against overtopping.

5.3.3 SEDIMENT RESERVE

Reservoir storage capacity is lost over time because of sedimentation. The rate of sediment deposition varies greatly between reservoir sites, depending on flow rates and sediment loads in the rivers flowing into the reservoirs and the trap efficiencies of the reservoirs. Since sediment transport increases greatly during flood events, reservoir sedimentation also varies greatly over time with the random occurrence of floods. Sediment deposits occur throughout the reservoir in each of the designated pools. As stream flow velocities decrease in the upper reaches of a reservoir, sediments are deposited, forming deltas. Smaller particles will move further into the reservoir before depositing. Reservoir sediment surveys are performed periodically to determine current bottom topography and resulting storage capacities. However, since the measurements are expensive, many reservoirs have existed for decades without sediment surveys ever having been performed. Thus, storage capacity estimates may be somewhat uncertain.

For many smaller reservoirs constructed by local entities, no special provisions are made to allow for sedimentation. Although it is recognized that the storage capacity of these reservoirs will significantly decrease over time, no attempt is made to estimate the volume and location of the sediment deposits at future points in time. However, for most federal projects and other large reservoirs, sediment reserve storage capacity is provided to accommodate sediment deposition expected to occur over a specified analysis period, typically 50 to 100 years. The volume and location of the sediment deposits and resulting changes in reservoir topography are predicted using methods outlined by the USBR (1987) and USACE (1995). Storage capacity reserved for future sediment accumulation is reflected in water supply contracts and other administrative actions.

5.3.4 RULE CURVES AND WATER CONTROL DIAGRAMS

The terms *rule curve* and *guide curve* are typically used to denote operating rules that define ideal or target storage levels and provide a mechanism for release rules to be specified as a function of storage content. Rule curves may be expressed in various formats such as water surface elevation or storage volume versus time of the year. Although the term *rule curve* denotes various other types of storage volume designations as well, the top of conservation pool is a common form of rule curve designation.

The top of a conservation pool may be varied seasonally, particularly in regions with distinct flood seasons. The seasonal rule curve illustrated in Figure 5.4 reflects a location where summer months are characterized by high water demands, low stream flows, and a low probability of floods. The top of conservation pool could also be varied as a function of watershed moisture conditions, forecasted inflows, floodplain activities, storage in other system reservoirs, or other parameters as well as season of the year. A seasonally or otherwise varying top of conservation pool elevation defines a joint use pool, which is treated as part of the flood control pool at certain times and part of the conservation pool at other times. Figure 5.5 illustrates such an operating plan where upper and lower zones are used exclusively for flood control

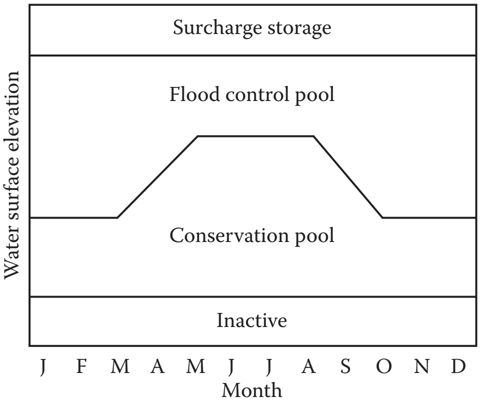


FIGURE 5.4 Seasonal rule curve operations are based on varying the top of conservation pool elevation during the year.

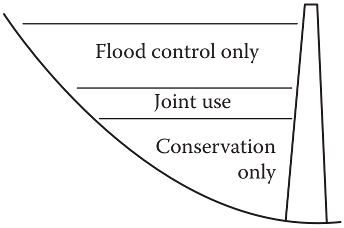
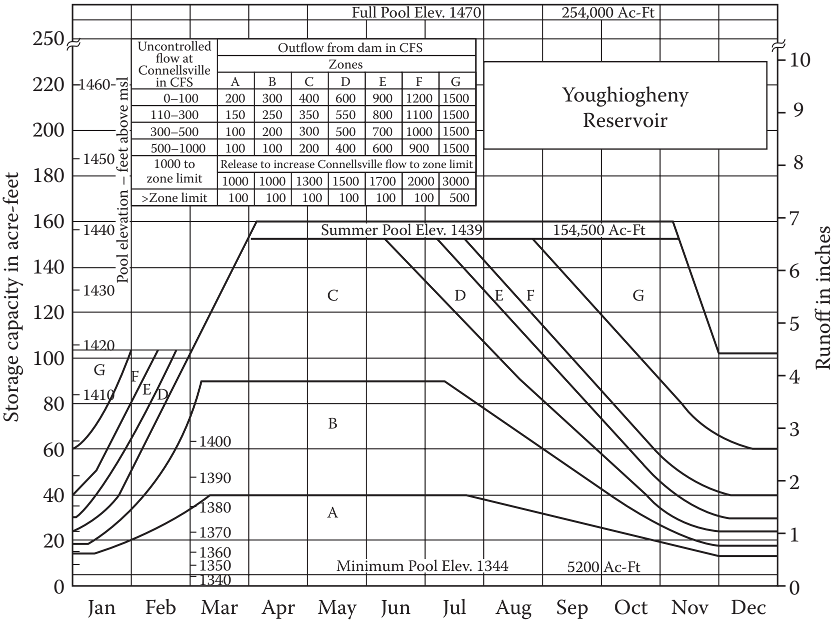


FIGURE 5.5 A reservoir may include exclusive and joint use pools.

and conservation purposes, respectively, and the storage capacity in between is used for either purpose depending on the season or other factors. Also, either the flood control or conservation pool can be subdivided into any number of vertical zones to facilitate specifying reservoir releases as a function of amount of water in storage.

Operating plans may be expressed in various formats. A water control diagram represents a compilation of regulating criteria, guidelines, rule curves, and specifications that govern the storage and release functions of a reservoir. A water control diagram or set of rule curves specifies release rules as a function of storage levels, season of the year, and related factors. The format and types of rules reflected in water control diagrams vary greatly for different reservoir projects.

An example of a water control diagram for a particular reservoir is presented in Figure 5.6 (USACE 1987). The Youghiogheny Reservoir on the Youghiogheny



Uncontrolled flow at Connellsville in CFS	Outflow from dam in CFS						
	Zones						
	A	B	C	D	E	F	G
0–100	200	300	400	600	900	1200	1500
110–300	150	250	350	550	800	1100	1500
300–500	100	200	300	500	700	1000	1500
500–1000	100	100	200	400	600	900	1500
1000 to zone limit	Release to increase Connellsville flow to zone limit						
	1000	1000	1300	1500	1700	2000	3000
>Zone limit	100	100	100	100	100	100	500

FIGURE 5.6 Storage allocations vary seasonally in this water control diagram developed by the USACE for the Youghiogheny Reservoir. (From U.S. Army Corps of Engineers. 1987. Management of water control systems. Engineering Manual 1110-2-3600. Washington, DC.)

River, a tributary of the Monongahela River, in Pennsylvania is operated as a component of a multiple reservoir system in the Ohio River Basin. The Youghiogheny Reservoir is operated for flood control, hydroelectric power, and low flow augmentation for downstream navigation, water quality, and recreation. Releases from the conservation pool are specified in the water control diagram of Figure 5.6 as a function of uncontrolled stream flow at a gaging station located downstream, time of the year, and storage content. Reservoir storage levels are expressed alternatively as volume, volume equivalent in depth of runoff depth over the 434–square mile (1120 km^2) watershed above the dam, and water surface elevation. Storage capacities at the top of an inactive pool and the top of a flood control pool are 5200 acre-ft (6.4×10^6 m^3) and 254,000 acre-ft (3.13×10^8 m^3), respectively. The 248,800 acre-ft (3.07×10^8 m^3) of active storage capacity is allocated to flood control and conservation purposes by a designated top of conservation pool that varies from 103,500 acre-ft (1.28×10^8 m^3) during December through February to 154,500 acre-ft (1.91×10^8 m^3) from April to early November.

5.4 FLOOD CONTROL OPERATIONS

Flood control pool operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint of assuring that the maximum design water surface is never exceeded. Flood control pools must be emptied as quickly as downstream flooding conditions allow to reduce the risk of future highly damaging releases being necessitated by filling of the available storage capacity. Minimizing the risks and consequences of storage backwater effects contributing to flooding upstream of the dam is also an important trade-off consideration at some reservoir projects.

One type of reservoir system operation problem consists of developing an operating plan, often called a regulation schedule. Another related but distinctly different reservoir system operation problem involves making release decisions during real-time flood control operations, within the framework of the regulation schedule. The operation plan provides guidance for real-time release decisions but typically still leaves a significant degree of flexibility. Information regarding current storage levels and stream flows is used, in combination with the regulation schedule, to make release decisions. Real-time operations often involve collection of current precipitation and stream flow data and forecasting flows to be expected at pertinent locations during the next several hours or days, to enable more effective release decisions. During normal nonflooding conditions, flood control operations consist simply of passing inflows to maintain empty storage capacity.

The USACE is responsible for operating a majority of the major flood control reservoir systems in the nation. Flood control regulation plans are developed to address the particular conditions associated with each individual reservoir and multiple-reservoir system. Peculiarities and exceptions to standard operating procedures occur at various projects. However, operating schedules for most reservoirs follow the same general strategy, which is outlined as follows.

Release decisions depend on whether or not the flood control storage capacity is exceeded. Although reservoir storage capacities at many reservoirs are exceeded more frequently, federal reservoirs are typically sized to contain at least a 2% annual exceedance probability flood and, for many projects, design floods greater than the 1% annual exceedence probability flood.

A specified set of rules, based on downstream flow rates, are followed as long as sufficient storage capacity is available to handle the flood without having to deal with the water surface rising above the top of flood control pool. Operation is switched over to an alternative approach, based on reservoir inflows and storage levels, during extreme flood conditions when the anticipated inflows are expected to deplete the controlled storage capacity remaining in the reservoir. The reservoir release rates necessitated by the flood control storage capacity being exceeded will contribute to downstream flooding. The objective is to assure that reservoir releases do not contribute to downstream damages as long as the storage capacity is not exceeded. However, for extreme flood events that would exceed the reservoir storage capacity, moderately high damaging discharge rates beginning before the flood control pool is full are considered preferable to waiting until a full reservoir necessitates much higher release rates.

5.4.1 Regulation Based on Downstream Flow Rates

Flood control operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding. Maximum allowable flow rates and stages at downstream control points are set based on bank-full stream capacities, stages at which significant damages occur, environmental considerations, and constraints such as inundation of road crossings or other facilities. Stream gaging stations are located at the control points. Releases are made to empty the flood control pool as quickly as possible without contributing to stream flows exceeding specified maximum allowable flow levels at downstream gages.

When a flood occurs, the spillway and outlet works gates are closed. The gates remain closed until a determination is made that the flood has crested and flows are below the target levels specified for each of the gaged control points. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the downstream locations.

Normally, no flood control releases are made if the reservoir level is at or below the top of conservation pool. However, in some cases, if flood forecasts indicate that the inflow volume will exceed the available conservation storage, flood control releases from the conservation storage may be made if downstream conditions permit. The idea is to release some water before the stream rises downstream, if practical, to maximize storage capacity available for regulating the forecasted flood. Prereleases are particularly important in operating reservoirs with only limited amounts of flood control storage capacity.

For many reservoirs, the allowable flow rate associated with a given location is constant regardless of the volume of water in storage. In other projects, the allowable flow rates at one or more control points vary depending on the volume of water currently stored in the flood control pool. This allows stringently low flow levels to be maintained at certain locations as long as only a relatively small portion of the flood control pool is occupied, with the flows increased to a higher level, at which minor damages could occur, as the reservoir fills.

Flood control reservoirs are typically operated based on maintaining flow rates at several gages located various distances below the dam. The most downstream control points may be several hundred kilometers below the dam. Lateral inflows from uncontrolled watershed areas below the dam increase with distance downstream. Thus, the impact of the reservoir on flood flows decreases with distance downstream. Operating to downstream sites requires stream flow forecasts. Flood attenuation and travel time from the dam to the control point and inflows from watershed areas below the dam must be estimated as an integral part of the reservoir operating procedure.

Most flood control reservoirs are components of basinwide multiple-reservoir systems. Two or more reservoirs located in the same river basin will have common control points. A reservoir may have one or more control points that are influenced only by that reservoir and several other control points that are influenced by other reservoirs as well. For example, in Figure 5.7, stream flow gage 3 is used as a control point for both reservoirs A and B, and gage 4 controls releases from all three reservoirs. Multiple-reservoir release decisions may be based on maintaining some specified relative balance between the percentages of flood control storage capacity utilized in each reservoir. For example, if unregulated flows are below the maximum allowable flow rates at all the control points, the reservoir with the greatest amount of water in storage, expressed as a percentage of flood control storage capacity, might be selected to release water. Various balancing criteria may be adopted. Releases from all reservoirs, as well as runoff from uncontrolled watershed areas, must be considered in forecasting flows at control points.

Maximum allowable rate of change of release rates are also specified. Abrupt gate openings causing a flood wave with rapid changes in stage are dangerous from the perspective of downstream hazards to public safety. Rapid variations in flow rates also contribute to streambank erosion.

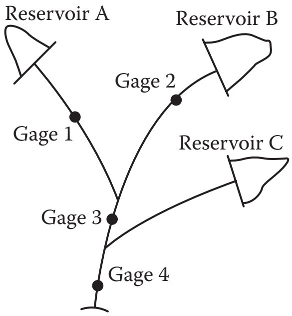


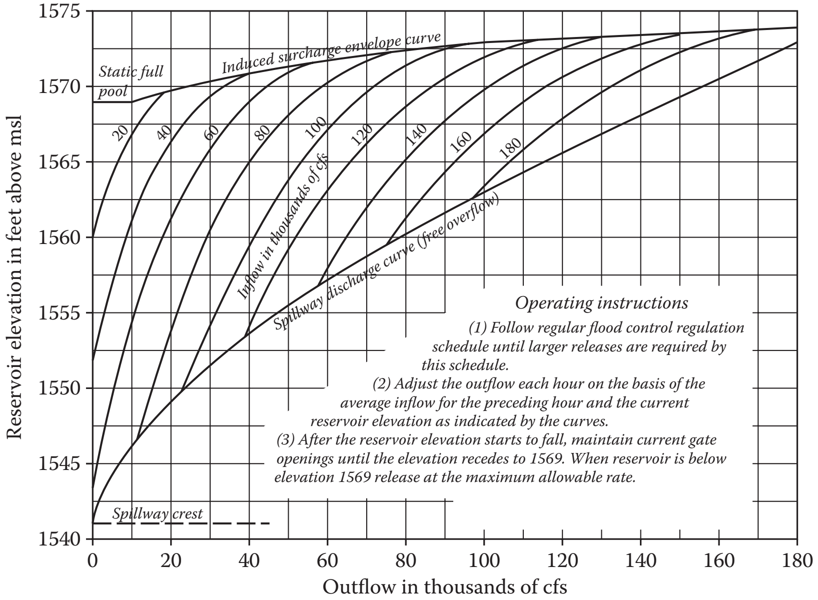
FIGURE 5.7 Flood control operations may involve operating multiple reservoirs based on flow limits at multiple downstream gages.

5.4.2 REGULATION BASED ON RESERVOIR INFLOWS AND STORAGE LEVELS

For an extreme flood event, limiting reservoir releases on the basis of allowable downstream flow rates, as discussed above, could result in the storage capacity of the flood control pool being exceeded. If the releases are based on downstream target flows until the flood control pool fills, later uncontrolled spills at high flow rates could result. The higher peak release rate necessitated by this hypothetical release policy would typically be more damaging than a lower release rate with a longer duration beginning before the flood control pool is full. On the other hand, an operator would not want to make releases in excess of allowable downstream flow rates during a storm and then later learn that the flood control pool never filled and the releases unnecessarily contributed to downstream damages. Although stream flows that will occur several hours or days in the future are often forecast during real-time operations, future flows are still highly uncertain.

Consequently, the overall strategy for operating the outlet works and spillway gates of a flood control reservoir typically consists of two component types of regulation procedures. The type of procedure requiring the largest release rate controls for given flooding and storage conditions. The regulation approach discussed previously, on the basis of downstream allowable flow rates, is followed until such time, during a flood, that the release rate indicated by the schedule outlined next is higher than that indicated by the downstream allowable flow rates. The regulation procedure outlined next is based on reservoir inflows and storage levels.

An example regulation schedule is presented in Figure 5.8 (USACE 1987). This type of schedule controls releases during an extreme flood, which would otherwise



Operating instructions

(1) Follow regular flood control regulation schedule until larger releases are required by this schedule.

(2) Adjust the outflow each hour on the basis of the average inflow for the preceding hour and the current reservoir elevation as indicated by the curves.

(3) After the reservoir elevation starts to fall, maintain current gate openings until the elevation recedes to 1569. When reservoir is below elevation 1569 release at the maximum allowable rate.

FIGURE 5.8 Releases are based on inflows and storage levels during extreme floods that threaten to exceed the flood control storage capacity.

exceed the capacity of the flood control pool. Downstream flooding conditions are not reflected in the family of curves illustrated in Figure 5.8. The reservoir release rate is read directly from the graphs, as a function of current water surface elevation and inflow rate. An alternative version of the schedule provides release rates as a function of the current water surface elevation and rate of rise of water surface. The two forms of the schedule are intended to result in the same release rate. Release rates are typically determined at a reservoir control center that has access to real-time stream flow measurements and can base release rates on inflow rates. If communications between the control center and operator at the project are interrupted during a flood emergency, the operator can determine gate releases based on rate of rise of the water surface without needing measurements of inflow rates.

The operating plan is prepared during preconstruction planning of the project. The regulation schedule curves are developed based on estimating the minimum volume of inflow that can be expected in a flood, given the current inflow rate and reservoir elevation. Having estimated the minimum inflow volume to be expected during the remainder of the flood, the outflow required to limit storage to the available capacity is determined by mass balance computations. For a given current inflow rate, the minimum inflow volume for the remainder of the storm is obtained by assuming that the inflow hydrograph has just crested and computing the volume under the recession side of the hydrograph. For conservatively low inflow volume estimates, the assumed recession curve is made somewhat steeper than the average observed recession. The complete regulation schedule that allows the outflow to be adjusted on the basis of the current inflow and empty storage space remaining in the reservoir is developed by making a series of computations with various assumed values of inflows and amounts of remaining storage available.

The family of curves of Figure 5.8 also illustrates the concept of incorporating induced surcharge into the regulation plan. The release rates are set to allow specified encroachments into surcharge storage, above the static full flood control pool. For most of the range of conditions reflected in the regulation schedule, the gates are not fully open, and thus additional storage in the surcharge pool is induced over that which results from fully opening the gates sooner. The example regulation schedule of Figure 5.8 is for a gated spillway. However, the same general approach is applicable for reservoirs with uncontrolled spillways combined with outlet works with ample release capacity.

5.5 CONSERVATION STORAGE OPERATIONS

A multitude of factors and considerations may be important in the operation of specific reservoir systems for water supply, hydropower, recreation, and other conservation purposes. Each reservoir and multiple-reservoir system has unique aspects, and a variety of mechanisms are used to define operating rules. There is no standard format for specifying operating rules that is applicable to all situations. However, several basic concepts pertinent to a wide range of operating policies are noted in the following paragraphs.

In general, conservation operations can be categorized as being primarily influenced by either seasonal fluctuations in stream flow and water use or long-term threat of drought. In some regions of the United States and the world, a reservoir will be filled during a distinct season of high rainfall or snowmelt and emptied during a dry season with high water demands. Thus, the reservoir level fluctuates greatly each year in a predictable seasonal cycle. In other cases, surface water management is predominately influenced by a long-term threat of drought. Water must be stored through many wet years to be available during drought conditions. Although reservoir storage may be significantly depleted within several months, severe drought conditions are characterized as a series of several dry years rather than the dry season of a single year. Reservoir operation during infrequent drought periods is significantly different compared to during normal or wet conditions. Although the relative importance of seasonal fluctuations versus long-term threat of drought varies between reservoir systems, both aspects of reservoir operations will typically be of some concern in any system. The terms *within-year storage* and *carryover storage* are sometimes used to differentiate between storage capacity required to handle seasonal variations in stream flows and water demands and the additional capacity required for variations between years.

Conservation storage capacity serves a variety of project purposes or types of water use. Reservoir operation for municipal and industrial water supply is based on meeting demands subject to institutional constraints related to project ownership, contractual agreements, and water rights. Municipal and industrial water supply operations are typically based on assuring a high degree of reliability in meeting demands during anticipated infrequent but severe droughts. Supplying water for irrigation often involves acceptance of greater risks of shortages than municipal and industrial water supply and is based more on maximizing economic benefits. Irrigation involves consumptive withdrawals and significant fluctuations in reservoir storage levels. Conversely, in steam–electric power plant cooling water reservoirs, most of the water withdrawn is returned to the reservoir and water surface levels fluctuate very little. Hydroelectric power plants are typically components of complex energy systems, which include thermal–electric as well as hydroelectric generation. Reservoir operations are based on maintaining a high reliability of meeting hydroelectric power and energy commitments while minimizing the total costs of both thermal and hydro generation. Reservoir storage for navigation purposes involves assuring sufficient water depths in downstream navigation channels and sufficient water supply for lockages. The environmental instream flow needs also include maintenance of stream flow for water quality, fish and wildlife habitat, livestock water, river recreation, and aesthetics. Reservoir operating policies may include specified flow rates to meet instream needs. Operating considerations for reservoir recreation typically involve maintenance of desirable storage levels and minimizing fluctuations in storage levels.

Reservoir operations also address requirements other than the primary project purposes. For example, due to water rights considerations, releases may be required to pass inflows through the reservoir to other more senior water users and management entities located downstream, which are not directly served by the reservoir. Such requirements may be specified in terms of maintaining minimum release rates at specified downstream locations, subject to the stipulation that reservoir releases in excess of inflows are not required. Another consideration involves restricting the rate of change in release rates to prevent public safety hazards. Rapid increases in stage and velocity can be dangerous for people recreating in the river downstream of a reservoir. Rapid changes in release rates are also undesirable from the perspective of riverbank erosion. Storage level fluctuations are sometimes made to help control vectors such as mosquitos. Water quality storage has been included in reservoirs, as a primary project purpose, to provide releases for low flow augmentation. Water quality is often an important incidental consideration in operations for other purposes. The quality of downstream flows and water supply diversions is sometimes controlled by selection of the vertical storage levels from which to make the releases. Operation during floods is an important consideration for conservation-only projects without flood control storage capacity.

5.5.1 MULTIPLE-PURPOSE AND MULTIPLE-USER OPERATIONS

Multiple-purpose reservoir operation involves various interactions and trade-offs between purposes, which are sometimes complementary but often competitive or conflicting. Reservoir operation may be based on the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space available for storing future flood waters to reduce downstream damages. Conservation pools are shared by various purposes that involve both consumptive withdrawals and in-reservoir and instream uses.

A common practice is to operate a reservoir for conservation only, flood control only, or a combination of flood control and conservation with separate pools designated for each. Interactions between flood control and conservation purposes in a multiple-purpose reservoir involve allocation of storage capacity as represented by the designated top of conservation pool elevation, which is a form of a rule curve. Modifications to the operations of completed projects may involve either permanent long-term reallocations of storage capacity or establishing or refining seasonally varying rule curves for joint use storage. Studies of long-term storage reallocations and designing seasonal rule curves are two important types of reservoir system modeling applications.

Interactions between flood control and conservation purposes may also involve flood control pool release rates. For example, in some cases, flood control pool releases may be passed through hydroelectric power plants and limited to the maximum discharge that can be used to generate power. Also, releases from conservation storage may be made to partially draw the pool down in anticipation of forecasted flood inflows. Releases from the conservation pool in anticipation of forecasted flood inflows are particularly important for reservoirs with little or no designated flood control storage capacity.

Conservation pools typically serve multiple purposes with at least some complementary characteristics. Water stored for water supply and hydroelectric power provides opportunities for recreation and reservoir fisheries. Hydroelectric power releases contribute to other instream flow uses and can be diverted at downstream locations for water supply. Sharing of reservoir storage capacity and limited water resources by multiple users also involves conflicting demands.

Conservation operations may include design of a triggering mechanism by which certain demands are curtailed whenever storage falls below prespecified levels. This allows water supply withdrawals, instream flows, or hydroelectric energy levels with different levels of reliability to be provided by the same reservoir. Specifying the release or withdrawal rate as a function of storage (or storage plus inflow) is sometimes called a *hedging rule*. The storage designations, or rule curves, used as a triggering mechanism in allocating water between competing users and uses are sometimes called buffer zones. Full demands are met as long as the reservoir water surface is above the top of buffer pool, whereas certain demands are curtailed whenever the water in storage falls below this level. The top of buffer pool elevation may be constant or may be specified as a function of time of the year or other parameters. A range of different storage levels in one or more reservoirs may be designated as triggering mechanisms for various management decisions.

Certain water users require a high degree of reliability. For other water users, obtaining a relatively large quantity of water with some risk of shortage may be of more value than a supply of greater reliability but smaller quantity. Storage triggering designations may also provide a mechanism for reflecting relative priorities or trade-offs between purposes. For example, a reservoir operating plan may involve assuring a high degree of reliability for a municipality and lesser reliability for agricultural irrigators. All demands are met as long as storage is above a specified level, but the irrigation demands are curtailed whenever storage falls below the specified level. Release requirements for maintaining instream flows for fish and wildlife habitat and freshwater inflows to estuaries may be conditioned upon storage being above a specified buffer level. Implementation of drought contingency plans may be triggered by the storage level falling below a specified buffer level. More severe demand management options may be implemented as storage contents fall below various prespecified levels. Conjunction management of groundwater and surface water sources may involve shifting to greater use of groundwater whenever reservoir storage falls below designated levels.

5.5.2 MULTIPLE-RESERVOIR SYSTEM OPERATIONS

Multiple-reservoir release decisions occur in situations in which water needs can be met by releases from two or more reservoirs. In Figure 5.9, diversions 1 and 3 are from specific reservoirs, but diversion 4 can be met by releases from any of the three reservoirs. Instream flow as well as diversion requirements at diversion location 4 can be met by releases from the reservoirs.

One criterion for deciding from which reservoir to release is minimization of spills, since they represent water loss from the system. Spills from an upstream reservoir (such as reservoir A in Figure 5.9) may still be stored in a downstream reservoir (reservoir B) and thus are not loss to the system. The term *spill* refers to discharges through an uncontrolled spillway or controlled releases made simply to prevent the reservoir surface from rising above the designated top of conservation pool. For reservoirs in series, such as reservoirs A and B in Figure 5.9, the downstream reservoir would be depleted before using upstream reservoir water to meet downstream

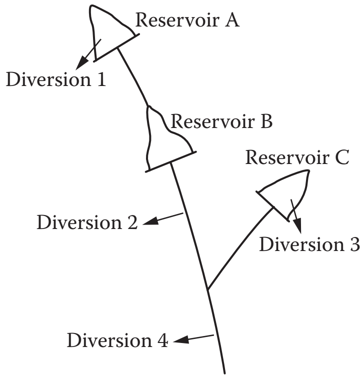


FIGURE 5.9 Releases from multiple reservoirs supply multiple water supply diversion sites.

demands. In addition to minimizing spills from the downstream reservoir, this procedure maximizes the amount of water in storage above and is thus accessible by gravity flow to each diversion location. For example, water stored in reservoir A can be used to meet diversions 1, 2, and 4, but water stored in reservoir B can be used to meet only diversions 2 and 4.

For reservoirs in parallel, such as reservoirs B and C in Figure 5.9, minimizing spills involves balancing storage depletions in the different reservoirs. The simplest approach might be to release from the reservoir with the largest ratio of conservation pool storage content to storage capacity. Thus, release decisions would be based on balancing the percent depletion of the conservation pools. Other more precise and more complex approaches can be adopted to select the reservoir with the highest likelihood of incurring future spills.

Numerous other considerations may be reflected in multiple-reservoir release decisions. If the reservoirs have significantly different evaporation potential, minimization of evaporation may be an objective. The criteria of minimizing spills or evaporation are pertinent to either single-purpose or multiple-purpose systems. Multiple-purpose, multiple-reservoir release decisions can involve a wide variety of interactions and trade-offs. For example, releases to meet downstream municipal, industrial, or irrigation water supply demands may be passed through hydroelectric power turbines. Thus, multiple-reservoir water supply release decisions may be based on optimizing power generation. Likewise, recreational aspects of the system could motivate release decisions, which minimize storage level fluctuations in certain reservoirs.

As illustrated in Figure 5.10, conservation pools can be subdivided into any number of zones to facilitate formulation of multiple-reservoir release rules. The multiple-zoning mechanism can be reflected in the operating rules actually followed by reservoir operators. Also, even in cases where operating rules are not actually precisely defined by designation of multiple zones, the multiple-zone mechanism can be used in computer models to approximate the somewhat judgmental decision process of actual operators. The zones provide a general mechanism or format for expressing operating rules. Multiple-reservoir release rules are defined based on

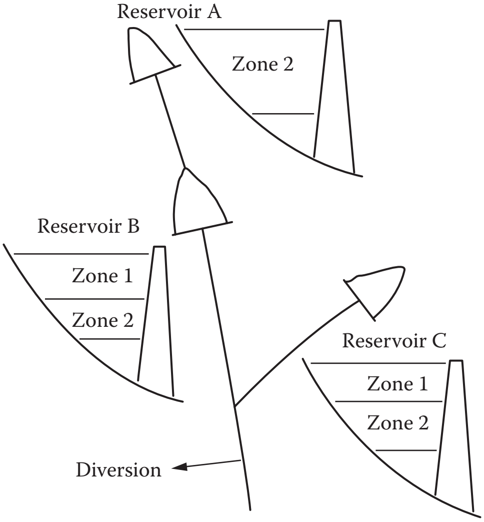


FIGURE 5.10 Multiple-reservoir release rules are based on designated storage zones in each reservoir.

balancing the storage content such that the reservoirs are each in the same zone at a given time to the extent possible. For example, in meeting the downstream diversion (or instream flow) requirement of Figure 5.10, water is not released from zone 2 of one reservoir until zone 1 has been depleted in all the reservoirs. Since zone 1 in reservoir A is assigned zero storage capacity, no releases are made from reservoir A until zone 1 is empty in the other two reservoirs. With the storage content falling in the same zone of each reservoir, the release is made from the reservoir that is most full in terms of percentage of the storage capacity of the zone. For example, if the storage capacities of zone 2 of reservoirs A, B, and C, respectively, are 55%, 60%, and 68% full, a release is made from reservoir C to meet the downstream diversion requirement. Variations of this general type of multiple-reservoir release rule can be formulated.

5.5.3 Water Supply

Water is diverted or withdrawn from rivers and reservoirs for municipal, industrial, agricultural, and other beneficial uses. During normal hydrologic conditions, real-time reservoir operations involve meeting water demands in accordance with the commitments and responsibilities of the water supply agencies. During low flow or drought conditions, operations may involve allocating limited water resources to competing users within the institutional framework of project ownership and agency responsibilities, contractual agreements, legal systems for allocating and administering water rights, and political negotiations.

Developing and administering water supply contracts and agreements, water rights allocation systems, and reservoir operating plans involve various types of reservoir system operation decision problems, which can be categorized as follows:

- Allocation of a limited amount of water between competing uses and users
- Within-year temporal allocation of a limited amount of water (e.g., distributing available water over the irrigation season)
- Determination of the trade-off between the amount of water to use during the current water year and the amount of water to be carried over in storage into the next year
- Coordination of water supply operations with demand management strategies and other sources of supply such as groundwater
- Coordination of water supply operations with other project purposes
- Coordination of the releases from each reservoir of a multiple reservoir system
- Various combinations of the above

Maintaining a high reliability for meeting water needs during infrequent drought or low flow conditions expected to occur at unknown times in the future is a key consideration in water supply management. Municipal and industrial water supply typically requires a particularly high level of reliability. Project planning and design, contractual agreements, and water rights are typically based on assuring a very dependable supply.

Supplying water for irrigation often involves acceptance of greater risks of shortages than municipal and industrial water supply. Obtaining a relatively large quantity of water with some significant risk of shortage may be of more value than a supply of greater reliability but smaller quantity. An operating plan may involve allocating water to the various users at the beginning of each water year or irrigation season on the basis of current reservoir storage levels and present and forecasted future hydrologic conditions.

The amount of water required to meet the demands for growing crops for the entire season is called water duty. This is equal to the amount of water supplied to the land by means of gravity diversions from rivers and reservoirs or pumped from rivers, reservoirs, or groundwater aquifers. Net duty is the amount of water delivered to individual farm units, considering losses in canals, laterals, and waste from the point of diversion to the point of application to the land. Irrigation water diverted from reservoirs, diversion dams, or natural river channels is controlled in a manner to supply water for the irrigation system as necessary to meet water duty requirements, which vary seasonally. In most irrigated areas of the western United States, the agricultural growing season begins in the spring months of April and May. The diversion requirements gradually increase as the summer progresses, reaching their maximum amounts in July or August. By the end of the growing season, irrigation requirements are terminated. The return flow of water from irrigated lands is collected in drainage channels and flows back into natural creeks and rivers. The return flows may vary from essentially zero to greater than half of the diversion amounts. Increases in salinity concentrations are often associated with irrigation return flows.

Shifting to a greater reliance on demand management is a major emphasis in all sectors including municipal, industrial, and irrigation. Implementation of appropriate demand management strategies is an important consideration in determining water needs to be supplied by reservoirs. Implementation of short-term or emergency demand management measures is dependent on current reservoir storage levels and associated risks of future shortages in supply. Coordination of reservoir operations and demand management programs is important.

Multiple-reservoir system operation involves coordinated releases from two or more reservoirs to supply common diversions or instream flow needs at downstream locations. Under appropriate circumstances, multiple-reservoir system operations can significantly increase reliabilities, as compared to operating each individual reservoir independently of the others. Coordinated releases from two or more reservoirs increase reliabilities by sharing the risks associated with the individual reservoirs not being able to meet their individual demands. Operated independently, one reservoir may be completely empty and unable to supply its users while significant storage remains in the other reservoirs. At other times, the other reservoirs may be empty. System operation balances storage depletions. Multireservoir system operation can also serve to minimize reservoir spills and evaporation and channel losses caused by seepage and evaporation. In some systems, water treatment costs and electrical pumping costs for water conveyance and distribution may vary significantly depending on which demands are met by releases or withdrawals from which reservoirs.

Another key aspect of system operation involves the use of unregulated flows entering the river below the most downstream dams but above the location of water supply diversions. For example, the diversion in Figure 5.10 is partially supplied by surface runoff and baseflow from subsurface sources entering the river below reservoirs B and C. This unregulated stream flow does not flow into any reservoir but flows past pumping plants where water is diverted from the river for beneficial use. Unregulated river flows are typically highly variable, of significant magnitude much of the time, but zero or very low some of the time. Thus, unregulated flows have firm yields of zero or very little. However, when combined with reservoir releases during low-flow periods, the unregulated stream flows may significantly contribute to the overall stream/reservoir system water supply capabilities.

5.5.4 HYDROELECTRIC POWER

Hydroelectric plants are generally used to complement the other components of an overall electric utility system. Because the demand for power varies seasonally, at different times during the week, and during the day, the terms *base load* and *peak load* are commonly used to refer to the constant minimum power demand and the additional variable portion of the demand, respectively. Hydroelectric power is typically used for peak load while thermal plants supply the base load. Hydroelectric power plants can assume load rapidly and are very efficient for meeting peak demand power needs. In some regions, hydroelectric power is a primary source of electricity, supplying much or most of the base load as well as peak load. Availability of water is generally a limiting factor in hydroelectric energy generation.

Hydroelectric plants may be classified as storage, run-of-river, or pumped storage (USACE 2008). A storage-type plant has a reservoir with sufficient capacity to permit carryover storage from the wet season to the dry season or from wet years through a drought. A run-of-river plant has essentially no active storage, except possibly some pondage to permit storing water during off-peak hours for use during peak hours of the same day or week, but may have a significant amount of inactive storage that provides head. Flows through the turbines of run-of-river plants are limited to unregulated stream flows and releases from upstream reservoirs. A pumped-storage plant generates energy for peak load, but during off-peak periods, water is pumped from the tailwater pool to the headwater pool for future use. The pumps are powered with secondary energy from some other plant in the system.

In many projects, reservoir releases are made specifically and only to generate hydroelectric power. In other projects, hydroelectric power generation is limited essentially to releases that are being made anyway for other purposes, such as municipal, industrial, or agriculture water supply. An upstream reservoir may be operated strictly for hydropower, with the releases being reregulated by a downstream reservoir for water supply purposes.

The objective of an electric utility is to meet system demand for energy, capacity (power), and reserve capacity (for unexpected surges in demand or loss of a generating unit) at minimum cost. Power is the rate at which energy is produced. Capacity is the maximum rate of energy production available from the system. The value of hydroelectric energy and power is a function of the reliability at which they can be provided. Three classes of energy are of interest in hydroelectric power operations: average, firm, and secondary. Average energy is the mean annual amount of energy that could be generated assuming a repetition of historical hydrology. Firm energy, also called primary energy, is estimated as the maximum constant annual energy that could be generated continuously during a repetition of historical hydrology. From a marketing perspective, firm energy is electrical energy that is available on an assured basis to meet a specified increment of load. Secondary energy is energy generated in excess of firm energy. Secondary energy, expressed on an average annual basis, is the difference between average annual energy and firm energy.

Reservoir operating rules for hydroelectric power generation assume different forms depending on characteristics of the electric utility system and reservoir system, hydrologic characteristics of the river basin, and institutional constraints. Designation of a power pool and power rule curve, illustrated in Figure 5.11, is a key aspect of hydroelectric operations. The power pool is reserved for storage of water to be released through the turbines. Inactive or active storage below the power pool provides additional head. If the reservoir water surface is at the top of power pool, net inflows less evaporation and withdrawals are passed through the reservoir. Flows up to the maximum generating capacity of the plant may be used to generate energy, and the remainder of the flow is spilled. If the reservoir contains flood control storage, water will be stored in the flood control pool above the top of power pool during flood events. Power generation is curtailed any time the water surface elevation drops below the designated minimum power pool elevation.

Hydroelectric power operations are typically based on two objectives: (1) to assure firm energy in accordance with contractual agreements or other commitments and

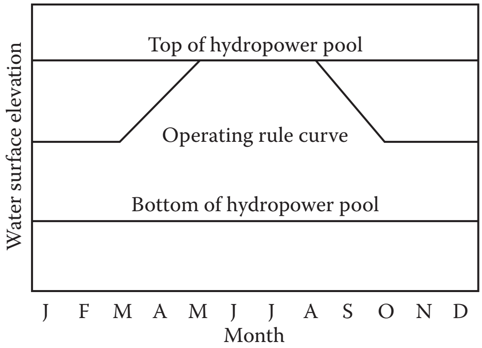


FIGURE 5.11 Rule curves for hydropower operations may vary seasonally.

(2) to meet total system energy and power demands at minimum cost. The rule curve is designed to assure firm energy. Operation is based on meeting firm energy commitments continuously as long as the power pool contains water. Additional secondary energy is generated only if the reservoir storage content is above the rule curve. The seasonal variation of the rule curve over the year is tailored to the hydrologic conditions and power demands of the particular area. For example, the rule curve shown in Figure 5.11 reflects the following considerations. Power storage must be at maximum during the middle of the calendar year in anticipation of high summer power demands coincident with low inflows. Droughts usually begin during the early summer in this area. A low pool elevation is acceptable in the fall and winter season because demands are lower and inflows are higher.

The power rule curve is typically developed based on the historical hydrologic period-of-record stream flows. Droughts more severe than the critical drought of record can result in depleting the power pool and interrupting firm energy generation. Although power rule curves are discussed here from the perspective of a single reservoir, rule curves can also be developed for a multiple reservoir system on the basis of total system storage or potential energy.

Determining day-to-day and hour-to-hour releases when the storage is above the power rule curve represents a basic real-time decision problem. Only firm energy can be generated if the storage is at or below the rule curve. However, secondary energy can be generated with storage above the rule curve. A variety of approaches can be adopted for utilizing this water. Although, in some systems, detailed guidelines have been developed to guide secondary energy generation decisions, typically considerable flexibility exists for operator judgement on a day-to-day basis. If opportunities exist for displacing very expensive thermal generation, secondary hydroelectric energy can be very worthwhile. The optimization problem consists of timing secondary energy generation to minimize thermal generation costs or to maximize hydroelectric revenues. However, drawing the storage down to near the rule curve increases the risk of not meeting firm energy requirements, if a future inflow sequence is more adverse than the critical period of historical inflows upon which rule curve development was based. Thus, a trade-off also exists between minimizing thermal generation fuel costs or hydroelectric power revenues and maintaining a high reliability of firm energy commitments being met in the future. The impacts of secondary energy generation decisions on average annual energy also involve trade-offs between maintaining a high head and minimizing the probability of spills. In multiple-reservoir systems, the decision problem involves balancing storage and releases between reservoirs as well as timing of releases.

Developing, modifying, and refining reservoir operating policies often involve interactions between hydroelectric power and other project purposes. If the reservoir includes flood control, the top of power pool coincides with the bottom of the flood control pool. The top of power pool may be a seasonally varying rule curve defining a joint-use pool used sometimes for flood control and sometimes for power. Design of the rule curve must reflect both hydroelectric power and flood control objectives. Rule curves can also be established to optimize hydroelectric power operations subject to the constraint of maintaining highly reliable supplies for municipal, industrial, agricultural, and/or low flow augmentation purposes. Likewise, water supply release decisions may be based on optimizing hydroelectric power operations while meeting water supply demands. Hydropower operations may be constrained by minimum stream flow requirements for fish and wildlife or other instream flow needs. Minimizing the adverse impacts of storage level fluctuations on recreation may be an important consideration. The rate of change of release rates is often limited to reduce streambank erosion.

5.5.5 Navigation

The USACE is the primary agency in the United States responsible for navigation improvements. During the past century and a half, the Corps of Engineers has been involved in the improvement for navigation of some 35,000 km of inland and coastal waterways. Navigational improvements include canals, locks, dams and reservoirs, maintained channels and estuaries, bank protection, and channel stabilization measures.

Reservoirs provide slack pools for navigation and releases that supplement natural flows in maintaining minimum flow depths in downstream channels. Use of reservoir releases to maintain stream flows for navigation is limited because of the large quantities of water required. Slack water waterways, such as the Tennessee Valley System, provide required depths by maintaining reservoir storage levels and dredging. Open river waterways like the Missouri and Mississippi rely on channel constriction, dredging, and normal depth of flow to maintain the minimum depth for navigation. When available water is limited, navigation is concerned with depth, width, and channel alignment and length of navigation season at authorized depth. During floods, navigation is affected by flow velocities, cross currents, bridge clearances, docking and locking difficulties, and shoaling.

Reservoir operations for navigation involve optimizing the use of available water for maintaining storage levels to provide slack pools and releases to augment flows in downstream channels and to provide water for locking operations. Reservoir operations also involve minimizing the adverse impacts of floods on navigation. Typical objectives considered in developing and evaluating reservoir operating plans for navigation include the following:

- Maximizing the length of the navigation season
- Maximizing the reliability of the dependable minimum depth
- Minimizing fuel and other operating costs
- Minimizing dredging costs
- Minimizing the volume of water released from storage to meet navigation requirements

5.5.6 Recreation

The general public uses reservoirs and rivers for boating, swimming, fishing, and other recreational activities. Reservoir operating plans include consideration of recreation in the reservoir, along the shore, in the river just below the dam, and at river locations further downstream.

Recreational aspects of reservoir operations involve maintaining storage levels and minimizing fluctuations in storage levels. Reservoir water surface area, depths, length of shoreline, area and quality of beaches, and usability of facilities such as marinas, docks, and boat ramps are related to storage level. Under most circumstances, the optimal recreation use of reservoirs would require that the water level be maintained at or near the top of conservation pool during the recreation season. This is often infeasible because of other project purposes.

In streams below reservoirs, recreation is influenced by flow rates, variations in flow rates, and water quality. Both high flows and low flows can reduce the recreation potential. Reservoir releases can also cause safety hazards for downstream recreationists. Operating plans often include specification of minimum stream flows and possibly augmented flows during short periods for special activities such as river rafting.

The effects of reservoir regulation on the aesthetics of the riverine environment are closely related to public use. Aesthetic considerations in reservoir operating plans may involve maintaining minimum stream flows, releasing water for special aesthetic purposes, or minimizing the duration of exposure of mud flats or unsightly shoreline resulting from drawdowns.

Water quality affects body contact activities such as swimming and water skiing. Temperature, fecal coliform count, dissolved oxygen, and turbidity are important water quality parameters for recreation.

5.6 WATER QUALITY MANAGEMENT

Water quality encompasses the physical, chemical, and biological characteristics of water. Both natural water quality and man-induced changes in quality are important considerations in river/reservoir system management.

5.6.1 Water Quality Aspects of Reservoir System Operations

Water quality and the aquatic environment may be significantly affected by reservoir management practices (Jobin 1998; Jorgensen et al. 2005). Water quality requirements for reservoir releases may involve both flow rates and quality parameters. Low flow augmentation, or maintenance of minimum stream flow rates at downstream locations, is a primary water quality operating objective at many reservoir projects. The quality of the releases is controlled at many projects through multiple-level selective withdrawals.

Common reservoir water quality problems include turbidity, suspended solids, and algae. Pollution from watershed activities, such as acid mine drainage, oil field operations, agricultural activities, and municipal and industrial wastewater effluents, is a problem in many areas. Problems are often related to eutrophication. Eutrophication is the process of excessive addition of organic matter, plant nutrients, and silt to reservoirs at rates sufficient to cause increased production of algae and rooted plants. Symptoms of eutrophication include algae blooms, weed-choked shallow areas, low dissolved oxygen, and accumulation of bottom sediments. Resulting problems include elimination of reservoir fisheries, adverse impacts on downstream ecosystems, degradation of water supplies, and reduced storage capacity.

Reservoir water quality problems may also be related to seasonal stratification. As illustrated in Figure 5.12, in a stratified lake, the well-mixed surface layer, called the *epilimnion*, and the colder bottom layer, called the *hypolimnion*, are separated by a layer of sharp temperature gradient, called the *metalimnion*. Most impoundments exhibit some degree of temperature stratification. In general, deeper lakes are more likely to become highly stratified each summer and are not as likely to become mixed by wind or short-term temperature changes. When the surface of the lake begins to receive a greater amount of heat from the sun and air than is lost, it becomes warmer and less dense, while the colder, denser water remains on the bottom. In the layer of colder water near the bottom, little if any oxygen is transferred from the air to replace that depleted by oxidation of organic substances, and, eventually anoxia may develop. Under this condition, a reducing environment is created, resulting in elevated levels of parameters such as iron, manganese, ammonia, and

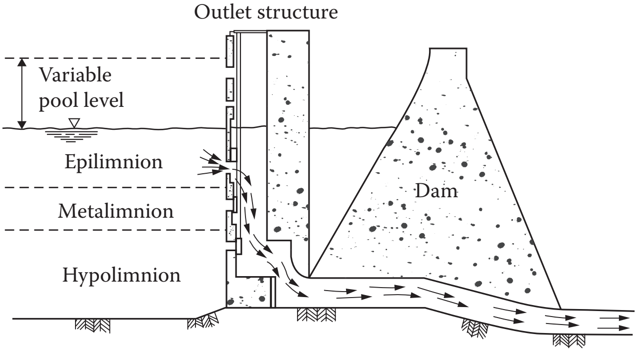


FIGURE 5.12 Reservoirs are affected by varying degrees of thermal stratification.

hydrogen sulfide. Changes such as these may result in water that is degraded and toxic to aquatic life.

A primary means of managing the water quality of reservoir releases is to control the vertical levels at which water is withdrawn from the reservoir. Many reservoir projects include outlet works intake structures providing multilevel withdrawal capabilities. The reservoir operating decision problem involves establishing the desired temperature, dissolved oxygen, and other water quality criteria and selecting the elevations at which to make releases to meet the criteria. Water from different levels may have to be mixed to meet the different water quality criteria. Management of water quality in the reservoir pool may also be a consideration in selective withdrawals from multilevel intake structures. Good- and poor-quality water can be blended to meet the release criteria with a minimum of good-quality and a maximum of poor-quality water. This type of release policy will help prevent a deterioration of quality in the reservoir, which could lead to an eventual inability to meet the release criteria.

5.6.2 Salinity

Dissolved solids or salts are the inorganic solutes that occur in all natural waters because of weathering of rocks and soils. Total dissolved solids (TDSs) or salinity increases as waters move over the land surface and through soils and aquifers. Evaporation and transpiration increase concentrations. Human activities such as irrigated agriculture and construction of reservoirs increase evaporation and the salinity of land and water resources. Groundwater pumping, oil field operations, and municipal use and wastewater disposal activities may also increase salinity. Salinity plays an important role in water resources development and management throughout the world, particularly in relatively arid regions. In the United States, salinity is particularly important in the states located west of the Rocky Mountains and in Texas and neighboring states.

Geologic formations underlying the upper watersheds of the Rio Grande, Pecos, Colorado, Brazos, Red, Canadian, and Arkansas Rivers in Texas, New Mexico, Oklahoma, Kansas, and Arkansas contribute large salt loads to these rivers that severely constrain the use of water supplied by a number of large reservoirs (Wurbs 2002). This semiarid region consists of gypsum and salt-encrusted rolling plains containing numerous salt springs and seeps. The mineral pollutants consist largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids. The primary salt source subwatersheds of these major river basins have streams with extremely high TDS concentrations that exceed the TDS concentration of seawater at some locations. Salt concentrations in the downstream reaches of the rivers decrease with dilution from low-salinity tributary inflows. Dilution is affected by reservoir releases.

5.7 ENVIRONMENTAL MANAGEMENT

Ecological systems are the interacting components of air, land, water, and living organisms including humans. From a water resources perspective, an ecosystem could be anything from a drop of water to the entire global hydrologic cycle. From the perspective of river basin management, the concept of ecosystem management emphasizes protection and restoration of natural resources including fish and wildlife, vegetation, and various aquatic and riparian ecosystems including streams, lakes, wetlands, estuaries, and coastal waters (Mac et al. 1998).

Environmental resources management opportunities and problems associated with reservoir operations vary widely between regions and between reservoirs. Reservoir operations influence fish, wildlife, and ecological systems both in the reservoir pool and in the river downstream.

Reservoir releases contribute to the maintenance of instream flows necessary for the support of aquatic habitat and species, protection or enhancement of water quality, preservation of wetlands, and provision of freshwater inflows to bays and estuaries. Reservoir operating plans may include maintenance of specified minimum flow rates at downstream locations. Periodic flooding as well as low flow augmentation may be important for certain ecosystems. The required flow rates may be specified as a function of season, reservoir storage, reservoir inflows, and other factors.

Releases for downstream fishery management depend on water quality characteristics and water control capabilities. Achieving optimal temperatures for either cold or warm water fisheries through selective multilevel releases may be an operating objective. Maintenance of dissolved oxygen levels may be an objective. Releases can be beneficial for maintaining gravel beds for certain fish species. Dramatic changes in release rates, typically associated with hydropower and flood control operations, can be detrimental to downstream fisheries.

Migration of anadronomous fish, such as salmon in the Pacific Northwest and striped bass in the Northeast, is a concern in some regions. Declines in anadronomous fish populations have been attributed to dams as a result of blockage of migration, alteration of normal stream flow patterns, habitat modification, blockage of access to spawning and rearing areas, and changes in water quality. Regulation for anadromous fish is particularly important during certain seasons of the year.

Project regulation can influence fisheries in the pool as well as downstream. Water surface level fluctuations are one of the most apparent influences of reservoir operation. Periodic fluctuations in water levels present both problems and opportunities in regard to reservoir fisheries. The seasonal fluctuations that occur at many flood control projects and daily fluctuations at hydropower projects often eliminate shoreline vegetation and cause subsequent shoreline erosion, water quality degradation, and loss of habitat. Adverse impacts of water level fluctuations also include loss of shoreline shelter and physical disruption of spawning and nests. Beneficial fisheries management techniques include pool level management for weed control; forcing forage fish out of shallow cover areas, making them more susceptible to predation; and maintaining appropriate pool levels during spawning.

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6 Sustainable Urban Water Management

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and Robert W. Peters

CONTENTS

6.1 INTRODUCTION

There is no shortage of water on planet Earth, only a shortage of freshwater. Of all the water on Earth, 97.5% is salty, and of the 2.5% freshwater, two-thirds is locked in frozen states—ice caps, glaciers, and permanent snow. In a National Academy of Engineering study, *A Century of Innovation*: *Twenty Engineering Achievements that Transformed our Lives*, Constable and Somerville (2003) included urban water supply in the top five engineering achievements of the 20th century. In a survey by the *British Medical Journal* (2007), sanitation was rated the single most important factor in improving public health in the past 150 years. Sustainable and efficient water management is crucial to public health, a viable economy, and a livable urban environment (Daigger 2011). Securing adequate water resources for various uses is one of the grand challenges. The social, economic, and environmental impacts of past water resources development projects and expected future water scarcity, especially in urban areas, are driving a shift in how water resources are managed, which will increasingly rely on sustainable technologies (Chemical Engineering Progress [CEP] 2015; Uribe et al. 2015). Water is needed for domestic, commercial, industrial, and irrigation uses, and for maintaining and improving local environments, such as parks

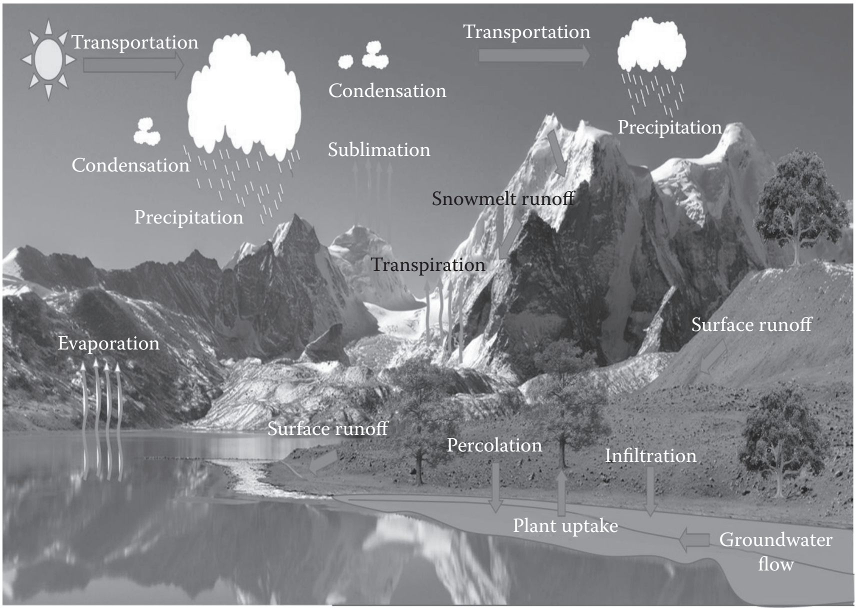

FIGURE 6.1 The water cycle. (From United States Geological Survey [USGS], 1993. The Water Cycle; http://water.usgs.gov/edu/watercycle.html. Reston, Virginia.)

and recreation. In addition, storm water and used water must be managed to prevent flooding and environmental damage, and pollution abatement.

To understand the management of water resources, one needs to study the water cycle. The water cycle, also known as hydrologic cycle (see Figure 6.1), describes the movement of the Earth's water. Various processes determine the movement of water between the atmosphere, ground, glaciers and ice caps, and oceans, lakes, and rivers (United States Geological Survey [USGS] 1993).

6.2 COMPONENTS/PROCESSES IN THE WATER CYCLE

The atmosphere plays an important role in moving water around the globe. Evaporation and transpiration (evaporation of water from plants), collectively called evapotranspiration, change liquid water into water vapor, which is carried into the atmosphere by rising air currents. Cooler temperatures allow vapor condensation in clouds. Strong winds move the clouds around the world until the water falls as precipitation to replenish the earthbound parts of the water cycle. About 90% of water in the atmosphere is produced by evaporation from water bodies, while the other 10% comes from transpiration from plants (USGS 1993).

Freshwater existing on the land surface, known as surface water, includes rivers, creeks, streams, ponds, lakes, canals, and freshwater wetlands. Freshwater, by definition, contains less than 1000 mg/L of dissolved solids.

Inflows from precipitation, overland runoff, and groundwater seepage; tributary inflows and outflows from evaporation; movement of water into groundwater; and withdrawals by people cause changes in the amount of water in rivers and lakes. Groundwater exists in the subsurface and is typically less polluted than surface water. However, if groundwater is contaminated because of industrial and domestic discharges of hazardous wastes, it is much harder and costlier to clean up than surface water. Groundwater is a major contributor to flow in many streams and rivers and has a strong influence on river and wetland habitats for plants and animals. Life on Earth depends on both groundwater and surface water.

When the water falls as rain and snow, part of it percolates and infiltrates into the subsurface soil and rock. The amount of infiltration depends on a number of factors. Some water that infiltrates into the subsurface will remain in the shallow soil layer, where it will gradually move vertically and horizontally through the soil and subsurface material. Eventually, it might enter a stream by seepage into the stream bank. Some of the water may infiltrate deeper, recharging groundwater aquifers. Water may travel long distances or remain in groundwater storage for long periods before returning to the surface or seeping into other water bodies, such as streams and oceans (USGS 1993).

6.3 GLOBAL WATER DISTRIBUTION

At any time, water exists in various forms noted in the water cycle of Figure 6.1. Distribution of water is shown in Figure 6.2. The water allocation is shown in Table 6.1.

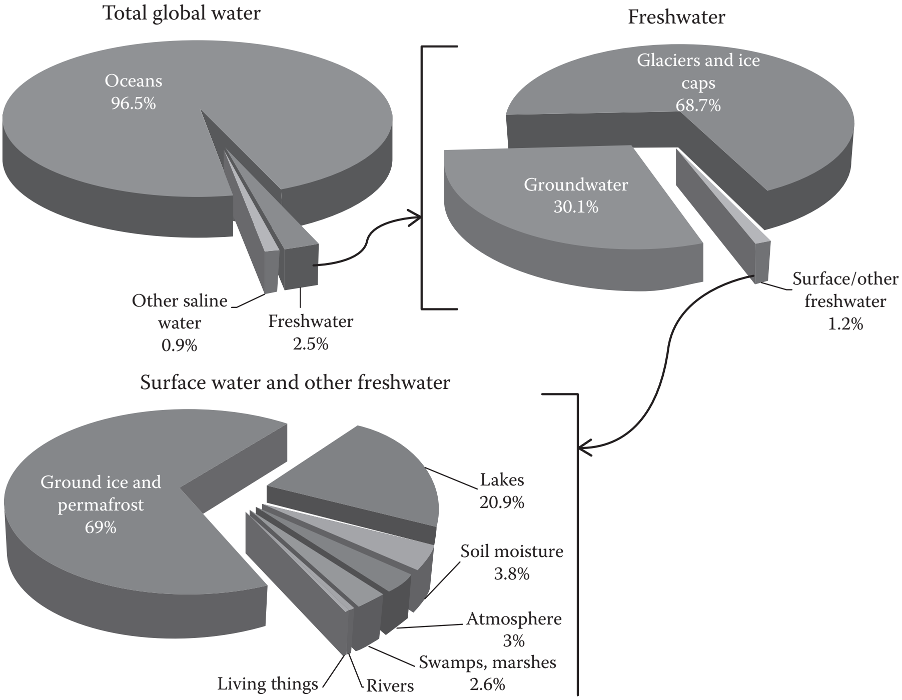

FIGURE 6.2 Global water distribution. (From Shiklomanov, I., 1993. World fresh water resources, chapter in *Water in Crisis*: *A Guide to the World's Fresh Water Resources*, Peter H. Gleick [editor], Oxford University Press, New York.)

TABLE 6.1
Estimate of Global Water Distribution (Numbers Are Rounded)

Water Source	Water Volume (km^3)	Water Volume ($mile^3$)	Percentage of Total Water	Percentage of Freshwater
Oceans, seas, and bays	1,338,000,000	321,000,000	96.5	–
Ice caps, glaciers, and permanent snow	24,064,000	5,773,000	1.74	68.7
Groundwater	23,400,000	5,614,000	1.69	–
Fresh	10,530,000	2,526,000	0.76	30.1
Saline	12,870,000	3,088,000	0.93	–
Soil moisture	16,500	3959	0.001	0.05
Ground ice and permafrost	300,000	71,970	0.022	0.86
Lakes	176,400	42,320	0.013	–
Fresh	91,000	21,830	0.007	0.26
Saline	85,400	20,490	0.006	–
Atmosphere	12,900	3095	0.001	0.04
Swamp water	11,470	2752	0.0008	0.03
Rivers	2120	509	0.0002	0.006
Biological water	1120	269	0.0001	0.003

Source: Adapted from Shiklomanov, I., 1993. World fresh water resources, chapter in *Water in Crisis: A Guide to the World's Fresh Water Resources*, Peter H. Gleick (editor), Oxford University Press, New York.

Of the world's total water supply of about 333 million cubic miles (1386 million km^3) of water, 97.5% is saline, and of the total freshwater (2.5%), more than 68% is contained in ice and glaciers and 30% is in the subsurface as groundwater. Rivers and lakes that supply surface water for most human uses only constitute about 22,300 cubic miles (93,100 km^3), which is about 0.007% of the total water (USGS 1993).

In a USGS circular, Hutson et al. (2005) reported the detailed distribution of freshwater usage during calendar year 2000. About 408 billion gallons per day (Bgal/day) were withdrawn for all uses during 2000. This total has varied less than 3% since 1985 as withdrawals have stabilized for the two largest uses—thermoelectric power and irrigation. Fresh groundwater withdrawals (83.3 Bgal/day) during 2000 were 14% more than during 1985. Fresh surface water withdrawals for 2000 were 262 Bgal/day, varying less than 2% since 1985. Figure 6.3 uses a "cylinder" and "pipe" layout to show where our nation's water comes from and how it is used. The top row represents the source of water (surface water or groundwater). Most of the water (262,000 million gallons per day [Mgal/day]) came from surface water sources, such as rivers and lakes and about 83,400 Mgal/day came from groundwater (from wells). The next two rows down represent a category of water use where the water was sent after being withdrawn (domestic, public supply, irrigation, agriculture, etc.). The industrial cylinder, for example, shows that in 2000, about 18,500 Mgal/day of water was used for industrial purposes, with about 14,900 Mgal/day coming from surface

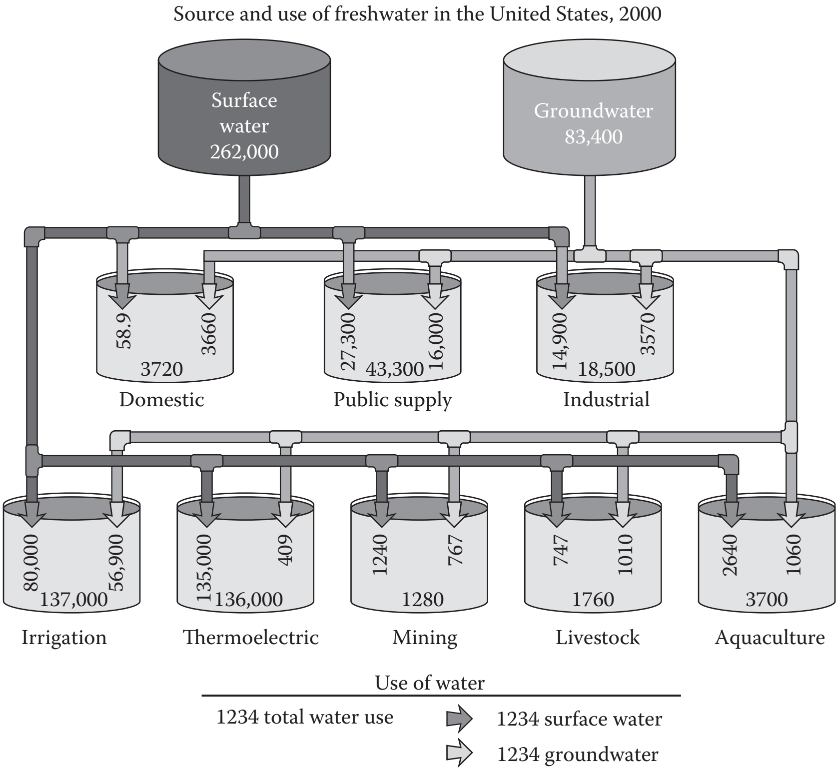

FIGURE 6.3 US water use (Mgal/day) in 2000. (From Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin, 2005. United States Geological Survey [USGS], *Estimated Use of Water in the United States in 2000*, USGS Circular 1268, [released March 2004, revised April 2004, May 2004, February 2005].)

water and about 3570 Mgal/day coming from groundwater. The distribution of water usage between surface water (58.9 Mgal/day) and groundwater (3600 Mgal/day) is reversed, where most of the water usage for domestic purposes comes from groundwater sources.

6.4 SUSTAINABILITY

The most broadly accepted definition of sustainability developed in 1987 by the World Commission on Environment and Development (the Brundtland Commission) states, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In addition to sustainability, terms like *sustainable development*, *sustainable management*, or *sustainable process* are often used.

The American Institute of Chemical Engineers (AIChE) Institute for Sustainability (IfS) defines sustainability as follows (CEP 2007): "Sustainability is a path of continuous improvement, wherein the products and services required by society are delivered with progressively less negative impact upon the earth." On the basis of this definition, the IfS developed the AIChE Sustainability Index (SI) for the quantification of sustainability efforts.

The SI uses publicly available data to assess the sustainability performance of companies with respect to seven factors (Chin et al. 2015; Cobb et al. 2007):

i. Strategic commitment
ii. Environmental performance
iii. Safety performance
iv. Product stewardship
v. Social responsibility
vi. Sustainability innovation
vii. Value-chain management

Although these factors were developed for the chemical industry, they can be adapted to urban water management. Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, which allow fulfilling the social, economic, and other requirements of present and future generations. Sustainability is critical to making sure that we presently have and will continue to have the water, materials, and resources to protect human health and the environment in the future.

Urban water management has to balance social, economic, and environmental aspects in planning and management of water resources with optimal use of energy and other resources for it to be sustainable. With increased population and climate change, water is becoming increasingly scarce, especially in urban areas, leading to competition among users (Daigger 2007). Water not only is an essential public service but also can serve as a resource for enhancing and beautifying the urban environment (Novotny and Brown 2007). An example of this effort is appropriate management of storm water by taking advantage of natural systems, thereby reducing the burden on infrastructure resulting in enhancement of natural areas, reduction of heat-island effects, and creating a nicer urban environment. The International Water Association Cities of the Future Program (IWA 2011) promotes the idea of water-centric urban design (Hao et al. 2010; Novotny and Brown 2007).

6.5 SUSTAINABLE URBAN WATER AND RESOURCE MANAGEMENT

Urban water and resource management involves the following steps:

i. Collecting water in sufficient quantities to meet needs throughout the urban area
ii. Treating collected water to achieve the quality required for specific purposes
iii. Distributing water to end users
iv. Collecting used water
v. Treating used water for reuse, including for environmental enhancement

vi. Managing residuals from treatment processes
vii. Extracting useful materials, such as heat, energy, organic matter, and nutrients, from the used water stream

This approach, proposed by Daigger (2009), differs from the historical approach in several respects: (1) In addition to imported surface and groundwater, water-supply options also include locally collected rainwater and used water for reclamation and reuse; (2) all used water is reused, either to meet water-supply needs or to enhance and restore the environment; and (3) the used water can be used to extract useful products, energy, and nutrients. Infrastructure for implementing this system requires a significantly different approach to urban water and resource management (see Figure 6.4) (Daigger 2009).

Water supply, optimized costs, functions, and configurations are briefly discussed below.

1. *Source of water*: Water supply has historically depended on importing relatively pristine water from remote sources. Because of the lack of pollution-control systems and technologies, local water supplies inevitably become

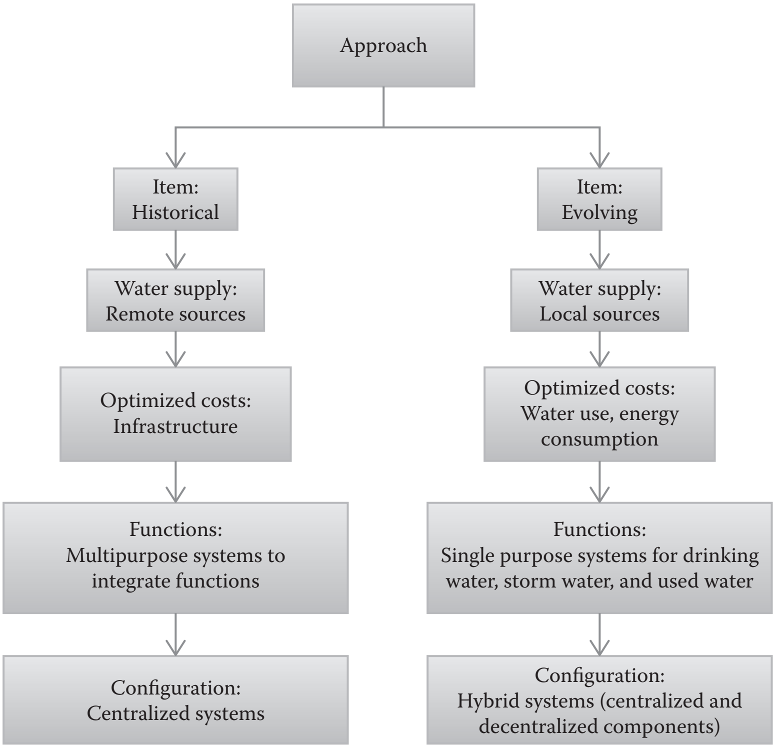

FIGURE 6.4 Comparison of historical and evolving approaches to urban water and resource management. (From Daigger, G.T., 2011. *The Bridge*, *41*(1): 13–18.)

polluted, making it impossible to produce safe drinking water in sufficient quantities. Thus, remote sources of water had to be used. This situation has changed because of two trends: (1) the development of effective treatment technologies that can produce clean water from a wide variety of sources (Daigger 2003, 2008), and (2) remote, pristine sources of water have diminished greatly to supply adequate water to the growing human population. Thus, local water supplies are necessary for urban water management.

2. *Cost optimization*: The historic system evolved during the era when water was abundant and energy was inexpensive. Today, the situation is reversed. Water supplies are limited and energy is expensive; therefore, the focus is more on increasing water efficiency and minimizing energy use.
3. *Functions*: Water management systems have evolved from single-purpose to multipurpose systems. Urban water and resource management systems were historically implemented sequentially as specific needs were identified and funding was obtained. As a result, systems for handling drinking water, storm water, and used water were often separate (except for sewers, which collected and conveyed both storm water and used water). Today, these functions are integrated into a single system (Daigger 2008, 2009; Hao et al. 2010; Novotny and Brown 2007).
4. *Configuration*: Systems have evolved from a centralized to a hybrid configuration consisting of both centralized and decentralized components (Daigger 2009). Because water was historically imported from outside the urban area, the most cost-effective infrastructure was a single or small number of systems, referred to as centralized systems for the treatment and distribution of water throughout the urban area. Similarly, because the storm water was polluted, it had to be collected and removed from the urban area and the most cost-effective approach was a single or small number of collection and transport systems. The same situation also applied to the used water system.

The following sections address two key components of the evolving urban water and resource management infrastructure paradigm: (1) hybrid systems and (2) water-supply and used-water source separation.

6.6 HYBRID SYSTEMS

Enabled by improved treatment technologies, local water resources are becoming increasingly usable, and treatment systems are being distributed throughout service areas. The resulting hybrid systems include both centralized and decentralized components. Three examples of hybrid systems are described below (Daigger 2011).

6.6.1 GREEN INFRASTRUCTURE

Conventional, centralized storm water management systems generally consist of drains and collection points that direct rainwater into pipes that convey it to existing streams and waterways. The objective is to collect and remove storm water rapidly to prevent local flooding. These water management strategies have not solved persistent storm water problems, trading urban flooding for pollution and hydromodification of nearby rivers, streams, lakes, and estuaries (Nylen and Kiparsky 2015). First, storm water picks up pollutants from urban surfaces and conveys them into local waterways. Second, by inhibiting the infiltration of rainwater into the local groundwater, the system ultimately depletes local water resources. Third, fast-moving water directed through local waterways causes significant erosion (Daigger 2011).

Analyses of the hydrology of urban areas have shown that rainfall often has two principal components: (1) long-duration, low-intensity storms that produce significant volumes of storm water, which tends to build up pollution because of their frequency; and (2) short-duration, high-intensity storms, which are less frequent and therefore carry less pollution overall (Daigger 2009).

Distributed storm water management and rainwater-harvesting systems collect rainwater and direct it either to storage areas for later use or to natural systems that reduce the velocity of the water, infiltrate rainwater into the subsurface, and thereby remove pollutants. Such systems are often referred to as “green infrastructure,” because they (1) typically rely on vegetative plants to control pollution and (2) maintain or increase local water resources by recharging groundwater.

A different approach to storm water management is a holistic approach that employs a locally tailored mix of on-site and off-site retention, treatment, and use along with pollutant source controls to protect local waters and meet other community and regulatory objectives. Green storm water infrastructure works by addressing storm water where rain or snow falls. It uses distributed installations to mimic natural storm water retention and treatment processes. The goal is to minimize the quantity and maximize the quality of runoff that flows to local waters (Nylen and Kiparsky 2015). Green infrastructure systems also have added benefits, such as the restoration of local ecosystems, reductions in urban heat-island effects as a result of replacing impermeable surfaces with natural surfaces that reflect less heat, and a more aesthetic, livable urban environment.

The City of Philadelphia has instituted the Green City, Clean Waters Program to reduce storm water pollution currently entering its Combined Sewer System through the use of green infrastructure. The US Environmental Protection Agency (EPA) and the City of Philadelphia have partnered to advance green infrastructure for urban wet weather pollution control. This partnership assures the EPA’s support of Philadelphia’s adoption of green infrastructure to improve both water quality and the sustainability of its neighborhoods. The program is designed to recreate the living landscapes by adding green to its streets, sidewalks, roofs, schools, parks, parking lots, and more—any impermeable surface that is currently funneling storm water into sewers and waterways has potential for greening. The goal is to make rivers and streams swimmable, fishable, and drinkable. By employing green tools instead of just relying on traditional infrastructure like pipes and storage basins, Clean Water Act standards can be met while saving money. Since Green City, Clean Waters was adopted in June 2011, Philadelphia Water and private developers have added more than 1100 green storm water tools to their landscape (Philadelphia Water website 2015).

6.6.2 USED-WATER RECLAMATION AND REUSE SYSTEMS

Another hybrid system is the distributed used-water reclamation and reuse system (Jimenez and Asano 2008). Driven by the increasing scarcity of water and enabled by modern treatment technology, used water is increasingly being reclaimed and reused in a variety of ways, such as nondrinking and food preparation. Nonpotable water produced from used water can be reused for irrigation and to supply industry. Potable water is achieved by treating used water to levels beyond those required for typical drinking water and introducing it into the local groundwater or surface water, where it mixes with the existing water supply. Water can then be withdrawn for further treatment and distribution.

Used water reclamation and reuse require extensive collection and distribution systems, especially for centralized, nonpotable systems that necessitate separate distribution for potable and nonpotable water. The need for dual water distribution systems presents a significant cost barrier, especially in existing urban areas, as well as a substantial increase in energy to convey both water supplies.

In distributed used-water reclamation and reuse systems, treatment facilities are located adjacent to used-water pipelines. When sufficient capacity has been reached, enough used water can be removed and reclaimed to meet nonpotable water demands in a modest service area. This approach not only reduces the size of the nonpotable water distribution system but also reduces the required size of the used-water conveyance system downstream of the diversion point. Thus, significant system savings in cost and energy can be realized.

6.6.3 IN-HOME TREATMENT DEVICES

Several kinds of water treatment devices that are used to provide potable water are available for home use (National Sanitation Foundation 2015):

- **Whole house/point-of-entry (POE) systems** typically treat all or most of the water entering a home, usually installed after the water meter (municipal) or pressurized storage tank (well water). A water softener is an example of a POE system.
- **Point-of-use (POU) systems** typically treat water at the point of consumption, such as at the kitchen sink, refrigerator, or shower head. These include personal water bottles, pitcher or pour-through filters, faucet mount filters, countertop filters, and refrigerator filters.

The widespread consumption of bottled water serves the same purpose on a smaller scale. However, bottled water uses more water to produce than the amount distributed.

6.7 SEPARATION OF POTABLE AND NONPOTABLE WATER SUPPLIES

A relatively small volume of water, on the order of less than 40 liters per person per day (L/capita-day), is needed for truly potable purposes (e.g., direct consumption and food preparation). A much larger volume of water, ranging from 100 to 400 L/capita-day, is used for other purposes (e.g., laundry, toilet flushing, bathing, and outdoor water use) (Jimenez and Asano 2008). When water supplies were pristine and abundant, a separate supply of potable and nonpotable water was not needed. Today, however, because of the small amount of water used for drinking and cooking, treating all water to potable standards may be overkill. Moreover, water quality deteriorates in the distribution system. Thus, water exiting a drinking-water treatment plant may exceed potable water-quality standards, but water that reaches the consumer may not.

One approach to addressing this problem, referred to as distributed water treatment (Weber 2004), has been contemplated but not implemented at full scale. This approach consists of treating water on a centralized basis to nonpotable standards, distributing it through a centralized system, and using some of it to supply distributed treatment systems that can treat small, necessary quantities of water to potable standards. A second approach is dual distribution of nonpotable and potable water (Daigger 2011).

Water infrastructure systems of the future will involve an integration of centralized and decentralized treatment approaches to effectively deliver economical, flexible, and sustainable water services to communities. Distributed water management will require integrated planning, design, and management using system infrastructure at various scales—from decentralized to centralized, based on an equitable approach that considers suitability and sustainability. The US EPA defines a decentralized wastewater system as a managed on-site and cluster system(s) used to collect, treat, and disperse or reclaim wastewater from a small community or service area (Daigger 2011).

Numerous examples of both approaches can be found, but in general, treatment for potable water continues to be centralized, while treatment of nonpotable water is either centralized or decentralized. Decentralized systems are less expensive, however, and have the advantage of treating locally harvested rainwater and reclaimed used water to nonpotable standards, as required, and distributing it to meet local needs.

Another idea being evaluated and selectively implemented is the separation of used water into various components (Daigger 2009; Henze and Ledin 2001). The logic for separating components is based on an analysis of the domestic wastewater stream. The principal constituents in this used water stream are biodegradable organic matter, expressed by 5-day biochemical oxygen demand (BOD_5), and nutrients (nitrogen, phosphorus, and potassium). Organic matter can be treated by conventional technology, which requires significant amounts of energy, or it can be used as a source of energy in and of itself. The nutrients have obvious value for agriculture if they can be recovered in a useful form (Daigger 2011). This approach requires separation of waste constituents at the source, community education, and acceptance by the public.

There are three principal contributors to the used water stream: gray water, black water, and yellow water (Weber 2004). Gray water, which is used for laundry, bathing, and similar purposes, is the largest volume of domestic water. When separated out, gray water, which is only modestly polluted, can be readily treated to nonpotable standards. Black water (feces) and kitchen waste, a relatively small volume of water, contain most of the organic matter in used domestic water. A variety of technologies are available for converting this organic matter into useful energy.

Most of the nutrients in used water are contained in yellow water (urine), less than 1.0% of the total volume of used water (generally 1 to 2 L/capita-day). Because the body excretes most unused pharmaceuticals and hormones through the kidneys, yellow water also contains a disproportionate amount of these materials. Thus, separating out yellow water reduces the treatment required for gray and black water. Conceptually, this is a simple concept but infrastructural needs and public education and acceptance are very challenging.

6.8 CHALLENGES AND OPPORTUNITIES

Even though much remains to be learned about the potential of highly integrated urban water and resource management systems, they have significant potential advantages. This will require change from centralized, single-purpose components to hybrid, integrated systems. The transition from past, centralized systems to hybrid, integrated systems presents many challenges (Figure 6.5). In the past, the various

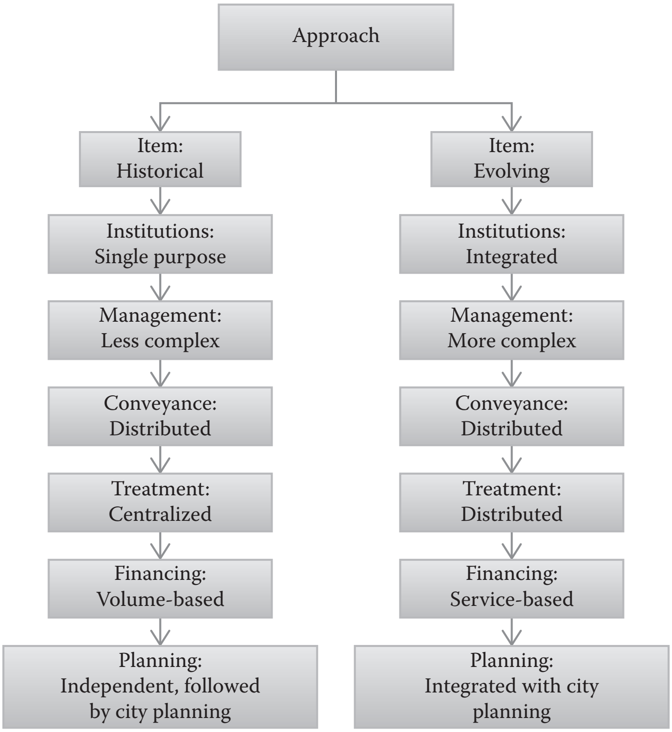

FIGURE 6.5 Implementing integrated urban water and resource management systems (From Daigger, G.T., 2011. *The Bridge*, *41*(1): 13–18.)

components of urban water and resource management systems were managed separately, often by different utilities or different departments in a utility. Integrated systems will require a new management structure and, hence, institutional reform (Daigger 2011).

Management of a hybrid, integrated system is more complex than management of a traditional system. Distributed water treatment and integrated potable and nonpotable water supplies, storm water, and used water significantly increase the complexity of management and will require the development of new managerial systems.

The most difficult challenge, however, may be associated with planning and implementing urban infrastructure as a whole. Historically, the planning and expansion of urban areas occurred with minimal consideration of water and resource management, often with the assumption that traditional, centralized systems would be used. However, evidence is accumulating that water can be a central feature of sustainable urban areas, and the concept of water-centric urban areas is becoming more common (Hao et al. 2010; Novotny and Brown 2007). Achieving this vision will require that water professionals become strategic partners with urban planners. The International Water Association Cities of the Future Program promotes such partnerships (Daigger 2011; IWA 2011).

6.9 SUMMARY

Urban water and resource management systems are evolving: (1) from the use of remote water supplies to the use of local water supplies, such as rainwater and reclaimed used water; (2) from optimizing the cost of infrastructure to optimizing water use, energy production, and nutrient extraction; (3) from independent, single-purpose components to integrated, multi-purpose systems; and (4) from centralized systems to hybrid systems that incorporate centralized and decentralized components (Daigger 2011). These developments are contributing to changes in institutions, system management, financing, and urban planning, leading to more sustainable urban water systems.

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7 Water Management for Shale Oil and Gas Development

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CONTENTS

7.1 SHALE OIL AND GAS

Shale oil and gas have recently launched an energy boom in the United States and it will continue to lead the growth of fossil fuel production in the near future. Six shale oil and gas plays accounted for nearly 90% of domestic oil production growth and virtually all domestic natural gas production growth since 2012 [1]. According to the US Energy Information Administration (EIA) Energy Outlook [2,3], shale oil

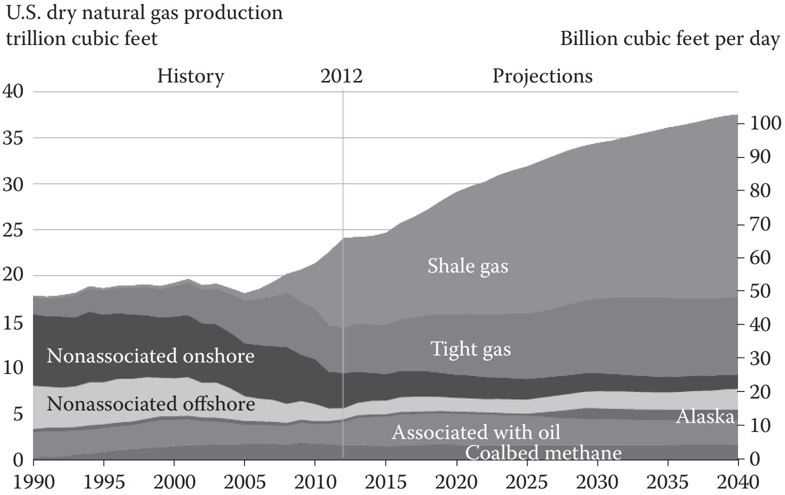

FIGURE 7.1 Shale gas leads growth in total gas production to 2040 in the United States. (From U.S. EIA Annual Energy Outlook 2014 Early Release.)

(or tight oil) production currently has a rapid annual growth of 0.8 million barrels per day (MMbbl/day) and it will hit a historical high at 9.5 MMbbl/day in 2016, and then slowly decline after 2020. On the other hand, shale gas production (trillion cubic feet or Tcf) is anticipated to grow steadily. It accounted for less than 5% of the total US natural gas production in 2000 (19.1 Tcf), and went up to 23% (5.0 Tcf) in 2010, and now is projected to reach 55% (19.6 Tcf) in 2040 in the reference case, contributing to 64% of the total growth of the US natural gas production from 2010 (21.6 Tcf) to 2040 (35.5 Tcf) (Figure 7.1 [1]). Globally, North America accounts for nearly all shale gas supply currently and it will continue to occupy 75% by 2035 when shale gas production in other parts of the world becomes commercial [4]. Also, shale gas production grows much faster (3.3 times) than conventional gas and has been estimated to take a third of the increase in global natural gas supply through 2035. Despite the political and economic uncertainties, there are plenty of reasons to believe that shale oil and gas will continue to reshape the energy supplies and rejuvenate the fossil fuel producers.

7.2 WASTEWATER GENERATION

The rapid growth of shale production is mainly boosted by recent advancements in technologies such as three-dimensional seismology, horizontal drilling, and hydraulic fracturing, which enables the extraction of previous hard-to-reach shale formations bearing oil and gas and drastically increased the production efficiency. The shale formation is an organic-rich rock layer, typically present in thin lateral layers that have a very low permeability (less than 1 μD), which makes it a good cap for hydrocarbon traps. Horizontal drilling extensively increases the exposure area of the shale rock and hydraulic fracturing perforates the formation and enables the flowback of oil and gas. In normal hydraulic fracturing, water-based fracking fluids are pumped in the shale rock at high flow rates and pressures to cause fissures in the rock, and this is called "well stimulation." The fracking fluid is made up of 90% water and 10% of other ingredients, such as sand (9.5%) and chemical additives (0.49%). Components in the fracking fluid are shown in Figure 7.2 [5].

After the well stimulation, the hydraulic pressure is reduced and the downhole fracking fluid flows back to the surface along with the indigenous or connate water containing dissolved minerals from the formation. It is estimated that 50%–60% of the chemicals are spent downhole and only a fraction of the original chemicals used in the fracking fluid makeup return to the surface with the flowback water in the initial weeks. To make the downhole flowback water useful for future fracking jobs, it needs to be temporarily stored on-site and sometimes treated to get rid of certain constituents in the water before transportation to other sites.

Water continues to be produced with oil and gas after the initial weeks of hydraulic fracturing. The produced water has much higher contents of dissolved salts and minerals from the rock formations than the flowback water mentioned above. The volume of flowback and produced water during the well life are shown in Figure 7.3 [6]. Overall, a typical shale gas well requires 3–6 million gallons of water for hydraulic fracturing, and the volume of the flowback recovered from a well ranges widely from 10% to 70% of the initial volume [7].

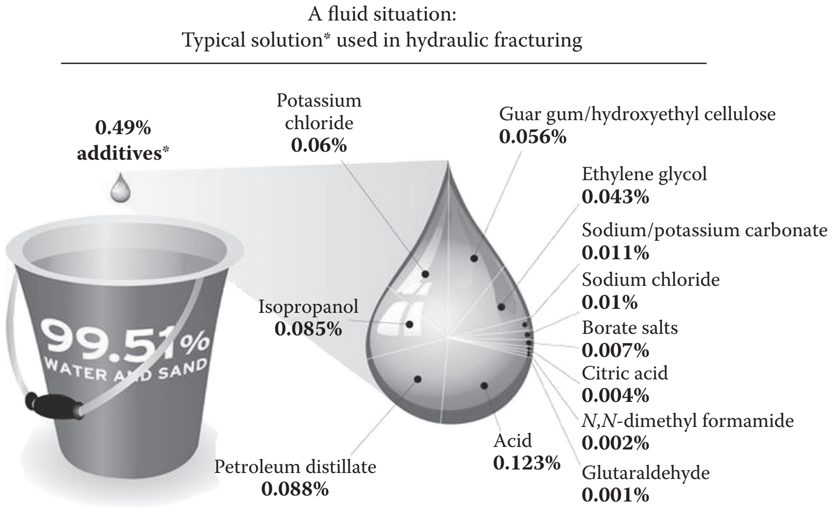

FIGURE 7.2 Typical fracking fluid makeup. *The specific compounds used in a given fracturing operation will vary depending on source water quality and site, and specific characteristics of the target formation. The compounds listed above are representative of the major material components used in the hydraulic fracturing of natural gas shales. Compositions are approximate. (From Ground Water Protection Council and ALL Consulting. *Modern shale gas development in the United States: A primer.* 2009, United States Department of Energy, Office of Fossil Energy: Washington, D.C. p. 96.)

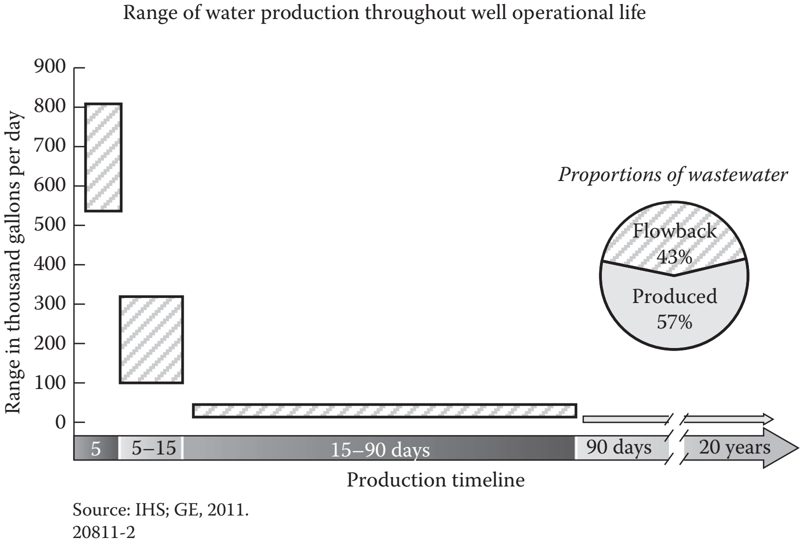

FIGURE 7.3 Water production timeline. (Reprinted with permission from Gay, M.O. et al. *Water Management in Shale Gas Plays*. 2012; Available from: http://connect.ihs.com/StaticDocuments/LandingPage/WaterManagement.pdf.)

Although discharge and disposal are common practices for flowback and produced water for years among the upstream industry, their reuse and recycle are gaining popularity in certain arid areas since they can drastically decrease the local freshwater demand and reduce the waste stream. If properly treated, flowback and produced water can be used as workover fluid, as pressure maintenance fluid, and for water flooding during hydraulic fracturing.

7.3 ENVIRONMENTAL PROTECTION LAWS AND REGULATIONS

The Clean Water Act (CWA) protects the quality of surface water bodies by regulating the direct and indirect disposal of pollutants in surface water. Regulatory agencies issue permits to the operators for the proper surface discharge of produced water (which includes hydraulic fracturing fluids and naturally occurring connate water from the formation) from oil and gas well sites [8]. The Environmental Protection Agency (EPA) follows the regulations proposed in the Safe Drinking Water Act (SDWA), which mandates underground injection activities that protect groundwater sources from contamination. The Underground Sources of Drinking Waters (USDWs) are primarily protected by the Underground Injection Control (UIC) program, which regulates the subsurface injection of the fluids. There are some exemptions in the UIC added by the 2005 Energy Policy Act regarding the hydraulic fracturing fluids, but in all cases, prior authorizations through the applicable UIC programs are necessary in the case of subsurface disposal by the operators [9]. In addition to CWA and SDWA, several other federal and state environmental laws and policies dictate the oil and gas activities and development including the Resources Conservation and Recovery Act (RCRA), which manages the disposal of hazardous waste, and the National Pollutant Discharge Elimination System, which regulates the pollutants discharged by the municipal wastewater treatment plants into surface waters [10]. The 2012 report from the US Government Accountability Office lists eight federal environment and public health laws that apply to the development of the shale oil and gas sources and they are listed below [10]:

1. Safe Drinking Water Act (SDWA)
2. Clean Water Act (CWA)
3. Clean Air Act (CAA)
4. Resource Conservation and Recovery Act (RCRA)
5. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)
6. Emergency Planning and Community Right-to-Know Act (EPCRA)
7. Toxic Substances Control Act (TSCA)
8. Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)

On top of the federal laws and regulations, the operators in the oil and gas industry have to comply with the state laws and regulations, which are often more rigorous and firm in protecting the natural resources of their respective states. The planning and development of a well is a serious undertaking and can have substantial impact on various environmental and social avenues [11]. Various committees and working groups such as the State Review of Oil and Natural Gas Environmental Regulations, the Interstate Oil and Gas Compact Commission, and the Ground Water Protection Council are already working toward strengthening the regulatory practices while striving to elevate the health, safety, and environment condition [12–15].

7.4 WATER MANAGEMENT

Water management for shale oil and gas operations incorporates water acquisition, storage, transportation, reuse/recycle, and disposal, and the goal is to optimize the water use efficiency in a cost-effective way. Major challenges come from the significant variations of the wastewater quantity and quality along the time and across the areas. The costs associated to water sources, treatment, and disposal have become a major factor in the decision-making process for water management. It is estimated that freshwater withdrawal accounts for less than 1% of the total water management costs; however, on-site water management and handling, which include sourcing, storage, transportation, and disposal, account for up to 10% of a well's operating expense [6]. This estimated cost varies across locations and is heavily dependent on resource availability, infrastructure, competing uses from other industries, and climate of the region. Nonetheless, the existing vulnerabilities in water management affect the profit margins of the operators and some water-related issues are discussed in this chapter.

From a broad perspective, water management in shale oil and gas operations can be categorized into the following:

1. **Source acquisition** from different water bodies
2. **Storage** for future use
3. **Transportation** to nearby production sites
4. **Reuse or recycle** involving treatment when necessary
5. **Discharge or disposal** according to the local requirement

7.4.1 SOURCE ACQUISITION

For hydraulic fracturing, the operators use various sources of water depending on the region and water availability. It can be acquired from surface water sources such as lakes, ponds, rivers, and creeks, as well as groundwater sources such as aquifers. Operators have tried many different ways to reduce the freshwater acquisition such as exploring new sources or substitution with non–water-based fluids.

7.4.1.1 Brackish Aquifer

Brackish groundwater is defined as the groundwater that contains 1000–10,000 mg/L of total dissolved solids (TDS); for comparison, seawater has a TDS of approximately 35,000 mg/L. Brackish groundwater resources after desalination are important for replenishing freshwater demands [16]. The location of the major aquifers in proximity to the shale plays (Figure 7.4 [17]) offers an ideal potential source of water that has not been fully utilized in the past. In 2010 according to the USGS, the saline groundwater withdrawal was almost 53% of the total water withdrawn for mining (including oil and gas) use. The states with rapid increase in shale gas operations such as Oklahoma and Texas mainly accounted for 79% of the total saline groundwater withdrawal [18]. The lack of complete understanding of the parameters responsible for the unique characteristics of a saline aquifer and additional constraints such as increased potential for corrosion and contamination risks limit the development of advanced additives for fracking with brackish water [19]. However, studies need to be conducted to completely characterize and understand the yield, water quality, and sustainability of individual aquifers to be a feasible potential source of water.

7.4.1.2 Non–Water-Based Fluid

In addition to developing approaches to maximize water efficiency in the shale oil and gas operations, alternative fracturing fluids can reduce the usage of water. Although it is still in its infancy, experiments with non–water-based fluids have been conducted in the industry bringing about its own set of challenges. According to some operators, propane-based fracturing was successful in the onshore Canadian tight reservoirs [20]. Some of the benefits associated with the liquid propane fracturing include the boost of initial production rate and reduction in wastewater disposal. The liquid propane can be either flared on-site or reused after removal of impurities.

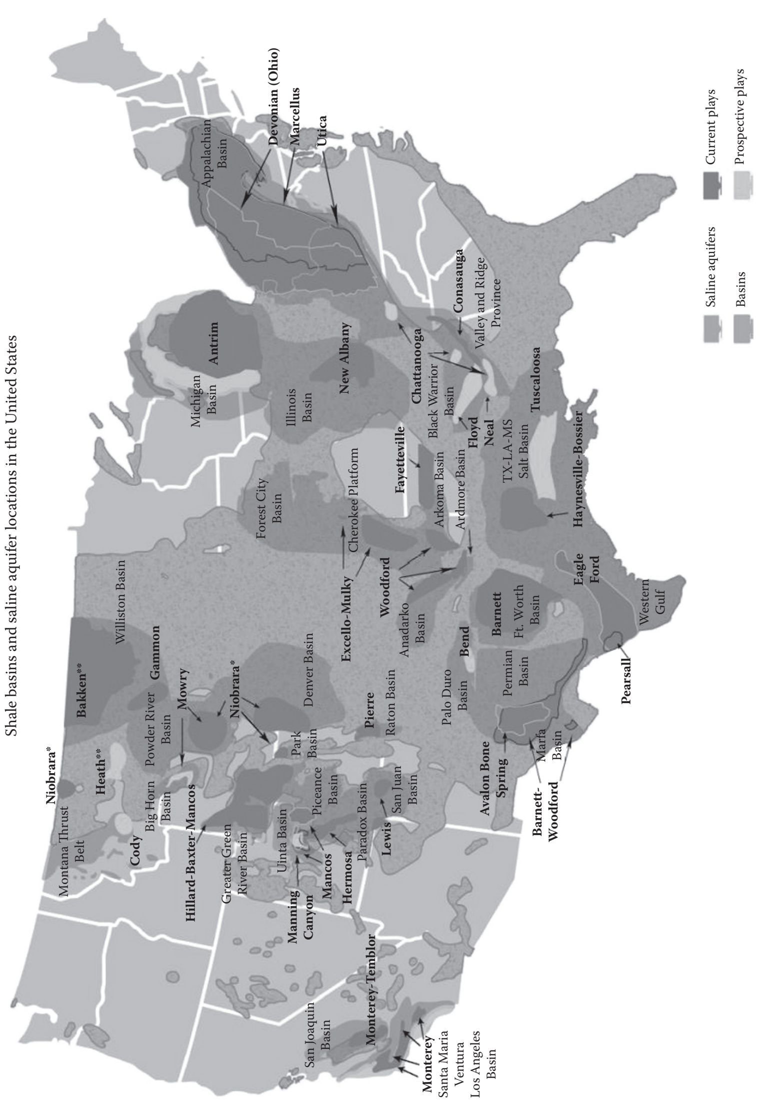

FIGURE 7.4 Shale basins overlain on top of saline aquifers. (Reprinted with permission from Zhu, H. and R. Tomson. *Exploring water treatment, reuse and alternative sources in shale production*. 2013 [cited May 9, 2015]; Available from: http://www.shaleplaywatermanagement.com/2013/11/exploring-water-treatment-reuse-and-alternative-sources-in-shale-production/.)

7.4.1.3 Volume

Water is used intensively for drilling and hydraulic fracturing locally. Data from several major shale plays show that the average water use per well ranges from 2 to 6 million gallons [21], and water used for hydraulic fracturing is an order of magnitude higher than that used for drilling. The volume depends on factors such as the geology of the formation, the operating environment, and the overall well development program. Rapid increase of new wells may lead to concerns about the local water stress in the communities in proximity to shale development locations.

Despite the large local water withdrawal, it was reported [5] that water associated with hydraulic fracturing takes only 0.1%–0.8% of total water consumption. Figure 7.5 [18] shows the overall water use among different sectors in the United States in 2010. The combined withdrawal for thermoelectric power, irrigation, and public supply accounted for almost 90% of the total withdrawal. However, the water used for mining activities (including shale operations) only accounted for approximately 5320 million gallons per day, which is approximately 1% of the total water withdrawal. Furthermore, compared to other fuels, the water use intensity (gal/MMBtu) for the extraction of shale gas is relatively low, that is, 0.6–1.8 gal/MMBtu, while it is 2.6 gal/MMBtu for coal mining, 62 gal/MMBtu for enhanced oil recovery, 893–1155 gal/MMBtu for biofuel [22].

Furthermore, sustainable water management practices have been proven to stabilize or even decrease the surge of local water demand. Texas has the longest history of shale gas production and the water demand data there can be cited to see the impact of water management in shale gas operations. In Texas, it was estimated that the water used for hydraulic fracturing was 35,800 acre-ft in 2008, and

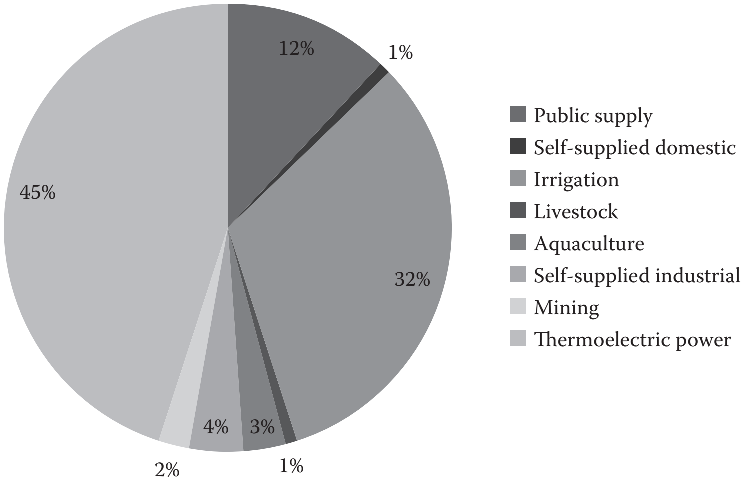

FIGURE 7.5 USGS estimate of water use in the United States in 2010. (From Maupin, M.A. et al. *Estimated water use in the United States in 2010.* 2014, U.S. Geological Survey: Reston, Virginia.)

it climbed up to 81,500 acre-ft in 2010 [23]. However, the water use in 2012 was recorded as only 76,722 acre-ft, a slight decrease of water consumption as a result of the conservation of water and effective water management [24]. In addition, experts estimated in 2011 that water use in Texas would peak at 145,000 acre-ft/year between 2020 and 2030, but the value decreased down to 125,000 acre-ft/year within a year in an updated report [25]. The water use volume is expected to be lower than 40,000 acre-ft/year by 2060. The decline in water use mainly results from advancements in recycle and reuse and decreased activities in maturing shale plays.

7.4.2 STORAGE

7.4.2.1 Storage Tanks

The fluids produced from a single well or from multiple wells are typically piped to a central oil lease site with tanks, which are often called the tank battery for intermediate treatment and temporary storage. A typical tank battery includes a few pairs of interconnected oil and saltwater storage tanks, gas separators, heater treaters, and gas flare systems as shown in Figure 7.6 [26]. In most cases, saltwater is coproduced with the production fluid stream and a gravity oil/water separator called a “gun barrel” is also installed on-site. A containment dike is installed around the tank battery

FIGURE 7.6 A typical oil field tank battery. (Photo courtesy of NIOSH and OSHA. Available from: http://blogs.cdc.gov/niosh-science-blog/2014/05/19/flowback/flowback2-4/.)

to ensure containment of the fluids in case of overflow or leaks in the tanks. The oil volume is measured and tested at the tank battery and then pumped into the pipeline system for transport.

The storage tanks are manufactured in various sizes and configurations and vary in material composition. Many states do not have a specific standard for the construction material of tanks; hence, a variety of materials such as plastic, steel, fiberglass, and wood can be used to store fluids on-site [27]. Not all types of tanks are compatible with particular fluid types, and in most cases, steel tanks are used to store produced water. The extreme weather conditions such as hot desert climate in Texas and cold temperatures in Colorado and other northern states combined with the corrosive produced water and hydrogen sulfide gas create very acidic environments, and this can cause the tanks to deteriorate over time and result in leaks and failures. Several techniques are used to protect the integrity of the storage tanks. Coating the inner walls of the tank with a corrosion-resistant coating can form a physical barrier between the tank body and the corrosive fluids. Cathodic protection (CP) is another way of protecting the metal against corrosion. CP works by applying direct current to counteract the corrosion reactions. Similar protection techniques are applied for pipelines that carry the oil field fluids. In case of leaks or spills attributed to overflow of the tanks, a containment dike is built around the tank battery. In a report finding by the US Department of Energy, the majority of oil- and gas-producing states require dikes (or firewalls) to hold the fluids that may be spilled or leaked around the tank battery [27].

7.4.2.2 Storage Pits

During drilling and completion operations, pits are the most common method of storing fluids. Pits are mostly used for storing freshwater and produced water but sometimes they can also be used to temporarily store emergency overflow, waste fluid, and treatment fluid. Depending on the type of fluid being stored, authorizations via regulatory permits are required before using the pit. In order to prevent the infiltration of the storage fluids into the subsurface, pit liners becomes necessary as shown in Figure 7.7 [28].

Natural or artificial liners can be designed as required for produced water and washout pits. Liners are manufactured with naturally compacted clay or using synthetic plastic materials such as polyethylene. Additional precautions include maintaining a minimum distance from the surface water sources and keeping the fluid a certain level below the top of the pit wall to prevent contamination of the surface waters in case of a spill owing to overflow of the fluids or in case of significant rainfall in the area [27]. Additionally, an inspection and maintenance plan should also be followed for safety and environmental concerns [29].

7.4.3 TRANSPORTATION

7.4.3.1 Logistics and Cost

The magnitude of water that needs to be moved along with the remote nature of the operation locations and disposal wells makes water logistics a key aspect in

FIGURE 7.7 Freshwater pit with liners at the oil field. (Reprinted with permission from Unit Liner Co., Ltd. *Fresh water pit with liners at the oil field*. 2015; Available from: http://www.unitliner.com/frac_pit_liners.html.)

sustainable water management operations. With strict health and safety regulations, on-time delivery and economically managing the cost of water transportation are critical in the overall shale gas operation. During the drilling phase, a very small quantity of water is required for making drilling fluids. However, as the wells are prepared for the fracking and completion phase, the logistics become critical because huge quantities of water are required to make up the fracture fluid for stimulation of the well. It is estimated that on a per-well basis, 60%–80% of the daily road volume is required in the initial 15–30 days of the well to support time-sensitive fracking or completion operations [30]. Within the initial 10 days of operation, the flowback volume (depending on the geology and the shale play) is approximately 500,000–600,000 gallons per well after completion [31]. This flowback needs to be transported away for disposal or reuse. In order to minimize the bottleneck and environmental footprint, flexible and efficient water management strategies are required for smooth operation.

Transportation of water is needed throughout the well life, and the corresponding costs are often the primary economic driver influencing water management decisions. Permanent pipelines are generally the preferred method for carrying large volumes of oil, natural gas, and petroleum liquids because of their efficiency, ease of management, and low cost. However, the development of permanent pipeline infrastructure could not catch up with the rapid emergence of new shale plays. For this reason, road transportation is commonly used in new shale plays or remote regions where no pipeline infrastructure is readily available, but with a higher cost. Centralized water storage site for multiple wells also helps reduce the transportation cost.

7.4.3.2 Road Transportation

The rapid increase in drilling and production operations in shale plays recently has significantly increased the road traffic of heavy trucks hauling drilling rigs, oil field equipment, chemicals, and wastewater in rural areas on state and county roads. In the Eagle Ford Shale region, a study reports an increase of road traffic by at least 24% on Interstate Highway 35 (IH-35) and as much as 86% in highly active regions of IH-35 from 2009 to 2012 [32]. An estimate shows that 1200 loaded truck deliveries are needed to bring one gas well into production, more than 350 are required per year for maintenance of a gas well, and 1000 are needed every 5 years to re-fracture a well. This heavy traffic load puts a strain on local roads and it accelerates the premature formation of tears, ripples, potholes, and torn shoulders on the highways, therefore reducing the service life of highway systems and farm-to-market roads by 30% owing to natural gas well operations and by 16% owing to crude oil well operations [32].

The frequency and intensity associated with road transportation in shale plays expose several risks for personnel involved in the shale gas operations. Lack of skilled drivers and irresponsible driving behaviors along with deteriorating road conditions have become causes of concern about public safety in local communities. Common issues associated with logistics include traffic congestion, road damages, and noise and air pollution. The Center for Sustainable Shale Development has developed several standards in regard to shale gas operations that take into consideration the geology, infrastructure, and population in the Appalachian basin [33]. Texas Department of Transportation and the Railroad Commission of Texas also created guidelines or trucking plans to reduce the exposure to health and safety risks, which include the following commitments by the operators [32]:

1. Avoid peak traffic hours
2. Establish quiet periods
3. Adequate off-road parking to avoid lane and road blockage

7.4.3.3 Pipeline

Pipeline and processing capacity has moved to the forefront as an issue governing growth in the shale plays. Increasing use of pipelines and railroads along with access points for storage and inventory locations is being proposed in shale plays because of the aforementioned advantages. The US Department of Transportation Pipeline and Hazardous Materials Safety Administration ensures safe movement of hazardous material via all means of transportation including pipelines [34]. Currently, the produced water from oil and gas activities is not regulated under the federal pipeline safety rules but states can opt to regulate the pipelines carrying the flowback and produced water locally and any spills or leakage of this produced water will fall under the federal regulations of the CWA.

7.4.4 REUSE OR RECYCLE

The traditional sources of freshwater are facing increasing tension especially in populated or arid areas because of the intensive demand of water in shale operations. Therefore, reuse (with little or no treatment) and recycle (with treatment) of the flowback and produced water present a promising future that will likely reduce the withdrawal of freshwater from sensitive local ecosystems.

The quality and recovery rate are two key characteristics that will determine the reuse or recycle option. The total suspended solids (TSS), TDS, and organic content (oil and grease) along with the overall water quality can vary by geologic basins. Table 7.1 [35] lists some of the important parameters evaluated for produced waters in some of the major shale plays in the United States. The high degree of variability and diversity of concentrations of key components make treatment and handling of produced water a challenging task for operators [36].

7.4.4.1 Options

It is not always necessary to remove all the TDSs as long as it meets the requirement for reuse or discharge. The following are common management options for flowback and produced water:

1. Direct reuse without treatment
2. On-site treatment and recycle
3. Off-site treatment and recycle
4. Off-site treatment and disposal

Direct reuse is the cheapest option, but it only applies to the high-quality flowback water, and it poses many risks such as well plugging, high mineral scaling tendencies, incompatibility with fracking fluids, and so on. The on-site treatment and recycle option can reduce certain components in the flowback and produced water, affecting the reuse with the cost of treatment to various degrees. Off-site treatment and recycle includes transportation costs to and from the site while off-site treatment and disposal also includes disposal costs.

7.4.4.2 Economics

Produced water normally needs to be treated for reuse and recycle opportunities. The treatment cost is mainly affected by the water quality. Common components that need to be removed are TSS, TDS, and microbial contamination. TSS needs to be removed before reuse to prevent clogging of the pore spaces in the formation, which ultimately reduces its permeability and gas production [36]. TDS beyond a certain level could reduce the effectiveness of friction reducers, and mixing of freshwater is normally required before reuse if no treatment is involved [30]. Produced water may contain an extremely high level of multivalent ions such as calcium, magnesium, iron, and barium, and they need to be reduced under a certain level to avoid fast scale formation on the equipment, casing, and formation downhole [30]. Scaling could also occur as a result of poor compatibility of makeup water and reused water.

TABLE 7.1

Summary of Produced Water Quality from Different Plays Monitored February 2012 to April 2013

	Bakken, North Dakota (26 Samples)			Eagle Ford, Texas (16 Samples)			Barnett, Texas (30 Samples)			Permian, Texas (93 Samples)			Woodford, Oklahoma (9 Samples)			Piceance, Colorado (13 Samples)		
	Ave	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**	**Min**	**Max**
pH	6.07	5.74	6.95	5.76	3.82	7.37	6.28	5.05	8.18	6.49	4.22	8.11	6.03	5.61	6.50	6.49	6.12	7.23
Alkalinity (mg/L)	202.8	122.0	376.0	385.8	122.0	768.6	310.3	85.4	603.4	434.9	146.4	3098.8	234.5	158.6	378.2	614.0	244.1	1372.5
TDS (mg/L)	271,485	136,500	339,000	22,504	4700	156,100	75,775	599	174,692	97,892	11,140	194,900	185,955	157,778	208,773	18,112	1810	24,559
Ba (mg/L)	25.9	13.1	44.5	1.8	0.1	5.5	117.3	1.7	337.5	10.8	0.3	25.4	5.1	3.9	6.7	44.5	7.9	90.6
Sr (mg/L)	1371.5	632.5	2421.0	62.7	0.7	199.8	1069.7	6.4	3430.7	743.8	10.0	1636.0	801.2	506.7	1221.8	31.3	3.6	43.9
Ca (mg/L)	14,175.0	7036.5	20,206.0	409.7	50.6	996.1	4515.8	47.6	16,417.0	3999.2	84.2	15,260.3	12,276.5	10,483.5	14,117.4	209.6	11.3	369.9
Fe (mg/L)	107.9	25.3	201.3	5.9	0.1	77.5	69.3	0.0	228.8	15.5	0.0	103.6	13.8	1.7	31.1	42.4	12.2	174.1
Mg (mg/L)	979.2	518.0	1358.4	41.3	9.9	105.2	458.9	1.6	1578.0	642.0	25.4	2394.7	1947.4	1597.5	2152.6	14.1	0.0	34.1
K (mg/L)	5367.5	2632.3	7249.8	462.8	68.3	5333.4	294.0	8.4	1080.9	224.3	51.3	652.7	617.0	432.0	870.4	92.5	44.2	207.7
B (mg/L)	373.9	168.1	509.1	7.6	0.6	17.7	26.7	0.0	44.8	21.8	1.6	63.2	6.2	3.1	10.4	7.7	0.4	18.6
Si (mg/L)	8.8	4.2	14.1	17.0	7.7	42.6	22.4	0.0	39.8	14.2	1.4	37.3	5.5	3.9	7.8	34.1	14.8	57.6
Na (mg/L)	84,890.9	42,830.5	106,816.6	10,002.6	2132.8	71,602.3	23,744.4	192.9	46,465.4	41,300.2	4916.4	79,014.7	70,759.9	57,932.6	81,466.0	6832.7	654.6	9322.2
Cl (mg/L)	164,839.7	82,789.8	205,793.1	11,493.0	2398.8	78,197.6	45,434.6	331.6	107,481.3	50,920.3	5362.0	102,848.7	99,522.2	85,023.8	111,530.3	10,725.7	1037.4	14,704.4
SO_4^{2-} (mg/L)	105.8	30.0	190.0	317.5	16.0	2440.0	5.9	0.0	140.0	374.9	0.0	4080.0	245.3	104.0	320.0	5.5	0.0	58.0
S^{2-} (mg/L)	0.3	0.0	1.4	0.2	0.0	2.0	2.0	0.0	9.5	0.3	0.0	3.1	0.0	0.0	0.0	0.8	0.4	1.6

Source: *Proprietary data from industrial sources*. 2014, Tomson Technologies, Inc.

Microorganisms should also be controlled because they cause biofouling and souring of the well attributed to the generation of hydrogen sulfide (H_2S) [36].

A number of treatment options have been developed, such as filtration, aeration and sedimentation, biological treatment, demineralization, thermal distillation, condensation, reverse osmosis, evaporation, freeze/thaw, crystallization, and ozonation. These treatment technologies will be discussed in more detail in Chapter 8, Volume II, of this book.

Water recovery is also important in deciding the treatment option and driving the economic decisions of water management. Unlike conventional wells, water production in a mature shale field declines significantly during the life of the well as most of the flowback is recovered in the early life (15–90 days) of the field. The treatment option is generally more lucrative for the initial period of the well production [30].

Despite the variability of economic benefits, there are obvious environmental and social benefits to reuse and recycle of flowback and produced water. It reduces or eliminates freshwater withdrawal that ultimately eases the local water tension and creates a positive environmental footprint. It also improves public relations with the local community and the government.

7.4.5 DISCHARGE OR DISPOSAL

As mentioned earlier, federal regulations prohibit direct discharge of oil and gas wastewater into surface water. After a certain number of recycles, the water needs to be either disposed in state and federally designated underground injection wells or treated in municipal treatment plants for surface discharge. A surface discharge permit is mandatory after the pretreatment at private or municipal wastewater facilities.

7.4.5.1 Underground Injection Control

Underground injection is the most common disposal option available for flowback and produced water [37]. Historically, disposal through injection has been recognized as well regulated and environmentally friendly in conventional oil and gas production. The EPA implements the UIC program under the authority of the federal SDWA, and flowback or produced water can be safely disposed in Class II wells under the UIC program (Figure 7.8 [38]). There are currently more than 150,000 Class II injection wells in the United States with more than 2 billion gallons of injected brine fluids associated with oil and natural gas production [38]. The majority of Class II wells are located in Texas, Oklahoma, Kansas, and California as shown in Table 7.2 [39].

There are three types of Class II wells:

1. Enhanced Recovery Wells—inject brine, water, steam, polymers, or carbon dioxide into oil formations to recover residual oil and gas.
2. Hydrocarbon Storage Wells—inject liquid hydrocarbons in underground formations (such as salt domes) to store as part of the US Strategic Petroleum Reserve.
3. Saltwater Disposal (SWD) Wells—inject brines (saltwater) and other produced water for disposal. SWD wells represent approximately 20% of Class II wells.

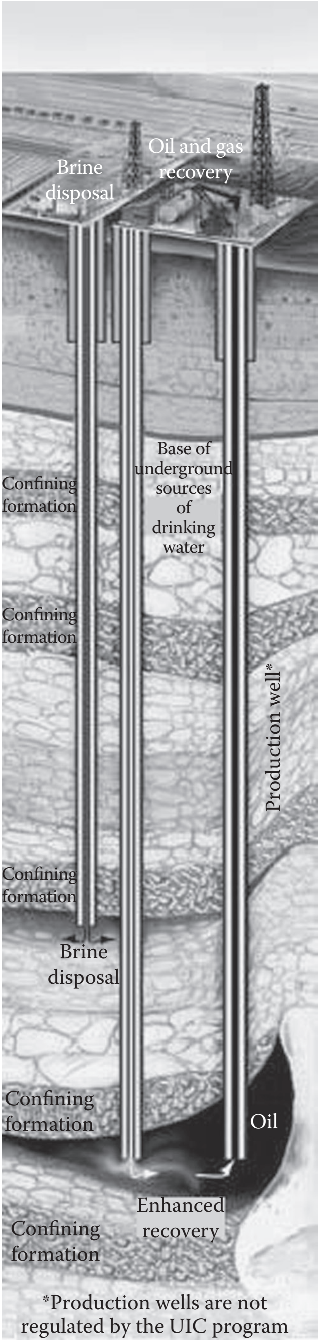

FIGURE 7.8 Class II well as regulated under the UIC program of the EPA. (From U.S. Environmental Protection Agency. *Class II wells—Oil and gas related injection wells (class II).* 2015 [cited May 20, 2015]; Available from: http://water.epa.gov/type/groundwater/uic/class2/.)

TABLE 7.2
Number of Class II Wells in the United States in 2012

State	Number of Class II Wells in 2012	State	Number of Class II Wells in 2012
Alabama	247	Montana	1149
Alaska	1347	Nebraska	661
Arizona	0	Nevada	18
Arkansas	1100	New Hampshire	0
California	49,783	New Jersey	0
Colorado	901	New Mexico	4556
Connecticut	0	New York	423
Delaware	0	North Carolina	0
Florida	60	North Dakota	1290
Georgia	0	Ohio	2439
Hawaii	0	Oklahoma	11,134
Idaho	0	Oregon	9
Illinois	7858	Pennsylvania	1865
Indiana	1260	Rhode Island	0
Iowa	7	South Carolina	0
Kansas	16,965	South Dakota	87
Kentucky	3221	Tennessee	19
Louisiana	3687	Texas	52,977
Maine	0	Utah	547
Maryland	0	Vermont	0
Massachusetts	0	Virginia	12
Michigan	1451	Washington	1
Minnesota	0	West Virginia	710
Mississippi	1212	Wisconsin	0
Missouri	455	Wyoming	5005

Source: U.S. Government Accountability Office. *EPA program to protect underground sources from injection of fluids associated with oil and gas production needs improvement*. 2014; Available from: http://www.gao.gov/assets/670/664499.pdf.

The primary objective of the UIC program is to protect the USDWs; therefore, strict federal and state regulations are followed and permits are issued after carefully reviewing the geology of the injection zones in the area. During the operation of an SWD site, UIC requires a mechanical integrity test of the well at least every 5 years and annual pressure monitoring. At the state level, these requirements could be more stringent. For example, in Texas, it is required to monitor and report the mechanical well integrity of the SWD once every 5 years at a minimum and the injection pressure is monitored monthly and reported annually [38].

7.4.5.2 Cost of Disposal

The cost of deep well injection for disposal at an SWD site varies with proximity to the nearest injection well, in compliance with federal and state regulations and the type of shale play. Typically, a commercial SWD facility will charge \$0.50–\$2.50 per barrel of fluid, not including the transportation costs to the SWD facility [38]. In Texas, there are approximately 35,000 active injection and disposal wells and approximately 7500 wells are dedicated to saltwater disposal in confining geologic formations [40]. Because of the large number of wells, trucking cost to many of the SWD options in Texas wells range from \$0.50 to \$1.00 per barrel per hour [38]. In Pennsylvania where the Marcellus play is located, there are merely eight Class II disposal wells because of the limitations created by unfavorable geology and state regulations. Therefore, most of the wastewater from Pennsylvania is injected in Ohio, which has approximately 200 disposal wells. The disposal cost of Pennsylvania wastewater in Ohio has been reported to be in the range of \$15–\$18 per barrel [41]. This high cost of disposal along with safety and spill risks associated with long trucking distances has driven operators to consider other options such as local treatment and reuse.

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8 Outreach Programs for Awareness of Water Resources Sustainability and Adoption of Best Management Practices

Jennifer L. Peterson, Larry A. Redmon, and Mark L. McFarland

CONTENTS

8.1 IMPORTANCE OF OUTREACH TO PROMOTE AWARENESS AND SUSTAINABILITY OF WATER RESOURCES

> In an age when man has forgotten his origins and is blind even to his most essential needs for survival, water along with other resources has become the victim of his indifference.
>
> **Rachel Carson**

Water is the most critical component of life's existence. On a global scale, humanity relies on this valuable resource for drinking water, sanitation, waste management, crop and livestock production, industry, irrigation, and recreation. Water is an essential component of many biological, molecular, and physiological processes that support and sustain plant and animal life. Without an ample supply of high-quality water, the survival of humanity and all species on Earth is greatly imperiled.

Not only is water an essential component of all life, it is one of the most limiting and finite of resources. While nearly 75% of the Earth's surface is covered with water, approximately 98% is saltwater stored in the world's oceans. The remaining 2% is freshwater, the vast majority of which is either frozen in ice caps and glaciers or stored deep in the Earth's crust. To date, it remains too costly to access and extract large amounts of frozen water or saltwater to support the Earth's growing population. It is estimated that only 0.007% of the water on Earth is directly accessible to humans. This includes surface water in streams, rivers, and lakes as well as water stored in shallow underground aquifers accessible at a reasonable cost. Unless scientists can discover a way to manufacture freshwater, the water currently present on Earth is all the water there will ever be. Consequently, protecting this limited resource to ensure its availability and suitability for human consumption and use is critical.

While the quantity of water on Earth remains constant, population growth continues at an unprecedented rate, recently topping 7 billion people. Not surprisingly, global water consumption is increasing as are landscape changes that threaten both water quantity and quality. Global water demand has tripled over the last 50 years, resulting in water shortages around much of the world. Unfortunately, consequences of water scarcity and water deprivation are felt most strongly in impoverished and undeveloped countries where access to clean water and sanitary conditions is minimal. Unsafe drinking water and waterborne illnesses are to blame for nearly 80% of all diseases in developing countries (World Health Organization 2008). However, serious water problems can affect developed nations as well. In China, for example, nearly 60% of the rivers are classified as severely polluted; some are even too toxic for human contact (Ministry of Environmental Protection 2009). In the United States, approximately 53% of streams and rivers are considered threatened or impaired. Major contaminants include pathogens, sediment, nutrients, polychlorinated biphenyls, and metals (United States Environmental Protection Agency 2013).

Research has been conducted in various parts of the world to assess citizen awareness and understanding of issues related to water quantity and quality. In the United States, for example, the National Institute of Food and Agriculture sponsored a nationwide project to evaluate public awareness and attitudes toward water resource issues. Land Grant University Extension programs conducted random surveys in 41 states and six territories between 2002 and 2011. While results varied from state to state, they generally suggested that citizens are concerned about the quality of drinking water and surface water resources but do not understand conditions and activities affecting water quality or who is responsible for protecting water resources (Mahler et al. 2010). In 2011, The European Parliament surveyed all 27 member states of the European Union to assess citizen attitudes toward climate change and the environment. Nearly 68% indicated lack of quality drinking water is one of the most serious problems facing the world, more than global warming/climate change, international terrorism, and proliferation of nuclear weapons. Roughly 42% of respondents indicated pollution of seas, rivers, lakes, and underground sources as the top environmental issue facing the world (European Commission 2011).

Yet, despite overwhelming evidence around the globe indicating extensive anthropogenic degradation of water quality and depletion of water resources, water scarcity and water pollution crises continue to be largely ignored by the population, especially in areas where the effects do not yet noticeably alter day-to-day activities (Moore and Seckler 1993). The majority of humanity remains ambivalent, disconnected, or unable to comprehend long-term consequences of human impact on the sustainability of water resources. Population and economic growth continue to outpace environmental protection; rivers, lakes, wetlands, and other valuable ecosystems continue to be degraded; precious freshwater resources are wasted; and the likelihood we will be able to meet future human needs for water diminishes (Palaniappan et al. 2010).

Conservation and protection of water resources are among the greatest challenges mankind will face. To meet these challenges, societies must engage existing adult populations and commit to teaching future generations about the importance of water resources. Outreach education will be essential to communicate the economic and environmental costs associated with degraded water resources to adult audiences (United Nations 2008). In the absence of more strict and intrusive regulation, only through education and training can individuals properly identify, adopt, and, most importantly, sustain necessary water and land management practices.

While water resource issues are a global problem, this chapter will focus specifically on outreach education efforts in the United States led by government, nonprofit, and corporate entities. It also will detail technical and financial assistance programs for implementing best management practices (BMPs) designed to reduce water pollution from urban and agricultural sources.

8.2 OUTREACH EDUCATION PROGRAMS

Water-related outreach education programs include any type of educational initiative focused on some aspect of water that strives to increase knowledge and awareness, and often have the goal of either changing or reinforcing behavior. Outreach can be conducted indoors, outdoors, or even remotely (web-based) and can include a wide range of participants from children to adults. To be successful, an outreach education plan should have specific goals, objectives, and activities, and include a carefully designed program evaluation that assesses impact and provides opportunity for feedback and modification (Jennings et al. 2012). Examples of outreach education activities include the following:

- Workshops and training events
- Watershed festivals or other community-based special events
- Volunteer water quality monitoring or other volunteer opportunities
- Student or community-based contests
- Print and electronic media campaigns
- Print and electronic publications, manuals, fact sheets, and other types of publications
- Field days and tours
- Home and on-farm demonstrations

In general, water-related outreach education initiatives are designed to

- Illustrate the hydrologic cycle and indicate the connectivity between various components of watersheds
- Educate participants about the importance of protecting and conserving water resources
- Train participants to identify threats to water quality and quantity
- Motivate participants to become involved in local water resources protection strategies
- Identify local, state, regional, and federal entities responsible for managing and protecting water resources, and those offering education and technical and financial assistance
- Enable participants to identify, implement, and sustainably manage water conservation and water quality BMPs

This section will detail key federal and state government agencies and selected examples of nonprofit and community-based organizations and corporations conducting water-related outreach and education across the United States. The purpose of this section is to demonstrate the diverse and extensive array of entities involved in water-related outreach education initiatives. Because the missions and educational activities vary between organizations and individual states, we provide a general overview of the purposes and targets for water-related outreach initiatives for each type of entity. In certain instances, specific examples have been included to provide more detailed information and understanding about the role and function of an organization.

8.2.1 US GOVERNMENT AGENCIES

Government agencies and organizations at federal, state, regional, and local levels conduct water-related outreach education activities to meet specific missions and functions. Many are closely linked through program funding components, levels of responsibility, and delegation of authority. Organizations belonging to each of these various levels are discussed in more detail.

8.2.1.1 Federal Agencies

A federal agency is a specific administrative unit of government created to fulfill an explicit purpose. Most federal agencies were created by legislative action, with the director appointed by the president of the United States. For the purposes of this chapter, the included federal agencies all share a unique function focused on some aspect of water resource protection and management. Water is by no means the only focus of any of the identified agencies. Instead, the water role is interconnected with other assigned responsibilities, which may include management of public lands, monitoring of air quality, management of federal farm subsidies, or various other duties.

8.2.1.1.1 Environmental Protection Agency

The Environmental Protection Agency (EPA) is responsible for administering the water quality standards outlined in the Clean Water Act (CWA), the federal law passed in 1972 to protect the chemical, physical, and the biological integrity of the nation's waters (33 USC § 1251). To fulfill this primary responsibility, the EPA manages, conducts, and supports a number of outreach education activities focused on varying aspects of water quality and watershed management. Certain sections of the agency website are set up as a clearinghouse for educational materials, to allow access and use by interested parties. The types of educational materials provided by the EPA include the following:

- Fact sheets
- Internet resources
- PowerPoint presentations
- Technical publications and reports
- Handbooks and resource manuals
- Surveys and evaluations
- Media campaign templates

In many cases, the EPA has designed educational materials to target different stakeholder groups including city government, agriculture producers, commercial businesses, disadvantaged communities, children, students, and homeowners. EPA water-based outreach education activities generally focus on the following issues:

- Storm water and polluted runoff
- Public involvement and participation
- Illicit discharge detection and elimination
- Protection of wetlands
- Construction and postconstruction site storm water runoff control
- Pollution prevention/good housekeeping for municipal operations
- Nonpoint source pollution control
- BMPs for urban and agricultural settings

One outreach education program sponsored by the EPA is the Watershed Academy, which provides training and information on a broad range of watershed topics. The EPA Watershed Academy Web provides access to more than 50 self-paced training modules on topics pertaining to watershed management. In addition, the Watershed Academy offers free webcast seminars led by expert instructors covering topics such as low impact development, watershed protection planning, and nutrient management.

8.2.1.1.2 Army Corps of Engineers

The Army Corps of Engineers (USACE) is a federal agency within the Department of Defense and is the world's largest public engineering, design, and construction management agency. The agency mission is to provide vital public engineering services in peace and war to strengthen national security, energize the economy, and reduce risks from disasters (United States Army Corps of Engineers 2012). Through its Civil Works program, the USACE offers a variety of water resource development activities including flood risk management, navigation, recreation, and environmental stewardship. In addition, the USACE is involved in wetlands and waterways regulation as well as ecosystem restoration activities. The agency's Environmental Protection and Regulatory Program authorizes protection of navigable waters of the United States by evaluating permit applications for construction activities affecting national water resources.

Generally, the USACE's outreach education efforts are focused on the following topics:

- Disaster response
- Engineering and construction
- Environmental protection
- Navigation
- Recreation
- Water resources development
- Research and development

Outreach education initiatives target children, students, adults, and communities who are interested in understanding the agency's function and discovering more information on various engineering, civil works, and restoration projects led by the agency. Specific goals for outreach education programs include the following:

- Sparking an interest in applied sciences
- Encouraging participants to think about the nation's role in world trade
- Understanding the importance of the nation's inland waterways transportation system
- Promoting wise use of natural resources

The Engineer Research and Development Center (ERDC), a research organization of the USACE, supports an outreach education initiative aimed at high school, college, and postdoctoral students interested in science, technology, engineering, and mathematics (STEM). The STEM program links scientists and engineers with teachers and students from across the nation to learn about real-world examples of flood control, navigation management, and other topics. Scientists and engineers from the ERDC also participate in STEM festivals, which educate participants with interactive displays and activities.

8.2.1.1.3 Department of Agriculture

The Department of Agriculture (USDA) is the federal executive department responsible for developing and implementing national policies on farming, agriculture, forestry, and food. The agency aims to meet the educational needs of farmers and ranchers, promote agricultural trade and production, work to assure food safety, protect natural resources, foster rural communities, and end hunger across the world (Kosecki et al. 2011).

The USDA's outreach education efforts target all types of citizens from children to teachers to agricultural producers. The education and outreach initiatives of the USDA are generally focused on the following:

- Agricultural research and productivity
- Plant information and identification
- Careers in agriculture
- Sustainable agriculture
- Agricultural literacy
- Soil science and education
- Emergency preparedness and response
- Reducing the impact of natural disasters

Three important organizations housed within the USDA are the Farm Service Agency (FSA), the Forest Service (USFS), and the Natural Resources Conservation Service (NRCS). Each of these organizations has some responsibility for water and natural resource outreach education.

8.2.1.1.3.1 Farm Service Agency The FSA administers farm commodity and conservation programs and also makes loans to farmers and ranchers who are unable to obtain conventional credit (United States Farm Service Agency 2007). Outreach education programs provided by the FSA primarily target socially and economically disadvantaged individuals, limited resource farmers, and members of racial and ethnic minority groups including African-Americans, American Indians/Native Americans and Alaska Natives, Asian and Pacific Islanders, Hispanics, women, and the disabled. The FSA strives to remove barriers associated with language, communication, loan qualification, education, and access to credit to increase participation of underserved populations in its commodity, conservation, and education programs. The education and outreach initiatives of FSA are generally focused on the following:

- Providing financial planning and resources
- Providing information on loans, farm commodities, and conservation programs
- Educating farmers and ranchers about FSA County Committee processes and encouraging participation in county elections

- Working with community-based organizations to provide technical assistance, training, and enhanced program delivery
- Translating program materials
- Helping participants understand USDA programs
- Providing assistance in completing forms and applications

8.2.1.1.3.2 Forest Service The USFS is the federal agency responsible for managing public lands located within national forests and grasslands, which encompass nearly 200 million acres in the United States (United States Forest Service 2007). Because healthy forests lead to healthy watersheds and improved water quality, the USFS regularly focuses on water-related issues through its outreach education initiatives. The agency strategic public outreach plan identifies four long-term goals including enhanced ecosystem health, multiple benefits to people, scientific and technical assistance, and effective public service (United States Forest Service 2000). Specifically related to water, the USFS conducts outreach to promote watershed health, water use and conservation, and watershed stewardship.

8.2.1.1.3.3 Natural Resources Conservation Service The NRCS provides financial, technical, and conservation planning assistance to farmers, landowners, land managers, conservation districts, and Native American tribes resulting in the protection of natural resources, more productive land, and healthier ecosystems (Natural Resources Conservation Service 2011). The NRCS has a wide variety of programs focused specifically on protection of water resources from agricultural activities. Specific technical and financial assistance programs encouraging the implementation of BMPs on agricultural lands will be discussed in the second part of this chapter. In addition to these programs, the NRCS supports a wide range of outreach education activities to inform communities about natural resource issues. Like the FSA, programs managed by the NRCS generally emphasize reaching underserved and socially disadvantaged farmers and ranchers; however, outreach strategies can target farmers, nonfarmers, rural communities, urban communities, and children. The education and outreach initiatives of the NRCS generally focus on the following:

- Assuring equity and accessibility to all agency programs and services
- Informing and educating existing and potential clientele about NRCS and USDA conservation programs and services
- Educating children and adults about the value of conservation
- Encouraging adoption of conservation practices

8.2.1.1.4 Department of the Interior

The Department of the Interior (DOI) is the federal executive department responsible for management and protection of federal lands and their natural resources as well as administration of programs relating to Native Americans, Alaska Natives, Native Hawaiians, territorial affairs, and insular areas of the United States (United States Department of the Interior 2011). Specifically concerning water, the DOI provides leadership and assistance to states, tribes, and local communities to address competing demands and challenges associated with national water supplies. The DOI funds and is involved in a variety of projects addressing America's water infrastructure, climate change, water supply, and water conservation. Outreach education initiatives are part of each of these projects and focus on informing citizens about projects, intended benefits, and the roles citizens can play in moving projects forward.

One outreach education initiative led by the DOI is the WaterSMART Program, which helps those working in water resource planning and management fields address national water challenges. This program identifies strategies to ensure current and future generations will have sufficient supplies of clean water for drinking, economic activities, recreation, and ecosystem health. Additionally, the program identifies adaptive measures to address climate change and its potential impacts on future water demands (United States Department of the Interior 2013). The WaterSMART Clearinghouse is a website providing access to information and reports related to water conservation and sustainability. The clearinghouse helps the DOI provide leadership and assistance to states, local governments, tribal nations, and other entities involved in water-related conservation and sustainability strategies.

Housed within the DOI are a number of other federal bureaus and agencies involved directly in water-related activities that conduct some level of water-related education and outreach. Several of these agencies are discussed in more detail below.

8.2.1.1.4.1 Bureau of Land Management The Bureau of Land Management (BLM) is the federal agency responsible for managing public lands and subsurface minerals underlying federal, state, and private lands to sustain their health, diversity, and productivity (United States Bureau of Land Management 2007). Many of the outreach education efforts conducted by the BLM integrate water since it is vital to the health and sustainability of lands the BLM manages. In February 2013, the agency released a 5-year national strategy for education, interpretation, and youth engagement.

The BLM's Learning Landscapes is one example of successful outreach education targeting children, teachers, adults, tourist, travelers, and volunteers. The website offers educational information about public lands, plants, animals, volunteering, rangelands, wildlife, and several other topics. Furthermore, the BLM's Soil, Water, and Air program manages water resources on public lands. Through their efforts to assess and restore water quality conditions, implement BMPs, and remediate impaired water bodies, the BLM initiates outreach education to better involve the public in local projects while increasing awareness of local issues concerning water resource use and protection. Some other examples of prominent educational initiatives sponsored by the BLM include the Hands on the Land and the Take it Outside programs. Both of these programs target schoolchildren and teachers and seek to reconnect youth to public lands, provide access to recreational opportunities offered on public lands, and promote stewardship of natural resources.

8.2.1.1.4.2 Bureau of Reclamation The United States Bureau of Reclamation (USBR) is the federal agency responsible for the oversight and operation of dams, power plants, and canals it built throughout 17 western states for irrigation, water supply, and hydroelectric power generation. The USBR is currently the largest wholesaler of water in the nation, supplying water to more than 31 million people and irrigation water to nearly 150,000 western states farmers (United States Bureau of Reclamation 2012). The agency is also the second largest producer of hydroelectric power in the western United States producing enough electricity to benefit 3.5 million people. The agency works primarily to balance increasing water demands with protection of valuable natural resources and the public's investment in water supply projects.

USBR offices routinely conduct outreach education initiatives in communities they serve by sharing scientific and environmental materials. Educational programs and resources target youth and adults and typically focus on water supply operations, drought, water research, canal safety, and water conservation. The agency website links to a variety of educational materials including publications, news releases, videos, curricula, and images. Specific examples of USBR's water-related educational programs include WaterLearn and WaterWise Gardens. The WaterLearn program helps students learn about water conservation through animated, interactive web modules. More detailed modules focus on how water affects issues related to nature, urban, and agriculture. This program also provides teacher lesson plans to integrate website material with classroom activities. The WaterWise Gardens program targets homeowners with information about water efficient landscapes and gardens.

8.2.1.1.4.3 Fish and Wildlife Service The United States Fish and Wildlife Service (USFWS) is a federal government agency dedicated to the management of fish, wildlife, and natural habitats. The USFWS is the lead agency responsible for implementing measures according to the Endangered Species Act. While primarily focused on fish and wildlife conservation and protection, the USFWS conducts outreach and education activities focused on management and protection of water resources associated with healthy wildlife habitats. Programs and initiatives targeting children and adults generally aim to

- Foster healthy interactions between people and the outdoors
- Demonstrate how the USFWS and conservation play important roles in local communities
- Introduce natural resource career opportunities to young adults
- Develop recruitment mechanisms for future employees
- Educate participants on the importance of the preservation of wildlife and habitat

Specific examples of water-related outreach education programs include the Youth Conservation Corps, Biologists in Training, Native Fish in the Classroom, School Yard Habitat Program, the National Fishing in Schools Program, and the Hatchery Outdoor Program. The agency website also contains a vast amount of educational materials including publications, videos, photographs, maps, audio files, and other types of materials.

8.2.1.1.4.4 Geological Survey The United States Geological Survey (USGS) is the sole scientific research agency of the DOI; it has no regulatory responsibility. The USGS studies the landscape of the United States, its natural resources, and natural hazards threatening it. Its four focus areas include biology, geography, geology, and hydrology (United States Geological Survey 2012). The USGS is also the lead federal water data collection agency and actively measures stream flow and conducts surface water quality monitoring.

The USGS hydrology educational resources are particularly extensive with detailed information related to surface water, groundwater, water quality, and water use. Materials generally target schoolchildren, college students, teachers, and adults. The agency has developed a Water Science School, which contains basic information about water in an interactive online format. They also offer additional online educational materials including publications, posters, videos, water resource seminars, animations, maps, images, and geographic information system (GIS) data. The USGS Publication Warehouse provides access to historical, technical, and popular publications related to water and the USGS Library is credited with being the largest earth science library in the world.

8.2.1.2 State Agencies

A state agency is an agency, board, or commission of state government. For the purposes of this chapter, the included state agencies all conduct some type of outreach education specifically related to water resource protection and management. As with the federal agencies discussed in Section 8.2.1.1, water typically is not the sole focus of a state agency. Rather, it is an interrelated part of other responsibilities assigned to state agencies or delegated to them by federal agencies in response to specific federal laws. The CWA is one example of federal delegation to a state. While the EPA is the primary federal agency responsible for implementing the CWA, it typically has delegated state-level responsibility for CWA implementation to state environmental agencies.

8.2.1.2.1 Cooperative Extension System

The Cooperative Extension System is a nationwide, nonformal educational network that is a collaboration among federal, state, and local governments and individual state land-grant universities. Each state and territory in the United States has a state office at its land-grant university and a network of local or regional offices. These offices are staffed by faculty, specialists, and technicians who provide nonbiased, research-based information, training, and education to agricultural producers, business owners, youth, and other clientele living in rural and urban communities. The National Institute of Food and Agriculture (NIFA), a research agency within USDA, is the federal partner in the Cooperative Extension System. NIFA provides federal funding to the system to support educational initiatives involving water, fish and wildlife, rangelands, soils, ecosystems, and other topics. The national Cooperative Extension System was established in 1914 with passage of the Smith–Lever Act.

Major educational focus areas for the Cooperative Extension System include agriculture and natural resources. Thus, water-related outreach education initiatives are a major component of the system mission. Extension employees across the nation offer water-related educational programming and outreach materials targeting both children and adults. Materials include online and face-to-face training courses, publications, presentations, lectures, videos, and more. One example of a successful water-related educational program is the Watershed Stewards program. The program is currently offered in about a dozen states and targets schoolchildren, teachers, engineers, business owners, homeowners, and other stakeholder groups. The main thrust behind the program is educating participants about the importance of being good stewards of water resources. Another successful program is the 40 Gallon Challenge. This national program was developed in 2011 and encourages participants to save a minimum of 40 gallons per person, per day, by adopting practices that conserve water. At present, conservation pledges across the United States are saving nearly 1.2 million gallons of water per day. Extension also developed the Master Gardener and Master Naturalist programs. Program enrollees learn about a variety of topics related to water and natural resources, participate in continuing education courses, and conduct volunteer work in their communities demonstrating conservation and stewardship.

8.2.1.2.2 Departments of Environmental Quality

State departments of environmental quality are the primary environmental agencies of each state. In Texas, for example, this is the Texas Commission on Environmental Quality (TCEQ), and in the state of Washington, it is the Department of Ecology. Generally, the mission of each state environmental agency is to balance protection of state public health and natural resources with sustainable economic development. Major goals of each state environmental agency will differ but typically focus on providing clean air, clean water, and safe management of waste. State environmental agencies conduct regulatory and compliance activities pursuant to federal and state laws. As previously mentioned, most state environmental agencies are responsible for administering policies and regulations outlined in the CWA. This includes developing the state's *303(d) list* of impaired waters and distributing CWA Section 319 grants to in-state partners. In addition, state departments of environmental quality are responsible for implementing state laws and applying state regulations related to natural resources management. In most cases, state departments of environmental quality have developed extensive partnerships with other state organizations and entities to carry out their mission and conduct effective water-based projects and educational programming.

Water-related outreach education initiatives carried out by state departments of environmental quality are varied and focus on the state's most pressing water-related issues. For example, water challenges and issues facing western states are much different than those facing eastern states. However, generally speaking, outreach education activities focus on water conservation, water reuse, water quality standards, watershed management, environmental violations, natural disasters, and discharge permits. A major emphasis for most state environmental agencies is increasing public involvement in local and regional water-related projects such as Total Maximum Daily Loads (TMDLs) and Watershed Protection Plans (WPPs). An important component of this effort has been development and use of educational programs and resources that raise awareness about existing and potential water quality impairments and encourage involvement and participation in watershed protection projects.

8.2.1.2.3 Soil and Water Conservation Agencies

State soil and water conservation agencies administer state soil and water conservation laws and programs that minimize agricultural and silvicultural nonpoint source pollution on private agricultural and grazing lands. State legislatures and the EPA provide funding to state soil and water conservation agencies to demonstrate and implement activities that control and abate nonpoint source pollution. In most cases, state soil and water conservation agencies have developed extensive partnerships with local government units, state agencies, federal agencies, and other organizations. In addition, state soil and water conservation agencies provide technical assistance to state soil and water conservation districts (SWCDs) that work directly with landowners and operators. The role of SWCDs will be discussed in Section 8.2.1.3.3.

Water-related outreach education initiatives undertaken and supported by state soil and water conservation agencies focus primarily on agricultural water resource issues directly benefiting state SWCDs and their members. Examples of educational materials include publications, reports, technical bulletins, fact sheets, and web resources. State soil and water conservation agencies also play a major role in funding and supporting other state entities active in water-related outreach education projects.

8.2.1.2.4 Water Resources Institutes

In 1964, Congress passed the Water Resources Research Act (WRRA), which established water resources institutes in each state and territory, and provided funding for peer-reviewed research projects focused on water-related issues. There are currently 54 institutes in the United States located at each state's land-grant university. Together, the institutes are organized as the National Institute for Water Resources, which links individual institutes with the federal funding partner, the USGS. Section 104 of the WRRA states that water resources institutes are responsible for

- Planning, facilitating, and conducting research to aid in resolution of state and regional water problems
- Promoting technology transfer, dissemination, and application of research results
- Training scientists and engineers through their participation in research
- Providing competitive grants awarded under the WRRA

To help carry out these responsibilities at local, state, regional, and national levels, water resources institutes are encouraged to form partnerships between state universities; federal, state, and local governments; business and industry; and nonprofit organizations. Most employ broad-based research, training, information transfer, and public service programs involving faculty and staff from state research universities as well as other key partners across the state.

Outreach and education efforts vary widely among individual state water resources institutes. However, a significant component is the education of undergraduate and graduate students. In 2012 alone, water resources institutes across the nation provided research support for more than 1400 undergraduate and graduate students studying in water-related fields such as biology, agriculture, public policy, and earth sciences. In addition, water resources institutes are charged with sharing results of their research with the public. Some institutes host an annual conference and series of workshops throughout the year to disseminate scientific water-related knowledge.

Most also publish electronic and print communications documenting research projects and opportunities for the general public to engage in water-related volunteer activities.

8.2.1.3 Regional and Local Entities

Regional and local entities include general-purpose and local/regional special-purpose entities operating at the third and even fourth tier of government. These types of entities are structured in accordance with laws of various individual states and generally act within powers delegated by legislation or directives at higher levels of government. Regional and local entities usually have a close working relationship with their counterpart at the state or even federal level. For example, a state agency will often rely on a regional or local entity to carry out mandates in federal and state law. With regard to water, regional and local entities have a direct connection to counties, cities, and municipalities and are therefore better equipped to lead local water-related projects and education initiatives than agencies at the state and federal level. Therefore, regional and local entities play a major role in water-related outreach education initiatives.

8.2.1.3.1 County and City Governments and Councils of Government

All states are divided into counties, cities, municipalities, townships, or other subdivisions for administrative purposes. Counties are geographical and political subdivisions of states and therefore serve an important role in administering state laws, programs, and services. Counties were some of the first units of local government established in colonial America. Specific administrative powers of counties are dictated by state law and therefore vary among individual states. However, county governments typically provide, at a minimum, courts, public utilities, libraries, hospitals, public health services, parks, roads, law enforcement, and jails. Counties are usually governed by an elected board of supervisors, county commission, county council, or other governing body. In the majority of states, county government is usually located in a municipality called the county seat.

City or municipal government, on the other hand, is a local government entity organized to provide general government for a defined population center. In most states, county and city governments exist alongside one another, although the relationship between the two can vary widely. Depending on the size of the city, municipal governments are usually subdivided into several different departments including urban planning/zoning, economic development, public works, parks and recreation, police, and more.

Councils of government are a regional body of government designed to serve several counties. While council responsibilities will vary across individual states, they typically address issues related to regional and municipal planning, economic and community development, watershed management, mapping and GIS, emergency planning, water use, pollution control, and more. Council members are drawn from county, city, and other bodies of government within its geographic area.

There is a tremendous amount of variability across the country in terms of organization and responsibilities of county and city governments as well as councils of government. With regard to water-related issues, county and city governments and councils of government actively participate in comprehensive water management activities including education, zoning, land development planning, watershed planning, and water quality monitoring. Outreach education initiatives focus on individuals living within the specific geographic region of the county (or counties) or city and typically target members of the general public including homeowners, business owners, landowners, and other stakeholders. County and city outreach education activities address storm water runoff, septic systems, water use and conservation BMPs, lawn irrigation, pet waste pickup, water pollution, and other key topics related to the particular region. To raise awareness about a specific water-related issue, city and county governments as well as councils of government often utilize newspaper articles, kiosks, signage, utility bill inserts, direct mail, public meetings, storm drain markings, contests, community events, stream cleanups, and workshops.

8.2.1.3.2 River Authorities

River authorities are public agencies created by state legislatures that develop and manage state water resources. While technically defined as state agencies, river authorities function at the regional and local level. Other names for river authorities include river flood authorities, water authorities, and river water authorities. Although not present in every state, river authorities play an important role in managing water resources and educating the public. In Texas, for example, river authorities control rights to more than 70% of state surface water, which is sold either to consumers or to other water suppliers. In addition, some river authorities are authorized to generate and sell electric power, regulate navigation, construct and operate reservoirs, and operate parks.

River authorities are naturally active in water-related outreach education activities since their sole focus usually involves water resource issues. Although activities vary widely among river authorities, most focus on educating the public about the function of the organization as well as the importance of safe and clean water for drinking, recreation, irrigation, and animal health. Types of educational activities and events often include workshops, hands-on demonstrations, presentations, and print and electronic media.

8.2.1.3.3 Soil and Water Conservation Districts

SWCDs are government entities providing technical assistance and tools to landowners and operators to manage and protect land and water resources in the United States. There are currently more than 3000 SWCDs across the nation. Depending on the state, SWCDs also may be known as soil conservation districts, resource conservation districts, or other similar names. SWCDs play a major role in helping improve water quality across the nation as they have a direct link with agricultural producers and landowners.

Education and outreach programs offered by SWCDs across the nation are varied, but generally seek to increase awareness of the importance of soil and water resources within each individual state and also help promote natural resource management through land conservation and implementation of BMPs. Because SWCDs are closely connected with their clientele, outreach programs are often tailored to local and regional water resource issues. SWCD educational resources are also diverse to reach a broad audience including students, teachers, landowners, farmers, and ranchers.

One example of an education and outreach program targeting students is the Meaningful Watershed Educational Experience (MWEE) provided by the Hanover-Caroline SWCD in Virginia. The MWEE is an initiative providing students a meaningful stream or bay outdoor experience before graduating high school. SWCD staff assist teachers and students with opportunities to develop and participate in local restoration and protection projects, including efforts on school property. SWCD staff are also active in educating landowners, farmers, and ranchers by providing current natural resource information, research data, mapping systems, and soil and water resource data to assist landowners in making informed decisions about land management.

8.2.2 Nonprofit Organizations

A nonprofit organization exists solely for educational or charitable reasons. By federal law, a nonprofit organization must provide a public benefit to society. As such, it is able to receive tax-exempt status from the Internal Revenue Service (IRS). Nonprofit organizations differ from for-profit organizations in that surplus revenues are not distributed to shareholders, but rather are reinvested into the organization to carry out activities directly meeting its mission and charitable purpose. One of the most common types of nonprofit organization is the 501(c)(3), which is created to conduct charitable, educational, scientific, religious, and literary work.

The National Taxonomy of Exempt Entities (NTEE) is a system used by the IRS to classify nonprofit organizations. Organizations classified under the NTEE Core Code C are concerned primarily with preserving, protecting, and improving the environment. More specifically, this includes “organizations that are involved in pollution control and abatement; conservation and development of natural resources; control or elimination of hazardous or toxic substances including pesticides; solid waste management; urban beautification and open spaces development; environmental education and outdoor survival; and botanical gardens and horticultural societies” (National Center for Charitable Statistics 2013). As of April 2013, there were nearly 34,000 registered environmental nonprofit organizations in the United States (National Center for Charitable Statistics Data Web 2013).

Classified within NTEE Core Code C are Common Codes specifically detailing the type of environmental work carried out by the nonprofit organization. Of most importance to water-related activities are C30 and C32 classified organizations. C30 organizations are concerned with natural resources conservation and protection and C32 organizations conduct work related to water resources, and wetlands conservation and management. C32 organizations account for nearly 25% of all registered environmental nonprofits. Organizations in this category are those “that preserve and protect water resources from indiscriminate waste and ensure that the supply of quality water is adequate to meet the needs of the public, agriculture, and industry. Also included are organizations preserving and managing coastal lands including shorelines, coastal waters and lands extending inland from the shore which affect coastal waters; bays, lakes, rivers, wetlands, estuaries, watersheds and other aquatic habitats" (National Center for Charitable Statistics 2013).

Nonprofit organizations working in the water arena play an increasingly important and complex role in brokering and implementing activities to achieve ecological goals (Breckenridge 1999) and are uniquely positioned to carry out meaningful water-related outreach education activities. For one, leaders and staff of nonprofit organizations are generally passionate people believing firmly in the organization's mission. Second, they are charitable organizations not concerned with making a profit. In addition, individuals donating to a nonprofit organization can receive an income tax deduction. For these reasons, nonprofit organizations are often able to develop and implement high-quality activities and programs at the local level that are effective in protecting water resources and raising awareness about community water issues.

Certainly, the missions of nonprofit organizations vary widely as do their outreach education activities. Typically, however, nonprofit organizations conduct water-related outreach focusing on important issues affecting an entire waterbody, watershed, or community. Outreach education initiatives usually target all members of the community, seek to raise awareness about issues and the organization itself, and raise money to help address the issue so the entire community will benefit. Specific examples of water-related nonprofit organizations are discussed below.

8.2.2.1 Chesapeake Bay Foundation

The Chesapeake Bay Foundation (CBF) was created in 1967 to help restore and protect the Chesapeake Bay, the nation's largest estuary located on the Atlantic Coast. One of the initial drivers behind the creation of the organization was an understanding that communities surrounding the Chesapeake Bay could not solely rely on government to fix the many problems facing the bay at that time; the communities would need to undertake some efforts on their own. One of the strengths of the nonprofit sector is the ability to fill gaps or "market failures" (Salamon 1987) left by government and market sectors. Initially, the CBF focused its resources on environmental education and natural resource protection. Specifically concerning its environmental education efforts, CBF founders and staff wanted to teach citizens about the bay both "on it and in it." The organization acquired a number of boats, trailers, land, and education centers to help carry out its educational mission. The CBF began conducting educational field trips for local school classes and utilized education centers to raise awareness about the bay and the importance of protecting it.

Today, education remains one of CBF's four main strategies. The organization states "CBF will educate the general public, school administrators, teachers, and students about the wonders of the Chesapeake Bay system, its historic productivity, its current challenges, and solutions to restore it to at least 40 percent of its legendary potential. Education will serve as a means to citizen engagement and behavior change" (Chesapeake Bay Foundation 2012). The CBF's website offers a variety of outreach education resources targeting citizens, students, and teachers including curricula, maps, photos, publications, and other types of materials. Educational initiatives carried out by the CBF including student field experiences, teacher professional development, leadership retreats, and classroom curricula have won numerous awards and have no doubt helped raise awareness about the importance of protecting and conserving the Chesapeake Bay.

8.2.2.2 Project WET Foundation

Another interesting example of a water-focused nonprofit organization is the Project WET Foundation, a 501(c)(3) nonprofit organization dedicated to informing children, parents, educators, and communities about water. The organization focuses entirely on water-related outreach education activities and initiatives empowering students and citizens to address local water issues. In fact, the organization is considered by some as the leading nonprofit in the field of water education in the United States. Examples of their outreach materials and initiatives include resource publications, classroom curricula, training workshops and presentations, community water events, and network building. Their website links to a wealth of information and educational materials concerning water conservation, water quality, watersheds, wetlands, and other pertinent water-related topics, and provides information on volunteer activities to help improve and protect local water resources.

8.2.2.3 Watershed Partnerships

Watershed partnerships at the local level have grown rapidly over the past several decades (Genskow and Born 2006). Watershed partnerships refer to a wide variety of loosely and formally structured organizations also referred to as watershed councils, action groups, associations, and coalitions. While this section focuses on formally incorporated nonprofit watershed partnerships, it is important to note that not all watershed partnerships and coalitions are nonprofit organizations.

Watershed partnerships are voluntary organizations made up of all types of stakeholders who share a common interest in protecting and conserving their watershed. Unlike other types of nonprofit organizations, watershed partnerships are truly community-based. An effective watershed partnership can help an entire community create a common vision for their watershed and work to keep the community focused on important issues. Contemporary watershed partnerships generally share the following characteristics (Born and Genskow 2001):

- Utilize watershed boundaries as a focus area for analysis and management
- Address the full scope of water-related issues
- Representatives from multiple stakeholder groups participate meaningfully and influence decisions
- Group decision making is based on biophysical, social, and economic information as well as local knowledge
- Oriented toward collaborative planning and problem solving

Although education and outreach initiatives undertaken by watershed partnerships have similar characteristics, specific topics and activities will vary greatly. Most utilize a number of different kinds of programs to involve the local community and raise awareness about target issues including watershed festivals, tours, school and community presentations, signage, posters, print and electronic media, as well as others. Two examples of nonprofit watershed partnerships are discussed below.

8.2.2.3.1 Superior Watershed Partnership and Land Trust

The Superior Watershed Partnership and Land Trust (SWP) is a nonprofit organization dedicated to protecting and restoring the watersheds of Lake Superior, Lake Michigan, and Lake Huron, and serving the communities of Michigan's Upper Peninsula. Through outreach education, the SWP promotes responsible individual and community actions ensuring a sustainable future, encouraging a sustainable economy, and improving quality of life (Superior Watershed Partnership and Land Trust 2010). The SWP prides itself on being a local organization working with local communities and local people including watershed councils, local government, churches, and Native American tribes. The organization has an online watershed viewer that helps users find the watershed they live in and the types of management efforts currently ongoing in the watershed. More importantly, the organization has been able to document their impact in the region. As a result of their programming, the SWP boasts a 40% reduction in mercury entering Lake Superior, a 70% increase in targeted fish populations, improved regional land use policies, thousands of tons of reduction in sediment entering local waterways, and a more informed citizenry.

8.2.2.3.2 Greater Gallatin Watershed Council

The Greater Gallatin Watershed Council (GGWC) was founded in 2004 as a locally led nonprofit organization promoting conservation and enhancement of water resources and the traditions of agriculture, community, and recreation. A concerned group of citizens recognized the need to address unprecedented demands facing Montana's Gallatin watershed and formed the organization to create a unified local voice to tackle these challenges. Education, outreach, and community dialogue are important components of the GGWC, which utilizes community events, newsletters, issue-specific forums, watershed tours, demonstration projects, and other mechanisms to raise awareness about the watershed and the need to protect it.

8.2.3 CORPORATIONS

In contrast to nonprofit organizations, corporations seek to maximize profits and distribute revenue to shareholders. There are many types of corporations in the United States working in water-intensive industries and performing some measure of outreach education as a part of their business function. However, corporations generally have the most impact in outreach education through their sponsorship of water-related educational events, serving on boards of nonprofit and other types of organizations, and philanthropic contributions supporting water-based nonprofit organizations or other entities at state, regional, and local levels.

One unique service provided by the Project WET Foundation is linking corporations with external opportunities to demonstrate their commitment to education, the environment, and corporate social responsibility. The foundation facilitates corporate sponsorship opportunities including website exposure, representation at water events, and funding Water and Sustainability Kits for classrooms. In addition, Project WET trains corporate employees about the importance of water conservation and protection and works with various companies to enhance sales promotions through strategic sponsorships of educational events.

Several of the nation's largest and best known corporations are involved in sponsorships and philanthropic giving supporting initiatives and programs to increase the public's understanding of water issues. For example, the Walmart Corporation sponsors a number of community educational activities and also supplies education outreach grants to local communities through its Local Giving Program. The philanthropic arm of the Coca-Cola Company, the Coca-Cola Foundation, supports community access to clean water and sanitation, watershed protection, and education and awareness programs promoting water conservation. In addition, in 2007, the Coca-Cola Company became one of the first six companies to commit to the CEO Water Mandate, which helps companies better manage water use in their direct operations and supply chains. As part of this program, the company has developed plant-level training and management tools to help local employees and bottling partners understand watershed issues and engage with local communities, governments, and conservation organizations to better manage them. Additionally, Scotts Miracle-Gro Company recently initiated a multiyear commitment to new consumer communication, education, and grassroots outreach regarding water quality and conservation. This commitment includes incorporating water quality and conservation messaging into consumer advertising, websites, and other digital outreach tools as well as funding for educational outreach with environmental partners and local organizations. As part of this effort, Scotts Miracle-Gro partnered with the Alliance for the Great Lakes and the National Wildlife Federation to initiate development of outreach programs and educational materials. In addition, the company partnered with Keep America Beautiful who will make the educational resources available through its 600 local affiliate offices as a means to enhance community education initiatives on storm water runoff prevention and water conservation.

8.3 TECHNICAL AND FINANCIAL ASSISTANCE PROGRAMS FOR AGRICULTURAL BMP IMPLEMENTATION

One major component of water-related outreach education initiatives at federal, state, and local levels involves programs specifically designed to enhance adoption of BMPs to protect water resources. Many of these programs are highly targeted compared to more general water-related programs and initiatives previously discussed. While BMPs can be implemented in both urban and rural areas, we have chosen to narrow our focus to technical and financial assistance programs available to farmers and ranchers in the agricultural sector that specifically strive to enhance adoption of water quality BMPs. This section also complements Section 1.6.1.1, which details specific types of agricultural BMPs that can be implemented on the landscape.

The EPA defines BMPs as "methods that have been determined to be the most effective, practical means of preventing or reducing pollution from nonpoint sources" (United States Environmental Protection Agency 2008). In general, agricultural BMPs are designed to control sediment and other contaminants carried from agricultural lands, encourage sound pest and nutrient management techniques, protect sensitive riparian areas, properly store and utilize manure, and properly handle animal mortality to ensure economic, environmental, and agronomic sustainability. Adopting agricultural BMPs ultimately can increase efficiency and profits, increase property values, improve water quality, and benefit local and downstream communities.

To motivate agricultural producers to implement conservation practices that protect water quality, some federal and state agencies and community-based organizations offer technical assistance for planning and practice design, as well as financial assistance to offset a portion of the installation and management costs. Outreach education is an essential component of the process to ensure that owners of critical source area land parcels are engaged to participate in these programs. In addition, education is often needed to help producers properly manage and sustain installed practices.

8.3.1 US Government Agencies

Federal and state government agencies are the primary entities responsible for design, implementation, and management of technical and financial assistance programs targeting installation of water quality BMPs.

8.3.1.1 Federal Agencies

8.3.1.1.1 Environmental Protection Agency

As previously discussed, the EPA is the federal agency responsible for administering water quality standards outlined in the CWA. They also are responsible for management of specific federal funds in the CWA used for state-level implementation of agricultural BMPs. The 1987 amendments to the CWA established the Section 319 Nonpoint Source Management Program, which addresses the need for greater federal leadership to help focus state and local nonpoint source efforts. Under Section 319, states, territories, and tribes receive grant money supporting a wide variety of activities including technical assistance, financial assistance, education, training, technology transfer, demonstration projects, and monitoring to assess the success of specific nonpoint source implementation projects.

Another potential major source of federal funding for agricultural BMPs is the Clean Water State Revolving Fund (CWSRF). While the CWSRF has traditionally been used primarily for infrastructure projects at the local or state level, more recently, it has increasingly been used to support agricultural BMP implementation (Arbuckle 2012). The CWSRF funds a wide variety of water quality projects including nonpoint source, BMP, watershed protection or restoration, and estuary management projects, as well as more traditional municipal wastewater treatment projects (United States Environmental Protection Agency 2012). Through the CWSRF program, each state and Puerto Rico maintain revolving loan funds to provide independent and permanent sources of low-cost financing for water quality projects. Funds to establish or capitalize CWSRF programs are provided through federal government grants and state matching funds (equal to 20% of federal government grants). To date, all 50 states and Puerto Rico operate successful CWSRF programs.

In addition to federal funding initiatives supporting BMP implementation, the EPA also provides a wide variety of technical assistance program materials available through the agency website and office locations across the nation. The EPA

Watershed Academy, previously discussed, offers training and technical information on the implementation and benefits of BMPs.

8.3.1.1.2 Department of Agriculture

Two organizations of the USDA, the FSA and the NRCS, play major roles in providing technical assistance to the nation's farmers, ranchers, and landowners regarding BMPs and cost-share assistance for implementation and maintenance.

8.3.1.1.2.1 Farm Service Agency The FSA administers several programs that promote BMP adoption and implementation, including the Conservation Reserve Program, Conservation Reserve Enhancement Program, Conservation Loan Program, and Source Water Protection Program.

Conservation Reserve Program (CRP): The CRP program provides annual rental payments and financial assistance to establish long-term, resource-conserving ground covers on eligible farmland. It helps agricultural producers safeguard environmentally sensitive land through practices that improve water quality, control soil erosion, and enhance wildlife habitat (United States Farm Service Agency 2006). After enrollment, the FSA pays an annual per-acre rental rate and provides up to 50% cost-share assistance for practices accomplishing the above goals. Portions of property enrolled in the program are under contract for 10 to 15 years and cannot be grazed or farmed. To be eligible for the program, agricultural producers must have owned or leased the land for at least 1 year before submission of an application.

Conservation Reserve Enhancement Program (CREP): This voluntary land retirement program helps agricultural producers protect environmentally sensitive land, decrease erosion, restore wildlife habitat, and safeguard groundwater and surface water (United States Farm Service Agency 2013). The program is a partnership among producers; tribal, state, and federal governments; and, in some cases, private groups. CREP provides farmers and ranchers with a financial package for conserving and enhancing the natural resources of farms. CREP is an offshoot of the CRP program addressing high-priority conservation issues of both local and national significance, such as those affecting water supplies, loss of critical habitat for threatened and endangered wildlife species, and reduced habitat for important fish populations such as salmon. CREP contracts require a 10- to 15-year commitment to keep lands out of agricultural production and provide payments to participants with eligible land. A federal annual rental rate, including an FSA state committee-determined maintenance incentive payment, is offered plus cost-share of up to 50% of eligible costs to install the practice. Further, the program generally offers a sign-up incentive for participants to install specific practices.

Conservation Loan Program: The FSA guarantees loans to promote conservation practices on farms and ranches that protect natural resources throughout the United States (United States Farm Service Agency 2010). The goal of this loan program is to provide access to credit for farmers who need and want to implement conservation measures on their land but do not have immediate funds available to implement practices. For conservation practices to be eligible for the loan program, they must be part of an NRCS-approved conservation plan.

Source Water Protection Program: This program is a joint project of the FSA and the nonprofit National Rural Water Association (NRWA). It is designed to help prevent source water pollution in 33 states through voluntary practices implemented by producers at the local level (Appendix A). For each state participating in the program, the NRWA hires full-time rural source water technicians with knowledge and experience in rural issues. The technicians work with FSA state executive directors, FSA county executive directors, and NRCS state conservation specialists to create operating plans identifying priority areas where local pollution prevention efforts are needed most in their respective states (United States Farm Service Agency 2009). Working with state rural water associations, the technicians facilitate creation of local teams composed of citizens with diverse backgrounds and federal, state, local, and private entities. These teams collaborate in development of Rural Source Water Protection plans promoting clean groundwater. Rural Source Water Protection plans outline voluntary measures that producers can install on their lands to prevent source water pollution. Voluntary measures may range from improved pesticide storage to relocation of waste lagoons. By working at the grassroots level, local team members inform and educate producers about source water protection measures that benefit their neighbors and communities.

8.3.1.1.2.2 Natural Resources Conservation Service Through a variety of technical and financial assistance programs, the NRCS helps landowners and managers reduce soil erosion, enhance water supplies, improve water quality, increase wildlife habitat, and reduce damages caused by floods and other natural disasters. The agency employs soil conservationists, rangeland management specialists, soil scientists, agronomists, biologists, engineers, geologists, and foresters. These personnel help landowners develop conservation plans, create and restore wetlands, and design and implement agricultural BMPs (Natural Resources Conservation Service 2012). Key technical and financial assistance programs provided by the NRCS are detailed below.

Field Office Technical Guide (FOTG): This technical resource is available online for every county in every state and is accessible through the NRCS website. Technical guides are the primary design and management references for NRCS. They contain technical information about conservation of soil, water, air, and related plant and animal resources. Technical guides used in each NRCS field office are localized; hence, they relate specifically to the geographic area for which they are prepared. FOTGs include maps, descriptions of land resource areas, soil and site information, conservation management systems, practice standards and specifications, cost estimates, and conservation effects (Natural Resources Conservation Service 2013e). Of most relevance to this section, the practice standards and specifications developed by NRCS detail specific types of BMPs, their purpose, design criteria and considerations for implementation, as well as operation and maintenance information. Also included are detailed cost estimates for BMP implementation.

Agricultural Management Assistance (AMA): The AMA program is available in 16 states and provides financial and technical assistance to agricultural producers to voluntarily address issues such as water management, water quality, and erosion control by incorporating conservation practices into their farming operations

(Appendix B). Through the AMA program, producers may construct or improve water management structures or irrigation structures; plant trees for windbreaks or to improve water quality; and mitigate risk through production diversification or resource conservation practices, including soil erosion control, integrated pest management, or transition to organic farming (Natural Resources Conservation Service 2013a). The program pays financial assistance of up to 75% of the cost of installing conservation practices.

Conservation Stewardship Program (CSP): The CSP program is a voluntary financial and technical assistance conservation program encouraging producers to address natural resource concerns by implementing conservation activities and improving, managing, and maintaining existing conservation activities (Natural Resources Conservation Service 2013b).

Conservation Technical Assistance (CTA) Program: NRCS employees provide technical assistance to clients through the CTA program. Technical assistance generally focuses on helping clients achieve the benefits of a healthy and productive landscape by reducing soil erosion, improving water quality, conserving water resources, and enhancing the quality of fish and wildlife habitat. Through this program, the NRCS is able to partner with other state and local entities as well as community groups to assist in developing and implementing resource management plans that conserve, maintain, and improve natural resources. In addition, this program facilitates information sharing between the NRCS and clients concerning implementation of BMPs and federal, state, and local conservation programs (Natural Resources Conservation Service 2013c).

Environmental Quality Incentives Program (EQIP): The EQIP program is a voluntary conservation program providing financial and technical assistance to farmers and ranchers to implement BMPs that improve soil, water, plant, animal, air, and associated natural resources on agricultural lands and nonindustrial private forestlands (Natural Resources Conservation Service 2013d). The program is designed to address both locally identified resource concerns and state priorities. The NRCS works with producers to

- Identify appropriate conservation practices or measures needed to address local natural resource concerns
- Implement conservation practices and activities that meet NRCS technical standards

Watershed and Flood Prevention Operations (WFPO) Program: This program provides technical and financial assistance to states, local governments, and tribes to plan and implement authorized watershed project plans designed to protect watersheds, mitigate floods, improve water quality, reduce soil erosion, and enhance fish and wildlife habitat (Natural Resources Conservation Service 2013f). Once a plan has been approved, the NRCS assists project partners in installing planned land treatment and conservation measures including detailed designs, specifications, engineering cost estimates, and technical assistance.

Wildlife Habitat Incentive Program (WHIP): The WHIP program offers both technical assistance and up to 75% cost-share assistance to establish and improve fish and wildlife habitat on agricultural land, nonindustrial private forest land, and tribal land. This program complements the Working Lands for Wildlife Initiative, a new partnership between the NRCS and the US Fish and Wildlife Service to combat the decline of the Lesser Prairie Chicken, New England Cottontail, Southwestern Willow Flycatcher, Greater Sage-Grouse, Gopher Tortoise, Bog Turtle and Golden-Winged Warbler (Natural Resources Conservation Service 2013g).

Wetland Reserve Program (WRP): The WRP is a voluntary program offering landowners the opportunity to protect, restore, and enhance wetlands on their property. The NRCS works directly with landowners to provide technical and financial resources supporting wetland restoration efforts. The primary goal of the program is to achieve the greatest wetland function and value along with optimum wildlife habitat on every acre enrolled in the program (Natural Resources Conservation Service 2013h).

8.3.1.2 State Agencies

8.3.1.2.1 Departments of Environmental Quality

Many state departments of environmental quality provide financial assistance to farmers and ranchers for BMP implementation, although typically indirectly through grants to watershed projects. In addition, these agencies work in concert with state and regional NRCS offices, soil and water conservation agencies, and other state and local entities providing technical assistance to agricultural producers. In states where agriculture plays a major role in the economy, many departments of environmental quality have developed state guidebooks or manuals for agricultural BMPs. These publications are a resource for producers seeking technical information about BMPs suitable for their landscape and operation.

State departments of environmental quality provide financial assistance for BMP implementation primarily through the CWSRF and the CWA Section 319(h) Nonpoint Source Grant Program. CWA Section 604(b) funds may also be allocated as they pertain to watershed management planning activities. In all cases, the EPA distributes these federal dollars to the state environmental agency to help fund and implement programs and projects aimed at reducing nonpoint source water pollution. Funds may be used to conduct assessments, develop and implement TMDLs and watershed protection plans, provide technical assistance, demonstrate new technology, implement BMPs, and provide education and outreach. In addition, state legislatures may also appropriate funds to the state environmental agency to carry out technical and financial assistance programs encouraging adoption of water quality BMPs.

8.3.1.2.2 Soil and Water Conservation Agencies

Soil and water conservation agencies are also very active in providing technical and financial assistance to farmers and ranchers wanting to implement BMPs on their property. These agencies most often provide technical assistance in partnership with local SWCD and NRCS offices. In addition to one-on-one technical guidance, print and electronic resources detailing BMPs and their effective implementation are utilized.

In many states, state legislatures appropriate state funds to soil and water conservation agencies to assist local SWCDs in their efforts to provide technical assistance to agricultural producers. These funds may be used to employ conservation technicians to work with owners and operators of agricultural or other lands on installation and maintenance of conservation practices. Another example of a technical assistance program provided by a state soil and water conservation agency is the Water Quality Management Plan (WQMP) program. Most states have a WQMP program or similar program created by the state legislature to help minimize agricultural nonpoint source pollution. A water quality management plan is site specific and developed through SWCDs for agricultural or silvicultural lands. The plan includes appropriate land treatment practices, production practices, management measures, and technologies, or combinations thereof. The purpose of a water quality management plan is to achieve a level of pollution prevention or abatement consistent with state water quality standards.

While allocation of federal CWA funds varies from state to state, some soil and water conservation agencies receive all or a portion of the CWA Section 319 funds to distribute to farmers and ranchers wanting to implement BMPs to protect water quality. Soil and water conservation agencies may also play a role in working with other federal, state, or local entities (i.e., NRCS, FSA, SWCD) to distribute and administer funds to agricultural producers for BMP implementation.

8.3.1.2.3 Cooperative Extension Services

As state educational agencies, Cooperative Extension Services play a major role in providing technical assistance to agricultural producers regarding BMP implementation. Specialists and technicians employed by state and district Extension offices conduct a wide variety of educational programming and demonstration projects related to the beneficial uses of BMPs for protecting water quality. In addition, Extension provides numerous publications about BMPs and their benefits. In some states, Extension works closely with local NRCS and SWCD offices to enhance technical assistance programs provided by these entities to farmers and ranchers wanting to implement BMPs.

8.3.1.3 Nonprofit Organizations

Nonprofit organizations can be instrumental in providing technical and financial assistance to agricultural producers in specific watersheds. Funding for their activities generally comes from federal and state grants as well as from private donations. In many watersheds across the United States, nonprofit organizations, including watershed councils and partnerships, play a major role in watershed planning and protection strategies. Most nonprofits work closely with farmers and ranchers, educating them about sound land management practices and BMP implementation to improve and protect regional water resources.

Private foundations, one type of nonprofit organization, generally play the largest role in providing financial assistance to agricultural producers. One example is the effort of the Sand County Foundation in minimizing impacts of production agriculture on water quality throughout the Midwest. In 2003, the foundation developed the Agricultural Incentives Program to find creative ways to address degradation of surface waters caused by nutrient runoff from agricultural land. Through this program, the foundation emphasizes control of nitrogen and phosphorus at the watershed scale and supports a number of demonstration projects and BMP implementation projects. It also brings together project directors and key stakeholders from projects operated by other groups throughout the Upper Midwest and other regions of the United States.

The National Fish and Wildlife Foundation (NFWF) provides another example of the role nonprofit organizations play in providing financial assistance to promote the implementation of water quality BMPs across the United States. The NFWF is one of the world's largest conservation grantors. They provide direct support for implementation of conservation programs to protect and restore fish and wildlife habitat. Key conservation strategies include technical assistance and coordination to guide management actions of public and private landowners, delivery of outreach and education initiatives, and development of BMPs and decision support tools.

8.4 OPPORTUNITIES TO ENHANCE THE SUCCESS OF OUTREACH EDUCATION PROGRAMS FOR WATER RESOURCE MANAGEMENT

As clearly described in this chapter, there are a multitude of agencies and organizations involved at various levels in development and delivery of water resources outreach and education programs. In theory, these efforts provide critical support to technical and financial assistance programs intended to achieve adoption of land management and conservation practices that protect water resources. As a result, one might assume that all target audiences are fully informed and engaged, and consequently, water resources are safe and sound, now and for future generations. However, recent reports in the United States by EPA and USGS provide clear evidence that the quality of national waters is, in fact, deteriorating. As mentioned in Section 8.1, similar indications exist for many other countries, including China. Without question, climate shift, drought, increasing population, and related factors are affecting our ability to maintain water quality standards and meet future water needs. However, other factors are contributing to our inability to successfully engage stakeholders at all levels and achieve a greater degree of success in water resource management and protection.

Most importantly, it is clear that current education, technical, and financial assistance programs are not as effective as they must be to provide a safe and adequate supply of water. One fact that becomes apparent in this chapter is many federal and state agencies and organizations involved in water have significantly overlapping or duplicative roles and responsibilities. In some cases, the primary mission or function of an entity has become diluted by unnecessary and often redundant distribution of effort and resources. Frequently, this is driven by competition for increasingly limited funds, which sometimes pits agencies against one another, rather than fostering partnerships. For some, misguided efforts toward self-preservation result in even greater mission drift and reduced performance. Obvious examples of these issues exist in many parts of the United States and actions should be taken to redefine and focus roles and responsibilities, particularly of federal and state agencies, to achieve higher levels of efficiency and success.

First, federal and state governments must ensure that education, technical, and financial assistance agencies have distinct roles and responsibilities, and charge each with optimizing its capacity to provide highly effective service. At present, some agencies attempt to duplicate core outreach functions of other agencies in many cases without adequate or appropriate personnel and resources to do so. As a consequence, the "message" can be poorly developed or delivered, thus wasting limited resources, or worse, providing information that is inaccurate or conflicts with other efforts. Second, agencies must be intimately coordinated with each other to maximize efficiency. Highly effective outreach programs communicate clear and consistent messages that motivate participation in conservation and water quality programs. However, it is not feasible or efficient for every agency to operate an independent outreach education effort. Federal regulatory, technical, and financial assistance agencies, including EPA, NRCS, the Agricultural Research Service, and FSA, as well as state water agencies must establish institutional collaborations with education agencies and organizations to optimize outreach efforts and enhance the potential to achieve environmental goals.

Finally, the future of water and, with it, the future of man lie with our youth. While adult education remains essential to stem the immediate tide of water quality degradation, most studies have shown that behavioral change in adults is slow and limited at best. True success in voluntary adoption and sustained use of appropriate water management practices will rely on instilling in the next generations the gravity and consequences of a continued course of failed individual, community, and corporate water quality and water conservation responsibilities. Core curricula must be developed and implemented at key stages of K–12 instruction to produce citizens with a deeply embedded sense of personal responsibility for protection of natural resources and the environment. This should not be a single section or class within a year of study, but rather an integration of training and experiential learning to engender a fundamental understanding, appreciation, and reverence for the Earth's natural resources, including the single most important of these … water.

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APPENDIX A: SOURCE WATER PROTECTION PROGRAM PARTICIPATING STATES

The Source Water Protection Program, a joint project by the USDA Farm Service Agency and the nonprofit National Rural Water Association, is designed to help prevent source water pollution through voluntary practices implemented by producers at the local level. The 33 states participating in the program were chosen on the basis of objective technical criteria relating to water quality and population. The program has been implemented in the following states:

Alabama
Arizona
Arkansas
California
Colorado
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Louisiana
Minnesota
Mississippi
Missouri
Montana
Nevada
New Mexico
Ohio
Oklahoma
Oregon
Pennsylvania
South Carolina
South Dakota
Tennessee
Texas
Utah
Virginia
Washington
West Virginia
Wisconsin
Wyoming

APPENDIX B: AGRICULTURAL MANAGEMENT ASSISTANCE PROGRAM PARTICIPATING STATES

Agricultural Management Assistance (AMA) provides financial and technical assistance to agricultural producers to voluntarily address issues such as water management, water quality, and erosion control by incorporating conservation into their farming operations. AMA is available in 16 states where participation in the Federal Crop Insurance Program is historically low. The program has been implemented in the following states:

Connecticut
Delaware
Hawaii
Maine
Maryland
Massachusetts
Nevada
New Hampshire
New Jersey
New York
Pennsylvania
Rhode Island
Utah
Vermont
West Virginia
Wyoming

9 Water Scarcity in Developing Regions

John Anthony Byrne, Pilar Fernández-Ibáñez, and Preetam Kumar Sharma

CONTENTS

9.1 IMPORTANCE OF WATER FOR LIFE

Water is essential for life. It is a necessity for human health and well-being, and a necessity for the preservation of the environment. In December 2003, the United Nations General Assembly, in resolution A/RES/58/217, proclaimed the period 2005–2015 International Decade for Action "Water for Life." The decade officially started on World Water Day, March 22, 2005 (United Nations 2014).

Safe drinking water is required for all usual domestic purposes, including drinking, food preparation, and personal hygiene. Diseases related to the consumption of contamination of drinking water place a major burden on human health. Therefore, interventions to improve the quality of drinking water will provide significant benefits to health. There are many standards published in relation to drinking water quality, and the nature and form of drinking water standards may vary among countries and regions. There is no single approach that is universally applicable; however, the World Health Organization (WHO) provides Guidelines for Drinking-water Quality (WHO 2011a). The guidelines are designed to support the development and implementation of risk management strategies that will ensure the safety of drinking water supplies by the control of hazardous constituents in water. The main purpose of the Guidelines for Drinking-water Quality is the protection of public health. They provide recommendations for managing risks associated with hazards that may compromise the safety of drinking water. To increase confidence in the safety of drinking water, a holistic approach to the risk assessment and risk management is adopted. This involves the systematic assessment of risks throughout the drinking water supply (from catchment to consumer) and the identification risk management strategies.

In addition to meeting the basic needs of humans, the provision of a safe water supply and sanitation services, and access to freshwater for agriculture and industry, is essential for sustainable development.

9.2 GLOBAL DISTRIBUTION OF FRESHWATER RESOURCE

It is estimated that greater than 70% of the Earth's surface is covered by water, but only 2.5% is freshwater. Approximately 70% of that freshwater is trapped in the ice caps of Antarctica and Greenland, with most of the remaining present as soil moisture, or lying deep in underground aquifers as groundwater, which is not readily accessible for human use. Less than 1% of the world's freshwater is accessible for direct human uses and is obtained from lakes, rivers, reservoirs, and underground sources, which are readily accessible. Only this amount is regularly renewed by rain and snowfall, and is therefore available on a sustainable basis (Gleick 2000).

Water scarcity affects every continent and approximately 1.2 billion people (one-fifth of the world's population) live in areas of physical scarcity, with a further 0.5 billion approaching the same situation. It is estimated that around 1.6 billion people are facing an economic water shortage where there is a lack of the necessary infrastructure to take water from rivers and aquifers (Figure 9.1). The term *water stress* is used when the annual water supplies drop below 1700 m^3 per person; the term *scarcity* is used when annual supplies are below 1000 m^3 per person, and the term *absolute scarcity* refers to resources below 500 m^3 per person per annum. Water scarcity is one of the main problems to be faced by mankind in this century.

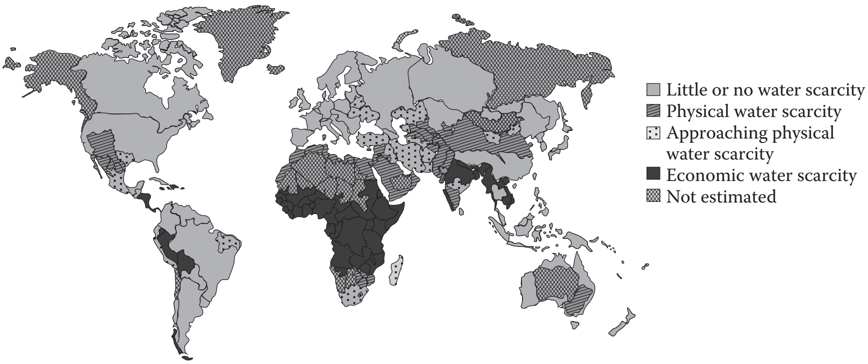

FIGURE 9.1 Global physical and economic water scarcity. (Reprinted with permission from United Nations, International Decade for Action, Water for Life 2005–2015, Water Scarcity, 2014.)

Water use is growing at more than twice the rate of population increase. There is enough water on Earth for everyone, but it is not evenly distributed and an increasing number of regions are chronically short of water. Much of the freshwater resource is not managed properly and is wasted or polluted. Water scarcity, poor water quality, and the absence of appropriate sanitation negatively affect food security for the poor people of the world. These will also affect lifestyle and livelihood choices, as well as educational opportunities.

Water challenges can only increase significantly in the coming years because of population growth and the associated demand for better quality of life. According to the UNESCO World Water Development Report, by 2050, at least one in four people are likely to live in a country affected by chronic or recurring shortages of freshwater (UNESCO 2014).

Observational records and climate projections provide evidence that the world's freshwater resources are extremely vulnerable and will be strongly affected by climate change (IPCC 2008). This will have wide-ranging consequences for humans, the environment, and ecosystems. Global warming, observed over several decades, has been linked to changes in the large-scale hydrological cycle, including increasing atmospheric water vapor content; changing precipitation patterns, both intensity and extremes; reduced snow cover and melting of ice; and changes in soil moisture and runoff. Throughout the world, the area of land classified as very dry has more than doubled since the 1970s (likely—IPCC terminology). Semiarid and arid areas (e.g., the Mediterranean Basin, western United States, southern Africa and northeastern Brazil) are at high risk owing to the impacts of climate change and are predicted to suffer a decrease in water resources because of climate change (high confidence). Increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas. The proportion of land under extreme drought at any one time is predicted to increase (likely), and there will be a tendency for drying in continental interiors during summer, especially in the subtropics and in low and mid-latitudes. Water supplies stored in glaciers and snow cover are projected to decline in the course of the century, thus reducing water availability during warm and dry periods (through a seasonal shift in stream flow, an increase in the ratio of winter to annual flows, and reductions in low flows) in regions supplied by melt water from major mountain ranges, where more than one-sixth of the world's population currently live (high confidence). Higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution—from sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, with possible negative impacts on ecosystems, human health, and water system reliability and operating costs (high confidence). In addition, sea-level rise is projected to extend areas of salinization of groundwater and estuaries, resulting in a decrease of freshwater availability for humans and ecosystems in coastal areas. Changes in water quantity and quality caused by climate change are expected to affect food availability, stability, access, and utilization. This is expected to lead to decreased food security and increased vulnerability of poor rural farmers, especially in the arid and semiarid tropics and Asian and African megadeltas. Given that many countries are already under extreme water stress, global warming and climate change may only act to exacerbate the problem in the coming years.

9.3 ACCESS TO SAFE DRINKING WATER

Since the Millennium Development Goals (MDG) were adopted, the WHO and United Nations Children's Emergency Fund (UNICEF) Joint Monitoring Programme for Water Supply and Sanitation has reported periodically on progress toward achieving Target 7c: "reducing by half the proportion of people without sustainable access to safe drinking water and basic sanitation" (WHO and UNICEF 2014). In 2010, the drinking water target for coverage of 88% was met. In 1990, 76% of the global population had access to an improved drinking water source, whereas in 2012, 89% of the global population had access. This corresponds to an increase of 2.3 billion people with access to an improved water source for drinking over the 12-year period. Almost 4 billion people (56%) of the global population have access to a piped-in drinking water source on premises. In 2012, only three countries (Democratic Republic of the Congo, Mozambique, and Papua New Guinea) were reported where less than half the population had access to an improved drinking water source. Coverage of improved drinking water supply was between 50% and 75% in 35 countries, 26 of which are in sub-Saharan Africa. For Latin America and the Caribbean, the lowest levels of coverage were found in Dominican Republic, Ecuador, Haiti, Nicaragua, and Peru (see Figure 9.2).

Although the world met the MDG drinking water target of 88% coverage in 2010, 748 million people still lack access to an improved drinking water source, and these are mostly the poor and marginalized. Almost a quarter of those 748 million people rely on surface water, which is untreated, and more than 90% live in rural areas. It has been predicted that if current trends continue, 547 million people will still be without an improved source of drinking water in 2015.

An "improved" drinking water source is one that, by the nature of its construction and when properly used, adequately protects the source from outside contamination, particularly fecal matter. Table 9.1 lists definitions of improved and unimproved

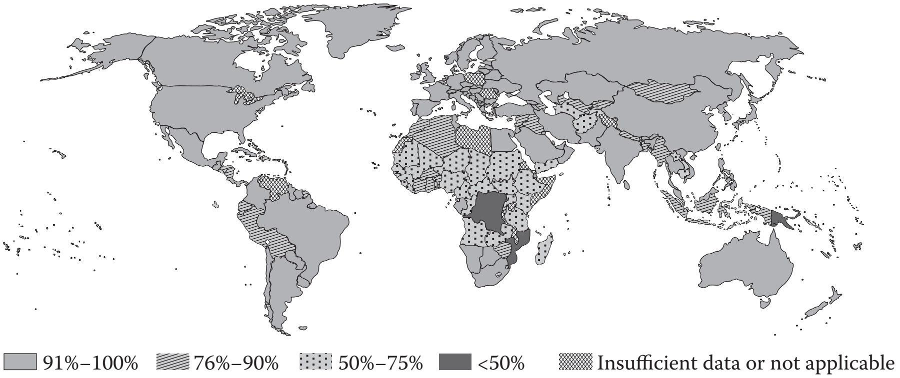

FIGURE 9.2 Proportion of the population using improved drinking water sources in 2012. (Reprinted with permission from United Nations and UNICEF, Progress on Sanitation and Drinking Water: 2014 Update; World Health Organization, UNICEF: Geneva, Switzerland, 2014.)

TABLE 9.1
Definitions of Improved and Unimproved Sources of Drinking Water

	“Improved” Sources of Drinking Water
Piped water into dwelling	Also called a household connection, it is defined as a water service pipe connected with in-house plumbing to one or more taps.
Piped water to yard/plot	Also called a yard connection, it is defined as a piped water connection to a tap placed in the yard or plot outside the house.
Public tap or standpipe	Public water point from which people can collect water. A standpipe is also known as a public fountain or public tap. Public standpipes can have one or more taps and are typically made of brickwork, masonry, or concrete.
Tubewell or borehole	Deep hole that has been driven, bored, or drilled, with the purpose of reaching groundwater supplies. Boreholes/tubewells are constructed with casing, or pipes, which prevent the small-diameter hole from caving in and protect the water source from infiltration by runoff water. Water is delivered from a tubewell or borehole through a pump, which may be powered by human, animal, wind, electric, diesel, or solar means. Boreholes/tubewells are usually protected by a platform around the well, which leads spilled water away from the borehole and prevents infiltration of runoff water at the well head.
Protected dug well	Dug well that is protected from runoff water by a well lining or casing that is raised above ground level and a platform that diverts spilled water away from the well. A protected dug well is also covered, so that bird droppings and animals cannot fall into the well.
Protected spring	The spring is typically protected from runoff, bird droppings, and animals by a “spring box,” which is constructed of brick, masonry, or concrete and is built around the spring so that water flows directly out of the box into a pipe or cistern, without being exposed to outside pollution.
Rainwater	Rainwater that is collected or harvested from surfaces (by roof or ground catchment) and stored in a container, tank, or cistern until used.
	“Unimproved” Sources of Drinking Water
Unprotected spring	This is a spring that is subject to runoff, bird droppings, or the entry of animals. Unprotected springs typically do not have a “spring box.”
Unprotected dug well	This is a dug well for which one of the following conditions is true: (1) the well is not protected from runoff water; or (2) the well is not protected from bird droppings and animals. If at least one of these conditions is true, the well is unprotected.
Cart with small tank/drum	This refers to water sold by a provider who transports water into a community. The types of transportation used include donkey carts, motorized vehicles, and other means.
Tanker truck	The water is trucked into a community and sold from the water truck.
Surface water	This is water located aboveground and includes rivers, dams, lakes, ponds, streams, canals, and irrigation channels.
Bottled water	This is considered to be improved only when the household uses drinking water from an improved source for cooking and personal hygiene; where this information is not available, bottled water is classified on a case-by-case basis.

Source: WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation, http://www.wssinfo.org/definitions-methods/watsan-categories/ (accessed January 3, 2015).

drinking water sources from WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation (2015). The proxy indicator used in the global survey methodology, that is, "use of improved drinking water sources," does not necessarily mean that the water from these sources is safe to drink (Figure 9.3). Many people are forced to rely on sources that are microbiologically unsafe, leading to a higher risk of contracting waterborne diseases, including typhoid, hepatitis A and E, polio, and cholera. It was estimated that diarrheal disease claimed the lives of 2.5 million people in 2008 (WHO 2011b). This is greater than the combined burden of HIV/AIDS and malaria, for children under 5 years (Liu et al. 2012). Fifty-eight countries, from all continents, reported a cumulative total of 589,854 cholera cases in 2011, representing an increase of 85% from 2010. The greatest proportion of cases was reported in Latin America and Africa.

In developing countries, diarrhea accounts for 17% of all deaths in children under 5 years (United Nations 2006). Diarrheal diseases may not necessarily result in death but, nevertheless, they can have a significant impact with respect to increased health costs and lost time at school, work, and other activities, with associated loss to the local economy. It has been estimated that 94% of all diarrheal diseases can be attributed to the environment and risk factors include unsafe drinking water, lack of appropriate sanitation, and poor hygiene (Pruss-Ustun and Corvalan 2006). Table 9.2 shows the principal infectious diseases related to poor drinking water, along with annual morbidity and mortality.

A rapid growth in the use of boreholes and tubewells has been observed. In Southern Asia, 310 million more people used boreholes in 2008 than in 1990. The poor water quality compliance for boreholes is very concerning (Figure 9.3).

It is generally agreed that conventional interventions to improve water supplies at the source (point of distribution) are effective for the prevention of diarrheal disease; however, some researchers suggest that household-based (point-of-use) interventions

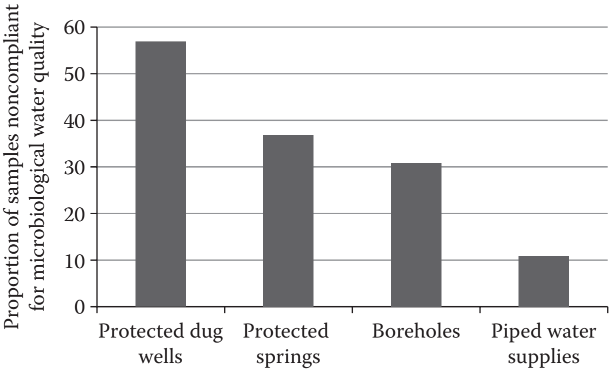

FIGURE 9.3 Noncompliance with microbiological water quality guideline values by improved drinking water source type. The survey was conducted by rapid assessment of drinking water quality in five countries: Ethiopia, Jordan, Nicaragua, Nigeria, and Tajikistan. Proportion refers to percentage. (With permission from UNICEF and World Health Organization, Drinking Water Equity, Safety and Sustainability, JMP Thematic Report on Drinking Water 2011.)

TABLE 9.2
Principal Infectious Diseases, Disease Agents, and Annual Morbidity and Mortality Related to Poor Drinking Water

Disease	Etiological Agent	Morbidity	Mortality
Diarrhea (dysentery, cholera)	Viruses *Rotavirus* *Norovirus* Bacteria *Escherichia coli* *Shigella* sp. *Salmonella* sp. *Vibrio* sp. *Campylobacter* sp. Protozoa *Giardia lamblia* *Cryptosporidium parvum* *Entamoeba histolytica*	4 billion (annual)	1.8 million
Hepatitis A	Hepatitis A virus	1.4 million	unknown
Hepatitis E	Hepatitis E virus	20 million	70,000
Dracunculiasis	Guinea worm	<2000	
Typhoid and paratyphoid fever	*Salmonella* sp.	26 million	216,000

Source: WHO, Household water treatment and safe storage, manual for the participant, World Health Organisation, Western Pacific Region, 2013.

might be more effective than treatment at the source. Therefore, there has been growing interest in the development and deployment of household-based interventions that should deliver the benefits of safe drinking potable water and potentially at lower cost than conventional point-of-source treatment (Clasen et al. 2006; Clasen and Haller 2008).

9.3.1 HOUSEHOLD WATER TREATMENT AND SAFE STORAGE

Household water treatment and safe storage (HWTS) is being promoted as a means of improving the safety of potable water within the home. This is particularly important in situations where recontamination is a real risk between the point of collection and point of use, and recontamination during storage is likely. Access only to distant sources, piped supplies that are unreliable, and reliance on rainwater collection for potable water are all factors that make household storage a necessity. There is also a need for effective HWTS in crisis situations. However, HWTS is a stop-gap measure only and *does not replace the obligation of a service provider to supply access to safe drinking water.*

HWTS is intended for those people who do not have access to improved drinking water sources, or for people who may have access to improved sources but outside of their home or premises. HWTS is also appropriate for those without reliable piped supplies and those who need to store water during periods or delays between water deliveries. Those people who are relying on unimproved drinking water sources, even if they use an appropriate HWTS, are not considered to have sustainable access to safe drinking water. Therefore, the providers are still held accountable for providing safe drinking water (UNICEF and WHO 2011).

HWTS interventions can help reduce the risk of transmission of waterborne disease, especially where drinking water is collected from an unimproved or unsafe source. Interestingly, the use of appropriate household water treatment (HWT) is relatively high for those consumers who have piped-in water supplies, suggesting a lack of confidence with respect to the quality of the tap water provided. Unfortunately, less than a quarter of those people who rely on unprotected dug wells and unprotected springs actually employ appropriate HWT. Appropriate HWT is practised by more than 50% of people using protected wells but only by 23% of those using unprotected wells. Therefore, many households with the poorest drinking water quality do not employ HWT technology.

Methods that are recognized as appropriate HWT include boiling, filtration, chemical disinfection using chlorine or bleach, and solar disinfection. Straining water through a cloth or letting it settle is not considered an appropriate method. Although energy intensive, households are four times more likely to boil their water than to use other HWT methods (Figure 9.4).

HWT options include boiling, chemical disinfection, flocculation/clarification, filtration, adsorption, chemical disinfection, solar disinfection, and UVC disinfection. Of course, boiling one's water will inactivate most microorganisms, including protozoan parasite oocysts (e.g., *Cryptosporidium parvum*). Certain spores may be thermally resistant and may survive normal boiling of water. Boiling water requires substantial energy and the use of fuel, which may not be readily available. Filtration can be carried out with commercially available ceramic filters or home-made filtration systems. The efficiency of removal is of course dependent on the pore size and viruses may not be removed unless attached to larger particles in the water. Filtration

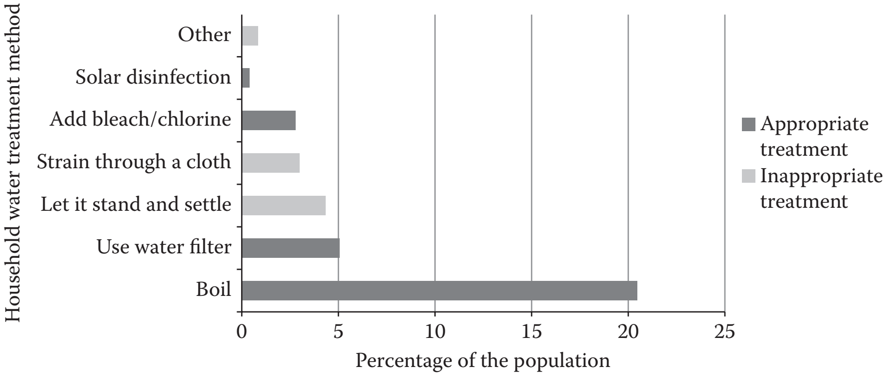

FIGURE 9.4 Prevalence of household water treatment methods reported across selected countries. (With permission from UNICEF and World Health Organization, Drinking Water Equity, Safety and Sustainability, JMP Thematic Report on Drinking Water 2011.)

may be combined with activated carbon adsorption, which will remove microorganisms and chemical pollutants. Commercial filtration systems and materials will need to be purchased and distributed. Chemical disinfection is easy to adopt and different chemical disinfectants can be utilized. Again, these must be purchased and distributed. Iodine may be used in crystallized form or in tablets containing tetraglycine hydroperiodide, although it is not effective for all waterborne pathogens. Chlorine is a more effective disinfectant than iodine, and sodium dichloroisocyanurate tablets are widely used for chlorine-based water disinfection. Bleaching powder (calcium hypochlorite) is also widely used for point-of-source disinfection. UVC disinfection is well known and effective against a wide range of microorganisms. UVC must be supplied from a source and therefore energy is required to power the source. In an innovative solution for community-based UVC disinfection, Naiade has developed a stand-alone system that operates using solar PV panels to provide the power to drive the UVC source for disinfection. The system has quite a high capital investment (ca. 5000 Euro) but can supply water for whole communities (see Figure 9.5).

Solar water disinfection is a simple and cost-effective approach to making water safer to drink. The combined effects of infrared, visible, and ultraviolet energy from the sun can inactivate pathogenic organisms present in water, with the UVA and

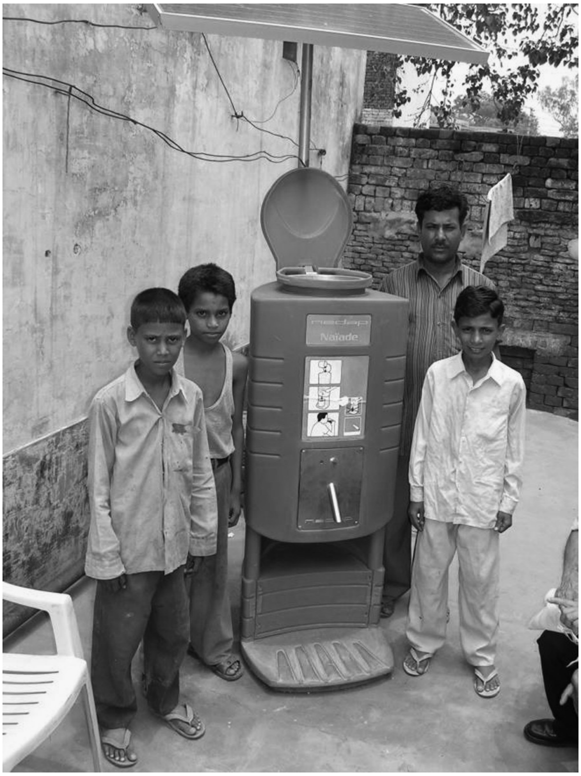

FIGURE 9.5 Naiade solar-powered UVC disinfection system on-site in India. (From Naiade 2015. http://www.nedap-naiade.com [accessed January 9, 2015].)

UVB components in sunlight providing the most important ones. Thermal effects can be synergistic and are important above 40°C. The SODIS process is listed as an appropriate HWT and a simple diagram showing the process is given in Figure 9.6. However, there are a number of parameters that affect the efficacy of the SODIS process. The efficiency of microbial disinfection will depend on the solar irradiance, which in turn depends on the latitude of the location, time of day, and atmospheric conditions. On cloudy days, it is recommended to use the SODIS process over 2 days to ensure the water is safer to drink. Also, the process efficacy will depend on the quality of the water to be treated. Some pathogens are more resistant to SODIS than others.

Research has shown SODIS to be effective against a wide range of pathogenic microorganisms (Boyle et al. 2008) and field trials have demonstrated significant health benefits from the consumption of SODIS-treated water (Conroy et al. 1999). The effectiveness of SODIS against cholera was also demonstrated in a Kenyan health impact assessment, where an 86% reduction cholera cases was observed in households regularly using SODIS (Conroy et al. 2001). Studies to improve the efficiency of the SODIS process using low-cost, commonly available materials have been conducted; however, the simple approach of exposing a 2-L PET bottle to full sun for a minimum of 6 h is the most commonly promoted and practiced method. Research continues to find inexpensive methods for enhancing the solar disinfection of water. One such approach is to utilize semiconductor photocatalysis to increase the disinfection efficiency. Titanium dioxide is a common material that is found in a wide range of products. In fact, it is used as a food colorant recognized as E171 and is found in coffee creamer, powdered donuts, and candy sweets. When irradiated with

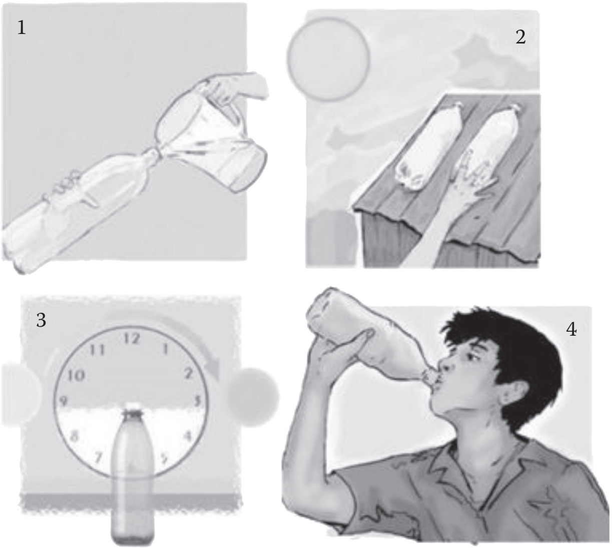

FIGURE 9.6 SODIS process. (Courtesy of Kevin McGuigan, Royal College of Surgeons in Ireland, drawn by Maria Boyle.)

UVA photons, TiO_2 becomes a powerful photocatalyst, generating reactive oxygen species (ROS), including hydroxyl radical, superoxide radical anion, hydroperoxyl radical, and hydrogen peroxide. These ROS are effective disinfectants and can inactivate a wide range of microorganisms including bacteria and bacterial spores, fungi and fungal spores, viruses, and protozoa (Byrne et al. 2011).

In 2008, Clasen and Haller published a report examining the cost and cost-effectiveness of household-based interventions to prevent diarrhea (Clasen and Haller 2008). They compared four approaches to household-based water treatment interventions, that is, chlorination using sodium hypochlorite following the "Safe Water System" developed and promoted by the US Centers for Disease Control and Prevention, gravity filtration using either commercial "candle"-style gravity filters or locally fabricated pot-style filters developed by Potters for Peace, solar disinfection following the "SODIS" method in which clear 2-L PET bottles are filled with raw water and then exposed to the sun for 6–48 h, and flocculation disinfection using Procter & Gamble's PUR sachets, which combine an iron-based flocculant with a chlorine-based disinfectant and treat water in 10-L batches. They concluded that chlorination was the most cost-effective with SODIS being only slightly less cost-effective. The costs were similar but SODIS was slightly less effective. However, household-based chlorination requires the distribution of sodium hypochlorite or chlorine tablets, whereas solar energy is widely and freely available.

9.3.2 HWTS and the Need for More Field Research

In many developing countries, water for potable purposes can be collected from communal sources, which are either unimproved (e.g., unprotected wells, unprotected springs, and rivers) or improved (e.g., protected wells, boreholes, and public standpipes). As such, these sources can be large distances from the household, especially in rural areas. Microbiological contamination of potable water, both during and after collection from the source, is a problem even where the water source is not contaminated. Post–source contamination may remove any health benefits of new water source installations. Other exposure routes to pathogenic microorganisms, such as contaminated food or dirty hands, might be more important in causing disease than contaminated water. Gundry et al. (2004) undertook a systematic review of health outcomes related to household water quality in developing countries. Their review focused on two health outcomes, general diarrhea and cholera, and their relationship with water quality at point of use. They found a clear relationship with contaminated water and the incidence of cholera, and HWTS interventions were found to reduce the incidence of cholera; however, for general diarrhea, there was no clear relationship found with point-of-use water quality, although HWTS interventions did significantly reduce the incidence of diarrhea. They suggested a need for further field studies to assess the effectiveness of HWTS interventions, and water policy in developing countries needs to pay greater attention to the water quality at the point of use, if diarrheal morbidity is to be reduced. Consideration should be given to the factors that affect post–source contamination. A more holistic approach to community water, sanitation, and hygiene may produce better health outcomes than water source improvements alone.

Schmidt and Cairncross (2009) questioned the evidence for scaling up household water treatment interventions in poor populations. They concluded that widespread promotion of HWT interventions, without targeted evaluation of health effects, is premature. HWT may reduce the incidence of diarrheal disease in some poor populations where waterborne transmission is the predominant pathway; however, there are concerns over commercial interests in HWT, particularly where the intervention requires a product purchase (and sometimes repeat purchase). They recommend that more evidence is needed, particularly with respect to the effect of safe water handling and storage, which does not require the use of HWT (commercial or otherwise), and can be promoted at little or no cost. Where industry is involved with trials of HWT interventions, strict ethical guidelines and protocols must be implemented to remove any bias of the reported results and outcomes.

The WHO has published a manual for the implementation of HWTS (WHO 2013).

9.4 SANITATION

The progress with the MDG with respect to sanitation has not been as significant as that with access to improved sources for drinking. In 1990, it was estimated that 2.7 billion people in the world did not have access to an improved sanitation facility. An improved sanitation facility is defined as one that hygienically separates human excreta from human contact. Table 9.3 gives definitions of improved and unimproved sanitation taken from WHO and UNICEF (2015). The JMP report for 2014 (WHO and UNICEF 2014) estimated that, in 2012 (over 12 years), a decrease of only 7% had been achieved, with an estimated 2.5 billion people still not having access to an improved sanitation facility. Projections indicate that if current trends continue, 2.4 billion people will still be without access to an improved sanitation facility in 2015 and the MDG for sanitation will not be achieved (WHO and UNICEF 2014). Most of the people without access to an improved sanitation facility live in rural areas. Open defecation is where people defecate in gutters, behind bushes, or in open water bodies, with no dignity or privacy. This practice is strongly associated with poverty and exclusion. In order to accelerate the progress toward the MDG sanitation target, it is imperative to reduce the incidence of open defecation. There has been a decrease in the incidence of open defecation with a 21% decrease from 1990 to 2012. Nine out of 10 people who practise open defecation live in rural areas; however, the incidence of open defecation in urban areas is gradually increasing. In some 46 countries, less than half of the population have access to an improved sanitation facility (see Figure 9.7).

Sub-Saharan Africa has made much slower progress than other areas in relation to sanitation, with only a 5% improvement in coverage from 1990 to 2012. In fact, Nigeria has actually observed a decline in the coverage of improved sanitation facilities from 37% in 1990 to 28% in 2012. Of the estimated 2.5 billion people who do not have access to an improved sanitation facility, 784 million of these have access to a public or shared facility, 732 million use a facility that does not meet minimum hygiene standards, whereas the remaining 1 billion engage in open defecation. According to the United Nations, open defecation perpetuates the vicious cycle of disease and poverty and is an affront to personal dignity. In countries where open

TABLE 9.3
Definitions of Improved and Unimproved Sanitation

	"Improved" Sanitation
Flush toilet	Uses a cistern or holding tank for flushing water, and a water seal (which is a U-shaped pipe below the seat or squatting pan) that prevents the passage of flies and odors. A pour flush toilet uses a water seal, but unlike a flush toilet, a pour flush toilet uses water poured by hand for flushing (no cistern is used).
Piped sewer system	A system of sewer pipes, also called sewerage, that is designed to collect human excreta (feces and urine) and wastewater and remove them from the household environment. Sewerage systems consist of facilities for collection, pumping, treating and disposing of human excreta and wastewater.
Septic tank	An excreta collection device consisting of a watertight settling tank, which is normally located underground, away from the house or toilet. The treated effluent of a septic tank usually seeps into the ground through a leaching pit. It can also be discharged into a sewerage system.
Flush/pour flush to pit latrine	Refers to a system that flushes excreta to a hole in the ground or leaching pit (protected, covered).
Ventilated improved pit latrine (VIP)	A dry pit latrine ventilated by a pipe that extends above the latrine roof. The open end of the vent pipe is covered with gauze mesh or fly-proof netting and the inside of the superstructure is kept dark.
Pit latrine with slab	A dry pit latrine whereby the pit is fully covered by a slab or platform that is fitted either with a squatting hole or seat. The platform should be solid and can be made of any type of material (concrete, logs with earth or mud, cement, etc.) as long as it adequately covers the pit without exposing the pit content other than through the squatting hole or seat.
Composting toilet	A dry toilet into which carbon-rich material (vegetable wastes, straw, grass, sawdust, ash) are added to the excreta and special conditions are maintained to produce inoffensive compost. A composting latrine may or may not have a urine separation device.
Special case	A response of "flush/pour flush to unknown place/not sure/DK where" is taken to indicate that the household sanitation facility is improved, as respondents might not know if their toilet is connected to a sewer or septic tank.
	"Unimproved" Sanitation
Flush/pour flush to elsewhere	Excreta being deposited in or nearby the household environment (not into a pit, septic tank, or sewer). Excreta may be flushed to the street, yard/plot, open sewer, a ditch, a drainage way or other location.
Pit latrine without slab	Uses a hole in the ground for excreta collection and does not have a squatting slab, platform, or seat. An open pit is a rudimentary hole.
Bucket	The use of a bucket or other container for the retention of feces (and sometimes urine and anal cleaning material), which are periodically removed for treatment, disposal, or use as fertilizer.

(*Continued*)

TABLE 9.3 (CONTINUED)
Definitions of Improved and Unimproved Sanitation

	“Unimproved” Sanitation
Hanging toilet or hanging latrine	Toilet built over the sea, a river, or other body of water, into which excreta drops directly.
No facilities or bush or field	Defecation in the bush or field or ditch; excreta deposited on the ground and covered with a layer of earth (cat method); excreta wrapped and thrown into garbage; and defecation into surface water (drainage channel, beach, river, stream or sea).

Source: WHO and UNICEF. Joint Monitoring Programme for Water Supply and Sanitation, http://www.wssinfo.org/definitions-methods/watsan-categories/ (accessed January 3, 2015), 2015.

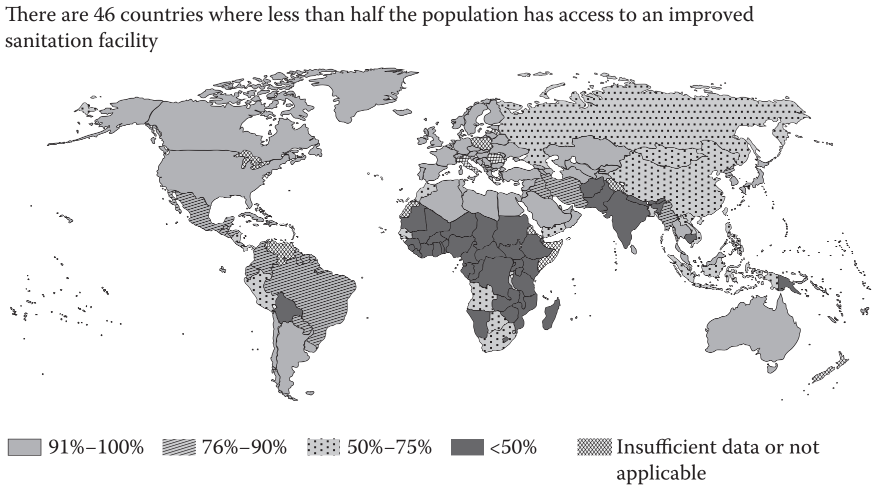

FIGURE 9.7 Proportion of the population using improved sanitation in 2012. (Reprinted with permission from United Nations and UNICEF, Progress on Sanitation and Drinking Water: 2014 Update; World Health Organization and UNICEF: Geneva, Switzerland, 2014.)

defecation is most widely practiced, the highest numbers of deaths of children under the age of 5 have been recorded, in addition to high levels of malnutrition, high levels of poverty, and large gaps between the rich and poor. There are also strong gender impacts relating to the lack of improved sanitation facilities; for example, the lack of safe, private toilets makes females vulnerable to violence.

The greatest lack of improved sanitation facilities is observed in South Asia, with serious shortfalls in East Asia and Sub-Saharan Africa. The lack of improved sanitation facilities has an enormous detrimental effect, particularly among young children, the poor, and those living in rural areas. Poor sanitation contributes to millions of people contracting fecal-borne illnesses, including diarrheal diseases and parasitic infections. Around 1.7 million people die each year because of unsafe water, lack of sanitation, and unhygienic practices, with 90% of those who die being under the age of 5. Nearly all deaths occur in the rural regions of developing countries, where sanitation problems are most acute.

The Water and Sanitation Programme (WSP) is a multidonor partnership administered by the World Bank to support poor people in obtaining affordable, safe, and sustainable access to water and sanitation services. The WSP's Economics of Sanitation Initiative reveals the many costs of poor sanitation (WSP 2012). This research indicates, for example, that poor sanitation costs the equivalent of 1% of the gross domestic product (GDP) in Tanzania and more than 6% of the GDP in India. Also, research shows that investment in improved sanitation facilities in both rural and urban contexts can actually generate substantial economic returns.

9.5 WASTEWATER REUSE

According to the Food and Agriculture Organization of the United Nations (FAO), only approximately 9000 to 14,000 km^3 of freshwater are economically available for human use each year (FAO 2010). Meanwhile, the world's population is expected to grow by 2 billion by 2030. Providing adequate water for all these people is actually a major concern, especially when basic human needs are affected, such as direct human water consumption, water for domestic uses, water for food production and processing, and water for goods manufacturing. Countries meet current water needs by exploitation of freshwater resources still available. This problem becomes actually unsustainable not only because of the high increase in the world's population but also by increasing standards of living, which increase the per-capita freshwater consumption.

Agriculture has evolved from rain-fed to irrigated crops, which increased yields and exploitation surface from 100% to 400%, which increases the income value associated to different crops. Irrigated agriculture requires that water is available at unnatural times and locations, requiring infrastructure, energy, and labor, even if it is groundwater directly withdrawn. The immediate consequence of irrigation is salinization of soils with further problems of increased water needs. Compared to the minimum drinking water needs of 2 to 4 L per person per day, producing a day's food requirement takes 2000 to 5000 L of water per person. As a result, agriculture is by far the largest freshwater consumer, accounting for 70% to 95% (developing countries) of all withdrawals (FAO 2010).

Water scarcity has consequences in our society at all levels. From the environmental point of view, water stress decreases river flows, which rebound at some stage on the supply of water for human needs. Rivers need around 30% of their flow for environmental purposes, but irrigation activities take around 80% of the river water, putting in compromise the ecosystem equilibrium. Some rivers are stressed by human withdrawal. From the economic point of view, the losses attributed to droughts or long periods of water scarcity in arid regions become very important in the following order to sectors such as industrial production, hydropower, agriculture, and livestock output (World Bank 2010). Actually, 75% of the areas in the world account for water withdrawals approaching or exceeding sustainable limits, and they are described as areas of physical water scarcity. Nevertheless, economic water scarcity can occur where water resources are abundant, but deficiencies in human, institutional, or financial capital limit the access to it.

Competition between industry, agriculture, and urban uses for freshwater comes from increased demand of water. The constant increase in the size of cities and industrial activities compromises water supply for agriculture and traditional small-scale economies and put these sectors at risk. When these problems arise, economic and political infrastructure involved in water management becomes critical. According to the MDG, in the competition for water, human needs must prevail over others like aquatic needs to sustain ecosystems and fisheries.

Conventional water surface and groundwater resources are in question owing to lack of quality (contamination and salinization of natural reservoirs) and quantity (overexploitation of natural freshwater resources); furthermore, extraction and treatment of fresh water resources is becoming technologically very complex and expensive. Given the limitations for conventional water resources, the use of nonconventional resources or demand management is receiving increasing attention. Development of new resources means bringing technological approaches (cost and energy demands) to reclaim water at the desired quality. This innovative view is also controversial because of several reasons, that is, conservationists are concerned that reuse in the upper part of basins can reduce the availability of water for ecosystems further downstream, health authorities and society worry about health risks associated to the use of reclaimed (treated) water, and salinization of soils. This aspect is in line with using efficient water and wastewater treatment technologies to minimize any harmful impact on agriculture and food products.

9.5.1 Nonconventional Water Resources

Seawater desalination as source is still a relatively expensive approach for irrigation in agriculture even though there has been huge progress in membrane technology. More efficient water management and use among urban and agricultural users is one of the lowest cost alternatives to align supply and demand. Wastewater treatment technologies such as removal of chemical contamination by biological processes combined with physicochemical processes as pretreatment will permit to reduce the load of organic matter and chemical pollutants and convert the treated wastewater into proper water resource for different uses. To refer to reclaimed water use as "nonconventional" does not imply that wastewater is uncommon, or indeed unproven, as a water supply source. Domestic wastewater has been used for centuries for irrigation and fertilization in agriculture, and the use of treated wastewater has been practiced for at least 100 years.

9.5.2 Wastewater Reuse for Coping with Freshwater Shortage

Wastewater reuse is an important component for integrated water resource management. The latter is concerned with managing all aspects of the water cycle and with optimizing water use overall. All countries are called to develop their own management of water resources and water efficiency plans, which mainly include assessment of water needs in collaboration with all end users, analysis of all the water sources available, and water supplies in terms of their quantity, quality, and technical and economic reliability for different purposes. According to the Dublin Statement on Water and Sustainable Development of 1992, water is recognized as an economic good for all its uses, although its value and its cost and price are seen to be quite different (FAO 2010). Water is considered part of the natural capital of all nations.

Developed and developing regions are both driving wastewater reuse practise and management. Both have common concerns about increased and increasing population, food and water demands, water resources contamination, and shortages. These are the original forces that make reclaimed water a potentially valuable resource all over the world. Water reuse requires changes in the conventional water structures; policy makers and actors in the water scenario may change the traditional mentality and move into new strategies for water treatment, water distribution, water quality standards, regulatory frameworks about water reuse, and institutional mandates.

Wastewater reclamation worldwide has gained a lot of interest in the last decades. Globally, there are more than 3300 water reclamation facilities, with a range of treatment levels for different applications. The main applications are agricultural irrigation, urban landscaping and recreational uses, industrial cooling and processing, and groundwater recharge. The number of wastewater reuse sites is increasing rapidly, with sites predominating in the following order: Japan, the United States, Australia, EU, the Mediterranean and Middle East, Latin America, and finally Sub-Saharan Africa (AQUAREC 2006).

The number of water reuse sites and facilities will grow even more in the future because of the increasing competition between the agricultural and urban water demands for high-quality freshwater supplies. These needs will be more apparent in arid, semiarid, and densely populated regions, where the freshwater demands continuously increase but are not balanced by precipitation and aquifer recharge.

9.5.3 WASTEWATER REUSE IN DEVELOPING COUNTRIES (AGRICULTURAL IRRIGATION)

The reuse of treated or untreated wastewater for agricultural irrigation is practiced in almost all arid areas of the world. Many countries have established water resources planning policies that recommend the maximum reuse of urban wastewater. In arid regions, particularly in developing countries in Asia, Africa, and Latin America, the use of inadequately treated wastewater for irrigation of crops is commonly practiced. The use of treated and untreated wastewater for food crop irrigation poses a major health risk and makes it imperative for stakeholders to ensure proper reuse planning and practices are employed, which emphasize public health and environmental protection. Proper water reuse projects are those that substitute reclaimed water for use in irrigation, environmental restoration, cleaning, toilet flushing, urban, and industrial uses, considering economic viability and public acceptance. The main benefits of using reclaimed water situations are the conservation of water resources and the reduction in pollution of water resources. The Water Environment Research Foundation reviewed nonpotable water reclamation planning and management practices worldwide, which included 65 international nonpotable water reuse projects.

The purpose was to document planning and management approaches for agricultural, urban, and industrial water reuse projects in both developed and developing regions in the arid and semiarid belts around the globe.

The reclamation of wastewater and reuse in agriculture are gaining wider acceptance in many parts of the world. Particularly for countries under water stress, wastewater is an important resource for bridging the demand and supply of water for different uses. Farmers recognize the value of recycled water as a water resource for irrigation and also as a source of nutrients for plant growth and soil conditioning. According to the FAO, the total land irrigated with raw or partially diluted wastewater is estimated at 20 million hectares, over 50 countries, which is approximately 10% of total irrigated land.

Irrigation of food crops with wastewater presents a significant public health risk owing to potential contamination with pathogenic microorganisms, heavy metals, and toxic organic chemicals. Independently of crop type, the minimum wastewater safety use requirements should be that set by WHO, in microbiological variables and physical chemistry quality set by FAO's organization. Also, pollutants within the wastewater can affect crop development and affect the soil characteristics; for example, heavy metal contaminants and also parameters such as Na, Ca, Mg, and B contents should be considered. Wastewater treatment technology for water recycling and reuse should be considered in the context of use (i.e., soil type and crops irrigation). To ensure good wastewater management in agricultural activities and to minimize risks, stakeholders use appropriate integrated water resource management schemes that consider all aspects concerned with environmental and agricultural issues. This will of course require the involvement of governmental and nongovernmental stakeholders including agricultural and environmental departments.

Governments are somewhat inclined to redirect clean freshwater from crop farms to urban areas since water has a higher economic value in urban and industrial use than for most agricultural purposes. In this context, the use of reclaimed water for agriculture enables freshwater to be exchanged for more economically and socially valuable purposes, while providing farmers with reliable and nutrient-rich water. This change in the water management may bring three main benefits: (i) environmental—reducing the pollution of wastewater disposals and increasing the output per unit of water; (ii) urban—increasing the high quality of reclaimed water for urban users; and (iii) agricultural—increasing water availability for irrigation and increasing the presence of nutrients for plants.

For developing regions, reports on nonconventional sources of water are only available for a few countries. They refer to four categories of source, in order of predominance, that is, produced wastewater, treated wastewater, reused treated wastewater, desalinated water.

In Africa, countries with reported nonconventional water resources are those with very limited renewable water sources (precipitations, river basin availability, and dams) and are mostly located in the northern region. Countries practising desalination are, in order of production, Egypt, South Africa, Libyan Arab Jamahiriya, Algeria, Tunisia, Morocco, Mauritania, Cape Verde, Seychelles, Sudan, and Djibouti. Other African countries have also developed facilities for irrigation with treated wastewater, predominantly in urban and periurban agriculture, although there are no available numbers on produced or treated wastewater (FAO 2005).

In South America, the arid and semiarid areas of Chile, Argentina, and Brazil, crop production relies totally on water supply by irrigation for plant growth and development, while in other areas, such as in the southeastern part of Brazil, irrigation is supplemental to natural precipitation (de Oliveira et al. 2009). Although it is recommended that wastewater is treated before use, in practice, this is not always achieved in Latin American countries. Raw sewage, diluted with surface water and, to a lesser portion, treated water, is reused; the treatment may not be adequate for use. The safe reuse of water for agriculture activities means appropriate treatment and management is essential. Wastewater reuse in South America is recommended mainly for the irrigation of crops, which include food crops (e.g., vegetables). In most arid and semiarid zones (Argentina, Chile, the coast of Peru and Ecuador), increase in the irrigated land will require efficiency improvement in conveyance, distribution, and application, as well as more efficient use of water for plants. Improved designs and modernization of irrigation techniques and schemes will improve the actual situation. Furthermore, an increase in areas under irrigation is foreseen for more humid zones. In tropical and some humid climate areas (the Pampa in Argentina, Lesser Antilles, Central America, Colombia, and Amazonian basins of the Andean countries) programs for supplementary irrigation on crops during dry periods are being used (FAO 2014). Among others, another possible increase in the irrigated land of arid and semiarid zones could be by the use of treated wastewater, although this use does not appear to have great relevance in the region. In some countries (Argentina and Chile) where public, private, or mixed entities are being formed to manage wastewater treatment, treated wastewater is viewed as a possible source of additional income. Most of the Latin American countries have no regulations about quality for reuse of treated wastewater.

For example, Argentina has different regional water guidelines depending on the region, but no unified rules about this. The largest water reuse system in Argentina is located in the arid region of Mendoza, in the western part of the country near the Andes. More than 160,000 m^3/day of urban wastewater (1 million inhabitants, 100 Mm^3/year) is treated by one of the largest lagooning systems in the world at the Campo Espejo wastewater treatment plant with a total area of 290 hectares (643 acres) to meet the WHO standards for unrestricted irrigation by means of facultative stabilization ponds (Kotlik 1998). Reuse water in this region is a vital water resource, enabling the irrigation of more than 3640 hectares (8995 acres) of forests, vineyards, olives, alfalfa, fruit trees, and other crops. Improved water reuse practices are under development to avoid contamination of aquifers, including establishment of special areas for restricted crops and restrictions in the choice of irrigation technologies.

Water scarcity in certain zones of Latin America is a source of conflict among different sectors. To reduce conflict, there is a tendency to promote the concepts of integrated water management, that is, creating a development plan and a management institution representing the public sector and main users' groups, granting water concessions, planning and implementation of large hydraulic works, pollution control, flood protection, estimation of the ecological flow, and so on. This is the case in Bolivia, Brazil, Chile, Guatemala, Honduras, Mexico, and the Dominican Republic.

According to the FAO, indiscriminate and unplanned disposal of effluents (including agricultural drainage water and municipal and industrial wastewater) into rivers, canals, and drains, causing deterioration of water quality in the downstream parts, is a major concern in Southern and Eastern Asia (FAO 2011). Twelve of the 22 countries in the Southern and Eastern Asia overexploited their renewable groundwater resources, which led to problems such as lowering of the groundwater reservoirs, saltwater intrusion, groundwater pollution, and so on. Statistics for direct use of treated wastewater are available only for China and Vietnam and usually underestimate real numbers. Produced and treated wastewater data are available for only nine countries, of which for five countries the latest information is 15–20 years old (FAO 2011). Only six countries reported the use of desalinated water. Pakistan accounts for the highest percentage (41%) of mixed surface water and groundwater, followed by Philippines (16%). Facts on direct use of treated wastewater and agricultural drainage water are available for only three countries. China reported 13,390 million m^3 of direct use of treated wastewater in the previous survey (2011), and Vietnam reported 175 million m^3 in 2011. Direct use of agricultural drainage water is reported by India, accounting for 11,347 km^3 in 2007.

9.6 SUMMARY AND CONCLUSIONS

Access to clean and safe freshwater is essential for life, food production, and sustainable economic development. Many regions and countries throughout the world are experiencing water stress. In developing regions, it is estimated that 748 million people do not have access to an improved source for drinking, and many more rely on sources that are unsafe for drinking as a result of contamination with pathogenic microorganisms. One approach to reduce the incidence of waterborne disease is to provide effective household-based water treatment and storage, although it is a matter of debate as to whether or not HWT interventions might actually influence the incidence of diarrheal diseases without a holistic approach to safe drinking water, sanitation, and hygiene. More concerning is that 2.5 billion people do not have access to improved sanitation facilities and open defecation is still widely practiced in many developing countries. One solution to addressing water scarcity and sanitation in combination is the reuse of wastewater, although this requires strict planning and monitoring to avoid the associated risks.

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10 Perspectives on Managing Freshwater Systems for Sustainable Use

Jeffrey A. Thornton, Walter Rast, and Hebin Lin

CONTENTS

10.1 INTRODUCTION

A century ago, naturalists began to report that the condition of rivers, lakes, and other water bodies appeared to be influenced by the nature of the landscape in which they were located and the demands placed on them. Thienemann (1918) and Naumann (1919) were among the first to introduce the concept of the drainage basin or catchment area (also called watershed) in which a water system was located as the landscape element affecting water quality and water body condition. With this observation, these pioneers launched the science of limnology, the study of the biology, chemistry, and physics of inland waters. In the decades that followed, other pioneering limnologists characterized waters located in areas extending from Europe outward to North America to the tropics. In so doing, they identified many of the basic principles that underlie human interactions with the life-sustaining freshwater resources of our planet. Among other products of this “voyage of discovery” was the seminal *Treatise on Limnology* (Hutchinson 1957), which remains a standard text on the behavior of water, particularly in lakes and reservoirs.

Humans have a range of freshwater concerns (freshwater flows, overabstraction, pollution, fisheries exploitation, water level changes, shoreline degradation, recreation and tourism uses, etc.). This chapter, however, focuses primarily on assessment and management of freshwater quantity and quality issues. As pointed out by Illueca and Rast (1996), freshwater displays three defining characteristics in this regard. It is *finite*, in that there is a fixed quantity on our planet that is continuously being recycled via the hydrologic cycle. It is *sensitive*, in that it is readily degraded by human activities in the surrounding watershed. Finally, it is *irreplaceable*, in that there are no substitutes for water for its many human uses. It had become alarmingly clear by the 1960s, however, that humanity’s impact on these water bodies so critical to human survival and socioeconomic well-being was reaching a critical stage. Pollution, for example, the presence of elements, compounds, and microbial organisms that can render water resources less suited or unfit for human uses, was becoming rampant. It was obvious that action was required to reduce or halt this continuing trend of degradation. It was during this period, for example, that the Clean Water Act was adopted in the United States, building on the foundation of the federal Water Pollution Control Act, with the US Environmental Protection Agency being created to spearhead the remedial efforts. The overall US goal was to return all inland waters to a “fishable and swimmable” state, or a condition in which full-body contact recreation was possible and aquatic life could exist in a way that maintained the balance between producer organisms and consumer organisms. Subsequent complementary activities were the launching of the National Eutrophication Survey in the United

States and the establishment of the Pollution from Land Use Activities Reference Group (PLUARG) for the Laurentian Great Lakes by the US–Canada International Joint Commission (IJC). Terms such as *point source* and *nonpoint source pollution* entered the vocabulary as a means of distinguishing pollutant discharges originating from a known (point or pipeline) source from those originating from more storm-generated runoff and other diffuse (nonpoint) sources.

These actions focused on two aspects of water quality degradation, namely, the causes and consequences of pollution, and the engineering mechanisms necessary to moderate the polluting materials being discharged and dispersed into the environment. In many cases, pollution controls produced beneficial results for water bodies that had been affected by wastewaters historically discharged into them. There also were water bodies, however, that failed to respond to the application of wastewater treatment practices, an example being the lack of response of Shagawa Lake (Minnesota, USA) to reduced municipal wastewater nutrient loads (Malueg et al. 1975). This and other “failures” led to more scientific studies, as well as the development and application of new engineered “solutions” designed to reverse the undesirable conditions affecting the world’s waters.

As a noteworthy observation, the IJC PLUARG (1978) study concurrently revisited the founding concepts of limnology, taking a landscape-based look at underlying reasons behind the lack of adequate response of the Laurentian Great Lakes, particularly Lake Erie, to major point source pollution controls that had previously been applied with successful results to other lakes. Simply stated, the Great Lakes were continuing to exhibit symptoms of eutrophication of greater magnitude than would normally be expected solely on the basis of the nutrient inputs from municipal wastewater treatment plants. The only credible conclusion for this anomaly was that other significant nutrient sources existed in the Great Lakes Basin that needed to be identified, characterized, and quantified in order to properly address the degradation of the lakes from eutrophication. By changing the focus from nutrient point sources to the drainage area tributary to the Great Lakes, the PLUARG clearly demonstrated that human activities in the landscape surrounding the lakes could mobilize varying quantities of sediments and pollutants from the land surface in the runoff after precipitation or snowmelt, as well as via airborne transport, ultimately moving them to rivers, lakes, wetlands, and other receiving water systems. By changing land use practices, therefore, the quantity of such contaminants could either be reduced or increased. The PLUARG (1978) study findings were catalytic in setting engineering and administrative actions into motion that subsequently led to the implementation of such concepts as Total Maximum Daily Loads and Municipal Separated Storm Sewer System (MS4) permitting in the United States, as well as underpinning the Great Lakes Water Quality Agreement (IJC 2015) between the United States and Canada. These actions also broadened the scope of the practice of river and lake management to maintain an emphasis on science and engineering, and even more importantly incorporated elements that targeted human actions and activities as well, particularly with the backing and support of legal, legislative, and financial authorities.

It is noted that water-based issues can involve human activities occurring directly within a river or lake (e.g., overfishing, excessive water abstraction) and activities occurring in a water body's surrounding drainage basin (e.g., land degradation, population growth). In fact, there are a range of technical and engineering approaches and remedial measures to address water quantity and quality issues affecting inland waters, including rivers, lakes, wetlands, and aquifers. Expanding the emphasis of remediation to include considerations of human-based activities in a drainage basin or overlying an aquifer worked to address the nub of a then-continuing conundrum; namely, what was missing from the equation that was limiting the efficacy of protective and remedial measures, particularly point source controls, being implemented for the protection and rehabilitation of freshwater systems? To this end, this chapter highlights drainage basin–based human activities as seminal causes of water resources degradation, with an emphasis on pollution of water systems. It explores several perspectives for addressing this missing link in the water resources management arena, particularly the increasing important role of societal involvement, particularly basin stakeholders, in water resources management intervention decisions.

10.2 POINT AND NONPOINT POLLUTION SOURCES

Point sources of pollution have received much attention from a technical and engineering perspective. The construction and operation of municipal wastewater treatment plants, and pollutant recycling and recovery at industrial plants, are examples of a technology-based approach to addressing this pollution, particularly in developed countries. Developing countries also utilize such approaches to varying degrees, although they also often utilize less technology-based approaches in favor of more labor- and sometimes time-intensive approaches, including settling ponds, wetlands, manual harvesting of vegetation, and so on. In regard to nonpoint sources of pollution, the PLUARG study was instrumental in demonstrating that all human activities on the land surface (and above the land surface, in the case of emissions from smokestacks and chimneys) can have significant impacts on the waters and waterways in the Laurentian Great Lakes basin, and presumably elsewhere around the world. Many of these impacts were found to be predictable. Row crop agriculture, for example, can result in the runoff of large quantities of pollutants after precipitation events, including soil (sediment), nutrient fertilizers, and pesticides, while runoff from urban areas can produce a different suite and quantity of contaminants (PLUARG 1978). Further, the loads of such contaminants to receiving waters could be estimated in the form of "unit area loads" (UALs), the quantity of contaminant generated per unit area of land devoted to specific purposes (agriculture, urban, industry, forests, etc.). An example of UALs by major land use type is provided in Table 10.1. In the absence of, or inability to conduct, direct measurements, and on the basis of knowledge of the population and range of land uses in a particular basin, this approach allowed for prediction or estimation of the quantity of specific contaminants likely to be produced through human and natural processes in the basin. Nevertheless, simply estimating the quantity of pollutants generated from a particular type of land use does not equate to understanding how a water body may actually respond to these inputs. In fact, it was clear that something was happening between the generation of such pollutants on the land surface and their inputs into receiving water bodies that was altering their impacts on the water bodies.

TABLE 10.1
Typical Unit Area Loads by Land Use Type

	Unit Area Loads (kg ha^{-1} Year^{-1})				
Land Use Type	**Total Suspended Solids**	**Phosphorus**	**Lead**	**Copper**	**Zinc**
	Urban				
Residential—low density	21.8	0.22	0.01	0	0.01
Residential—medium density	112.1	0.30	0.04	0.22	0.16
Residential—high density (no alleys)	269.0	0.95	0.31	0.13	0.91
Residential—high density (with alleys)	356.5	0.95	0.41	0.13	0.91
Residential—multifamily	269.0	0.95	0.41	0.13	0.91
Commercial	878.9	1.35	0.60	0.25	1.67
Industrial	843.0	1.31	0.60	0.25	1.67
Governmental and institutional	572.8	1.51	0.28	0.08	0.90
Communications and utilities	10.6	0.12	0.01	0	0
Transportation—highway	123.3	0.12	0.19	0.27	0.96
Transportation—railway	10.6	0.12	0	0	0
Recreational	26.9	0.30	0.01	0	0
	Rural				
Agricultural—cropland	504.4	0.96	0.01	0	0
Agricultural—pasture	504.4	0.96	0.01	0	0
Forest and woodland	4.1	0.04	0	0	0
Wetland	4.1	0.04	0	0	0
Open land	10.6	0.12	0.01	0	0
Nature reserves	4.1	0.04	0	0	0

Source: Adapted from SEWRPC. 1979. Planning Report No. 30, *A Regional Water Quality Management Plan for Southeastern Wisconsin–2000*, Volume One, Southeast Wisconsin Regional Planning Commission, Waukesha, Wisconsin. 438 pp.

10.2.1 LENTIC AND LOTIC WATER SYSTEMS

It is important in considering water resources management options to distinguish between lentic and lotic water systems. Each has its defining characteristics and associated management challenges. For a long period, water resources have been viewed within a hydrodynamic–hydrostatic perspective, with a focus on their value as a commodity. Lotic water systems include rivers, tributaries, drainage channels, and other similar systems in which “flowing” or moving waters exist (i.e., hydrodynamic). As such, they represent water transport systems. In contrast, lentic water systems denote water in a pooled or “standing” state, including lakes, reservoirs, wetlands, estuaries, and even standing water in rivers (i.e., hydrostatic). Water obviously moves through these latter systems as well, but at a much reduced rate because of the longer water residence time of the latter. This characteristic also ensures that water problems can exist for a long time in lentic water systems and that implementing solutions for them also can take a long time.

More recently, the concept of lentic versus lotic waters has gained greater significance in regard to water resources management goals. The lentic–lotic concept denotes an expression of the ecological and anthropogenic state of water, including its evolutional and historic “memories” of the interactions between humans and nature. As a brief description, key features of lotic water systems such as rivers and tributaries include their *transporting nature* in moving everything from upstream to downstream, their relatively short water residence times that can impart a *transient nature* to many problems affecting them, particularly after implementation of remedial actions, and complex response dynamics in which “everything can affect everything else” in the water, even within a short period because of rapid mixing and transporting, and biological components adapting to the significant aquatic motion in a water transport channel.

In contrast, lentic water systems such as lakes and wetlands are characterized by an *integrating nature* ensuring that all problems come together in a lake basin, meaning in-lake issues are mostly inseparable and not amenable to treating only part of a lake; by a long water residence time that dictates that in-lake problems can be incremental in impact and take a long time to become evident; and by characteristic nonlinear responses to inputs and other environmental disturbances. This buffering capacity of lentic water systems, attributable to their large water volumes, long residence times, and nonlinear responses, is especially problematic in implementing effective management interventions. This capacity can mask incrementally occurring environmental stresses until they have become serious problems, as well as masking positive responses to remedial actions for varying periods, thereby facilitating possibly erroneous conclusions regarding the efficacy of management interventions.

Despite these unique characteristics, in one sense it is pointless to differentiate between the importance of lentic versus lotic water systems since their relative utility is a function of such factors as their location, their watershed characteristics, the prevailing climatic conditions, and the range and magnitude of the uses of their water and related resources. It is noted, however, that lentic waters are generally not receiving the attention they merit in global freshwater fora. Ironically, they contain more than 90% of the liquid freshwater on the surface of our planet, provide the widest range of life-supporting ecosystem goods and services, and are the primary water infrastructure components constructed by humans to address their water needs (RCSE and ILEC 2011).

Interestingly, most surface freshwater basins represent a linked mosaic of lentic and lotic water systems (Figure 10.1). Although not shown in Figure 10.1, groundwater linkages also are important freshwater considerations in many parts of the world, often being the only freshwater resources in many arid regions, as well as providing the base flow of rivers during low-flow periods. Thus, managing freshwater systems for sustainable use, whether lentic or lotic in character, should take into consideration the other water systems to which they are linked, including even downstream coastal areas into which they may ultimately drain. Further, as discussed later in regard to payment for ecosystem services, downstream water needs can dictate the magnitude and nature of water resources management interventions.

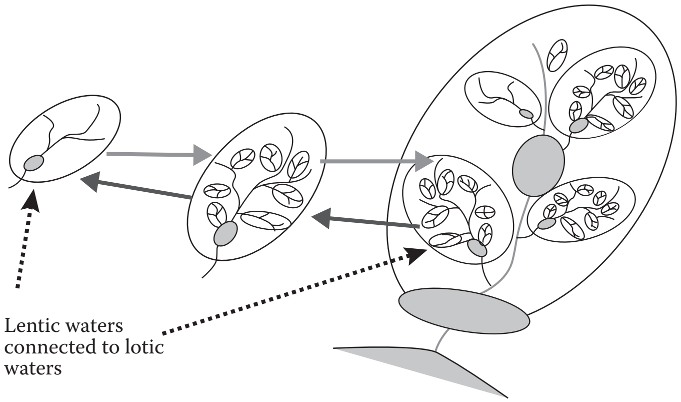

FIGURE 10.1 A water basin typically consists of multiple linked lentic and lotic water bodies; groundwater aquifers also might underlie part or all of the basin. (From RCSE and ILEC. 2011. *Development of ILBM Platform Process: Evolving Guidelines through Participatory Improvement*. Nakamura, M. and W. Rast [eds.]. Research Center for Sustainability and Environment–Shiga University and International Lake Environment Committee Foundation, Kusatsu, Shiga, Japan. 76 pp. [Downloadable from ILEC website: http://www.ilec.or.jp])

An example is Lake Biwa in Japan, with the water needs of the downstream city of Osaka essentially dictating the nature of the upstream management interventions in the Lake Biwa basin needed to ensure a sustainable water resource for this downstream city (RCSE and ILEC 2011).

Further discussion on the importance of consideration on the nature of lentic versus lotic water systems, and the implications for their management interventions, is provided by RCSE and ILEC (2011). Consideration of these linkages, and their scientific and management implications, is fundamental in developing and implementing timely, effective, and sustainable management interventions, whether national or transboundary in scope.

10.2.2 RIVER CONTINUUM CONCEPT

One scientific response to investigating the previous discussion regarding what was happening between pollutant generation on land and resulting pollutant impacts in receiving waters was to investigate in-stream processing and contaminant retention in riparian areas. Concepts such as the River Continuum Concept (Vannote et al. 1980) were derived to attempt to explain the observed differences. This concept assumes a river system is an ecosystem constantly interacting with its bank, thereby changing its condition in its flows from its headwaters to the river mouth because of such factors as water flow volume and timing, river channel physical characteristics, biotic interactions, and so on. The lessons learned from such concepts, while generally indicating that the River Continuum Concept was too simplistic in its formulation (Bunn and Arthington 2002), led to the development of the concept of environmental flow requirements (Dyson et al. 2003). Environmental flow requirements, in turn, have influenced the operational regimes of some in-stream structures, particularly hydropower dams and other structures constructed to control river water flows (Esselman and Oppermann 2010). These types of linkages introduced and highlighted the need to balance basin-scale and shoreline-based human activities with the demands imposed by engineering constructions (e.g., water supply or hydropower infrastructure) versus the ability of the aquatic environment to sustain such activities and associated water demands without undergoing significant degradation or overuse.

10.2.3 Modeling Approaches and Water Management

The ability to estimate contaminant loads moving across the land surface in storm-generated and other runoff events, combined with the pioneering work of Sakamoto and colleagues (Sakamoto 1966) in demonstrating that knowledge of the in-lake concentration of phosphorus allowed forecasting of the likely responses of a lake to this nutrient, in the form of phytoplankton production, initiated a sequence of actions designed to assist decision makers, planners, and engineers to design infrastructure more in harmony with the aquatic environment. In regard to accelerated nutrient enrichment of lakes (i.e., cultural eutrophication), key advances made during this period included development of nutrient load-lake response models, a primary example being the OECD (Organisation for Economic Co-operation and Development) suite of load-response models (OECD 1982; Ryding and Rast 1989). More dynamic mathematical models, such as the soil and water assessment tool, the soil and water integrated model, and the agricultural nonpoint source pollution model, were subsequently developed to assist decision makers and managers to better predict and evaluate the impacts of alternative land use practices on the status of receiving water systems (Novotny and Olem 1994; Thornton et al. 1999).

The development and application of such quantitative techniques applied to the field of aquatic sciences facilitated our ability to better integrate the scientific concepts associated with managing the aquatic environment, with the quantitative techniques already employed by engineers. Such models made it possible to estimate the effects of engineered interventions, ranging from constructing dams (Thornton 1980) to urban-density developments (Quick and Thornton 1991). Planners and designers could utilize such forecasts, for example, to recommend appropriate placement of storm water management facilities, municipal wastewater treatment plants, and other infrastructure designed to minimize the impacts of human-generated polluting activities on the aquatic environment, including sustaining the ecosystem goods and services they provide to humanity, while also maintaining ecosystem integrity (MA 2005).

10.3 INTEGRATED WATERSHED AND CATCHMENT MANAGEMENT

One of the first “integrated” responses to water resources management was the concept of Integrated Catchment Management (ICM), also known as Integrated Watershed Management. A key feature of ICM was inclusion of all elements of the hydrologic cycle within the sphere of water resources management (Figure 10.2). In

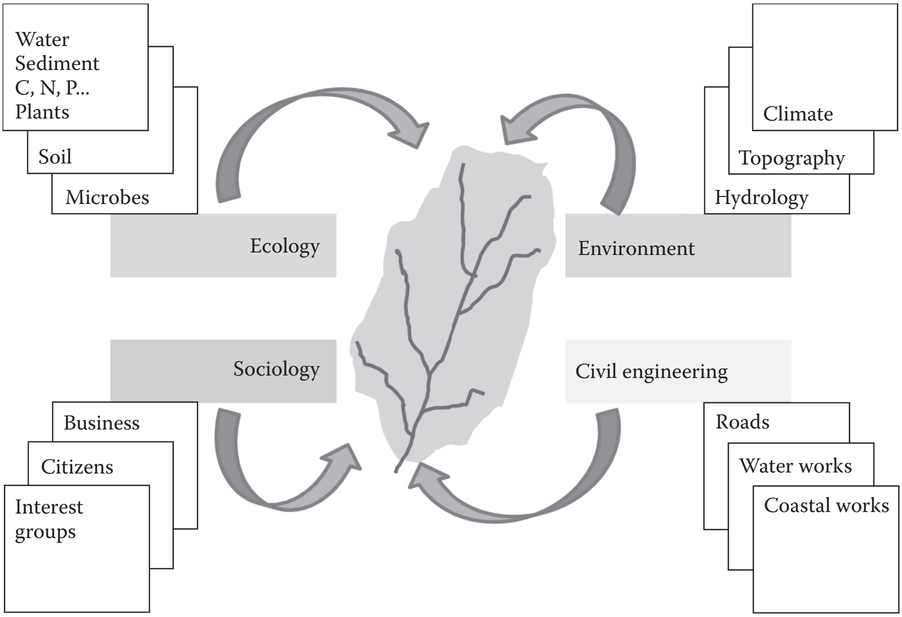

FIGURE 10.2 Graphic representation of the elements of Integrated Catchment Management. (Adapted from Bowden, W.B. 1999. Integrated catchment management rediscovered: An essential tool for a new millennium. Presentation at the national conference, "Cherishing the Land," Te Papa, Wellington, April 21–23, 1999. Published on the Landcare Research New Zealand website at: http://www.landcare.cri.nz/conferences/manaakiwhenua/papers/index.shtml?bowden.)

addition to considering precipitation events within a watershed, and the resulting surface runoff and subsurface water flows (groundwater), ICM sought to include structural components such as stream morphology, with the biological components dependent on the presence and quality of the water within the system (Ashton et al. 1995). Recognition of the connectivity between the aquatic ecosystem and the hydrological system, and indeed between elements of the hydrological system, represented a major step forward in water resources management, which was historically driven by sectoral interests to the exclusion of most other considerations. Additionally, the overt inclusion of ecological considerations represented a significant advance in the management of rivers, streams, lakes, and reservoirs.

ICM represented an important step toward linking science and engineering practices and provided a means for water managers to seek to address the causes and consequences of pollutant generation and input into receiving water systems through primarily structural interventions. Nevertheless, a fundamental shortcoming of the approach was its generally limited consideration of the important human element in the water resources management equation. In fact, people (stakeholders) typically were considered only indirectly in the evaluation of their role in modifying land uses in a way that generated contaminants and altered their inputs to aquatic systems. Reliance was placed primarily on engineering as the basis for controlling undesirable consequences arising from development or other human activities. Although ICM recognized that the human element was a major advance in water resources, this recognition remained tacit, rather than explicit, thereby remaining a significant shortcoming of this management approach (Ashton et al. 1995). In other words, there was a need for a major paradigm shift from managing a water system focusing solely on engineering or technological considerations, to focusing on managing the human activities in the basin that affected the water system. This unmet need introduced a complex range of social, economic, cultural, political, and financial elements to be considered in the water resources management equation.

10.4 INTEGRATED WATER RESOURCES MANAGEMENT

Recognition of the need to better account for the human element in water resources management decisions and better address the intersectoral issues associated with water demands, uses, and treatment, by linking water resources management to the increasingly globally recognized concept of sustainable development, resulted in the definition of Integrated Water Resources Management (IWRM). Defined as "a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP 2000), this approach introduced the idea of forecasting future conditions as a means of implementing management measures at the present time in order to minimize or avoid future conflicts. A positive effect of IWRM was to explicitly introduce the appropriate consideration of humans in the water resources management equation, in terms of its focus on ensuring both current and future generations would benefit from available water resources (Figure 10.3). In considering future water demands and uses, IWRM also introduced concepts such as equity in water use and availability, and limits to growth, into the water resources management sphere, adding some consideration of humans into water resources discussions, in addition to the previous engineering and natural sciences linkages.

The introduction of IWRM concepts coincided with the adoption of concepts such as sustainable development and equity that predated considerations of social justice (Bullard 1994). Through the introduction of such concepts, IWRM included consideration of biological diversity (biodiversity) and resilience (the ability of ecosystems to adjust/respond to changes or external stimuli), thereby broadening the idea of managing water systems in a more holistic manner. Nevertheless, although focusing on sustainability allowed the human element to be more fully incorporated into the management sphere, consideration of humans still remained largely outside direct consideration in this management approach, rather being viewed in the abstract as beneficiaries of the management measures, rather than as participants in the decision-making process.

The advent of IWRM resulted in a resurgence of planning efforts aimed at balancing human uses and the ability of the aquatic systems to support these uses. In some countries, such as Brazil and South Africa, this led to the redrafting of country-level water laws to include policy mechanisms necessary to give effect to this balance. Water resources management devolved in both countries to more localized units

FIGURE 10.3 The IWRM framework. (Adapted from UN Water and Global Water Partnership (GWP). 2007. *Roadmapping for Advancing Integrated Water Resources Management (IWRM) Process*. International Conference on Managing Water Resources Towards 2015, Copenhagen, 7 p. [Downloadable from website: www.ucc-water.org])

of government that effectively became the interface between resource managers at the national level and water users at the catchment level. Under such reformulated water laws, the national governments established the overarching policies necessary to ensure consistency of application at the local level, while decision making within the scope of the national laws was undertaken at the watershed level. Provision was also made to ensure environmental water use in South Africa. Noting that the overall global water crisis includes such elements as safe drinking water and sanitation, water for food versus environmental needs, and the uncertainties associated with climate change, in attempting to address such challenges, IWRM clearly influenced water resources policy reforms, particularly in developing countries.

10.5 INTEGRATED RIVER BASIN MANAGEMENT

As the knowledge and experience with ICM and IWRM continued to develop, the need to explicitly include basin water use stakeholders in the management process became increasingly more noticeable. Previous initiatives had successfully brought together engineers and scientists and introduced the idea of sound governance as a foundation for managing water resources in a way as to sustain future development of human civilizations, while preserving the ecological building blocks upon which human economies are sustained. Thus, another perspective in the scope of water resources management efforts was articulation of Integrated River Basin Management (IRBM). Within this framework, humans were more closely engaged in the management process (Figure 10.4). IRBM was founded on a shared and more focused vision of a river system developed from considering the water needs and demands of human water stakeholders in a specific drainage basin. Under this shared vision, all human development activities in a given basin could be considered and an agreed balance could be achieved among the relevant stakeholders. A key element of IRBM was to link management objectives across sectoral boundaries, inclusive of poverty reduction strategies. Local decision making was a hallmark of this facet of water resources management. Development of strategic plans was fundamental to document and identify competing water use requirements in a transparent and informed manner, including the water needs required to sustain the functions of the natural environment. The principles of collective decision making were embodied in the formulation of management strategies under this framework. It was thought that adequate investment in resource management could be encouraged through this process and, by promoting the participation of the basin stakeholders, management would be firmly grounded on a knowledge of both natural and socioeconomic influences.

The framework spawned the creation of numerous river basin organizations, having been established for most of the world's great rivers. Examples include the Amazon (Amazon Cooperation Treaty Organization), Plata (Comite Intergubernamental Coordinador de los Paises de la Cuenca del Plata), Nile (Nile Basin Initiative), Congo (Commission Internationale du Bassins Congo–Oubangui–Sangha), Zambezi (Zambezi Watercourse Commission), Danube (International Commission for the Protection of the Danube), Rhine (International Commission for the Protection of the Rhine), St. Lawrence (International Joint Commission), and Mekong (Mekong River Commission) Rivers. These organizations have proven to be effective in promoting international cooperation in managing the shared water resources of these large basins. The same principles also have been applied to smaller rivers, usually with the same effect. Similar multilateral organizations have been developed around some of the larger lakes, with the IJC serving a coordinating role between the United States and Canada relative not only to the St. Lawrence River but also to the Laurentian Great Lakes and elsewhere along the common US–Canada border. Similar organizations focus on Lake Geneva (International Commission for the Protection of

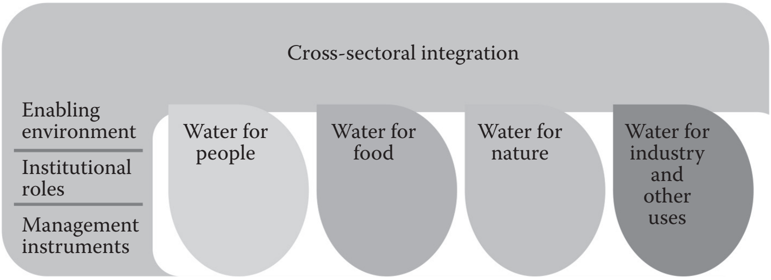

FIGURE 10.4 The IWRM planning framework. (Adapted from GWP. 2000. *Integrated Water Resources Management*. Technical Advisory Committee Background Papers No. 4, Global Water Partnership, Stockholm. ISBN: 91-630-9229-8.)

Lake Geneva), Lake Titicaca (Autoridad Binacional Autonoma del Sistema Hidrico del Lago Titicaca, Rio Desaguadero, Lago Poopo y Salar de Coipassa), and Itaipu Binacional, while several commissions serve the African Great Lakes (e.g., Lake Chad Basin Commission, Lake Tanganyika Authority, and Lake Victoria Basin Commission). All these organizations are governmental in nature and seek to address shared concerns between basin countries. There are also numerous smaller organizations, generally binational in character, that provide a forum for promoting equity in managing shared water resources between countries. Because representation on these various commissions and organizations is frequently at the governmental level, however, representation by individual stakeholders is often limited. To some extent, these limitations have been addressed in the "basin parliaments" created under innovative water laws such as those of Brazil and South Africa. In considering the global degradation of river basins, it is clear that IRBM had significant impacts on policy and program development in river basin management. Nevertheless, while bridging some of the gaps between science, engineering, and governance, this framework still primarily focuses on the technical aspects of water resources management.

10.6 INTEGRATED LAKE BASIN MANAGEMENT

A more recent contribution to the concept of integrated management of water resources is the Integrated Lake Basin Management (ILBM) framework, designed as an integrated management framework to address both lentic (pooled) and lotic (flowing) water systems (ILEC 2005). It is important to note that ILBM complements IWRM through its emphasis on the importance of the unique characteristics of lakes and other lentic water systems and the challenges this represents in regard to their management for sustainable use (see ILEC 2005). The ILBM framework considers six major elements underlying water resources governance (Figure 10.5). Humans are central to the process of managing water resources, with the concept of sustainability facilitating the continuity of the structure and functioning of the underlying ecosystem necessary for supporting, regulating, and generating a range of life-supporting, aquatic ecosystem-based goods and services. As noted above, this human—or anthropocentric—focus has always been an unspoken element in water resources management. By explicitly recognizing and acknowledging this focus, however, ILBM now directly links people (basin stakeholders) to the aquatic resources that address their water and related needs. It retains a solid grounding in science and engineering (collectively shown as technology; see Figure 10.5). However, ILBM also greatly enhances the role played by water stakeholders in the environmental management process. Not only are functional and functioning institutions critical for successful water resources management, sound and practical policies, effective stakeholder participation, and wide dissemination of relevant information are also recognized as essential elements of lakes, wetlands, and other lentic water systems. The fundamental role of sustainable and appropriately applied finances is also highlighted.

It is important to recall that lakes and reservoirs represent the greatest volume of readily accessible freshwater available to meet human needs, containing at any given instant more than 90% of the liquid freshwater on the surface of our planet. Further,

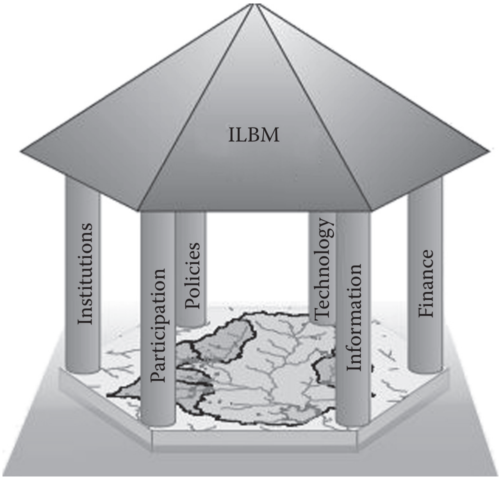

FIGURE 10.5 The six pillars of Integrated Lentic-Lotic Basin Management, as exemplified in ILBM. (From ILEC. 2005. *Managing Lakes and Their Basin for Sustainable Use: A Report for Lake Basin Managers and Stakeholders*. International Lake Environment Committee Foundation, Kusatsu, Shiga, Japan. ISBN: 4-9901546-2-2.)

they represent one of the largest reserves of biological diversity, including readily available reserves of fish and other food resources. They also serve as “mirrors” that collectively reflect the conditions and impacts resulting from human activities within their watersheds and drainage basins. The *World Lake Vision* stated these features of lakes and reservoirs in the following seven principles (ILEC 2003):

- A harmonious relationship between humans and nature is essential for the sustainable use of lakes.
- A lake drainage basin is a logical starting point for planning and management actions for sustainable lake use.
- A long-term preventative approach to preventing the causes of lake degradation is essential.
- Policy development and decision making for lake management should be based on sound science and the best available information.
- The management of lakes for their sustainable use requires the resolution of conflicts among competing users of lake resources, taking into account the needs of present and future generations and of nature.
- Citizens and other stakeholders should be encouraged to participate meaningfully in identifying and resolving critical lake problems.
- Good governance based on fairness, transparency, and empowerment of all stakeholders is essential for sustainable lake use.

The efficacy of these principles in supporting effective management of the water bodies and their watersheds was subsequently documented in the *World Lake Vision Action Report* (ILEC 2007). This latter report highlights case studies in countries around the world in most ecoregions and climatic zones that demonstrated the universality of the *World Lake Vision* principles and the value of engaging stakeholders in water resources management.

10.6.1 THE LAKE BRIEF AS AN ILBM KNOWLEDGE BASE

Implementing ILBM is facilitated with the use of a planning tool known as a Lake Brief. The ILBM process comprises a set of stepwise activities guided by the main themes of a Lake Brief; namely, (1) acknowledging the state of lake basin management; (2) identifying and analyzing the issues, needs, and challenges regarding the six fundamental governance elements; and (3) integrating the ways and means to meet identified governance challenges and implement needed actions to address them. The Lake Brief is composed of a series of directed diagnostic queries designed to identify, rank, and respond to issues of concern. The general flow of the questions is outlined in Figure 10.6. It includes descriptive information on the lake and its watershed, the state of the lake environment, the human communities, and the major issues of concern, with this knowledge meant to facilitate identification of appropriate interventions (Nakamura and Rast 2012). The design and content of a Lake Brief are sufficiently comprehensive, however, they can also be used in a diagnostic mode for other lentic and lotic water systems.

In this discussion of the Lake Brief, the term *lake* is meant to include all lentic water bodies, including natural lakes, constructed lakes (reservoirs), and wetlands. In developing lake and watershed management plans, it is important to identify and characterize the water body that is the focus of the plan. Thus, the first step in the planning process is to clearly identify a water body and its drainage basin. A description of the nature of the water body is also an important element of the Lake Brief. Natural lakes, for example, can be glacial, tectonic, or volcanic in origin, whereas

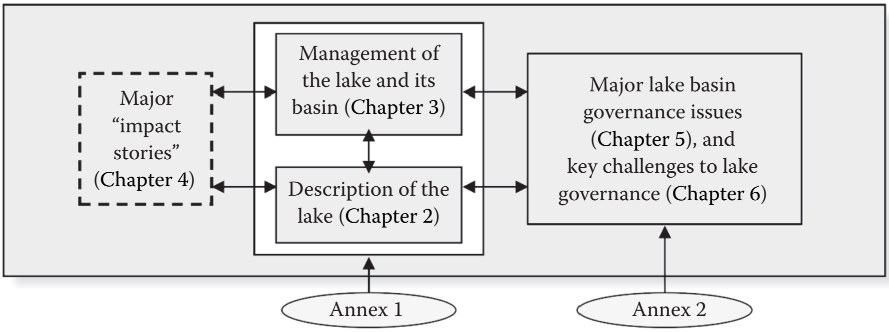

FIGURE 10.6 Preparing the Lake Brief to facilitate implementation of ILBM. (From ILEC and RCSE. 2012. *Primer: Development of ILBM Platform Process. Evolving Guidelines through Participatory Improvement.* Nakamura, M., W. Rast, T. Kagatsume, and T. Sato [eds.]. Research Center for Sustainability and Environment–Shiga University and International Lake Environment Committee Foundation, Kusatsu, Shiga, Japan. 26 pp. [Downloadable from ILEC website: http://www.ilec.or.jp])

constructed or artificial lakes (reservoirs) will have construction specifications, preferably in the form of "as-built" measures.

10.6.1.1 Description of the Lake and Watershed

The water body, including its name(s) and location, should be documented via a clearly stated geographic reference system. Latitude and longitude are generally used, although other coordinate systems can be used to accurately locate a water body. If a lake has an outlet, its discharge point location should be recorded. The water surface elevation also should be recorded, including the range of water levels if the water body exhibits fluctuating water levels.

Information on the drainage basin or watershed should also be documented. The basin extent should be delineated, and the topography of the landscape containing the basin and its lake should be described and mapped. The civil jurisdiction(s) in which the water body is located should be recorded. Usually, information on governmental units can be found in historical records and land office information. The name(s) of the inflowing river(s) should be noted, and the locations of major settlements, including population number, distribution and density, water discharge and abstraction points, and other relevant information germane to the state and character of the basin, should be documented. Any significant groundwater inputs should be documented, and delineation of the areal extent of the local aquifer(s) should be recorded if possible. Soil types should be described and mapped.

10.6.1.2 Lake Morphology

In much the same way as the drainage basin or watershed topography is documented, the water body dimensions should be recorded. These include the lake and drainage basin surface areas, water volume, maximum and mean depth, shoreline length, lake length and width, and average water level (or water level range in case of fluctuating water levels). The mean depth can be calculated as the ratio between lake volume and lake surface area, which is an important measurement for many mathematical lake response models used to forecast future lake conditions, evaluate lake fisheries, and so on.

10.6.1.3 Climate

Climate data are important in determining the water balance of a lake. Information and data on rainfall, evaporation, wind velocity and direction, temperature, and seasonality can facilitate better understanding of how a lake will respond to external and internal stimuli.

10.6.1.4 Water Balance

The water balance represents the sum of the volumes of water flowing into and out of a lake. Inflow includes precipitation (both directly onto the lake surface and in the watershed), while outflow includes evaporation, river flow, and abstractions, adjusted for the gain or loss of water within the water body. Groundwater volumes should be included in these estimates, if known. This information facilitates calculation of the water residence time (ratio of lake volume to outflow volume; alternatively, inflow volume could be used, depending on where water flow volumes are measured relative to the lake). Knowing the water residence time is important in evaluating the potential impacts of contaminants on a water body. Rapid water flow-through rates, for example, can moderate the negative impacts of nutrients on a lake (Dillon 1975).

10.6.1.5 State of the Lake Ecosystem

Knowledge of the general state of the ecosystem, and any changes over time, is important for characterizing and prioritizing possible management needs and interventions. In considering the eutrophication process, for example, lakes are typically classified in descriptive terms such as nutrient poor (oligotrophic), nutrient rich (eutrophic), or moderately enriched (mesotrophic). Extremely nutrient-enriched water bodies are often described as hypertrophic. Humans affect the rate at which nutrients enter a water body from land-disturbing activities, application of artificial fertilizers, municipal wastewater disposal, and so on. Developed countries generally desire nutrient-poor, transparent water bodies, suitable for the maximum range of human water uses. In contrast, the increased biological productivity characterizing nutrient-enriched water bodies often is desired where fish farming and other aquaculture activities are practiced, particularly in developing countries. Thus, even human perceptions can play a major role in defining the condition of a water body as "good" or "bad," with the same eutrophication process being viewed within diametrically opposed perspectives in these two environmental settings (Thornton et al. 2013).

10.6.1.6 Physical Characteristics of the Lake

These characteristics refer to water behavior within a lake. The thermal or temperature characteristics drive many biological and chemical responses in a water body, including the magnitude and rate of algal growth and the nature of the fishery. Knowledge of water temperature by depth and time helps define a water body's mixing regime. Tropical lakes, for example, tend to exhibit complete mixing of the entire water column from the top to the bottom of the lake once a year, generally at the end of the warm season. Temperate lakes tend to mix completely twice a year, in spring and autumn. These two types of lakes can stratify thermally, developing a warmer surface water layer and a cooler bottom water layer. The lower water layer in lakes experiencing serious eutrophication can exhibit low oxygen concentrations because of the decomposition of algal blooms originating in the upper water layer, which subsequently sink to the bottom, resulting in oxygen depletion in the bottom waters. This condition can be detrimental to fish and other aquatic organisms in the lower water layer. It can also force fish to move into the upper layer of a lake, thereby also affecting potential fish production through both crowding and predation. The degree of light penetration into the water column is also important since it drives algal production and aquatic plant growth in a water body, particularly lakes. It is also a measure of the trophic state of a lake. Periods of ice cover, if any, should be recorded.

10.6.1.7 Chemical Characteristics of the Lake

Water chemistry is the most direct measurement of the lentic "hydroclimate." Chemical contaminants can affect the nature and extent of aquatic plant growth in a lake, and the abundance and types of fishes and other aquatic organisms it can support. Typical measurements include nutrient concentrations and forms (particularly of phosphorus and nitrogen), dissolved oxygen concentration, pH, electrical conductivity (or salinity), biological oxygen demand or chemical oxygen demand, and concentrations of major cations (sodium, magnesium, manganese, and calcium) and anions (chloride, carbonate, and sulfate). Other contaminants such as pesticide (e.g., DDT), polyvinyl chloride, polyaromatic hydrocarbon, and mercury concentrations may also be measured, depending on the specific water quality concerns and water quality management goals.

It is noted that rivers also undergo degradation from pollutant inputs within their watersheds. The symptoms of this degradation, however, may not become visible until after they enter a lake, mainly because of the previously noted larger water volumes and longer water residence times in lakes and their nonlinear responses to contaminant inputs, which introduce a lag time before the symptoms become evident. Increased nutrient loads provide an excellent example of this phenomenon. Although rivers can contain high nutrient concentrations, visible signs of high nutrient concentrations may only become visible in the form of algal blooms in lakes receiving the nutrients, rather than in the flowing rivers themselves. In fact, lakes are often triggers for remedial actions directed not only to the lakes but also to the upstream rivers that deliver contaminants to them. Thus, they represent a "barometer" of sorts regarding the impacts of human activities in their watersheds. Such knowledge is also useful for targeting remedial interventions by allowing managers to focus on watershed areas and land uses generating the largest pollutant loads. The contaminants delivered to a water body through direct rainfall are also relevant in management decisions, as the atmosphere can facilitate contaminant movement to a lake, particularly in rural or isolated regions.

10.6.1.8 Biological Characteristics of the Lake

Organisms in a lake or river require the same growth factors as for terrestrial plants and animals, namely, sunlight, nutrients, appropriate temperature, and space. The physical and chemical regime of a lake will influence its biological response to both internal and external stimuli. Enriched lakes, for example, will support a greater mass of plants and animals than less-enriched lakes but may contain fewer species, even if there are numerically more organisms overall. Needed information to determine the biological characteristics of a lake include the numbers and kinds of algae, aquatic plants, zooplankton, and fishes, as well as the biomass and species of bottom-dwelling organisms and the numbers and species of birds. The length, mass, and species of fish can also be important information. The numbers and types of plants and animals collectively define the biological diversity of a water body, with several indices being available to evaluate it (e.g., Shannon–Weaver index for algae). Shore land vegetation, terrestrial vegetative cover, and wetland distribution within the drainage basin should also be determined.

The presence and abundance of nonnative species should also be documented, since they can disrupt a lake ecosystem by outcompeting native species, consuming, or shading native plant and animal communities, and affect the utility of a water body for human purposes. The introduction of Nile perch (Kees et al. 2008) into

Lake Victoria, for example, increased fish biomass and productivity, but at the cost of annihilation of some species of native cichlid fishes. The perch also proved to be less desirable to anglers and commercial fishing operators, who found that these larger fishes could not be as readily preserved with the commonly employed sun-drying techniques of local communities.

10.6.1.9 State of the Water Body and Its Basin

The collected information about a water body and its drainage basin should be analyzed and synthesized into a diagnostic statement about its status. The physical, chemical, and biological data on the lake will allow its classification in regard to its utility for addressing human water demands. The context of a lake within a basin should also be noted, such as determining whether or not a lake was part of a cascade or chain of lakes, and its position within the cascade (e.g., terminal lakes often benefit from contaminant retention in upstream water bodies). Land use trends should be summarized and future land uses should be forecast to the extent possible. The latter can allow calculation of future nutrient and other pollutant loads and, consequently, the potential future condition of the water body. This summary sets the stage for consideration of the desired water uses, compared to the extent to which a lake can meet and sustain these uses.

10.6.1.10 Lake Resources and Uses

Lakes serve a range of human purposes, from drinking water supply, to fisheries, to navigation and power generation, to recreation and tourism, as well as many uses that are more qualitative in nature (e.g., cultural or spiritual significance and aesthetics). Identifying and cataloguing these uses are helpful in determining the desirable water quality and water quantity conditions to best meet and sustain them. Lake water uses can be consumptive (e.g., irrigation and domestic water supply) or nonconsumptive (e.g., navigation and fisheries) in nature. Further, using water bodies as recipients of municipal wastewater discharges can radically affect their water quality, depending on the degree of wastewater treatment. In the case of hydropower generation, water releases from a dam or reservoir can affect both the quantity of water within the reservoir and in the downstream river. Large dams can moderate river floods, but perhaps to the detriment of aquatic species dependent on the sediments carried and deposited in the floodplains by the floodwaters. Small dams and commercial waterways, in contrast, can retain water on the land surface for use during dry periods and promote navigation possibilities, as in the case of the Sault Sainte Marie Locks between Lakes Superior and Huron-Michigan in the Laurentian Great Lakes system.

As noted above, while humans tend to focus on provisioning ecosystem services that benefit them financially or materially (e.g., fisheries production), and regulating services that keep the environment stable (e.g., flood control), lakes also support cultural services via providing water for religious observances or serving as aesthetic icons and inspirations for artists and authors (MA 2005). They also provide supporting services in modifying sediment transport, microclimate, and related functions often ascribed to "nature." Such ecosystem services should be considered in this section of the Lake Brief, as well as future desired water uses. A water body may not be providing irrigation water at present, for example, but could provide irrigation water in the future, and such uses should be considered to the extent that such a change in water use is warranted.

10.6.1.11 Water Use Impairments

After defining the desired lake water uses, it is necessary to determine whether or not the current lake conditions can actually support these uses. Water use impairment exists when the current conditions fail to support the desired uses. Such impairments should be described and quantified to the extent possible, since it can help determine the nature and extent of required remedial measures. The impairments can be physical (e.g., wetland destruction and shore land erosion), chemical (e.g., nutrient enrichment, salinization, and chemical contamination), or biological (e.g., excessive algal or aquatic plant growths, changes in fish abundance or composition, or the presence of nonnative species). Both current and likely future concerns should be documented, since it is always easier (and typically less expensive and time consuming) to avert a future impairment with proactive actions than to attempt to correct a situation after it has occurred as a reactive action. In those cases where a water body meets all current and anticipated uses, attention can be given to measures to protect the lake, rather than to rehabilitate it.

10.6.1.12 Determine Proximate and Root Causes of Lake Impairments

Knowledge of the desired and anticipated lake uses, and the degree to which a water body can meet these uses, will allow determination of the causes of present or potential future impairments. This includes the proximate causes of specific symptoms, as well as the root causes leading to specific impairments. Excessive algal growth, for example, typically is a result of high in-lake nutrient concentrations that, in turn, can be linked to a number of possible causative factors, including excessive fertilizer applications, municipal wastewater discharges, and so on. Rates of application or discharge might be attributable to agricultural subsidies and land management practices or to discharge permit requirements and pollution controls. Such factors, in turn, may be traceable back to government policies and laws. Thus, mitigating the excessive algal growth in such cases may require changing the laws governing agriculture and municipal wastewater discharges, which can include both point and nonpoint pollutant sources.

10.6.1.13 Addressing Lake Impairments

Responses to the foregoing analysis can take the form of actions to protect a water body currently meeting existing and forecasted water quality and quantity demands or via interventions in the lake or its watershed when a water body is failing to meet demands. Interventions can be structural (with engineered approaches) or nonstructural (with behavior changes or landscape management approaches). Both approaches have merit in specific situations and, in fact, a combination of structural and nonstructural may be needed to effectively protect or rehabilitate a water body. Rarely is a single action fully effective in addressing a water issue of concern, and the combination of efforts is usually site specific. Indeed, the notion that "one size does *not* fit all" is often an appropriate conclusion.

10.6.1.13.1 Structural Responses

Structural lake management responses generally include a range of engineered approaches to addressing water issues of concern. Managing municipal wastewater discharges is often the first management intervention to be pursued to address nutrient enrichment, for example, particularly in developed countries. This can include installation of municipal wastewater conveyance and treatment systems, ranging from simple on-site sewage disposal systems serving individual households or enterprises, to complex sewerage systems serving entire communities. Complex treatment can range from primary (removal of solids), to secondary (removal of oxygen demanding substances), to tertiary (removal of nutrients, primarily phosphorus) treatment stages, with direct recycling being an ultimate step in structural wastewater reclamation. Emerging concerns about contaminants not traditionally treated in wastewater management processes (e.g., complex organic molecules, carcinogenic and mutagenic substances, pharmaceuticals) also merit serious consideration and are spurring further research and development in municipal wastewater treatment technologies.

Similarly, infrastructure to treat storm water runoff is being engineered to address not only storm water as the historic focus but also the removal of sediment and other contaminants. In fact, the need for larger-scale mechanisms for storm water management and treatment has spawned the entirely new discipline of eco-hydrology, which draws on a combination of natural sciences and engineering to address complex problems associated with land runoff (Zalewski 2002).

Linkages between water pollution control and solid waste management include antilittering efforts (see below) and public health campaigns, forming a multifaceted approach to minimizing human impacts upon natural systems.

Finally, initiatives such as life-cycle analysis (Ryding 1998) are being applied to industrial and commercial activities as a means of reducing environmental degradation by recycling or reusing materials and components within existing industrial processes.

10.6.1.13.2 Nonstructural Responses

Nonstructural responses span the gamut from land use planning and management, and siting development to minimize environmental impacts, to enacting policies, laws, and regulations requiring compliance (including imposition of penalties for not doing so), to enhanced public awareness and voluntary action. The latter approach can often be effected at minimal cost and be most effective in protection efforts, with public awareness being key to changing stakeholder behaviors by altering public perceptions of issues and practices. Changing from "slash-and-burn" agriculture to terraced farming, for example, substantially reduced soil losses in the Bermejo River basin of Argentina and Bolivia (Binational Commission for the Development of the Upper Bermejo and Grande de Tarija River Basins, Global Environment Facility, United Nations Environment Programme, and Organization of American States 2000). Utilizing fencing to permit rotational grazing of sheep and goats in another part of the same basin allowed diversification of diet and pasture recovery, benefitting not only the environment (through reduced soil loss) but also public health in the area. In a similar vein, using native plants in public parks in Cape Town, South Africa, created greater awareness of their value and beauty, greatly enhancing support for creation of protected areas, reserves, and preserves (each area having differing levels of public access; Quick and Thornton 1991).

Ironically, many countries have various water pollution control laws “on the books.” However, many are frequently generic, simply stating that discharges of polluting substances are banned. Unfortunately, such laws often suffer from a lack of specificity regarding not only the required actions but also what actually constitutes pollution and polluting substances, particularly in developing countries. As previously noted, countries such as Brazil and South Africa have attempted to better address common concerns involving both water quality and water quantity through innovative water laws, giving stakeholders a voice in determining effective policies and practices, within the overarching umbrella of national water objectives. Such practices, however, remain the exception, rather than the rule.

As discussed further in Section 10.6.3, one mechanism found to be useful for implementing nonstructural management practices is the use of appropriate economic incentives, in the form of payment for improving ecosystem services through upstream–downstream interactions.

10.6.1.14 Socioeconomic and Political Responses

While the foregoing sections have touched on the topics of public policy, community engagement, environmental education, and economy, this portion of the Lake Brief highlights human connections with lakes and rivers and their watersheds, and with the natural environment. Consideration should be given to classroom-based environmental education and community-based public informational programming (frequently conducted in partnership with nongovernmental organizations). The use of linkages with religious and cultural institutions can also be a powerful force in raising environmental awareness, since they often involve on-the-ground connections. Water has played, and continues to play, for example, a central role in art, literature, entertainment (including recreation), and religion. Even when stakeholders within watersheds have little direct contact with a lake or other water body, they or their children often are exposed to the importance and beauty of nature through other media. Folk tales and local customs often directly result from human interactions with the environment, representing powerful vehicles for connecting with community members.

Public–private partnerships (e.g., between government and corporations) are also management opportunities to be evaluated within the Lake Brief. Many businesses are founded on, or rely on, access to and use of the natural resources, including those associated with recreation and tourism. The nexus between farmers and the land also merits attention. Many farms remain family concerns, particularly in developing countries, whereby the legacy of the land is handed down to succeeding generations. Good land stewardship in such cases often translates into sound watershed management.

Finally, an overriding goal of planning focuses on siting infrastructure and development in appropriate locations. The sustainability of the natural environment, especially those systems most closely associated with water resources (e.g., lakes, rivers, and wetlands), should be a major consideration in the decision-making process. It is often said, for example, that wetlands are not wastelands (Kadlec and Wallace

2009). Rather, they often form the "life blood" of streams and lakes and are conduits to and from groundwater aquifers, and flood lands essential for protecting human investments and human health and safety. Thus, the Lake Brief should consider the adage of "design with nature" (McHarg 1995) as a means of facilitating sustainable landscape development.

10.6.2 LAKE GOVERNANCE

In the absence of human disturbances, nature has repeatedly demonstrated that it can "manage" itself via a range of sometimes obvious, sometimes subtle, interactions and feedback mechanisms. As a simple example, rich grasslands might result from excellent seasonal rainfall. These grasslands, in turn, could trigger an explosive increase in the numbers of grassland-grazing animals such as elk. The increased number of elk, in turn, could excessively graze the grasses, thereby decimating the grasslands. The decimated grasslands, in turn, will cause the death of many of the elk as a result of lack of food and subsequent starvation. The reduced number of elk, in turn, will reduce the stress on the grasslands, thereby allowing them to recuperate to levels existing before the excessive grazing.

Humanity, however, appears to be unable to consistently imitate such feedback mechanisms. Rather, it can readily be argued that most environmental stresses or degradation related to human activities are the result of governance inadequacies. We may, for example, lack the necessary institutions or policies to effectively address environmental stresses, including those related to water resources. On the other hand, we may have such institutions or policies in place but lack the political will to implement and enforce them. It also may be a matter of inadequate, mismanaged, or unsustainable financial resources that constrain necessary actions or programs. All can usually be traced back to various kinds of governance "failures."

As noted earlier, IWRM as a means of promoting the coordinated development and management of water, land, and related resources has proven to be a valuable water resources management tool. Nevertheless, the process of "operationalizing" IWRM principles to deal with on-the-ground management challenges facing lakes, wetlands, and other lentic water systems has been problematic. Although both approaches are based on an integrated approach, ILBM focuses on on-the-ground governance improvement, in contrast to the usually higher-level policymaking on the national government level characterizing IWRM. Accordingly, ILBM provides a significant means of addressing governance inadequacies by focusing on the goals of sustainable management of lentic water systems through gradual, continuous, and holistic improvement of basin governance. The six governance elements or "pillars" of ILBM (see Figure 10.5) are directed to specific areas of human interactions with their environment. They include (1) institutional responsibilities, (2) policy directions, (3) stakeholder participation, (4) scientific and traditional knowledge, (5) technological possibilities, and (6) funding prospects. It is also noted that approaches for dealing with the highlighted ILBM governance elements are sufficiently encompassing to be considered for application to other water systems as well (e.g., rivers, aquifers, and even coastal areas) and can result in equally useful guidance regarding governance inadequacies. As summarized below, RCSE and ILEC (2011) developed a series of diagnostic questions to guide water resources professionals in preparation of a Lake Brief to provide the information needed to attempt to address these governance elements.

10.6.2.1 Institutions

- What institutions (governmental and nongovernmental) exist within the watershed?
- What does each institution do? Because all organizations have strengths and weaknesses, these should be identified in a constructive way such that weaknesses are formulated as opportunities.
- What are the institutional priorities, noting that one institution is rarely all things to all people? Communities should consider both formal and informal linkages between institutions so the strengths of the individual organizations can be blended into a cohesive set of actions and activities.

10.6.2.2 Policies

- What policies exist? These can be formal operating procedures, as well as informal, governmental, community based, or corporate.
- Are the policies being effectively implemented? It is noted that "good policies" are sometimes seen as an end in and of themselves, in that they may exist as a manual, but are not actually implemented. This is, in effect, similar to the policies not existing in the first place.
- Are new policies necessary? Needed changes can sometimes be effected by simply implementing an existing policy, rather than through duplicative or contradictory initiatives.
- Are there policy conflicts? The sectoral nature of policy development has historically led to situations such as agricultural agencies promoting the use of agro-chemicals, while environmental agencies are at the same time seeking to resolve nutrient enrichment or persistent organic pollutant concerns.

10.6.2.3 Participation

- Who comprises the "community"? To this end, while communities are composed of many individuals, these individuals may serve in many different roles, ranging from elected officials, to government agents, to members of conservation groups, to business and factory workers. Knowing the community composition is a first step in defining ways that individuals can actively support and participate in lake and watershed management.
- What stakeholder groups exist in the watershed? Identifying the main stakeholders is the first step in facilitating the implementation of a management plan. Many experiences around the world demonstrate that planning management interventions without stakeholder participation is a recipe for failure. Stakeholder groups can be both governmental and nongovernmental in nature, and can include environmental organizations as well as community groups.

- What mechanisms exist for stakeholder participation? Governmental entities particularly have mandates requiring public informational meetings. These often are only one-way channels of communication, however, flowing from the government to the communities. Participation that leads to true community involvement is a two-way process whereby stakeholder input is actively sought and acted upon.

10.6.2.4 Information

- What data and information exist? ILBM, as well as all forms of IWRM, should be based on sound science and good information. Identifying existing and reliable data sources is an essential first step and can include technical documentation, engineering analyses, and theses and dissertation existing in institutions of higher learning. Further, relevant information can include both formal and informal (or traditional) knowledge.
- What data and information are necessary to address lake basin problems? Compiling known sources of data and information can facilitate identification of data gaps, including specific investigations or more general surveys.
- How can the data and information be generated and disseminated? Although data are frequently acquired, they are not readily available or are poorly disseminated. Data dissemination should be considered an essential element of a data-gathering program. Unfortunately, data gathering is often viewed as an official function that neglects citizen scientists or volunteers that can substantially supplement the official workforce. Many highly skilled people retire, for example, and subsequently may seek a continuing useful role within their community. Employing such individuals as volunteer monitors can greatly multiply the data collection efforts of an agency or other institution. Further, partnering with local universities or colleges can be cost-effective, with such partnerships often being highly effective in addressing specific research questions (and in providing trained researchers to assist the community in the future).
- Have traditional and nontraditional sources of information been identified and explored? Anecdotal evidence is often ignored in the formal lake management planning process, even though properly interpreted oral histories can be a useful source of supplementary information and even of primary data in the absence of any other evidence (see Thornton and McMillan 1989; Thornton et al. 1989).
- Is regular monitoring conducted? Regular monitoring conducted both before and after an intervention is an important, and often overlooked, activity. Monitoring before an intervention is obvious and can often be the trigger for implementing remedial actions, and is frequently mandated as part of the planning and design process. Unfortunately, postintervention monitoring is frequently viewed as an unnecessary and expensive luxury. This conclusion is a fallacy for at least two reasons: (1) there is no other reliable means of providing a specific intervention was effective and (2) there

is no lesson to be learned if a specific intervention proves to be ineffective. Thus, continued monitoring, even if only volunteer monitoring by citizen scientists, should be an ongoing effort.

10.6.2.5 Technology

- What technological interventions have been used or proposed for use? To this end, modification or enhancement of existing interventions should be considered. As an example, upgrading an existing primary municipal wastewater treatment plant to provide secondary or tertiary treatment should be considered. Determining whether or not existing interventions are maintained regularly or upgraded periodically should also be considered. Poorly functioning or malfunctioning on-site municipal sewage treatment systems, for example, can do more harm than good if they discharge nutrients or bacteria into receiving water systems.
- What conservation measures have been considered and implemented? Conservation can be considered from the perspective of both natural resource conservation and conserving financial and human resources. Although highly sophisticated interventions are often effective, they are also often unaffordable, or unable to be serviced appropriately, at the community level. Even in the world of technological interventions, it is interesting that less complex approaches can prove to be very effective over the long term.
- What alternative technologies can be considered? Relying solely on engineered approaches, for example, often precludes consideration of working with nature and utilizing the characteristics of wetland systems as accreting systems (at least during certain periods of the year). It also can be less costly, for example, than constructing a tertiary municipal wastewater treatment plant.

10.6.2.6 Finance

- What funding is available within the drainage basin? Depending on the specific intervention being considered, funding sources can include tax revenues, license fees, and donations. For pollution control purposes, laws often make provision for fines and forfeitures (although these are frequently insufficient to be deterrents of bad practice, especially if the required pollution control is costly, which may result in the fines being viewed as merely the “cost of doing business”).
- Are external funding sources available? Grants and other temporary sources of funding may be available for specific projects and can include monies donated by private foundations or individuals, as well as governmental revenues redistributed through grants-in-aid.
- Are the funds ongoing and sustainable? Grant funds or other temporary funding sources are not sustainable. Many projects begun or constructed with these temporary funds fail during their operational phases because of the lack of community support for operations and maintenance (community support can be both financial and intellectual, in the sense of trained maintenance staff or operators).

- Can “sweat equity” be used? Cash money is not always the only revenue that can be used to facilitate implementation of integrated lake (or other water system) basin management practices. In-kind labor and provision of services is a frequently overlooked financial source. As noted above, many communities are gaining human resources in the form of skilled retirees that can perform specific useful functions, often based on years of knowledge and experience. Service organizations and youth groups, including schools, are also a frequently overlooked pool of human resources. Church groups, Scouts, service clubs (e.g., Rotary, Lions), and similar community-based organizations often engage in projects or participate in larger programs benefitting their communities. These groups are also generally committed to their specific communities as stakeholders.

In considering these governance elements, it is noted that transboundary water systems, whether lakes, wetlands, rivers, or aquifers, introduce an additional level of complexity to be considered, in that the interests of multiple countries must be appropriately accommodated if an acceptable integrated management program directed to the sustainable use of the water system and its ecosystem goods and services is to be achieved. Although relevant actions will necessarily occur on the national level, the focus will be the sustainability of the water resource to serve all the transboundary water demands, while also ensuring that the integrity of the water system is maintained, to the benefit of all basin inhabitants. To this end, there are remarkably few global-scale or even regional international waters agreements in effect. Several noteworthy lake-based agreements include the binational Great Lakes Water Quality Agreement, initially adopted by the United States and Canada in 1972 (IJC 2015), the regional Convention on the Protection and Use of Transboundary Watercourses and International Lakes, adopted by the UN Economic Commission of Europe in 1992 (UNECE 2015), and the global UN Convention on the Law of the Non-Navigational Uses of International Watercourses, adopted in 1997 (Loures et al. 2009). None of these international agreements, however, substantially address the range of constraints to sustainable use of lakes, their resources, and their basins, considering both human and ecosystem needs, and the actions needed to address the root causes of these constraints in a practical and effective manner.

10.6.3 PAYMENTS FOR IMPROVING ECOSYSTEM SERVICES AT THE WATERSHED SCALE

Economic considerations of various kinds are obvious and necessary components in developing and implementing water resources management interventions. Indeed, regardless of the language(s) spoken by water resources stakeholders, virtually everyone understands the concept of money, or its monetary equivalent in goods and services, as both a positive and a negative consideration, depending on the situation. In fact, within the context of command-and-control structures, economic instruments can be powerful forces in punishing water polluters or managing pollutant-generating activities, as well as controlling overabstraction of water, particularly if the associated fines and penalties are sufficiently high. Economic instruments can also be powerful incentives in changing human behaviors, in the form of tax breaks, subsidies, and other types of "rewards" for positive actions (RCSE and ILEC 2011).

Against this background, recognition of the fundamental role of "sustainable finances" as a critical element in implementing lake and river basin management interventions has gained prominence in recent years. In fact, decisions regarding management of shared water resources, whether locally, nationally, or internationally, often come down to consideration of their direct or indirect monetary impacts on water system stakeholders. Monetary policy characteristically has a shorter-term horizon than environmental policy, however, especially when a given environmental policy seeks to support sustainable outcomes whose benefits may accrue to future generations, rather than providing immediate stakeholder benefits. To bridge this gap, and building on the pioneering work of Costanza and colleagues (Costanza et al. 1989; Costanza and Folke 1997) and Daily (1997), the Millennium Ecosystem Assessment (MA 2005) subsequently proposed consideration of the life-supporting and economically valuable services provided by the natural world ("ecosystem services") to inform environmental management decision making. Rather than adopting the historic perspective of valuing nature as a commodity to be continually exploited, nature was valued more in terms of the life-supporting goods and services that the natural world provides. While this perspective still leaves some aspects of the natural environment unvalued or undervalued (mainly those elements considered as "supporting" services related to the occurrence of soils, water, and air), most other environmental elements could be readily accounted for in terms of "provisioning" services (e.g., fish, timber, produce, and other revenue-producing goods or services) and "regulating" services (e.g., flood prevention and control, navigation, and power generation), as well as "cultural" services valued more locally by specific communities. It has proven problematic, however, to place meaningful economic values on some ecosystem services of a more qualitative character, examples being the spiritual significance of water bodies considered to be sacred sites or the aesthetic appreciation associated with viewing a picturesque river or lake (Enger and Smith 2012).

Building on this foundation within the context of ILBM, Lin and coworkers (Lin et al. 2013; Lin and Thornton 2014) defined the institutional mechanism of "Payments for Improving Ecosystem Services at the Watershed scale" (PIES-W). For this discussion, PIES-W utilizes the principle of the "firm," as defined in New Institutional Economics (Williamson 1981), with the watershed in this case being designated as the firm. The following attributes of a watershed further elucidate its conceptualization as a firm. A watershed is the mechanism within which inputs (i.e., rainfall, runoff, groundwater discharges) are processed and conveyed to address beneficial human purposes. In its most elementary formulation, PIES-W utilizes partnerships between watershed stakeholders to achieve desirable environmental objectives in such a manner that maximizes the number of benefitted stakeholders. These partnerships are envisioned to be facilitated by a neutral third party serving as an intermediary between the service "provider" and service "beneficiary," thereby ensuring a fair price is paid and received for the services. As an example, if downstream (or down-gradient) stakeholders wished to acquire and utilize water of a certain quality or quantity, they have a choice, as stated in New Institutional Economic theory (Williamson 2002), of either "buying" water of the desired quality from other (usually upstream) sources or, alternatively, “making” or producing water of the desired quality within the community. The “buy” option would mean that the water entering a community from usually upstream sources would have to be of the desired quality at the point where it is withdrawn for use. In contrast, the “make” option could mean, for example, that downstream water users would invest in building a water treatment plant to produce water of the desired quality. In this example, the “honest broker” would be tasked with identifying landowners or land managers upstream of the water withdrawal point (“producers”) willing to implement various practices that would minimize water quality degradation, thereby ensuring (to the extent practicable) that their actions would not degrade downstream water quality. In exchange for these positive actions, the downstream beneficiaries (“users”) would be asked to consider making payments to the upstream water providers to offset the costs they incurred in implementing measures to minimize degradation of the water conveyed downstream. These costs could be either ongoing opportunity costs, for example, associated with changing land usage from growing crops to growing trees (afforestation), with a longer period for return on their investment. On the other hand, shorter-term costs would be those associated, for example, with changing an agricultural flood irrigation operation to a drip irrigation operation.

To continue this example, the downstream beneficiaries could then weigh the costs of paying the upstream provider to provide water of desired quality downstream versus the cost of installing and operating a downstream conventional water treatment system to produce water of the desired quality. The decision then becomes a relatively standard business transaction, namely, whether it is more or less expensive to pay to produce water of the desired quality using traditional engineering approaches downstream or to obtain water of the desired quality by paying to minimize upstream (up-gradient) contamination. Similarly, for the upstream partner, the decision becomes one of whether the payment offered to them by the downstream users to provide water of the desired quality is adequate to offset their direct costs of changing their activities, plus the cost of lost opportunities (e.g., farming less acreage if the management practice involved installing larger buffer strips alongside fields). These interactions are presented in diagrammatic form in Figure 10.7. In the watershed context, *production* refers to providing water of desired quality or quantity, with the conditions usually being more optimal at the upstream end of the basin, while the term *distribution* refers to downstream use of water of desired quality or quantity.

The decision to be made by the user is akin to the well-known cost–benefit analysis commonly used in business (Boardman 2006). A decision to use traditional engineering water and wastewater treatment practices can be viewed as a largely reactive action at the downstream water use end of a watershed. Alternatively, the use of cooperative approaches between upstream producers and downstream users, which can be nonstructural in character, can be viewed as a largely proactive action to protect the water before it becomes degraded in quality or diminished in volume. As noted on the left side of Figure 10.7, for the downstream water user (consumer), desired water quality can be obtained using traditional engineering approaches (e.g., construction of municipal drinking water and wastewater treatment plants). It is also noted that a failure to invest the funds needed to adequately treat the water resources

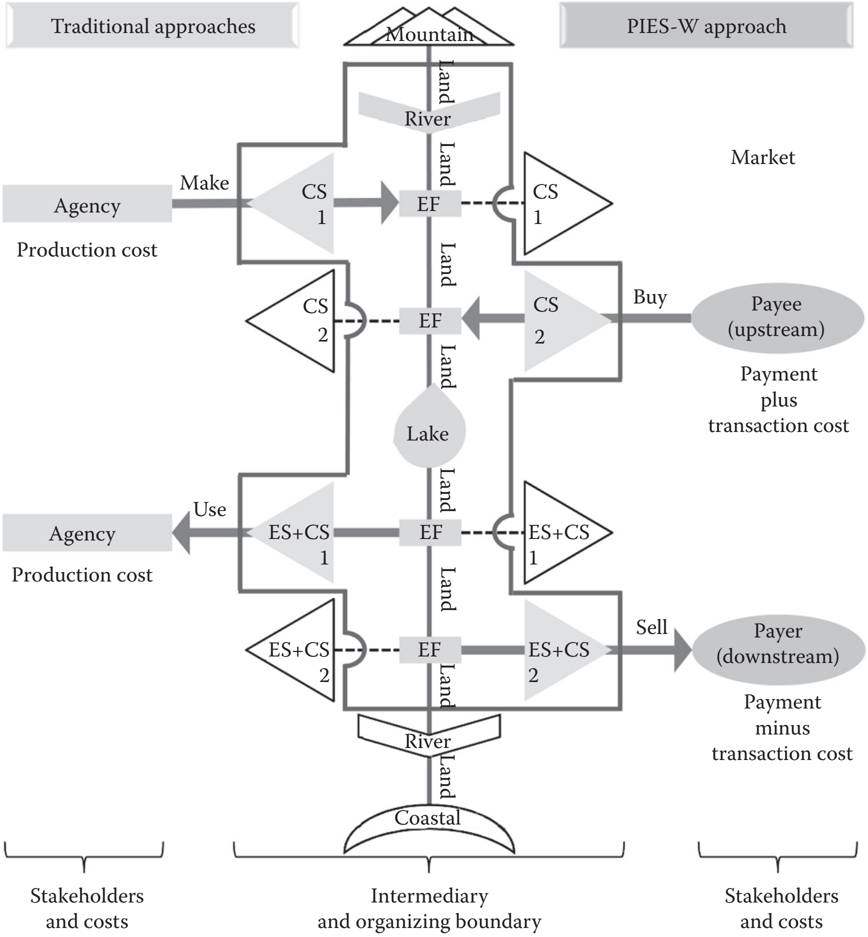

FIGURE 10.7 Payments for improving ecosystem services at the watershed scale. CS, conservation services; EF, ecosystem function; ES, ecosystem services; (ES+CS), bundled ecosystem and conservation services; MV, market value; PC, production costs; TC, transaction costs. (Adapted from Lin, H. and J.A. Thornton. 2014. *Integrated Payments for Ecosystem Services: A Governance Path from Lakes and Rivers to Coastal Areas in China*. In: E. Y. Mohammed, *Payments for Coastal and Marine Ecosystem Services: Prospects, Challenges and Policy Implications*. Earthscan, London.)

can still result in the downstream water user receiving water of less-than-desired quality (i.e., the value of the water related ecosystem service would be reduced).

PIES-W complements the objectives of the financial pillar of the ILBM framework and provides a "win–win" approach to resolving shared concerns within the context of a specific watershed. Instead of constructing often capital and maintenance cost-intensive structures, the downstream water consumer could invest in implementing upstream land management practices designed to directly reduce or eliminate human impacts (i.e., providing funds to the payee to utilize buffer strips, implement improved agricultural practices, etc.) as a means of obtaining water of desired quality or quantity. Downstream (down-gradient) consumers would benefit from a less expensive solution to address their water needs, while the upstream (up-gradient) producer would benefit from the downstream-generated income source. If the downstream water user is motivated to pay for obtaining water of the desired quality or quantity, their major decision rests in selecting the most cost-effective approach to achieving this goal, with this decision being embedded in the payer–payee interactions illustrated on the right side of Figure 10.7.

The case of the previously mentioned Bermejo Binational River basin is illustrative of the application of the PIES-W process within the ILBM framework. The Strategic Action Plan developed to facilitate the sustainable use of the water resources of the Bermejo Basin (shared by Bolivia and Argentina) was formulated with the primary objectives of reducing sediment loss from the watershed and maintaining the hydrological integrity of the river (OAS 2010). An essential element of the strategy was the building of terraces, and the implementation of crop rotation that maintained vegetative land cover, reduced soil loss, and allowed the conduct of more profitable and sustainable agriculture. Although the primary objective of these actions was soil conservation, it quickly became evident that the outcome, seemingly simple from a scientific perspective, was critically dependent on the participation of the watershed stakeholders. In other words, the program had to encompass linkages between basin citizens, scientists, policymakers, and managers in order to effect real changes benefiting both the stakeholders and the environment. This partnership was critical to creating a win–win approach to achieving harmony between the basin environment and its local communities.

From a purely technical/scientific perspective, the “solution” to the soil loss problem was simply to place sufficient control structures in the watershed to slow down water runoff and encourage sediment retention on the land surface. Previous efforts focused on rehabilitating the watershed by tree planting and revegetation activities. The failure to consider potential human needs within the watershed after these activities led to many of the reforested areas being subsequently cut and burned to form seasonal agricultural plots that were frequently used for only one growing season. On the other hand, recognition of the sheep-herding culture of the upper watershed inhabitants, and the introduction of rotational grazing, not only enhanced the quality of the sheep and their subsequent market value but also limited the degree to which these animals could devegetate the soil by grazing, thereby exposing it to erosion. By considering the “human element” of the watershed, and by partnering with local governments and nongovernmental organizations, the management interventions in the basin were able to achieve a high degree of soil stabilization while also providing an economic incentive to the local communities to encourage the long-term maintenance of the revegetation efforts. Further, an unexpected benefit of these interventions was that they not only restored soil organic content but also diversified the peoples’ diets, thereby also improving public health in the watershed. In other words, the program identified and built win–win relationships between basin stakeholders that were effective not only in achieving the ecologic objectives of the program but also in enhancing the economic well-being of the watershed’s human population. These successes were initially based on the definition and identification of the watershed as the management unit and the generation of knowledge as the foundation for management interventions acceptable to both the human and environmental stakeholders in the basin.

A detailed description of the ILBM framework, and considerations germane to its application, is beyond the scope of this review. However, the development and implementation of this integrated water management framework are highlighted in other sources (e.g., RCSE and ILEC 2011), including illustrative case studies.

10.7 CONCLUDING REMARKS

The discussions in this chapter admittedly only touch upon the topic of IWRM interventions applied to freshwater systems. On the basis of global experiences to date, if there is any overall statement to be made, it is that integrated management interventions directed to achieving the sustainable use of freshwater systems can be a complex and difficult undertaking. Among other considerations, such interventions are not a one-time activity, but rather a continuing effort, involving a range of stakeholders and their interests. Further, such interventions often are difficult to develop and implement, they can be very expensive, the end results are often uncertain, and the positive benefits may require a lengthy period to become evident. Of particular importance is the need to recognize that lakes, rivers, and aquifers are not isolated water bodies. Rather, as illustrated in Figure 10.1, a basin typically comprises a linked mixture of interacting lentic and lotic water systems, each with their defining characteristics and challenges, all requiring appropriate recognition and consideration in developing and implementing effective and timely management interventions. It is noted that relevant linkages to be considered can also extend beyond a purely hydrologic connection, including jurisdictional, economic, political, and cultural concerns as well, to cite just a few possibilities. Further, the linkages can be horizontal, involving multiple sectors and stakeholders between and among the microscale basins within a larger macroscale basin (see Figure 10.1). They can also be vertical, particularly in terms of the governance elements, through the hierarchical nature of the political decision-making process and relevant bureaucracies.

Integrated lake and river basin management is a logical extension of the process of watershed-based planning and management that was initiated in the 1980s. It is the embodiment of the Dublin Statement and subsequent global declarations and represents the nexus between science and engineering, on the one hand, and the human community and its surrounding environment, on the other hand. IWRM and IRBM represented major advances in uniting science and the decision-making process in water resource interventions. It has been repeatedly demonstrated, however, that development and implementation of plans and interventions directed to using and conserving freshwater systems are not sustainable without also ensuring an appropriate governance framework. To this end, ILBM continues the efforts begun with IWRM and IRBM by providing a governance assessment and strengthening framework that complements IWRM and IRBM, as well as giving a human face to the integrated management of lakes, wetlands, and other lentic water basins. ILBM is also sufficiently comprehensive to collectively address not only lentic water systems but also rivers, tributary streams and other lotic systems, and, with some modification, the aquifers to which they are linked. The ILBM framework considers essentially all human endeavors and economic activities, as well as the sustainability of the environmental components supporting these activities. It is based on the principles of shared governance, built upon the foundations of appropriate public and private institutions, facilitation of stakeholder engagement and participation, use of sound and scientifically based policies, development of effective practices and relevant technologies, enhancement of available information, and promotion of adequate and sustained financing (RCSE and ILEC 2011). In doing so, ILBM provides a framework wherein both humans and their environment can benefit in an affordable and cost-effective manner. It is a rational expression of the design with nature philosophy and a practical and useful approach for minimizing and controlling the human impact on the landscape so as to retain ecosystem benefits and choices from all lentic and lotic freshwater systems for future generations, whether in developed or developing countries.

The ILBM process is intended to be an iterative, participatory process. Like all plans, the Lake Brief and its associated documents are not static, but rather dynamic, living documents that must be periodically revisited, updated, and refined to reflect the changing goals and demands of watershed communities, and the human and environmental systems supported by a watershed. Such issues as climate change and its predicted future impacts on the hydrologic cycle suggested by the IPCC (2014) provide another level of uncertainty and risk to be considered within this context. Accordingly, by explicitly linking sound science, good policies, appropriate technology, and engineering with the human communities and their economic well-being, ILBM represents a continuing evolution of the process of landscape level water resources management that was begun with the ICM and IWRM initiatives of the previous decades. It consciously links the science and engineering aspects of integrated water management with the goals and needs of human societies and the ecosystems upon which they depend. Further, ILBM explicitly recognizes the economic drivers that always underlie the human demands placed upon the environment, seeking to utilize this recognition in such a way as to not only produce benefits for current generations but also preserve opportunities for future generations of humans, while maintaining a safe, sound, and healthful environment. This outcome is the result toward which water resources management has been evolving and toward which human interventions regarding the environment have been targeted since the earliest days when the human environmental impacts were first recognized. It is, and will remain, a continuing effort of setting goals, analyzing our abilities to meet these goals, making changes needed to meet the goals, updating and refining ongoing planning and management processes, and developing new approaches, all within the context of the gradual, continuous, and holistic improvement of basin governance.

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11 Climate Change and Future Water Supply

John W. Nielsen-Gammon

CONTENTS

11.1 INTRODUCTION

Historically, there have been two primary reasons for major infrastructure improvements to water supply systems. The first is improvement for its own sake: changes in technology or design that allow for improved water quality, efficiency, or reliability. The second is improvement in response to increased demand; such improvements often involve efficiency or reliability but more directly involve changes in capacity.

This chapter is the first of several that deal with water supply in the context of mankind's ongoing semi-intentional alteration of the environment. That context provides two additional reasons for changes in infrastructure: as a response to expected environmentally driven changes in water supply, and in order to reduce the impact of water infrastructure and usage upon the environment.

At first glance, the response to expected environmentally driven changes in water supply seems like it ought to be quite similar to the response to expected population-driven changes in water demand. Both simply require that supply be adjusted to be consistent with future demand. However, planning for population growth is much easier than planning for, say, the impacts of climate change. First, population growth tends to be predictable from year to year and decade to decade. Aside from temporary variations as a result of fluctuations in the economy or more permanent variations owing to major societal upheavals, changes in population trends are detectable fairly early and tend to last a long time. Not so for climate change impacts. Interannual variations in climate conditions are so large that they mask any underlying trends on a year-to-year or even decade-to-decade basis.

With historical data of little use for estimating climate change, the main resources for inferring future climate changes are computer model simulations of future climate. If only one simulation were available, we might be able to deceive ourselves into imagining that we can accurately project future climate changes. However, different climate models produce a broad range of hydrologic outcomes under identical sets of assumptions.

With large uncertainties no matter which way we turn, it can be tempting to conclude that future impacts of climate change are so uncertain that they are impossible to plan for. But the opposite is true: the large uncertainties introduced by climate change require a risk management approach that is fundamentally different from simpler planning strategies.

This chapter will first discuss the consequences of a changing climate on the use and interpretation of historical hydrologic data. Next, it will describe the often grossly misunderstood global climate models and approaches to converting climate model output into actionable information. The following three sections will discuss the basis for expectations of climate change on a global scale, in the context of weather and climate extremes, and at the level of individual water supplies. The chapter will conclude with advice on the proper use of climate projections in water supply planning.

11.2 THE CONCEPT OF NONSTATIONARITY

The foundation of design of water infrastructure and management for resilience to droughts and floods is historical analysis of weather and climate data. For example, reservoirs are designed to withstand events involving probable maximum precipitation, the greatest rainfall amount that can be conceived on the basis of existing and historic weather patterns. Infrastructure may be designed to withstand a 100-year flood event, one whose annual probability is estimated to be 0.01. Water suppliers may plan for a recurrence of the drought of record, which, for a 100-year record length, is a crude approximation to a 100-year drought event.

Historical data are nice because the more data you collect, the more information you get. As you observe more and more events, you would expect to be able to estimate the probability distribution of those events, and the odds of an extreme event, with greater and greater accuracy.

Of course, what you would really like to know is not the probability of an event occurring in the past, but the probability of an event occurring in the future. Since future data have not yet been collected, the assumption is usually made that the expected frequency of an event occurring is the same in the past as in the future.

The ideas that a longer data record leads to more precise probabilities, and that past probabilities equate to future probabilities, require that the physical process generating the data be stationary, meaning that the probability distribution does not change over time. Typically, the probabilities relevant to water management have an annual cycle, but the stationary assumption still applies if one deals with annual average probabilities or probabilities on a particular date.

An influential paper by Milly et al. (2008) was provocatively titled "Stationarity Is Dead: Whither Water Management?" Milly et al. noted that tools exist to deal with nonstationarity in a river basin from such causes as changing infrastructure, channel modifications, and land-use changes, in effect transforming the data so that they no longer represent what has actually happened but instead what would have happened given the current basin configuration. Climate variability and change are additional sources of nonstationarity. Climate variability is typically assumed to be encapsulated within the range of variability recorded in the data time series, and the estimated probability distribution is assumed to apply to the entire period of interest, with no attempt to refine the probability distribution to reflect some current or predicted future model of variability.

Other climate changes are longer term, such as millennial-scale variations in solar and volcanic output. These produce technical violations of the stationarity assumption. However, in practice, the estimated magnitude of the resulting changes in the probability density function (PDF) is typically much smaller than the uncertainties associated with estimating the PDF from a limited number of samples in the first place.

Milly et al. (2008) argued that we have reached the era in which quasi-permanent anthropogenic climate change has exceeded the typical uncertainties associated with historically estimated probability distributions. Hence, the assumption of stationarity is no longer apt, and the traditional tools for risk assessment and planning are based on a foundation that can no longer stand on its own.

For example, consider mean inflows to a reservoir. Because of channel changes and urbanization effects, runoff may be larger than it used to be. After correcting for those effects, suppose that there is an apparent trend in the data such that corrected annual inflows were centered around 150,000 acre-feet (af) in 1950 and 200,000 af in 2000.

In the absence of further information, one does not know whether this trend represents a systematic, ongoing change that will continue or is a manifestation of a multi-decadal variation that will reverse itself. Under the assumption of stationarity, the mean during the observation period, 175,000 af, would be taken (with a little bit of wiggle room for uncertainty) as the expected mean during the lifetime of the future project. However, if other evidence suggests that this observed trend is caused by ongoing anthropogenic climate change, the expected future mean value will indeed continue to grow. Under that circumstance, the appropriate annual mean inflow for design purposes is something greater than 200,000 af.

This raises a whole host of issues. The past is known, to the limits of data accuracy, and sources of uncertainty in observed historical data have been well characterized. How does one tell whether nonstationarity is present? How does one estimate the magnitude and nature of future changes to the probability distribution of interest?

Definitive answers to these questions are beyond the scope of this chapter. The extent to which imperfect inferences about the future should be combined with imperfect knowledge from the past to inform planning, design, and decision making is a question that may plague water planning for many years. One thing is clear, though: the future is not the past, and that difference should no longer be ignored.

11.3 FOUNDATIONS FOR EXPECTATIONS FOR FUTURE WATER SUPPLY

11.3.1 Fundamental Physical Principles

Water vapor is the third most common gas in the atmosphere and by far the most variable in concentration. The variability arises because water vapor can condense into liquid form at ordinary temperatures and pressures and can condense into solid form if the temperature is below freezing.

Over most of the Earth's surface, there is no shortage of moisture for evaporation (such as from the ocean surface) or for transpiration from plants. These two processes are lumped together as evapotranspiration and are constantly acting to increase the water vapor concentration in the atmosphere. If there were no removal process for water vapor in the atmosphere, the water vapor content would approach saturation (100% relative humidity) everywhere evapotranspiration is taking place.

The airborne concentration of water vapor at saturation is a strong function of temperature. The laws of thermodynamics may be used to formulate a precise mathematical statement of this functional relationship, but here a rule of thumb will suffice: the partial pressure of water vapor at saturation roughly doubles for every 10 K increase in temperature.

A fundamental aspect of evaporation and, to a lesser extent, transpiration is that the rate of flux of water vapor into the atmosphere is a linear function of the difference between the actual water vapor content and the water vapor content at saturation. This fact, combined with the temperature dependence of saturation, implies that the rate of evaporation would be expected to increase in a warmer climate, all other things being equal.

Precipitation production depends on the rate at which water condenses as air is ascending. Ascent causes air to cool; as the air cools, its relative humidity increases and eventually saturation is attained, and further ascent produces condensation. In a tropical thunderstorm, air may rise rapidly from near sea level to an altitude of 10–15 km, at which height very little water vapor can remain. Thus, for a given ascent trajectory of air, air that starts out warmer and with more water vapor will produce more condensation and precipitation. This fact implies that the rate of precipitation would be expected to increase in a warmer climate, all other things being equal.

These two predictions arise from two separate, independent physical principles. A third principle connects them: the rate of evaporation and precipitation is so large relative to the capacity of the atmosphere to contain water vapor that globally averaged evaporation must approximately equal globally averaged precipitation on time scales of a month or more. If evapotranspiration increases, so too must precipitation, and vice versa.

11.3.2 GLOBAL CLIMATE MODELS

Global climate models are typically combinations of several separate models. Since climate is composed of the statistics of atmospheric parameters, every global climate model includes an atmospheric model, sometimes called a general circulation model (both bear the acronym GCM). Three other common components are a land surface model, an ocean circulation model, and a cryosphere (snow and sea ice) model. Additional components may include a hydrologic model, a vegetation model, and a carbon cycle model.

The atmospheric and ocean circulation models are each composed of two parts. One part numerically integrates the mathematical forms of the laws of motion, conservation of mass, and first law of thermodynamics that apply to a continuous, ideal fluid. This part is known as the dynamical core. Each of the equations involves derivatives in time and space, and the numerical integration proceeds by solving for the values of the time derivatives in time at a given instant, computing an approximate value for the future values of the model variables at an instant slightly in the future, computing the spatial derivatives and other terms in the equations at that future instant, solving for the values of the time derivatives in that future instant, and so forth. A typical minimum set of model variables consists of velocity (the three components of motion), two thermodynamic variables (such as temperature and density), and the mixing ratio or concentration of any important variable constituents (at a minimum, water vapor for the atmosphere and salinity for the ocean).

The equations are known precisely for an ideal fluid, and the atmosphere and ocean behave sufficiently similar to an ideal fluid that the ideal fluid approximation is not an important source of error. This makes models of the ocean and atmosphere distinctly different from most other models. In most other models, the equations governing the behavior of the system are not precisely known, and the accuracy of the model is determined by how well the model equations approximate real-world behavior. In models of the ocean and atmosphere, while the physics governing the behavior is known exactly, it is happening on such a wide range of spatial and temporal scales (from meters to thousands of kilometers) that no model can simulate everything that is happening. Instead, a trade-off is made between the minimum spatial scale to be simulated and the length of time required to complete a simulation on a supercomputer. A minimum temporal scale is chosen to be consistent with the minimum spatial scale. For present-day state-of-the-art models, these scales may be a few dozen kilometers and a hundred seconds.

The primary sources of error in the dynamical core of an atmospheric or oceanic model are the limitation on resolvable spatial and temporal scales, the accuracy with which spatial derivatives are calculated, the accuracy with which future values of model variables are estimated from knowledge of past and present time derivatives, and the accuracy of any boundary conditions. Every phenomenon simulated by the dynamical core, such as the Hadley circulation, extratropical cyclones, jet streams, and so forth, is properly regarded as an emergent property of the model, which only "knows" that force equals mass times acceleration, that mass is neither created nor destroyed, that energy is conserved, and a few other details.

The limitation on resolved spatial and temporal scales is a severe one. Many processes that are important to the behavior of the atmosphere or ocean on resolved scales are nonetheless much too small to be simulated directly. For example, each cloud droplet is a few microns in diameter, and the processes by which such droplets interact are crucial to precipitation growth. Thus, we have the other part of atmospheric and oceanic models, the set of parameterizations.

Each parameterization attempts to estimate the effect of processes too small to be directly simulated on the resolvable scales of motion. The domain simulated by the model is divided into a three-dimensional grid, and each parameterization takes the simulated values averaged over a grid box (or vertical column of grid boxes), determines the magnitude of unresolved processes that are consistent with those values, and provides information on the resulting changes in resolved variables. Each parameterization can itself be regarded as a model; indeed, since such parameterizations typically involve equations that represent particular individual processes, with tunable parameters, they are much more akin to the types of models encountered in other fields.

11.3.2.1 Cloud and Precipitation Parameterization

Parameterizations of cloud and precipitation processes typically include two separate parameterizations, one for clouds that develop through convective instability and one for clouds that develop through large-scale vertical motion. There may even be additional parameterizations, such as for shallow clouds, even though clouds in the real atmosphere occupy a continuum.

A typical convective parameterization checks for the presence of convective instability and whether conditions would enable a convective cloud to form. If so, the parameterization needs to estimate the change in temperature and humidity per unit time that would be produced by the convective cloud or an assemblage of convective clouds within the grid column, as well as the precipitation that might be produced. Unlike the dynamical cores, which are all based on the same or similar sets of equations, the various convective parameterizations use different assumptions for how the convection is physically related to the large-scale conditions. For example, some are based on the instantaneous state of the atmosphere, while others are based on the rate of change of the state of the atmosphere.

The other parameterization, known as a cloud microphysics parameterization, diagnoses cloud and precipitation processes based on the temperature and moisture content simulated by the dynamical core. For example, it might estimate fractional cloud cover in a layer on the basis of the relative humidity. While it might seem obvious that clouds should be present when the relative humidity in a layer is 100%, what about when the relative humidity is 90%? In reality, when an area as large as a grid box averages 90% relative humidity, it is likely that there will be some portions of the grid box where the relative humidity meets or exceeds 100% and clouds will be present. At a minimum, under such circumstances, the presence of clouds will affect the radiative properties of the grid column.

More detailed microphysics schemes will keep track of the mixing ratio of certain hydrometeors. The most detailed microphysics schemes, usually too time and memory intensive to be used in a global climate model, will track five or six different types of hydrometeors, such as cloud water, cloud ice, snow, rain, graupel, or hail, and the many processes that cause the growth or transformation of each type. The combination of hydrometeor fall velocity and air motions simulated by the dynamical core can transport these hydrometeors from grid cell to grid cell, or in simpler cases the fall velocity of precipitation particles will be assumed to be infinite so that any precipitation particles produced are immediately recorded as precipitation on the ground.

The radiative properties of clouds are not determined merely by the amount of water contained in hydrometeors. The same water content might be associated with a few large hydrometeors or many small hydrometeors. Ordinarily, this might not be a big deal. However, such variations are driven largely by the concentration of aerosol particles in the atmosphere that can serve as cloud condensation nuclei or ice nuclei. The potential impact of changes in aerosol concentration on clouds, and the resulting impact on radiative transfer in the atmosphere, is one of the most important uncertainties in modern climate science: potential net impacts range from zero to an impact equal and opposite to that caused by anthropogenic increases in carbon dioxide concentrations. Thus, today's most advanced climate models parameterize the effect of aerosol concentrations on clouds, and to do so, they must track at least two variables for each hydrometeor, representing both the concentration and the size distribution of particles of each type.

Because clouds are parameterized in GCMs, it is fair to say that GCMs do not simulate clouds directly. Nonetheless, the presence of clouds and precipitation are inferred, and their impacts are likewise inferred. The presence and behavior of clouds is not specified from a climatology but instead is inferred solely from the instantaneous atmospheric properties simulated by the GCM. This allows the simulated wind and mass fields to respond to the latent heat released by the inferred clouds, and the interaction between the resolved dynamical processes and the parameterized clouds and precipitation are essential for simulating phenomena such as monsoons and tropical disturbances.

11.3.2.2 Parameterization of Turbulence

The parameterization of the effects of turbulence is known variously as a turbulence scheme or a boundary layer parameterization. Turbulence occurs on a wide range of spatial scales. The largest scales can be simulated directly by a GCM, but the effect of mixing on much smaller scales must be parameterized.

A great deal of turbulent mixing occurs within the planetary boundary layer. This mixing is especially important because it is the primary way energy is transferred into the atmosphere from the thin layer of air in contact with the land and ocean surfaces.

11.3.2.3 Radiative Transfer Scheme

The effects of radiation may be simulated by one unified parameterization or two separate ones, one for shortwave (solar/visible) radiation and one for longwave (terrestrial/infrared) radiation. Because long-term climate change is caused by changes in the energy balance of the climate system, and energy is gained or lost from the climate system via shortwave and longwave radiation, such schemes are crucial for properly representing the mechanisms of climate change.

The radiative transfer schemes are typically one of the most time-consuming parts of a GCM simulation. Each time radiation is calculated, the effects of absorption, reflection, and emission at each layer of the atmosphere must be calculated for each wavelength as a function of the vertical and horizontal distribution of clouds and the concentrations of water vapor, other greenhouse gases, and aerosol particles. Since wavelengths are continuous rather than discrete, each radiation scheme incorporates approximations for incompletely representing the full spectrum of radiation, guessing at the distribution and vertical overlap of clouds and water vapor within a grid column, and recalculating changes in radiation only after several time steps.

11.3.3 Downscaling

A typical GCM simulation of past or future climate spans at least several decades. With numerous GCMs and numerous different model runs with similar or different assumptions about the future, the amount of information that could in principle be generated from a GCM is enormous. Typically, only a small subset of GCM output is saved for later use. Output might be saved on a daily or monthly time scale, with emphasis on the state of the atmosphere at the ground and most information on the full volume of the atmosphere ignored.

Most hydrologic applications require much higher spatial and temporal resolution than a GCM archive can normally deliver. Even if information were to be saved from the GCM every hour, spatial resolution would still be a problem. Output is available at or close to the grid resolution of the model, which is typically in the neighborhood of 1° of latitude and longitude. A few GCMs are run at much higher spatial resolution, but the data storage problems multiply when high spatial resolution and high temporal resolution are combined. In most circumstances, it is necessary to generate hydrologic inputs at much higher spatial and temporal resolution than is available from the GCM archive.

The process of generating high-resolution information (in space and time) from low-resolution GCM output is called *downscaling*. There are two basic types of downscaling approaches, dynamical downscaling and statistical downscaling. Neither is clearly superior to the other.

In dynamical downscaling, a high-resolution (mesoscale) meteorological simulation is produced over the area of interest, using the GCM output as initial and boundary conditions. The simulation can be tailored to the particular needs of the problem, producing output at arbitrarily fine spatial and temporal resolution. The output is also guaranteed to be nearly internally consistent, to the extent that the mesoscale model itself is able to simulate the weather realistically. If the lateral boundaries of the mesoscale domain are far enough away from the area of interest, the model is able to generate realistic fine-scale weather structures despite the lateral boundary conditions being smooth.

Dynamical downscaling requires extensive computer resources, although some output from coordinated dynamical downscaling exercises such as North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2011) is already available. Also, because the mesoscale model has a different resolution and normally different parameterizations from the GCM, the climate the mesoscale model tries to produce may be in conflict with what the GCM has produced. This can lead to systematically excessive or insufficient rainfall in places as the temperature and moisture structure of the mesoscale model atmosphere adjusts to its different equilibrium.

The other form of downscaling is statistical. There are multiple statistical approaches available, and one approach will serve as an example here. In the analog method (Zorita and von Storch 1999), the large-scale meteorological conditions simulated by the GCM in the area of interest are identified with similar large-scale meteorological conditions in the historical record, and high-resolution meteorological information is then drawn from the historical record.

Because the climatic conditions simulated by the GCM are typically erroneous in one aspect or another, the GCM output is first corrected for climatological biases before a historical match is sought. One way of doing this is by using corresponding percentiles. For example, if a particular simulated event is a 1-in-5-year event in the GCM, the event would correspond to what is a 1-in-5-year event in the historical record.

While dynamical downscaling requires a mesoscale simulation whose resolution is adequate in space and time, the statistical downscaling approach requires historical observations to have adequate resolution in space and time. Statistical downscaling also assumes that the statistical relationships among meteorological parameters that have been observed historically will persist in the future. This assumption becomes less and less valid as the simulated climate becomes less and less like the 20th century climate. One also hopes that the GCM-simulated climate is reasonably similar to the actual climate so that the sequence of associated weather events would also be reasonably similar.

11.3.4 SOURCES OF UNCERTAINTY

Two sources of uncertainty in climate projections should already be apparent: uncertainty associated with imperfections in GCM simulations of the climate and uncertainty associated with estimates of local weather events given the GCM simulations.

Another source of uncertainty is lack of knowledge regarding the future composition of the Earth's atmosphere. Climate model projections are driven by particular assumed changes in emissions to the atmosphere or specified changes to the atmospheric composition itself. Such changes depend on the evolution of energy sources, technology, population, war, climate change policies, and many other factors. As a result of this uncertainty, the strength of the climate impact of changing atmospheric composition by the year 2100 is probably known only to ±35%.

Another source of uncertainty is the magnitude of the global temperature response to any changes in atmospheric composition. The magnitude of such a change is usually quantified as equilibrium climate sensitivity or transient climate response. Presently, the magnitude of the response to a given forcing is only known to approximately ±60%.

The final source of uncertainty to be considered here is natural variability. Many aspects of the climate system, such as internal multidecadal variability, solar variability, or volcanic activity, are either unpredictable or not predictable with present-day technologies. After several more decades, these natural factors will pale in comparison to man-made impacts on global temperatures. However, precipitation has much more natural variability than temperature, particularly when a limited portion of the globe is considered. In some areas, natural variability may be larger than the effect of manmade climate change for many decades to come. Although models can simulate natural variability and its effects, they cannot know the exact course of future natural variability, such as precisely when natural variability would be favoring warmer or wetter conditions versus colder or drier conditions. This is not a shortcoming of the models; it is a consequence of the chaotic nature of many aspects of the climate system, but this means that the weather simulated by a perfect climate projection may be substantially different in character from the actual weather that comes along.

11.4 GLOBAL-SCALE CLIMATE CHANGE IMPACTS

Most of what we know (or think we know) about climate change impacts on water supplies is obtained using the computer models discussed above. In principle, observations are more reliable, and the climate has been measurably changing for a century or more. However, most aspects of the water supply are quite noisy, with large interannual variability, making it difficult to identify a secular trend in many hydrological variables across the globe. In addition, once the precipitation reaches the ground, its fate is heavily influenced by nonclimatic factors such as stream management, land-use changes, and population growth. The paradox here is that by the time climate change becomes the dominant influence on a particular hydrological variable, the influence must already be very strong, and action to deal with the resulting changes would need to have already taken place. GCMs are useful as a quasi-realistic experimental framework for isolating the effect of a single external variable such as climate change, and the plausibility of such GCM results depends on consistency among models, agreement with the historical record, and an understanding of the physics behind the cause-and-effect relationships.

11.4.1 TEMPERATURES

The simplest and most basic global-scale climate change is temperature. This is because temperature is the mechanism through which most climate changes take place. Climate change typically is caused by a change in the energy balance of the climate system, attributed to either a change in the amount of energy absorbed from the Sun or a change in the amount of energy emitted by Earth into space. The immediate effect of a change in energy balance is a change in temperature. Furthermore, changing temperature has a direct effect on the energy balance.

Internal climate variability caused by atmosphere–ocean interactions typically rearranges the temperature pattern, making some parts of the globe warmer and other parts cooler. Changes in temperature caused by radiative forcing tend to be much more uniform, as long as the trend is calculated over a long enough period that natural variations are small.

Over the past century, most areas of the globe have experienced warming (Figure 11.1). Warming trends tend to be larger over continents than over oceans and at higher latitudes than at lower latitudes, though regional patterns show considerable variability. An area of cooling is found in all three data sets in the North Atlantic Ocean, apparently caused by a reduction in the overturning circulation of the Atlantic (Drijfhout et al. 2012). Two of the three analyses also indicate cooling in parts of the southeastern United States; this area has been called the southeast United States global warming hole, and the lack of warming has been attributed to natural variability (Kunkel et al. 2006), increased aerosol concentrations (Yu et al. 2014), and land-use changes (Pan et al. 2013). Not one of these cooling trends is statistically significant, though they are significantly different from their surroundings.

The increased warming over land is hypothesized to be caused by differences in the connection between surface temperatures and temperatures in the upper troposphere. Most terrestrial radiation escaping to space originates in the upper troposphere, and temperature is maintained at these altitudes primarily through condensation of water vapor that has evaporated from the surface, particularly over oceans where the supply of water for evaporation is effectively limitless. Because the value of the water vapor saturation mixing ratio is a strongly nonlinear function of temperature, large changes in upper-tropospheric temperature are associated with relatively small changes in lower-tropospheric temperature in those locations where evaporation and deep convection predominate (Byrne and O'Gorman 2013). However, observations tend to show much less upper-tropospheric amplification of temperature trends than expected (Mitchell et al. 2013).

The increased warming at high latitudes is partly explained by the presence of snow and sea ice albedo feedback, in which warmer temperatures lead to less snow and sea ice cover, allowing greater absorption of solar radiation to contribute to additional warming locally, though the relative lack of upper-tropospheric amplification at high latitudes may play a leading role (Pithan and Mauritsen 2014). This simple explanation is subject to two major complications. First, in the Northern Hemisphere, temperature trends are also strongly affected locally by variations in aerosol concentrations (Ramanathan and Feng 2009). Second, the Antarctic has shown no such increased warming, and net temperature changes at high latitudes probably involve a multitude of competing effects (Marshall et al. 2014).

11.4.2 CHANGES TO THE HYDROLOGIC CYCLE

Consistent with the increase of saturation mixing ratio with temperature, a warmer world is expected to have greater amounts of water vapor. This, in turn, would lead to greater precipitation amounts. However, neither the observational record nor the tendencies shown by global climate models are as simple as they are for temperature. This is in part because temperature has a fundamental global energy balance

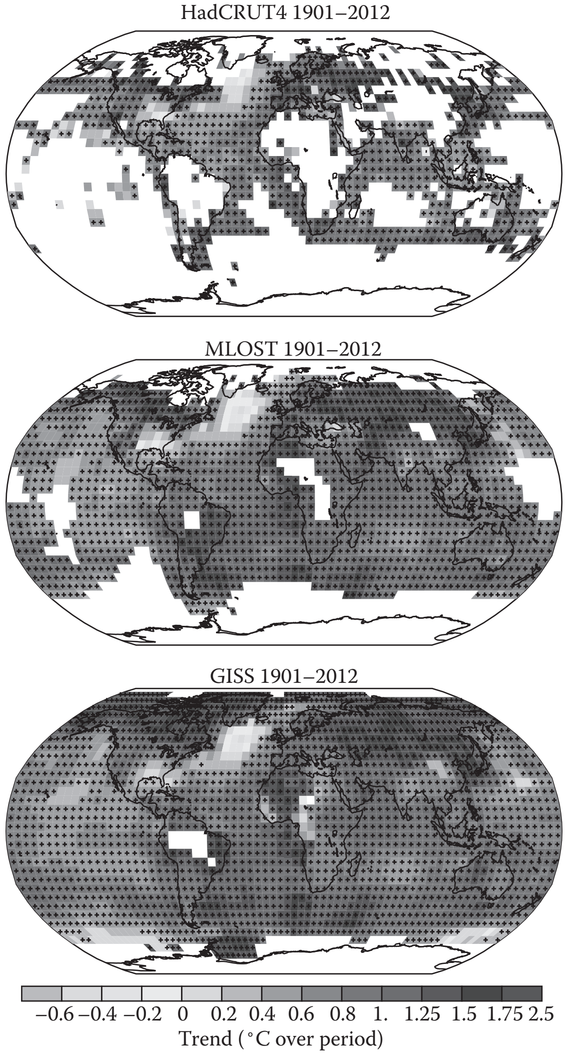

FIGURE 11.1 Trends in surface temperature from the three data sets of Figure 2.20 of Hartmann et al. (2013) for 1901–2012. White areas indicate incomplete or missing data. Trends have been calculated only for those grid boxes with greater than 70% complete records and more than 20% data availability in the first and last decile of the period. Black plus signs (+) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval). Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the data set providers ranging from none beyond grid box averaging (HadCRUT4) to substantial (GISS). (Figure 2.21 from Hartmann, D.L. et al. 2013. Observations: Atmosphere and surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F. et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, pp. 159–254, doi:10.1017/CBO9781107415324.008. Used with permission.)

constraint, while the only global constraint on precipitation is that it must approximately equal evaporation. Also, temperature changes tend to take place over much broader areas than precipitation changes. Because precipitation requires upward motion, areas of precipitation are inevitably accompanied by areas without precipitation, where downward motion is prevalent. As a consequence of this and other factors, it requires many more rain gauges to measure a rainfall trend than it does temperature gauges to measure a temperature trend.

Over the past century, some regional trends are present, such as a tendency for wetter conditions over North America, but for the most part, global precipitation measurements are strongly affected by climate noise. In the Northern Hemisphere, a long-term positive trend does seem to be present (Hartmann et al. 2013, p. 202). Long-term trends in snowfall also vary by region, and most attention has been focused on North America. In the United States, reductions in snowfall seem to be concentrated where warmer temperatures would cause snow to fall as rain instead (Kunkel et al. 2009).

Another precipitation-related trend that has been detected in many areas is an increase in extreme rainfall (Hartmann et al. 2013, p. 213). This has been defined in various ways, such as the amount of rainfall occurring in the wettest 5th or 10th percentile of rain days. Such a trend is expected to be more robust than trends in overall precipitation, despite the smaller sample size, because the "all else being equal" assumption works better here. Since warming temperatures lead to an increase in the saturation mixing ratio, rainfall events in which the air is warm and saturated with water vapor should tend to produce more rainfall.

Computer model simulations of future warming tend to predict an increase of precipitation in many parts of the tropics as well as at high latitudes and a decrease of precipitation in the subtropics (Figure 11.2). Sometimes, this pattern is described in simplified fashion as "the wet areas get wetter, and the dry areas get drier," but it would be more accurate to say that the dry areas expand poleward (Scheff and Frierson 2012). See, for example, that projected precipitation changes in much of the central Sahara Desert are indistinct, while there is a robust drying signal to its north and a robust wetting signal to its south.

11.4.3 WIND CHANGES

The expansion of the dry areas poleward is a consequence of the poleward expansion of the Hadley Cell, the primary circulation cell in the tropics. This expansion is consistently predicted by climate models and has been observed to be taking place during the latter half of the 20th century. There appear to be multiple causes, such as an increase in vertical scale caused by the warming of the troposphere and the cooling of the overlying stratosphere (Lucas et al. 2014).

At high latitudes, the jet stream is projected to migrate poleward, albeit by no more than a degree or two of latitude (Barnes and Polvani 2013). The jet streams also weaken slightly as the pole-to-equator temperature gradient weakens, and likewise low-level extratropical westerlies increase in the simulations. All three changes are consistent with thermal wind balance.

Beyond these generalities, there is typically little agreement among climate models regarding the details of changes in regional wind patterns. For example, patterns

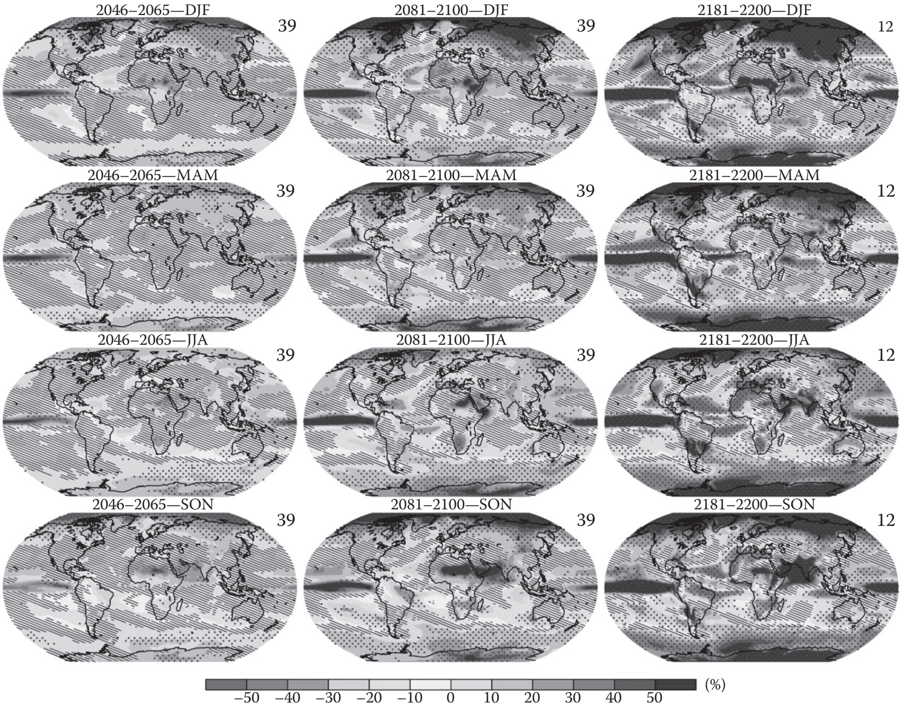

FIGURE 11.2 Multimodel CMIP5 average percentage change in seasonal mean precipitation relative to the reference period 1986–2005 averaged over the periods 2045–2065, 2081–2100, and 2181–2200 under the RCP8.5 forcing scenario. Hatching indicates regions where the multimodel mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multimodel mean change is greater than two standard deviations of internal variability and where at least 90% of models agree on the sign of change (see Box 12.1 in Collins et al. 2013). (Figure 12.22 from Collins, M. et al. 2013. Long-term climate change: Projections, commitments and irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F. et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, pp. 1029–1136, doi:10.1017/CBO9781107415324.024. Used with permission.)

of change of hurricane activity are rather uncertain because of the large variations from location to location in projections of vertical wind shear.

11.4.4 AEROSOL–CLOUD INTERACTIONS

While carbon dioxide and other greenhouse gases are affecting temperature by altering the clear-sky radiation intensities, aerosols are affecting temperature in large part by modifying the hydrologic cycle and the resulting impact of clouds on atmospheric radiative properties. Aerosols are any solid or liquid particles small enough to remain suspended in the atmosphere for an extended period. Cloud properties are strongly affected by the properties and prevalence of aerosols within the air mass in which they form.

The radiative aspects of this issue were discussed earlier in this chapter, but aerosols also have a direct impact on the hydrological cycle apart from their radiative effects. Such interactions are the basis, for example, for ongoing efforts in cloud seeding.

While the issue has been studied for many years, comprehensive observational evidence is lacking. Individual cases and numerical simulations tend to suggest that there is a sweet spot in the range of potential aerosol concentrations for which precipitation is maximized and that the existing aerosol concentrations in the atmosphere span that sweet spot. Thus, increases in aerosol concentration in otherwise pristine, oceanic air masses may tend to increase precipitation, while increases in aerosol concentration in polluted or continental air masses may tend to reduce precipitation (Rosenfeld et al. 2008).

The actual situation is much more complex than one would gather from this simple description. The type of aerosol particle matters too, especially when the atmosphere is cold enough to support the formation of ice particles.

Most scenarios of future emissions posit that aerosol concentrations will decrease, even as carbon dioxide levels continue to increase. Unlike carbon dioxide, aerosols pose a direct health hazard, although the dependence of health impacts on the type of aerosol particle is still not known. Thus, as developing countries improve their air pollution controls, aerosol concentrations will eventually decrease. As of this writing, China is perhaps approaching that point, but many other countries in Africa, India, South America, and Southeast Asia are still on the upward portion of the aerosol emissions curve.

11.5 CHANGES IN EXTREMES

While it seems to be conventional wisdom that weather extremes will intensify in a warmer climate, the best available science paints a much more nuanced picture. Part of the lack of clarity stems from differences in what people mean by weather extremes.

One type of extreme is extreme because it is extremely rare; that is, it lies at the extremes of the probability distribution. This type of extreme has impacts primarily regarding species distribution, as habitat margins are often determined by the extreme weather conditions that a species can tolerate. Such extremes typically change in increased/decreased couplets. For example, extreme high temperatures are expected to increase in frequency and have been observed to increase, while extreme low temperatures are expected to decrease in frequency and have been observed to do so. Though this appears at first to be a symmetric process, the total number of extremes actually increases, because the frequency of temperatures over a certain threshold can double, triple, or more, while the frequency of temperatures below a certain threshold can decrease by no more than 100%.

The other type of extreme is extreme because it carries high risk to life, health, or property. Such events need not be rare or at the end of a probability distribution; every tornado or hurricane is considered to be an extreme weather event, even though they are common in many parts of the world. The effect of global warming on this type of extreme weather cannot be generalized, but instead must be assessed on a case-by-case basis.

As noted earlier, the saturation vapor capacity of the atmosphere increases with warmer temperatures, and heavy rainfall events seem to be increasing in more places than they are decreasing (Donat et al. 2013). This is often summarized as an expected increase in floods, but flood intensities depend on many other factors besides rainfall. Conversely, if more rainfall falls in intense events, the gaps between rainfall events should become broader, and that change should combine with increased temperatures to make droughts more intense. Hence, global warming should increase the intensity of both droughts and heavy rainfall.

Such a general statement applies to the globe as a whole and not every single location. In many parts of the globe, the overall increase of rainfall will be large enough to reduce the intensity and frequency of droughts. Conversely, in other parts of the globe, local decreases of rainfall will be great enough to reduce the intensity and frequency of heavy rainfall events. It seems quite plausible that the total size of the overlap between areas seeing heavy rainfall increase and areas seeing drought increase will be much less than 50% of the globe.

11.6 REGIONAL CLIMATE-DRIVEN CHANGES IN WATER SUPPLY

The reader may have noticed that the preceding discussion of global-scale changes began with some sweeping generalizations but quickly bogged down into details. As noted earlier, precipitation changes are more local than temperature changes. For water supplies, even if one could predict the changes in average annual temperature and precipitation with perfect accuracy, one would still be at a loss to predict water supply changes because of all the other factors that affect hydrology and streamflow, including but not limited to seasonality, steadiness, water storage methods, vegetation, and geology.

This complexity makes it impossible to generalize about water supply changes in a warming world. Each location has its own special characteristics, and predicting future trends in some variables can often be little more than guesswork.

For example, warmer temperatures would be expected to lead to increased evaporation rates, all else being equal. The physics of the water cycle requires that the rate of evaporation will be proportional to the vapor pressure deficit, or the difference between the partial pressure of water vapor and the partial pressure of water vapor at saturation. Rising temperatures correspond to a rising partial pressure of water vapor at saturation. However, the bulk of pan evaporation measurements throughout the world show long-term decreases in evaporation rates. Existing explanations for this paradox include decreased sunlight reaching the surface, increased evaporation in the environment surrounding the pans, and decreased wind speed, and no single explanation seems to fit the available evidence at this point (Fu et al. 2009).

One area in which generalization might be undertaken with relative safety is with respect to water supplies that depend partially or entirely on meltwater. As temperatures warm, snow cover tends to melt earlier. This leads to measurable shifts in the

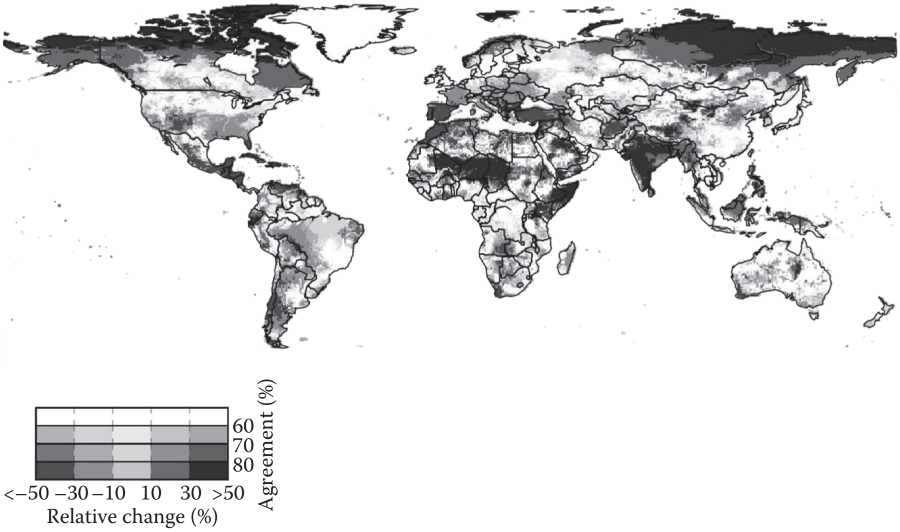

FIGURE 11.3 Relative change in annual discharge at 3°C compared with present day, under RCP8.5. Color hues show the multimodel mean change, and saturation shows the agreement on the sign of change across all GHM–GCM combinations (percentage of model runs agreeing on the sign). Greenland has been masked. (From Figure S1 of Schewe, J. et al. 2014. Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America* 111:3245–3250. Used with permission.)

timing of peak discharge driven by snowmelt in many areas of the globe (e.g., Tan et al. 2011). Also, while glaciers themselves are not typically a primary source of water, their near-global melting has produced an increase in streamflow. This so-called meltwater dividend is likely to peak and then decrease in most affected areas by the end of the 21st century (Jiménez Cisneros et al. 2014).

A map of streamflow projections (Schewe et al. 2014) from several global climate models coupled to several global hydrologic models shows some distinct patterns that are consistent across most or all models (Figure 11.3). Modeled streamflow increases in most or all models in most of the Arctic and Subarctic, many of the drier areas of Africa and the Middle East, and most of the South and Southeast Asia monsoon region. Modeled streamflow decreases in most or all models in central and southern Europe, North Africa, southern and central South America, most of the Caribbean region, and much of Mexico and the southern United States. Meanwhile, across most of China and the northern United States, the various models are fairly evenly split on the sign of future streamflow changes.

11.7 CLIMATE PROJECTIONS AND WATER SUPPLY PLANNING

Suppose you wish to take future climate projects into account in your long-range water planning. However, suppose you are in a location where the models are evenly split on the sign of future streamflow changes. Is there nothing to be done?

The first thing to remember is that lack of definitive knowledge regarding the effect of climate change is not the same thing as lack of definitive knowledge regarding climate change itself. As discussed in Section 11.1, the present situation is fundamentally unlike the situation 50 years ago when it was still reasonable to assume that the future would look like the past. At present, the climate system is being inadvertently altered rather strongly, and similarly large alterations in geological time produced large changes in climate, including transitions between glacial and interglacial periods during the Ice Age. Compared to a time in which no such alteration was taking place, the range of possible future climate conditions at particular locations is much, much larger.

Put another way, suppose that in 20 min you will walk blindfolded across your living room. If you are the only person in the living room, and you can keep other people out, you can be fairly certain that the various pieces of furniture will be in the same place 20 min from now as they are presently. You can thus proceed by quickly planning out your route, including the number of steps taken on each leg, before you put on your blindfold.

Suppose, on the other hand, the house is presently inhabited, among others, by three preteens and two large dogs. You might suppose that, as they run about the house during the next 20 min, they may nudge the furniture around a bit. While you might now plan to start in the same basic direction, you might go slower, feeling ahead and allowing for the possibility of a change in your planned route, or giving wider berth to obstacles.

So it is with climate change: even in those circumstances where there is little knowledge of the particular impacts of future climate change, it is virtually certain that future conditions will be different from what can be deduced from the historical record.

As discussed earlier, in some aspects of the hydrologic cycle and some locations around the globe, the evidence points strongly toward particular types of changes. In those cases, one can plan not only for an expansion of the range of possible conditions in the future but also for a change in average conditions.

Unfortunately, having confidence in a few aspects of climate change is not enough for a comprehensive evaluation of all future climatic impacts to water systems. For that, it is appropriate to develop and test scenarios, which are internally consistent descriptions of how all factors might evolve in tandem. Scenarios have been used to develop possible future emission pathways that then are utilized by climate models to determine possible effects of those emissions. A scenario-based simulation of future water supply conditions might begin with output from a model simulating the effects of an emissions pathway; then, the output might be downscaled and used as input to a local model of the hydrologic system. At the same time, the water supplier or stakeholders would develop possible local changes in industry, population distribution, power generation, and so forth that are consistent with the assumptions of the global-scale scenario.

A single modeled scenario such as the above can produce a simulation of one possible set of future conditions, but usually it is desirable to understand something about the envelope of possible future conditions or the degree of uncertainty associated with the particular simulation. To some extent, this uncertainty can be sampled by simulating multiple scenarios and using multiple models, but there are so many sources of significant uncertainty that it is difficult to sample them all.

These sources are as follows: (1) scenario uncertainty: we do not know exactly what future population growth or technology will hold; (2) model uncertainty: no model is perfect, from the global climate model down to the local hydrologic model; and (3) natural variability: scenarios usually incorporate the effects of humankind, but some natural drivers of the climate system are essentially unpredictable (e.g., volcanic activity) or only predictable a short time into the future (e.g., the Pacific Decadal Oscillation). Multiple scenarios can provide a sense of the uncertainty in (1), multiple models and model components can provide a sense of the uncertainty in (2), and multiple simulations from the same GCM of the same scenario can provide a sense of part of the uncertainty in (3). However, there is no guarantee, for example, that all models of a particular type do not share certain systematic biases that ensure that the future reality will fall outside the envelope of simulations.

In summary, scenarios allow people to visualize a possible future and its consequences. Because the climate system is being altered substantially, these possible futures will differ in various ways from the past. We do not have a comprehensive guide to the future. The past used to serve as an adequate guide to the future, but those days, so to speak, are past.

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12 Adapting Water Infrastructure to Nonstationary Climate Changes

Y. Jeffrey Yang

CONTENTS

12.1 CLIMATE CHANGE AND WATER SUSTAINABILITY ISSUES

12.1.1 NATURAL CONSTRAINTS IN THE SUSTAINABILITY OF WATER INFRASTRUCTURE

Water supply and sanitation are carried out by three major types of water infrastructure for drinking water treatment and distribution, wastewater collection and treatment, and storm water collection and management. Their sustainability is measured by resilience against and adaptability to an evolving factor; here, it refers to the change of climate and its hydrological impacts. The term *resilience* is defined as the ability to repair and recover its physical state and service function under the impacts of external forces (McDaniels et al. 2008; Milman and Short 2008). In this context, capacity reserve (CR) is one very important physical attribute of the system's resilience; further details will be described later in this section and in Section 12.2. While the service function of a water infrastructure varies geographically among municipalities, its general engineering and management follow a triple bottom line of objectives: system reliability, environmental sustainability, and engineering economics.

In the United States, drinking water treatment and distribution are designed for uninterrupted water supply and for compliance to drinking water quality standards. Centralized wastewater systems serve to collect wastewater from individual users and transfer it to a location for treatment and discharge of treatment effluent into a water body. The discharge is subject to flow and water quality limits regulated by a discharge permit under the historical Clean Water Act. On-site small wastewater systems and decentralized wastewater management are the alternative, serving some small communities and individual households (USEPA 2002), but they are not discussed here. Furthermore, storm water infrastructure of a massive scale has been constructed, providing drainage, sanitation, and flood control in an urban catchment. In the US Northeast and the Great Lakes region, storm water and wastewater networks often share the same piping structure in a combined sewer system (CSS). Combined sewer overflow (CSO) occurs during high-intensity precipitation, in which untreated wastewater bypasses treatment plants and pollutes receiving water bodies (Capodaglio 2004; USEPA 2001, 2008; Weinstein 2009).

Master planning in a municipality is conducted periodically to evaluate water infrastructure services against projected future water supply and sanitation needs. Typical process and considerations are shown in Figure 12.1. A planning horizon can be 30–50 years, varying with the service life of infrastructure assets, in which population change and land use projections are the two principal time variables. They are often established from urban development policies, municipal capital improvement programs, and land use master plans. In this widely adopted engineering practice, climate and precipitation are assumed to be stationary with time. Historical precipitation measurements are taken as a priori to statistically define the future design precipitation. Consequently, the assumed climate stationarity is inherited in subsequent development of hydrological design basis for each of the water infrastructure.

Now, the stationarity assumption has been reevaluated and known to be invalid (e.g., Easterling et al. 2000; IPCC 2007; Milly et al. 2008). As a direct consequence, water infrastructure built on the stationarity assumption could be either underdesigned or overdesigned leading to an improperly engineered system. Examples of hydroclimatic change have been reported on the seasoning and hydrograph of snowpack-related runoff in northwestern United States (Barnett et al. 2005; Stewart et al. 2004), water quantity and quality changes in surface water (Burns et al. 2007; van Verseveld et al. 2008), groundwater flow hydrodynamics (Scibek et al. 2007), and soil erosion and soil moisture (Miller et al. 2007; O'Neal et al. 2005). These changes can directly affect hydraulic and water quality engineering parameters.

Water infrastructure assets are inflexible and difficult to retrofit after construction. An improperly designed and engineered asset creates a "lock-in" condition, making future expansion and modification difficult, if not economically impossible. Thus, it is necessary to reevaluate long-term water infrastructure performance for improved sustainability. How to adapt the massive water infrastructure for uninterrupted and continuous service under present and future conditions is a challenge to all technical managers and policy makers. In this chapter, the need for infrastructure adaptation

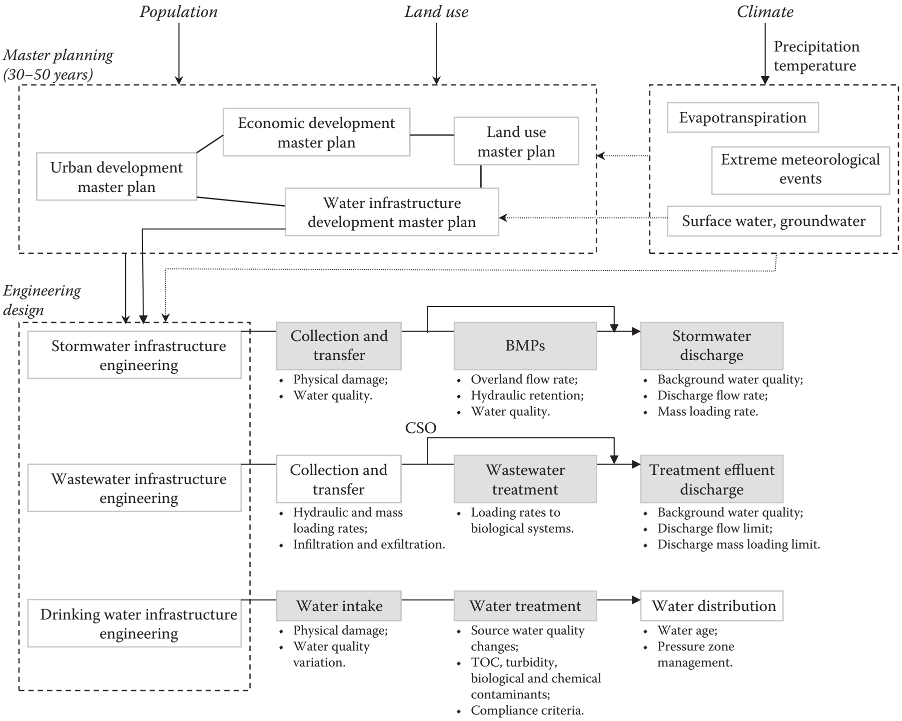

FIGURE 12.1 Principal engineering and planning variables (population, land use, and climate) and their relationships to the infrastructure design process. Engineering components of each infrastructure are shown on the bottom right along with primary design variables. The climate variable, presently assumed to be stationary with time, affects the process of master planning and engineering design as indicated by arrowed dashed lines. Solid line and arrow indicate engineering work flow. Gray pattern indicates components most vulnerable to climate change impacts. BMP, best management practice; CSO, combined sewer overflow.

for sustainability is evaluated by examining the rate of precipitation change against the CR installed in current engineering practice. In the subsequent Section 12.2, adaptation attributes are analyzed and adaptation strategies are examined on how the nonstationary precipitation change can be incorporated into the master planning process.

12.1.2 THE DIMENSIONS OF CLIMATE CHANGE IN PRECIPITATION

12.1.2.1 Long-Term Hydroclimatic Changes

Several sets of quantitative studies have shown seasonal and spatial shifting of precipitation regimes in the United States as well as globally (Bradley et al. 1987; Castro et al. 2007). The general overall increase in global precipitation is evident for the past century (Dore 2005; IPCC 2007, Chapter 11). Wentz et al. (2007) quantitatively analyzed satellite remote sensing data for the period 1987–2006. Their results indicated an increase in global precipitation and evaporation at a rate of 13.2 ± 4.8 mm/year/decade (or 1.4% ± 0.5% year^{-1}) and 12.6 ± 4.8 mm/year/decade (or 1.3% ± 0.5% year^{-1}), respectively. During the same period, the total water content in atmosphere has increased at a rate of 0.354 ± 0.114 mm/year/decade. The rate corresponds to a global precipitation increase by 0.14% year^{-1}.

Historical precipitation changes in the United States and North America were extensively analyzed (Dore 2005; Easterling et al. 2000; McKenney et al. 2006; Rajagopalan and Lall 1998; Yang et al. 2009). Yang et al. (2009) assessed the long-term (>100 years/station) precipitation trends for 1207 climate stations compiled by Williams et al. (2007) across the contiguous United States. The results led to a delineation of six hydroclimatic provinces; each has unique precipitation frequency and spatial variability (Figure 12.2a). The provinces include Florida and Southeast (P-I); Lower Mississippi–Ohio River valley–New England region (P-II); Great Plains and Midwest (P-III); Basin and Ranges (P-IV), West Coast (P-V), and Great Lakes (P-VI). For each climatic station, the long-term rate of precipitation change was determined by a regression of 12-month precipitation moving average and was normalized to the year 1950 precipitation:

$$\frac{\alpha}{P_{1950.00}} = \left[\frac{P}{P_{1950.00}} - 1\right]\frac{1}{(t - 1950.00)} \pm \frac{\sigma_{0.95}}{P_{1950.00}}, \tag{12.1}$$

where P and $P_{1950.00}$ are the log-transformed precipitation moving average at time t and in year 1950, respectively; α is the linear regression slope; P_0 is the regression intercept at $t = 0$; and $\sigma_{0.95}$ is the standard deviation at the 95% confidence interval for P_0.

Figure 12.2b shows the normalized rate of change for the six hydroclimatic provinces and their mixing zones (P-IIb, P-IIIb, and P-IVb). The rate of precipitation change has the smallest mean and variance in the P-I province (0.004% ± 0.021% year^{-1}, $n = 43$ stations). The rate is −0.004% ± 0.019% year^{-1} ($n = 33$ stations) after trimming the extremes in the <10th and >90th percentile. This indicates that the province as a whole has experienced a steady precipitation decrease over the past >100 years. On the contrary, both the Lower Mississippi River Basin (LMRB) subregion (P-IIb) and the Great Lakes province (P-VI) adjacent to large water bodies (Figure 12.2a) have registered the largest rates of precipitation increase. For the P-IIb subregion, the rates of precipitation increase have a mean and variance of 0.13% ± 0.35% year^{-1} ($n = 47$ stations); 0.12% ± 0.03% year^{-1} ($n = 37$ stations) after data trimming at the 10th and 90th percentiles. For the P-VI province, the rates of increase are 0.13% ± 0.18% year^{-1} ($n = 28$ stations) and 0.13% ± 0.03% year^{-1} after the trimming ($n = 22$ stations).

Within each province, precipitation extremes in the 10th and 90th percentiles represent the largest rate of precipitation decrease and precipitation increase, respectively. The average rate of the extreme precipitation increase is 0.33% ± 0.09% year^{-1} ($n = 108$ stations), and the maximum is 0.72% year^{-1}. The average rate in precipitation decrease is −0.30% ± 0.21% year^{-1} ($n = 108$ stations), and the maximum is −1.44% year^{-1}. Stations with extreme precipitation change are spatially clustered as shown in Figure 12.2a, coinciding with major physiographic futures.

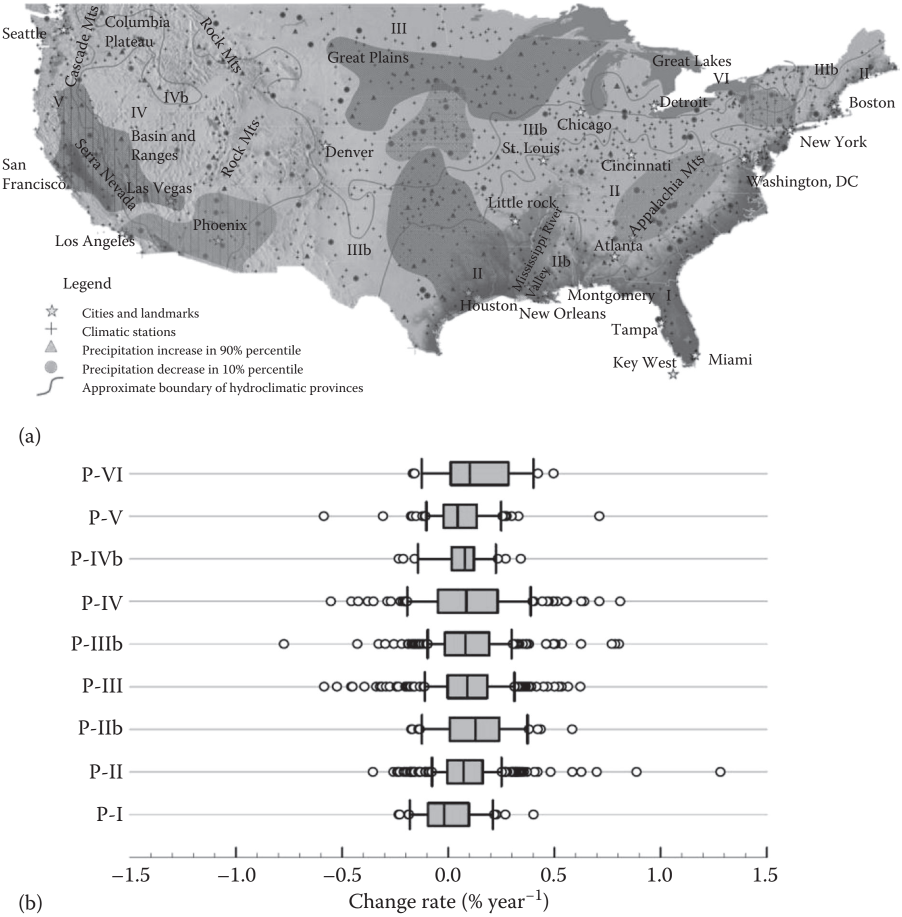

FIGURE 12.2 Determined rates of long-term precipitation changes and their spatial distributions in contiguous United States. (a) Six hydroclimatic provinces (Yang et al. 2009), and the areas of precipitation increase in the 90th percentile (dark shade and solid triangle) and precipitation decreases in the 10th percentile (light shade and solid circle) within each province. (b) Median, 90th and 95th percentile (center, box, and whiskers) plots for the normalized rate of precipitation change (see Equation 12.3). Hydroclimatic province P-I: Florida and Southeast; P-II: Lower Mississippi–Ohio River valley–New England region; P-III: Lower Mississippi River Basin subregion; P-III: Great Plains and Midwest; P-IIIb: Mixing Zone; P-IV: Basin and Ranges; P-IVb: Columbia Basin–Snake River Basin subregion; P-V: West Coast; and P-V: Great Lakes.

12.1.2.2 Future Projections and Uncertainty

Notably, the satellite remote-sensing data, global historical records, and the long-range precipitation measurements in the United States all agree to a likely rate of ~0.1% year^{-1} increase in historical precipitation. The variance of change is large among the hydroclimatic provinces (Figure 12.2b). Assuming a similar trend in the future, the average precipitation increase would be ~5% in the next 50 years or ~9%

by 2100. By 2060, extreme precipitation would increase by 16.7% ± 4.7% and the maximum would be 36.2%. For areas in the 10th percentile, average and maximum of the precipitation decrease would be −14.9% ± 10.3% and −72.2%, respectively. Accurate projection of this future change has been the focus of climate model simulations. Yet, their uncertainties are still large for water resource engineering, a factor that poses a challenge to adaptation planning and design.

12.1.2.2.1 Climate Model Projections of Future Precipitation Changes

The atmosphere–ocean global circulation model (AOGCM) simulations by international research organizations have generated a set of future atmospheric temperature and precipitation projections. In principle, the governing energy continuity equations are solved numerically over a spatial grid and temporal steps in Earth's hydrosphere and atmosphere. Approaches to compute the energy budget and its forms in atmospheric temperature gradient and moisture flow (e.g., precipitation) vary, but follow a similar general sequence. Both solar radiation and terrestrial radiation are first quantified. Solar radiation constantly changes as the Earth rotates around Sun in the solar system, yielding multidecadal and centennial cycles. The other component is future emission affecting the terrestrial radiation in the above equation. IPCC (2007) assumes four major emission scenarios in global climate simulations. It is also understood that these future emission scenarios are highly uncertain, and the current global emission trend has followed the worst emission scenario (IPCC 2014). Climate model results can be used only in reference to specific emission assumptions.

Second, AOGCM simulations calculate heat storage and transport in the Earth's atmosphere in the form of temperature or energy flux. The results depend on how accurately the Earth systems and processes are defined in a physical model and represented by governing equations and boundary conditions. Major Earth systems and their interactions include atmosphere, ocean and marine biogeochemistry, sea ice, land surface, and continental ice sheets. At a coarse spatial resolution normally by 1.25°, obviously, the AOGCM climate experiments cannot represent all major features in the Earth's boundary layer, such as high-altitude mountain peaks, large water bodies, and so on. This model deficiency in energy flux computation leads to uncertainty in precipitation projections.

A significant amount of research and advances have been undertaken to address uncertainties in the AOGCM climate projections. In one approach, AOGCM ensembles such as Coupled Model Intercomparison Project phase 3 and phase 5 (CMIP3 and CMIP5) are used for future climate projections (Bader et al. 2008; Brekke et al. 2009, 2013; IPCC 2014). The ensemble mean and variance are characteristic of future climate state. The other approach is to explore the use of downscaled regional climate models (RCMs). An RCM downscaling nests its model grids of much finer spatial resolution inside a coarse GCM grid (Figure 12.3). This computational treatment thus improves model description of fine physiographic features, atmosphere–land interactions, and the climate model performance. In this process, AOGCM outputs under future emission scenarios define grid boundary conditions in RCM computations. For the dynamic downscaling and the statistical downscaling techniques, Mearns et al. (2003) and Wilby et al. (2004) described the operational guidelines in model application.

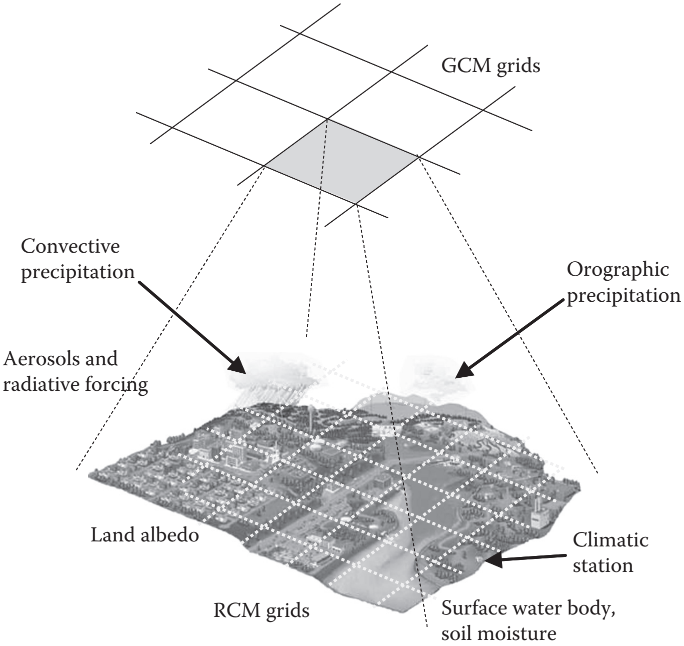

FIGURE 12.3 Schematic illustration of climate model downscaling in precipitation projections at a high spatial resolution for water resource engineering and adaptation planning.

The RCM methods and techniques are constantly evolving and vary substantially among applications. A lack of widely accepted techniques and evaluation criteria makes it difficult to conduct a reliable and objective method assessment. See downscaling methodology review by Fowler et al. (2007), Bader et al. (2008), and IPCC (2007, Chapter 8), and recently in IPCC (2014). For water resource planning and infrastructure engineering, Barsugli et al. (2009) summarized the advantage and major concerns on RCM downscaling in future climate projections:

- Dynamic downscaling is a technique that incorporates regional and local climate factors in future projections. The spatial resolution is improved from the course AOGCM model grid (e.g., 1.25° or ~100 km in middle latitudes) to as low as 32 km in spatial resolution. As stated in Barsugli et al. (2009), AOGCM outputs generally underestimate the occurrence of high-intensity precipitation events, poorly represent temporal precipitation variability related to the ENSO/PDO and NAO systems, and inadequately describe precipitation variability in mountain regions of high altitudes. These model uncertainties can be reduced by dynamic downscaling at a spatial resolution to account for the local climate forcing factors.
- Statistical downscaling, as the alternative to dynamic downscaling, can capture the high-intensity precipitation variability and implicitly represent the precipitation effects of local climate factors. However, several model

assumptions may affect the validity and reliability of future precipitation projections: (1) GCM outputs as the model boundary realistically and faithfully present the large-scale climate variables in control of the climate state; (2) the empirical mathematical predictor–predictant correlation established in training period will remain unchanged in the future. The second assumption is another form of climate stationarity that may not be valid under a changing climate.

12.1.2.2.2 Uncertainties and Implication for Planning and Engineering

The source and causes of climate projection uncertainties have been under debate. Nonetheless, it is accepted that synoptic precipitation variations are a result of larger-scale climate dynamics or climate state, yet many precipitation changes "tangible" to water resources in watersheds are related to local and regional factors (e.g., Barsugli et al. 2009; IPCC 2007). Examples can be found in convective precipitation in the Great Plains (Weaver and Nigam 2007), dynamic uplifting of air mass producing high-intensity rainfalls in the southeast and rain shadows in the central South Carolina (Changnon and Demissie 1996; Konrad II 1997), and regional synoptic patterns of short-duration (e.g., 24 h) precipitation attributed to orographic uplifting in the coastal state of Washington (Wallis et al. 2007). Yang et al. (2009) showed an increase of high-intensity 75% quartile 24-h precipitations in localized areas of the LMRB and attributed it to the topographic influence. These nonstationary climate dynamics will likely lead to a substantial change in the future precipitation intensity–duration–frequency relationships (Mailhot et al. 2007) and thus may change the basis of design storm intensity in water resource planning and infrastructure engineering.

With this understanding, it is helpful to illustrate the AOGCM model uncertainty and its relationship with regional factors using model validation results in Figure 12.4. In assessing modeling bias, the multimodel data (MMD) precipitation projections of 21 AOGCM climate experiments (IPCC 2007, supplemental materials) are compared against the observed precipitation data of Xie and Arkin (2006) for the western North America (WNA), eastern North America (ENA), and central North America (CAN). For precipitation means of four seasons, the large model overpredictions by 28%–93% are observed in the WNA model domain largely in the western contiguous United States of diverse physical geography (IPCC 2007). This model limitation for the region is also shown by the large spread of probability curves for all four seasons (Figure 12.4). The discrepancy can be much larger for daily or monthly precipitation, at one single location, than the seasonable average over the entire model domain. Comparatively, the MMD outputs are the best for the CAN model domain or the central continental United States. The average model mean bias ranges from 8% to 16%. Less robust are the model predictions with a bias of −4% to 21% in ENA (Figure 12.4), which encompasses the Appalachian Mountains and the northeastern United States. These results, as summarized in IPCC (2007), may reflect the model inadequacy for a full representation of ENSO, PDO and NAO periodicity, the Hudson Bay and Canadian Archipelago systems, tropical cyclones and landfall precipitation connections to the Labrador–Arctic climatic system in the northeastern United States, the snow albedo feedbacks, and climatic variations in high-altitude mountain regions.

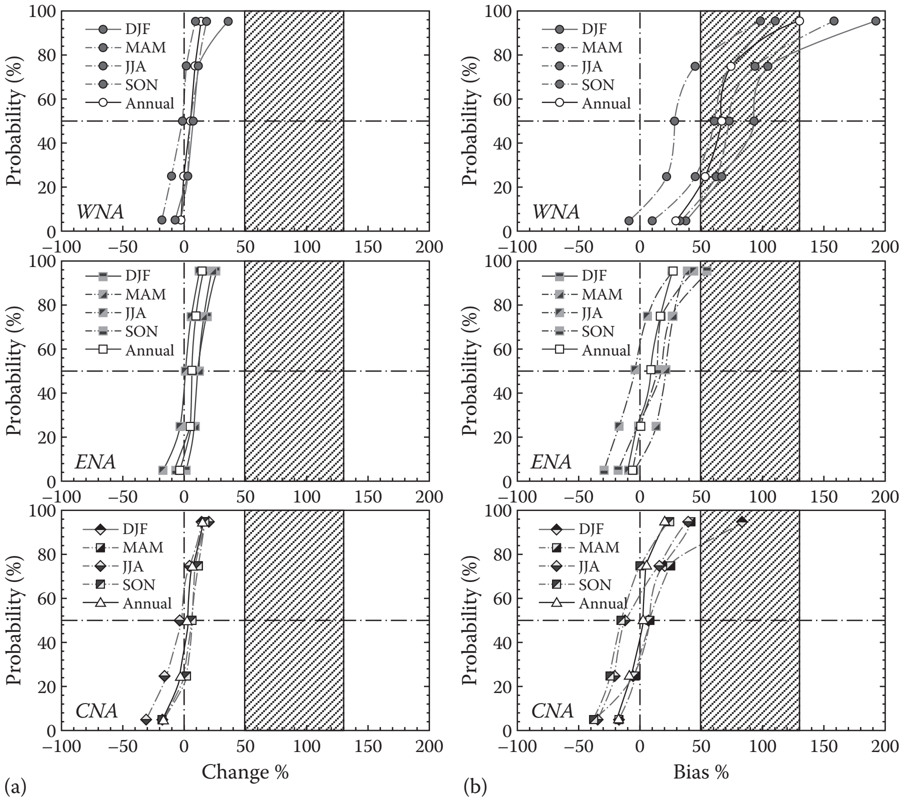

FIGURE 12.4 Percentage precipitation change and GCM projection bias % for the western North America (WNA), central North America (CNA), and eastern North America (ENA) model domains. (a) Probability distribution of domain-averaged precipitation change in 2090–2100 relative to 1990–2000. (b) GCM ensemble bias in the MMD outputs in calibration to observed precipitation of Xie and Arkin (2006). The infrastructure CR in percentage of design values is marked in patterns. Season abbreviations: DJF, winter months; JJA, summer months; MAM, spring months; and SON, autumn months.

Also shown in Figure 12.4 is a range of water infrastructure CR installed in the infrastructure planning and engineering. Examples include the use of an engineering safety factor in hydrological design. The range is shown in the shaded patterns. Apparently, for regions with complex climate factors (e.g., western United States or WNA), the precipitation variability is important and can exceed the water infrastructure CR range.

The current climate models cannot fully account for the ocean–atmosphere interactions, or for some regional and local climate factors. Neither is adequate quantification of uncertainties in precipitation projections. As a result, the precipitation projections at local watershed levels contain a degree of uncertainty greater than what can be managed in traditional water resource engineering. In practice, the projection uncertainties are commonly analyzed on a project-specific basis. For example, Brekke et al. (2013) instituted a rigorous model calibration and validation procedure for the precipitation projections in the southwestern United States. Their results indicated a high degree of model performance possible to achieve in precipitation projections. Mearns et al. (2003) concluded that the dynamic downscaling in the Appalachian region could not improve the projection uncertainties from those of the parent AOGCM inputs. Overall, the statistical downscaling requires less computational resources than dynamic downscaling. The methods include bias-corrected spatial downscaling, bias correction, and constructed analog (Brekke et al. 2013).

Despite several large-scale collaborations on climate simulations, breakthrough or significant improvement is unlikely to occur in the next 10–15 years (Barsugli et al. 2009). Thus, climate change adaptation at this time relies on the imperfect future projections. This unique property makes the adaptation planning significantly different from the traditional hydrological engineering; the latter is deterministic on the basis of well-defined hydrological variables.

12.1.2.2.3 Watershed-Scale Projections for Water Planning and Engineering

It is worth noting that water resource planning and engineering are based on hydrological parameters in local watershed rather than global or regional precipitation. Other processes in a watershed can modify the climate change impacts, thus requiring careful consideration in developing the design basis. Climate change occurs in small and incremental steps leading to the accumulative "creeping" effect on the watershed hydrological processes. The small change in a short monitoring period can be small and difficult to detect, and it can be overshadowed by other nonclimate variables. The central task for model simulation is to identify the accumulative climate change impact and to project the combined and the individual changes of interacting factors.

The combined effects in watershed hydrology are a function of two factors: future climate change (e.g., precipitation) and land use. When precipitation in the form of rain or snow falls to ground, it becomes direct runoff, evapotranspiration, soil moisture storage capacity (STC), and soil moisture storage (ST) in subsurface soil zones. The STC and ST can later become surplus runoff supplemental to river and stream base flow and also recharge groundwater in further vertical infiltration. The corresponding change can be in the form of water quantity and quality in streams, rivers, and in overland runoff; some changes are directly related to the service functions of a water infrastructure.

Because of this intimate interaction, model simulations are often used to consider both climate and land use changes simultaneously in future watershed hydrology. An integrated modeling process for both land use projection and hydrological modeling is shown in Figure 12.5. It begins with population model and land use simulation. Generally, population projections are available from the US Census Bureau, while such county-wide projections should be verified and fine-tuned against projections by local governments. The latter tend to incorporate considerations of specific local economic development actions that are often more accurate and often revised periodically. Examples include information contained in regional or municipal land use and economic master plans.

The combined hydrological effect has demonstrated to be significant for adaptation planning and engineering. Tong et al. (2011) and Chen et al. (2014) have shown

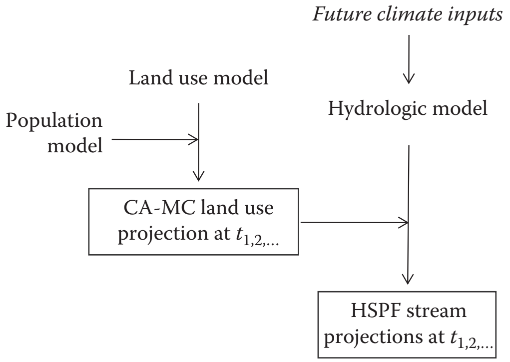

FIGURE 12.5 Schematic of an integrated modeling approach to project surface water quality and quantity changes in response to a combined effect of climate, land use, and population changes. The CA-MC and HSPF refer to cellular-automata Markov land use model and hydrological simulation program-Fortran, respectively.

that the land use and climate changes can interactively affect surface stream flow and water qualities. Degrees of compounding effect depend on regional climate condition, watershed characteristics, and land use patterns. In the suburban–rural Little Miami River watershed in the southwestern Ohio, the projected future land use changes may increase river flow by 29% and total nitrogen concentration by 3.3%. The climate change effects are in similar magnitudes (Tong et al. 2011). The land use change effect is much less for the Lower Virgin River watershed in semiarid Nevada of the western United States (Chen et al. 2014). Therefore, hydrological design in adaptation should consider the compounding effects for these watersheds, for which an integrated approach is illustrated in Figure 12.5.

12.1.3 THE DIMENSIONS OF WATER INFRASTRUCTURE SUSTAINABILITY

Climate change effects on watershed hydrology have uncertainties in projections as discussed in the preceding sections. For this reason, the other dimension in climate change adaptation is how to manage the uncertainty-related engineering risk. Two types of engineering analysis are often essential. One is to assess the realized CR in existing water infrastructure. The investigation yields a basis to assess likely engineering risk under climate change impacts and thus defines the need for infrastructure adaptation. This type of analysis is illustrated in this section for three types of water infrastructures. The other type of analysis is to change the infrastructure CR at a reasonable adaptation cost.

12.1.3.1 Water Infrastructure Types and Adaptability

Storm water, drinking water, and wastewater infrastructures in an urban catchment are schematically shown in Figure 12.6. Water withdrawal for consumption and water quality change in wastewater management occur in processes A and B (Figure 12.6) between the precipitation and discharge outflows leaving an urban catchment. Furthermore, storm water infrastructure manages overland runoff and channel flows.

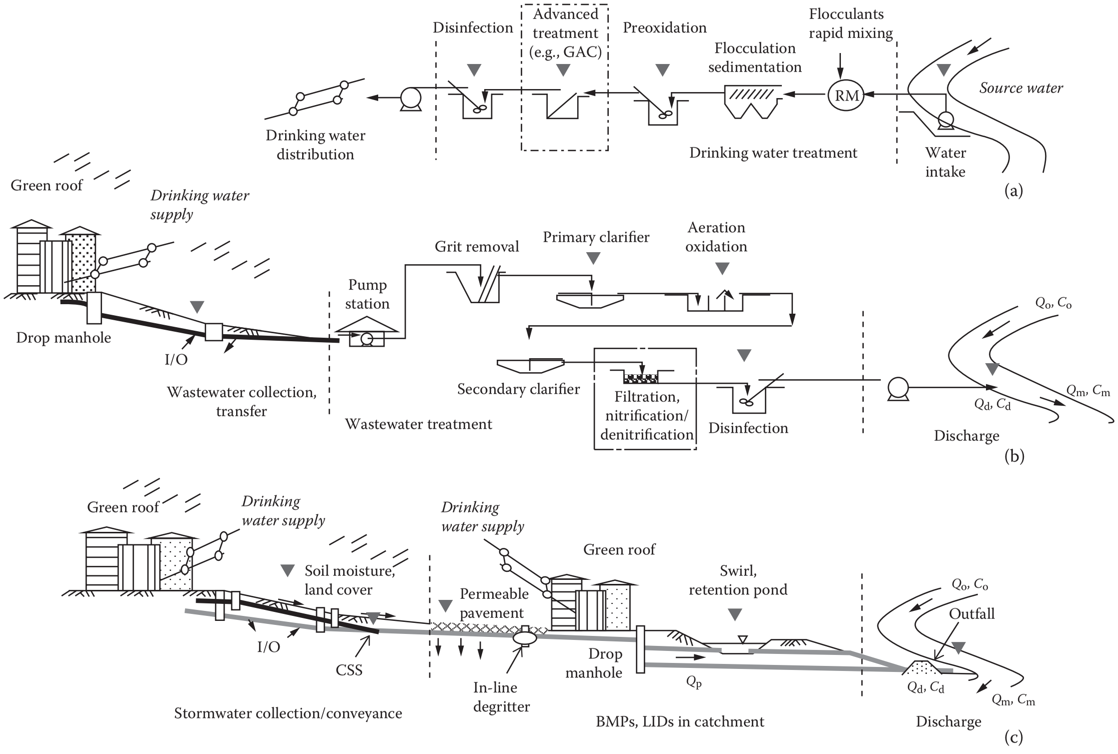

FIGURE 12.6 Process schematic diagrams for typical centralized (a) drinking water, (b) wastewater, and (c) stormwater infrastructures in an urban catchment. Combined sewer system (CSS), storm water, and wastewater treatment effluent discharges (Q_d, C_d) are regulated for stream flow (Q_o) and pollutant concentration before and after the discharge point (C_o and C_m). Solid arrow indicates water flow directions. I/O is water inflow and outflow in the buried pipes through infiltration and exfiltration. Solid triangle indicates process unit potentially vulnerable to future precipitation changes.

For the three types of water infrastructures, Table 12.1 lists major components, service functions, and likely vulnerability to precipitation change.

- *Storm water infrastructure*

  In a nonstationary climate, future runoff hydrograph in time–flow (t–Q) variations may significantly differ from that of the original engineering basis when the infrastructure was designed. This difference is mostly shown in the design conveyance capacity of a built storm water network. The difference can also adversely affect the hydraulic and water quality functions of low-impact development (LID) measures and storm water best management practices (BMPs).
- *Realized hydraulic CR*

  Carrying capacity and hydraulic profiles of a storm water network are specified, and structures such as drop manholes are designed to limit the nominal pipe flow to a range of 0.6–4.6 m/s. This design criterion is intended to prevent excessive sedimentation in or erosive damage to the conveyance structure and the receiving water bodies. For a fixed topography of land surface, the runoff t–Q profile or hydrograph for a given storm depends on the precipitation intensity, time to concentration, prestorm soil moisture content, vegetation cover, and land use patterns. Among the factors, precipitation intensity and soil moisture are climate dependent. Design precipitation intensity at a given return interval (e.g., 10-year design storm) is commonly determined from categorized precipitation charts such as NOAA precipitation Atlas 14 (NOAA 2007), National Weather Bureau Technical Paper 40 (Hershfield 1961), and the SCS 24-h rainfall curves (Guo and Hargadin 2009). These current methods are all based on the assumed stationary climate in precipitation variability.

  Nevertheless, the current civil engineering uses engineering safety factors and conservative pipe selections to accommodate hydrological uncertainties. Maximum-installed hydraulic CR for a storm water pipe could be as much as 230% of the design value.
- *Water quality limitations*

  Climate-driven water quality changes can significantly limit the storm water infrastructure CR for adaptation. Studies (e.g., Horowitz 2009; Whitehead et al. 2009; Yang et al. 2002) have linked the intensity of peak runoff to the increased turbidity, metal, chemical, dissolved organic carbon loading, and ecological health in urban streams. Peak pipe flow and high discharge velocity are also found to be responsible for soil erosion, water quality and ecological deterioration at outfalls, and their immediate downstream segment (see McCorquodale 2007; Novotny and Witte 1997). In particular, the CSO during intense precipitation is a major factor limiting infrastructure CR otherwise available for adaptation. Storm water runoff and untreated sewage are diverted for discharge when storm water peak flow exceeds hydraulic capacity of the wastewater treatment plants and the available retention facilities. The peak flow, on the other hand, is a function of the precipitation duration and intensity, catchment hydrograph, and the

TABLE 12.1
Water Infrastructure Design and Engineering Domains, and Their Attributes

	Deterministic Engineering Domain (1)		Adaptation Engineering Domain (2)		Redesign and Reconstruction Domain (3)	
	Attribute	**Potential Action**[a]	**Attribute**	**Potential Action**[a]	**Attribute**	**Potential Action**[a]
New Infrastructure						
Hydraulic capacity	Specific value	Process adjustment and retrofitting;	Range; capacity adaptively installed	Assessment–adaptation–monitoring for optimal cost–benefit balance; Go to Domain (3) for severe CR limitation	Specific value	Optimization, retrofitting; Management and objective reevaluation
Engineering flexibility	Limited in quantity Realized at construction	No large-scale asset modification; Go to Domain (2) or (3) in severe CR limitation	Flexible timing for extra capacity installation		Large CR expansion after reconstruction	
Water quality capacity[b]	Specified value		Range; capacity adaptively installed		Specified value	
Engineering flexibility	Limited in quantity Realized at construction		Flexible timing for extra capacity installation		Large CR expansion after reconstruction	
Techniques and examples						
Stormwater infrastructure	Hydraulic design using runoff rational methods for facilities (e.g., retention ponds and storm sewer)	Satellite retention facilities; Slice gate automation; Go to Domain (2) or (3) in severe CR limitation	Structure, LIDs/BMPs design for nonstationary precipitations; Module design, phased installation; System monitoring and forecasting	Adaptive capacity installation; Go to Domain (3) for severe CR limitation	New infrastructure network with or without use of existing assets	Optimization, retrofitting; Management and objective reevaluation

(*Continued*)

TABLE 12.1 (CONTINUED)
Water Infrastructure Design and Engineering Domains, and Their Attributes

	Deterministic Engineering Domain (1)		Adaptation Engineering Domain (2)		Redesign and Reconstruction Domain (3)	
	Attribute	**Potential Action**[a]	**Attribute**	**Potential Action**[a]	**Attribute**	**Potential Action**[a]
Wastewater infrastructure	Ten-state design standards, other design protocols	Process automation; Flow detention facility; Go to Domain (2) or (3) in severe CR limitation	Module design, phased installation; Decentralized wastewater system; On-site wastewater reuse; System monitoring and forecasting	Adaptive capacity installation; Go to Domain (3) for severe CR limitation	New designs and use of revolutionary technologies and concepts	
Drinking water infrastructure	Unit process and system modeling and specifications (e.g., disinfection chamber)	Disinfectant, dosage change; Go to Domain (2) or (3) in severe CR limitation	System optimization, retrofitting; Module design, phased installation; System monitoring and forecasting	Network expansion; Adaptive capacity installation; Go to Domain (3) for severe CR limitation	New designs and use of revolutionary technologies	

(*Continued*)

TABLE 12.1 (CONTINUED)
Water Infrastructure Design and Engineering Domains, and Their Attributes

	Deterministic Engineering Domain (1)		Adaptation Engineering Domain (2)		Redesign and Reconstruction Domain (3)	
	Attribute	Potential Action[a]	Attribute	Potential Action[a]	Attribute	Potential Action[a]
References	ASCE/AWWA (2004), Lin (2001), USEPA (1994, 2002, 2008), Salvato et al. (2008), engineering codes and guidelines		Carter and Jackson (2007), Chung et al. (2009), Semadeni-Davies et al. (2008), Gikas and Tchobanoglous (2009), Oron et al. (2007), Gupta and Shrivastava (2006), and USEPA (2009b)		Chang et al. (2006) and Neuman (2009)	
Existing Infrastructure						
Hydraulic capacity	Fixed	Infrastructure optimization, retrofitting; Go to Domain (2) or (3) for severe CR limitation	Range of values	Iterative assessment–adaptation–monitoring for optimal cost-benefit ratio; Go to Domain (3) for severe CR limitation	Specific value	Optimization, retrofitting; Management and objective reevaluation
Engineering flexibility	Limited, and deteriorated after construction		Large, adaptively installed		Large CR expansion after reconstruction	
Water quality capacity[b]	Fixed		Range of values		Specified value	
Engineering flexibility	Limited and deteriorated after construction		Large, adaptively installed		Large CR expansion after reconstruction	

(*Continued*)

TABLE 12.1 (CONTINUED)

Water Infrastructure Design and Engineering Domains, and Their Attributes

	Deterministic Engineering Domain (1)		Adaptation Engineering Domain (2)		Redesign and Reconstruction Domain (3)	
	Attribute	**Potential Action**[a]	**Attribute**	**Potential Action**[a]	**Attribute**	**Potential Action**[a]
Techniques and examples						
Storm water infrastructure	Operation and maintenance	CSO division adjustment; Go to Domain (2) or (3) for CR expansion	Urban LIDs, BMPs designed for nonstationary precipitation; Structure retrofitting; Recursive monitoring–adaptation–assessment	Adaptive CR installation (new infrastructure); Go to Domain (3) for severe CR limitation	New infrastructure network with or without use of existing assets	Optimization, retrofitting; Management and objective reevaluation
Wastewater infrastructure		Operational adjustment for CR increase; Process optimization without large asset change; Go to Domain (2) or (3) for severe CR limitation	Model-based system design and upgrading; Adaptive system retrofitting and improvement; Recursive monitoring–adaptation–assessment	Adaptive CR installation (new infrastructure); Go to Domain (3) for severe CR limitation	Application of new and revolutionary technologies	

(*Continued*)

TABLE 12.1 (CONTINUED)
Water Infrastructure Design and Engineering Domains, and Their Attributes

	Deterministic Engineering Domain (1)		Adaptation Engineering Domain (2)		Redesign and Reconstruction Domain (3)	
	Attribute	Potential Action[a]	Attribute	Potential Action[a]	Attribute	Potential Action[a]
Drinking water infrastructure		Operational adjustment for CR increase; Process optimization without large asset change; Go to Domain (2) or (3) for severe CR limitation	System optimization; Process retrofitting without large asset alteration; Recursive monitoring–adaptation–assessment	Adaptive CR installation; Network expansion; Go to Domain (3) for severe CR limitation	Application of new and revolutionary technology; New infrastructure expansion for CR	
References	ASCE/AWWA (2004), USEPA (2004), engineering codes and guidelines		Chung et al. (2009), Gikas and Tchobanoglous (2009), Montalto et al. (2007), and Donofrio et al. (2009)		Chang et al. (2006) and Neuman (2009)	

[a] Potential actions at the upper limits of infrastructure CR and flexibility.

[b] Refers to the capacity of a water infrastructure in maintaining performance on specific water quality criteria.

> groundwater infiltration rate into the pipes (Black and Endreny 2006; Diaz-Fierros et al. 2002; Lai 2008). More intense precipitation events projected in future climate will likely yield greater peak flows and more frequent CSO events (Alp and Melching 2009; Capodaglio 2004; USEPA 2009a).

Currently, storm water BMPs and LIDs for enhanced storm water retention and reduced peak runoff are engineered assuming a precipitation stationarity (e.g., Carter and Jackson 2007; Dietz 2007; Gilroy and McCuen 2009; Lai 2008; Marsalek and Chocat 2002; Montalto et al. 2007; USEPA 2004). Recently, the US Environmental Protection Agency has developed and published a storm water calculator that can be used to calculate surface runoff under climate change scenarios (Rossman 2013). A majority of the BMPs and LIDs built with the climate stationarity assumption, however, are vulnerable themselves in performance and effectiveness under a non-stationary climate. Koob et al. (1999) reported that the precipitation variations and their timing difference from vegetation growth season regulated the urban wetland performance in storm water mitigation. Semadeni-Davies et al. (2008) further suggested, explicitly, the need to consider climate and precipitation changes in storm water BMPs designs. Thus far, the impacts of climate change on BMP and LID engineering have not been adequately quantified. Nor have storm water BMP and LID measures been widely used in the United States to conduct a comprehensive evaluation. For this limitation, the maximum realized hydraulic CR, or 230% of the design value, is taken as the upper limit.

12.1.3.1.1 Drinking Water Infrastructure Functions and Resilience

Community water system dominates the US water supplies, serving 292 million people in 2008. Drinking water distribution after the treatment is engineered to meet water demand for both domestic consumption and firefighting throughout a service area. Long-term water demand variation, a prime engineering factor in water distribution design and operation, is linked to demographic and land use changes and to the transformation of water-intensive industries (Hummel and Lux 2006; Levin et al. 2002; Pires 2003). It is commonly captured in urban development master plans and regional economic development projections (Figure 12.1) that may have intrinsically included adequate hydraulic capacity for adaptation.

Water quality changes within a distribution system have been studied extensively, but little was directly related to climate change effects until recently. In a study of climate change effect on a large US Midwest utility, Li et al. (2009, 2014) concluded that an increased total organic carbon (TOC) level in source water under future climate scenarios will lead to higher TOC concentration in production water and subsequently greater disinfection by-product (DBP) formation at a level in violation of the US drinking water standards. This water quality effect can significantly reduce the available infrastructure CR, making adaptation a necessary management option. A variety of adaptation options in unit process engineering are available, such as enhanced TOC removal using granular activated carbon (GAC) or chemical flocculation (e.g., Clark et al. 2009; Crozes et al. 1995; Järvinen et al. 1991; Li et al. 2012), water age reduction, and chlorine addition optimization for DBP controls (Boccelli et al. 2003; Carrico and Singer 2009; Prasad et al. 2004). In addition, higher surface water and drinking water temperature in future climate will very likely change the disinfection kinetics, DBP formation rates, and biological stability in a distribution system. These areas of indirect climate change impacts are worthy of further investigations.

- *Realized CR in drinking water treatment*

  Water intake and water treatment are likely vulnerable to the direct impacts of precipitation changes. In the United States, a water treatment process is deterministically configured for a specific hydraulic capacity and predetermined treatment efficiency. Figure 12.6 shows a typical water treatment process that consists of preoxidation, rapid mixing, flocculation and sedimentation, granular filtration, advanced treatment if necessary (e.g., GAC filtration, reverse osmosis membrane separation), and finally disinfection in clear wells before distribution.

  A simple empirical safety factor of 1.2–1.5 is often used in process engineering and unit designs; some larger values have been used. For example, Kim and Bae (2007) proposed a safety factor of 2.0 in hydraulic design of a baffled GAC contactor for odor control. More advanced probability-based methods are developed for systematic reliability–cost trade-off evaluation. Boccelli et al. (2007) described process optimization guided by a cost–performance ratio in order to determine the safety factor in the flow rate design of an infiltration-based treatment plant. Gupta and Shrivastava (2006) introduced a water treatment design method based on Monte Carlo simulation to quantify performance uncertainties in suspended solid removal. Li et al. (2009, 2014) developed a Monte Carlo methodology to simulate the cost–probability curves in GAC contactor process modification. While these advanced design methods better quantify the capacity and cost probability density function (PDF) curves, they require extensive input data and computation. Instead, the traditional safety factor method is widely used in field engineering of the deterministic domain. This practice alone yields a maximum treatment capacity at 150% of the design value. For climate change impacts exceeding the CR limits, engineering adaptation is needed to increase the infrastructure CR, mostly through treatment plant retrofitting, process modification, or change of unit operations. An engineering adaptation example is given by Li et al. (2009, 2012, 2014) and Clark et al. (2009).

12.1.3.1.2 Wastewater Infrastructure Functions and CR

- *Realized CR in hydraulic loading*

  A general wastewater treatment process in the United States includes physiochemical pretreatment, biological oxidation of macronutrients (BOD, N, and P), optional tertiary treatment, and finally effluent disinfection before discharge (Figure 12.6). Hydraulic loading capacity is often specified for future wastewater generation within a service area and for groundwater infiltration into wastewater collection and transfer pipes (Lai 2008; Lin 2001). These variables are lumped into a single parameter—wastewater generation rate per capital in engineering designs, for example, 1900–4550 lpd/person (500–1200 gpd/person). In addition, an empirical safety factor of 1.2–1.5 is used to accommodate unexpected hydraulic variations. Values up to 2.0 are justified for special engineering conditions, such as complex hydrogeologic regions, aged water collection networks with extensive infiltration and exfiltration, or service areas of large variation in wastewater generation rates.

- *Realized CR in biological systems*

  Space-demanding aerobic and anaerobic biological treatment is often a limiting unit process that frequently determines available CR of a wastewater treatment plant. The limitation and vulnerability are illustrated in design or retrofitting of an aeration tank, a principal unit of activated sludge process. CR in biological treatment is recognized by using an empirical design safety factor (commonly 1.2–1.3) and by modifying unit operations without large physical asset alteration. In addition, the treatment CR is also made available through optimization of the biological process. One operational adjustment, for example, increases the capacity by changing biomass cell age, aeration rate, and efficiency.

By a combination of using design safety factor and operational adjustment, the total realized CR could reach 30%–80% of design value in an activated sludge process. One factor in CR evaluation is the performance deterioration over time for wastewater treatment facilities. Since the early study of Kincannon and Gaudy (1966), biological wastewater treatment is known for its sensitivity to both hydraulic and contaminant shock loading (Chen et al. 2008; Jing et al. 2009), leading to treatment process upset (Capodaglio 2004; Ray and Peters 2008) and performance deterioration (O'Reilly et al. 2009). Other causes for reduced treatment capacity include aging treatment equipment and wastewater infrastructure, poor process control, and operational inefficiencies. This portion of the treatment CR is recoverable by process monitoring, control, and adjustment, or by using advanced engineering techniques such as fuzzy logic control (e.g., Müller et al. 1997; Peng et al. 2007). The analysis here assumes that the performance reduction is minimized through process adjustment and optimization. The realized CR of 30%–80% design value is a reasonable estimate.

12.1.4 THE NEED FOR ADAPTATION

On the basis of the simple analysis in preceding sections, one can illustrate as in Figure 12.7 the range of infrastructure CR installed in current engineering practice. One could further compare the CR against the rates of precipitation change in the contiguous United States and assess the adaptation need. In this analysis, the likely precipitation changes are determined from long-term historical measurements, from which the average (US mean), the 90th and 10th percentiles (90 PCT, 10 PCT), and the maximum and minimum are calculated (Yang et al. 2009).

On average, the infrastructure CR available from current engineering practice is a magnitude of order larger than the national average rate of precipitation changes (Figure 12.7). One could also argue that the precipitation change is not equal to the

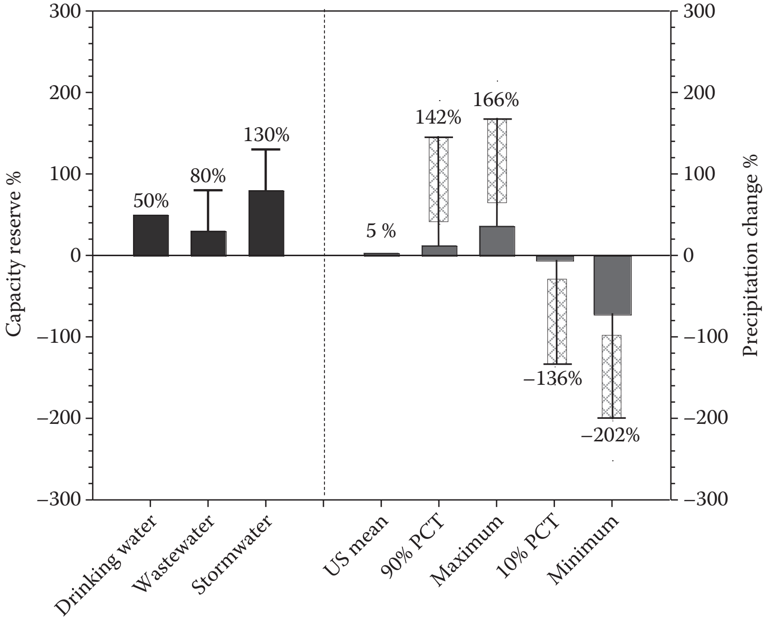

FIGURE 12.7 Relative magnitude of infrastructure CR installed in current engineering practice (left) compared with the relative precipitation change % (solid bar) and uncertainty (pattern and solid line with whisker) in the next 50 years in 2060.

changes in stream flow and water quality; the latter defines the engineering design basis of a water infrastructure. Studies published so far indicate that the watershed hydrological response to precipitation change is no more than an order of magnitude larger than the precipitation change itself. For example, integrated watershed simulation for three watersheds in Ohio and Nevada showed similar degrees of change in stream flow and water quality when compared to the future precipitation (Chen et al. 2014). For example, in the Little Miami River watershed, a 20% precipitation increase or decrease in 2050 would result in a 43.83% increase and 53.08% decrease in stream flow, respectively. The total phosphorus increases in both cases by 21.35% and 6.73%. Total nitrogen change is smaller. While watershed-scale analysis is necessary for specific watersheds, the simple envelop evaluation indicates that, on a national average, the average precipitation changes at ~5% by 2060 could likely be managed by the installed CR in existing infrastructure. This generalized conclusion validates current engineering practice that has been applied worldwide for decades.

It is important to note that precipitation distribution and future changes are unevenly distributed in the United States. In areas of extreme precipitation changes, for example, in the 10th or 90th percentiles, the relative magnitude of future precipitation change is larger than the installed CR of a water infrastructure (Figure 12.6). The adequacy is even more tenuous in many areas where aging water infrastructure has deteriorated.

The future climate change is characteristic of a large variability in precipitation across the United States (IPCC 2007). Climate stations with precipitation increase in the 90th percentile are spatially clustered in many regions such as the eastern Texas–Oklahoma region. For areas in Arizona and New Mexico, precipitation decreases in the <10th percentile are compounded by the high rate of population growth. The combined effect makes water availability the dominant adaptation factor for the region. Second, the generalized envelope analysis must be reexamined to evaluate the resilience of individual infrastructure at watershed scales. The national general conclusion need "downscaled" to each urban watershed and the infrastructure condition. As the water infrastructure ages and deteriorates, the degree of CR loss is location specific. The degree of such vulnerability is a focus of bottom-up infrastructure assessment.

12.2 WATER INFRASTRUCTURE ADAPTATION STRATEGIES FOR SUSTAINABILITY

12.2.1 Adaptation Objectives in Water and Energy

Water infrastructure adaptation to future climate and land use changes is effective when planned in the context of sustainable urban and socioeconomic development. Specific goals in adaptation vary among stakeholders and are specific to local conditions. However, overreaching and commonly shared objectives are to

- Enhance the water infrastructure resilience. The ultimate purpose is to provide uninterrupted water supply, water sanitation, and storm water management for a projected socioeconomic growth under both current and future climate conditions.
- Increase the ability to comply with the existing regulations and help the implementation of urban development policies.
- Achieve co-benefits in climate change adaptation and mitigation. Water infrastructure construction and operation consume a significant amount of energy-generating CO_2 emission. Thus, the co-benefit in CO_2 emission reduction is an important element in water adaptation planning and design. This is particularly pertinent in the view of urban growth and future energy needs (Dodder 2014; Yang 2010; Yang and Goodrich 2014).
- At the same time, minimize the systems' adaptation cost.

Water service function is the traditional and fundamental focus of water infrastructure development. It is also essential to climate change adaptation. The engineering components and functions of each of storm water, wastewater, and drinking water infrastructures were analyzed in Section 12.1.3.1. In addition to the traditional water management functions, attention has been galvanized recently on water availability on the supply side and water footprints on the consumption side. For water infrastructure, these fundamental concepts can be found in service functions such as water reuse or reclamation, water storage, water loss prevention, water conservation, and importantly in the water–energy nexus (PNNL 2012; Yang and Goodrich 2014 and references therein).

12.2.2 STRATEGIES TO IMPROVE CLIMATE RESILIENCE

Adaptation and mitigation co-benefits in water and energy are in the forefront of adaptation objective setting. This objective defines data acquisition and design basis development in the context of the climate projection uncertainties. A similar concept of "decision downscaling" was described in Brown et al. (2012), with the focus to increase the water infrastructure resilience. This type of adaptation takes place through changes in water infrastructure paradigm through urban-scale adaptive planning and through water master planning. A recent published example is given in Chang et al. (2012) for a county-wide water supply master planning. The other approach is to improve existing water infrastructure for better adaptation capacity with no regret (e.g., Barsugli et al. 2009; Felgenhauer and Webster 2013; Li et al. 2014; Wilby 2007) or, in engineering terms, the greater infrastructure CR.

The two adaptation approaches can be illustrated in Figure 12.8. In borrowing the ecological system resilience concept of Marshall and Toffel (2005), infrastructure functions follow four scenarios of trajectories under the climate and other external impacts. Scenario I is preferable, showing system resilience in providing uninterrupted service throughout the external impact. Scenario II represents temperature vulnerability of the infrastructure "out-of-service" below the desired capacity. This condition in urban water supply and sanitation happens with increasing frequency in recent decade, such as during the recent Hurricane Sandy in New York City and

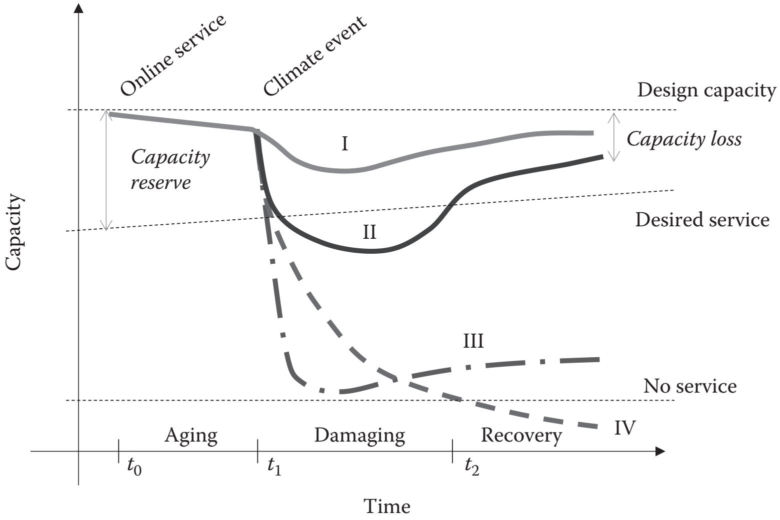

FIGURE 12.8 Four types of infrastructure vulnerability during external impact event (e.g., climate change). In all cases, CR is the capacity difference between the minimum service required and the design capacity. See text for more explanations.

the adjacent coastal states. Other examples include water supply stress during an extended period of drought, such as the droughts in Florida in the 2000s and the ongoing droughts in California. After the climatic disruptions, the urban water infrastructure recovers to a sustained level that is lower than the original infrastructure design capacity. The difference is capacity loss (Figure 12.8), often attributed to aging infrastructure and damages from external climate impacts.

On the contrary, infrastructure service changes in scenarios III and IV are not recoverable. The climate change impact at t_1 results in permanent impairment to the service functions; type IV marks the end member of a total loss in water service, a condition that water managers strive to avoid at all cost. In both cases, the infrastructure service functions are significantly below the desired service level (Figure 12.8), requiring capital rebuilt at a significant cost or paradigm shifting to avoid future recurrence of the service disruption. Examples of these potential scenarios include the inundation and damage by coastal hurricanes, storm surge and inundations (Comfort 2006; Gesch 2005; Wing et al. 2002), impacts from resulted water pollutions (e.g., Cann et al. 2012), and measures taken for adaptation and mitigations (e.g., Rosenzweig et al. 2007). During the 2012 Hurricane Sandy, drinking water advisory for boiling water was issued to a large numbers of customers and local health agencies, during and after the disruptive events.*

Significant function damage to water infrastructure in scenarios III and IV requires special adaptation attention because of their long-lasting effects. While conventional rebuilding and reconstruction are often the water resource measure, long-term sustainability has been discussed with considerations of long-term sustainability improvement. Some basic attributes in the redesign and reconstruction domain are listed in Table 12.1 for better climate resilience. For both new and existing water infrastructures, system optimization and retrofitting in system scale are basic adaptation actions to improve flexibility and resilience upon external impacts. The system reconstruction still aims to specify the CR value. However, postconstruction CR expansion and the potential to use new and advanced technologies are installed during the system reconstruction (Table 12.1).

Examples include water supply and sanitation paradigm changes (Gleick 2000; Pahl-Wostl 2007), urban system replanning and avoidance of disaster areas (Bull-Kamanga et al. 2003; Comfort 2006; Godschalk 2003), and urban-scale or region-scale water managements. Urban-scale adaptive planning is another approach in which urban resiliency is analyzed and improved through a systematic analysis of land use, population distribution, and transportation–water infrastructures. Recent attempts (e.g., Donofrio et al. 2009; Yang and Goodrich 2014; Yao et al. 2013) aim to integrate urban transportation and water infrastructure for the climate co-benefits in adaptive urban planning.

12.2.3 ADAPTIVE ENGINEERING FOR ADEQUATE CR

The most common is scenario II of Figure 12.8, which falls into the adaptation engineering domain (Table 12.1). In adaptive planning and engineering, adaptation need

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* https://www.health.ny.gov/environmental/emergency/weather/hurricane/

is assessed against the projected future hydrological conditions under the future climate and land use changes. Notably, the fundamental difference from traditional deterministic engineering (Table 12.1) is the infrastructure flexibility, expandability, and adaptability for adaptation. For both hydraulic and water quality design functions, adaptive engineering is focused on a range of CR and CR potentials rather than on a single CR value in deterministic engineering. This is accomplished through engineering measures such as modular design, structure retrofitting, and recursive monitoring–adaptation–assessment of infrastructure CR.

It is worthwhile to illustrate the way that adaptive engineering treats water infrastructure CR and service functionality. Adaptive engineering distinguishes the realized CR from the CR potential; the latter is installed but becomes available only through adaptation (Figure 12.9). In the deterministic planning and engineering practice, water systems are designed for a given set of parameters of small uncertainties. Progressive refinement of design basis and engineering objective is practiced in order to minimize engineering uncertainty or, in Lund et al.'s (1995) words, to reduce the spread of capacity and cost PDF curves (Figure 12.9). The small design uncertainty, under the assumed stationary precipitation, allows the use of simple engineering techniques such as a safety factor on key design parameters. This traditional engineering practice is challenged for the nonstationary precipitation and its excessive projection uncertainty. Conceptually, the uncertainty is inherited and translated into a range of possible values in hydraulic and water quality

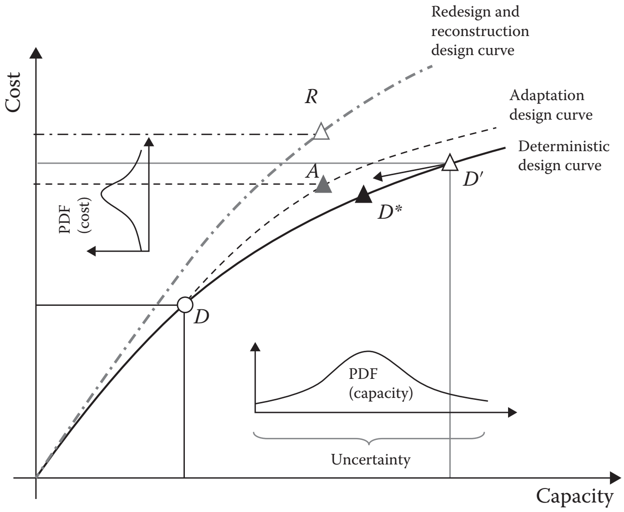

FIGURE 12.9 Infrastructure capacity and cost relationships for three engineering domains. In a deterministic engineering, design position D^* is the calculated design value D plus a CR for uncertainty-related risk management. For design with a large uncertainty as in precipitation change, the design position moves to D' at $p = 85\%$ for adequate CR. In adaptation engineering, design position A is specified later when CR is determined and engineering uncertainty is adequately reduced. Design position moves from D' to A. Redesign and reconstruction design position "R" is the most costly.

engineering parameters. This generates a large spread in the capacity and capital cost PDF curves, for which a large safety factor is required to assure engineering reliability at the expense of excessive capital cost. For example, the carrying capacity design of CSS is selected at $p = 0.85$ or 15% probability of failure (USEPA 1994). The conservative design point is labeled as D' and the required CR is $D'–D$ in Figure 12.9.

In contrast, adaptation engineering installs adequate CR potential. The potential is exercised later, when the engineering basis is adequately defined at a given level of managed engineering risk. The corresponding design point moves from D' to A, and the design CR is $A–D$ (Figure 12.9). Several widely used engineering practices with potential for adaptation are listed in Table 12.1. Examples include modular design and phased construction (Chung et al. 2009; Girard and Mortimer 2006), decentralized water supply, wastewater and storm water management (Gikas and Tchobanoglous 2009; Weinstein 2009), and model-driven water reservoir operations for river flow management under climate change (Hotchkiss et al. 2000). In Figure 12.6, the adaptive design curve marks a small cost increase over the deterministic engineering because the infrastructure CR potential, not the capacity itself, is installed for adaptation. Comparatively, a conservative deterministic design at $p = 0.85$ produces costly infrastructure reliability.

The adaptation engineering approach differs for existing infrastructure with no preinstalled adaptation potential. System retrofitting and process optimization, realignment and expansion of existing infrastructure assets, and operational changes are common engineering options; all may require substantial physical asset alteration (Table 12.1). To the extreme, a significant change in design basis or management objectives moves the engineering domain to reengineering/reconstruction. Accordingly, the design point changes from A to R in Figure 12.9 at a greater cost per unit capacity because of the underutilized existing assets and extra engineering cost in a complex and heavily built urban environment.

Finally, it is recognized that the CR adequacy is location dependent and system specific, requiring detailed comparison and analysis at local watershed scales. Engineering practice switches from the traditional deterministic to the adaptation domain under three conditions:

- Infrastructure planning horizon is long, for which future precipitation, land use, and population changes are not precisely determined. Only in this time reference can one evaluate whether the rate of hydroclimatic change is too small to be “tangible” for adaptation or too excessive for the infrastructure to adapt at a reasonable cost. For infrastructure and urban master planning, adaptation need analysis is often made in the next 30–50 years.
- The rate of precipitation change is larger than assumed in the original engineering design, or the rate is comparable to those of the other two nonstationary variables—population and land use changes.
- Large uncertainty in precipitation projection is translated and further propagated into infrastructure engineering parameters, affecting the CR determination. The uncertainty can decrease over time as the climate (precipitation) projection improves.

DISCLAIMER

The research described herein has been subjected to USEPA's administrative review and has been approved for external publication. Any opinions expressed in this chapter are those of the author and do not necessarily reflect the views of the agency; therefore, no official endorsement should be inferred.

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13 Integration of Water and Energy Sustainability

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CONTENTS

13.1 INTRODUCTION

Energy and water resources share an interdependency commonly referred to as the energy–water nexus. Ensuring a safe and abundant water supply requires energy for pumping, treatment, distribution, end use, and remediation. Providing energy services requires water for mining and refining primary fuels, irrigating crops, transporting finished fuels, and cooling thermoelectric power plants. Since each of these resources depends on reliable access to the other, a constraint in one can trigger a constraint in the other. As reliable access to clean water and energy services is a large differentiator between the privileged and the impoverished, managing the energy–water nexus wisely is critical to future growth and prosperity of any society. This chapter describes the relationship between energy and water resources, as well as the trends and challenges facing the energy–water resource management moving forward. It also provides a robust discussion of the technologies, policies, and institutional frameworks that might contribute to the responsible management of energy and water services moving forward.

13.2 THE WATER IMPACTS OF PRIMARY FUEL PRODUCTION

Primary fuels, such as coal, natural gas, petroleum, and biomass, require water for resource extraction (i.e., mining or agricultural cultivation) and energy conversion (refining and processing) before transport, end use, or electric power generation. The water requirements of these stages vary considerably according to the primary fuel utilized and the methods by which it is extracted or harvested. An overview of the water impacts of primary fuel recovery is provided in the sections below for a selection of primary energy resources.

13.2.1 Conventional Fossil Fuels

Coal is mined, cleaned, and transported via barge or rail to its intended end use, typically a coal-fired power plant (Fthenakis and Kim 2010; Kelic et al. 2009). There are two primary methods of coal extraction, including underground mining and surface mining. The water intensity of underground coal mining tends to be more water intensive (i.e., 3–20 cubic meters [m^3] per 10^{12} Joule-thermal [J]/0.84–5.6 gallons/MMBTU) than accessing coal via surface mining (2 m^3 per 10^{12} J/0.56 gallons/MMBTU) owing to the amount of water that is required to control dust within the mine, which represents approximately 70% of the water withdrawn for underground mining (Elcock 2010; Fthenakis and Kim 2010). Coal washing represents the majority of the remaining water use (Fthenakis and Kim 2010). After extraction, coal is refined to increase its thermal combustion properties and separated according to quality, requiring approximately 4 m^3 per 10^{12} J/1.1 gallons/MMBTU (Elcock 2010). Pipelines are used to pump coal slurry (i.e., coal suspended in water), requiring 40–85 m^3 per 10^{12} J/11–24 gallon/MMBTU; however, approximately 70% of water is recycled, reducing consumptive use (Elcock 2010; Mielke et al. 2010). The fraction of coal transported by slurry pipeline in the United States has decreased over time, only representing 7.1% of total domestic coal transported in 2012 (US Energy Information Administration 2013).

Conventional oil and natural gas require water for exploration and production of the fossil resource, most notably for drilling and well completion. Conventional wells typically utilize vertical wells that require approximately 1 million gallons per well (Vidic et al. 2013). After production, oil and gas resources are generally refined into a form that is appropriate for end use. Oil refining typically has a volumetric ratio of consumed water to refined product output of 1–2.5 to 1 (King and Webber 2008). Natural gas requires less refining but might require compressing to yield compressed natural gas. This process generally requires no water, aside from indirect water used to generate electricity used during the compression process.

13.2.2 URANIUM

Uranium is mined, enriched, and fabricated into a form appropriate for use in a nuclear power plant (Fthenakis and Kim 2010). Typically, water consumption for uranium mining varies between 1 and 6 gallon/MMBTU. Like coal, water consumption is dependent on whether uranium is mined in an underground or surface mine. Most water goes toward dust control, ore separation (i.e., beneficiation), and revegetation after excavation (Mielke et al. 2010). Uranium processing generally consumes between 4 and 8 gallons of water per MMBTU for milling, refining, and enrichment (Mielke et al. 2010).

13.2.3 UNCONVENTIONAL FOSSIL FUELS

Unconventional fossil fuels are typically located in deposits or in forms that are not accessible by conventional drilling (in the case of oil and natural gas resources). These resources are typically deemed “unconventional” because they “lack traditional traps” and are, therefore, more continuous than conventional resources that tend to collect in pockets more conducive to extraction (Cander 2012). They typically have low permeability-to-viscosity ratios that require alteration of rock permeability or fluid viscosity to recover the resource economically (Cander 2012). To do so, large quantities of carbon dioxide, water, or steam are often needed, increasing the overall water requirements in comparison to conventional methods of resource extraction.

13.2.3.1 Shale Oil and Gas

Shale oil and gas refer to oil and natural gas resources trapped within low-permeability, fine-grained sedimentary rock (Gregory et al. 2011). The large-scale production of unconventional shale oil/gas and tight gas (i.e., natural gas trapped in other types of low-permeable rock) has historically been limited because of the low natural permeability and the less-concentrated nature of the resource compared to conventional natural gas (Gregory et al. 2011). However, horizontal drilling and hydraulic fracturing enable economically viable large-scale production of these unconventional fossil fuel resources (Gregory et al. 2011).

There are several aspects of water quality and water quantity that are important to consider during the various stages of unconventional shale oil and gas recovery. First, unconventional fossil fuels typically require more water per well for resource extraction. The water required for shale resource development ranges according to shale play characteristics, but is generally in the range of 2–13 million gallons per well (Vengosh et al. 2014). While the volume of water consumed per well is generally higher than conventional drilling, factors such as the productivity of the well, the number of times a well is refractured, and the volume of water recycled also affect the net freshwater consumption of the well (Clark et al. 2013). In context to other water uses, the water consumed for hydraulic fracturing is quite small in most regions. In 2013, for example, water consumption for gas production in the Marcellus Shale region constituted approximately 0.2% of Pennsylvania's total water withdrawals (Vidic et al. 2013). However, in more water-scarce regions, this water consumption can conflict with other municipal and agricultural demands (Glazer et al. 2014).

During the hydraulic fracturing process, high-pressure water mixed with proppants (usually sand) and other chemical constituents is injected into a well to create fissures or to open existing fissures in the shale to increase the permeability of the source rock and improve the recovery of the hydrocarbon resource (Vidic et al. 2013). Once the pumping pressure is relieved, some of the injection fluid returns to the surface as "flowback" water. In addition to the water that is injected into the well, some water from the formation itself also flows to the surface simultaneously with active gas production (i.e., "produced water"). In the Marcellus Shale region, 10%–53% of the original fracturing fluid's volume returns to the surface (Gregory et al. 2011; Vidic et al. 2013); however, in other shale plays, total recovered water can be twice the volume of the original injection fluid over the life of the well (Glazer et al. 2014). After 3 years from start of production, wells in the Eagle Ford and Barnett Shales of Texas have median flowback and produced water of approximately 50% and 100%, respectively, of the water injected for hydraulic fracturing (Nicot and Scanlon 2012; Nicot et al. 2014).

Remediating of high-salinity flowback and produced water resulting from shale resource production can be difficult and expensive because of its complex physiochemical composition, which varies considerably temporally and spatially and often contains organic and radioactive components (Shaffer et al. 2013; Vidic et al. 2013). To date, injecting produced water into Class II Underground Injection Control (UIC) wells is the pervasive mode of wastewater management, as it is typically the most economical option for wastewater disposal (Gregory et al. 2011; He et al. 2013). However, this option is not always available because suitable geology is not present in the region of hydraulic fracturing activity (Gregory et al. 2011). For instance, wastewater injection is prevalent in Texas but not in Pennsylvania where there are currently only seven permitted disposal wells. Because injecting fluids into the subsurface via the Class II wells increases formation pressure, the increased fracturing wastewater injection activity has been linked with induced seismicity in many regions of the country (Frohlich 2012; Vidic et al. 2013).

The lack of permitted disposal wells in Pennsylvania has promoted the practice of on-site water recycling in the Marcellus Shale region for multiple fracturing jobs or multiple wells. However, the ultimate reclamation of the wastewater after a production site ceases production requires advanced treatment technologies to remove the suite of contaminants present in the water. Desalination treatment technologies, such as mechanical vapor compression (MVC), membrane distillation (MD), and forward osmosis (FO), can be effective in reducing the concentration of total dissolved solids (TDS) of produced water, which can range from 1000 to 400,000 mg/L (Shaffer et al. 2013). However, all of these technologies have shortcomings that range in scope from high energy requirements (e.g., MVC), membrane scaling and fouling (e.g., MD), or unique draw solution requirements that are difficult to regenerate on-site (e.g., FO) (Shaffer et al. 2013). Publically owned municipal wastewater treatment plants are generally not adequate for removing the constituents (e.g., normally occurring radioactive materials) present in wastewater resulting from hydraulic fracturing operations (Gregory et al. 2011).

Several aspects of the shale recovery process are important to consider to project water quality. Casing and cement sealing failures can occur in conventional and unconventional oil and gas production. These types of failures occur in approximately 1%–3% of unconventional resource wells. Sealing failures have been associated with gas migration (typically minor) into shallow aquifers (Vidic et al. 2013). Although the fate of unrecovered fracturing fluid and its potential of contaminating drinking water aquifers is unclear, it is likely that the hydraulic fracturing fluid is absorbed in the formation itself because of the nature of the shale as very little free water is typically present (Vidic et al. 2013). Migration can also occur through fractures (natural or induced) that develop outside of the target formation. Although such fractures have been documented, they typically fall well below drinking water aquifers (Vidic et al. 2013). A larger risk of fracturing fluid migration exists along abandoned or improperly plugged wells that intersect with newly developed wells (Vidic et al. 2013).

Although the link between groundwater contamination and shale oil and gas production has not been confirmed, numerous studies have cited elevated constituent levels in water wells in proximity to drilling activities, pointing to the need for more systematic studies of groundwater quality before and after drilling (Fontenot et al. 2014; Osborn et al. 2011). Surface spills caused by leaking impoundments, wastewater liners, or water trucks can also contaminate surface water and groundwater aquifers (Vidic et al. 2013).

13.2.3.2 Coalbed Methane

Coalbed (or coal seam) methane is another type of unconventional natural gas resource (in addition to shale and tight gas) that is characterized by methane that is generated and stored in coal seams. The majority of US coalbed methane production currently occurs in the Powder River and San Juan Basins of the Rocky Mountain region (Plumlee et al. 2014). Considerable production also occurs in Australia (Mauter et al. 2014). Production methods for coalbed methane vary considerably across basins according to the permeability of the formation. While the San Juan Basin commonly utilizes hydraulic fracturing for resource stimulation, it is infrequently used in the Powder River Basin because of much higher formation permeability (Plumlee et al. 2014). In the San Juan Basin, between 50,000 and 350,000 gallons of water are required for fracturing a formation, which is one to two orders of magnitude less than a shale gas well (Plumlee et al. 2014). Enhanced coalbed methane production utilizes carbon dioxide or nitrogen injection for increased gas recovery, rather than water (Jamshidi and Jessen 2012).

The production of coalbed methane exceeded the shale gas production until 2008 (US Energy Information Administration 2014b), and therefore served as the precedent for environmental studies related to hydraulic fracturing in the late 1990s and early 2000s. The Environmental Protection Agency (EPA) began studying the environmental impacts of hydraulic fracturing of coalbed methane production in 1999 to evaluate impacts to groundwater aquifers used for drinking water. The conclusions were not released until 2004 and concluded that fracturing imposed very little to no risk of contamination (Gilbert 2011). This study was highly criticized but served as a basis to modify section 1421(d) of the Safe Drinking Water Act (SDWA) to exempt fracking from the definition of "underground drilling" (except in the case of fracturing fluids containing diesel fuel), which was formally amended in Section 322 of the Energy Policy Act of 2005 (109th Congress 2005; Gilbert 2011).

Despite the EPA's conclusions, coalbed methane is typically coproduced with water as the coal seam is often saturated with water or is in communication with an adjacent groundwater aquifer, which can migrate as a result of the pressure differential created during production (Jamshidi and Jessen 2012). However, one of the largest potential environmental and social impacts from coalbed methane is the associated extraction of groundwater and a lowering of aquifer levels.

Like shale gas production, produced water is typically disposed of, utilizing deep well injection or treatment and discharge (Plumlee et al. 2014). Produced water quality from coalbed methane production varies considerably from 200 mg/L TDS (below EPA's secondary drinking water standard) to 170,000 mg/L TDS, which is five times higher than seawater (Plumlee et al. 2014). Thus, like shale gas production, the responsible extraction of coalbed methane resources and the subsequent management of produced water is an important area of research moving forward.

13.2.3.3 Tar Sands

Tar sands (also called oil sands) are classified as *heavy* petroleum resources, characterized by low API gravity (i.e., a measurement of the American Petroleum Institute that varies inversely with the density of water) (Veil et al. 2009). Tar sands are bitumen that have high viscosities that do not enable them to flow under ambient or reservoir pressures and temperatures (King et al. 2013). Other forms of heavy oils, more liquid than tar sands, but more viscous than conventional petroleum are found in California, Alaska, and Venezuela.

Tar sands are currently being produced in the Athabasca River basin of Alberta, Canada, and require approximately 1–7 volumetric units of water withdrawal per unit of oil extracted depending on the extraction method (Bazilian et al. 2011; King and Webber 2008). Surface mining requires more water than in situ (steam injection) extraction. Over the last decade, water recycling has become more prevalent, reducing the water consumption to less than 3 units of water per oil for mining and 1 unit for in situ extraction (Gosselin et al. 2010). Large tailing ponds typically store wastewater from oil sands operations. These ponds can contaminate surface water and groundwater resources, harm wildlife, degrade land, and deposit airborne contaminants to adjacent ecosystems (King et al. 2013; Seitz et al. 2013). Dust migration to snow is of particular concern as melting provides a means to transport contaminants to nearby water bodies. For example, polycyclic aromatic hydrocarbons loading in some regions downstream of oil sands operations in the Athabasca River are now 2.5–23 times that of 1960's levels (Kurek et al. 2013). On the other hand, the Athabasca River naturally cuts through some of the oil sands formation, releasing oil sands material into the river independent of human activity. Nonetheless, the water quality and quantity impacts of tar sands production continue to be contentious and one of the leading points of opposition to tar sands production.

13.2.4 RENEWABLE FEEDSTOCKS FOR BIOMASS AND BIOFUELS

Biomass is essentially stored solar energy in the form of chemical bonds. Thus, there are various forms of renewable feedstocks that contribute to energy in the form of heat, fuel, or electricity. While past civilizations mainly utilized biomass as feedstocks for creating heat and fire, today biological feedstocks are being converted into biofuels with similar chemical properties as liquid fossil fuels or for heat in thermoelectric power generation. In some cases, these feedstocks compete against the global food supply (e.g., corn and soybeans) for agricultural land and water. In other cases, nonfood crops such as plant waste products, algae, and perennial grasses are being explored as potential energy crops, but are typically not available at the commercial scale. The freshwater impact of each feedstock varies according to climatic characteristics, freshwater availability, farming and irrigation practices, photosynthetic water requirements, and so on.

The production of biofuels has raised concerns over water quantity, as many forms of biofuel crops require more water than conventional fossil fuels (Cooper and Sehlke 2012). Biofuel production can also raise issues regarding water quality, as the cultivation of many biofuel crops utilizes chemical inputs, just like most industrial-scale agriculture, that can runoff and pollute adjacent and downstream water resources (Twomey et al. 2010). The quantity and quality impacts of biofuel production vary significantly according to where and what types of feedstocks are grown for biofuel production (Fraiture et al. 2008; Gerbens-Leenes et al. 2009; Scown et al. 2011). For example, in California, 99% of the life cycle water consumption (including evapotranspiration) of ethanol fuel is for irrigation, but this water use varies from 500 to 3500 L per liter of ethanol fuel depending on what type of feedstock is used and where it was grown within the state, respectively (Fingerman et al. 2010). In regions of the Midwest, some forms of crop cultivation require no irrigation (but still might raise water quality concerns) (Wu et al. 2014).

In the case of irrigated biofuels, the water consumed for the production of E85 (assuming production from corn stover) and soybean biodiesel is generally on the order of two orders of magnitude more, measured as gallons per liter of water per mile/kilometer traveled, than conventional gasoline or diesel fuels (King and Webber 2008). The majority of this water consumption is for irrigating crops, rather than for processing and refining. Water for irrigation for the agricultural stage of crop production averaged 780 L of water per liter of cornstarch-based ethanol in 2003, while biorefinery water consumption was 3–10 L per liter for grinding, liquefaction, fermentation, separation, and dehydration (King et al. 2013; Mielke et al. 2010).

The water quality impacts of biomass and crops for biofuels cultivation vary according to slope, soil type, fertilizer input rates, cropping systems, tillage practices, and other management practices (Wu et al. 2014). Crops and other feedstocks often require large energy and chemical inputs that threaten nearby water supplies because of nutrient loading. Nutrient loading to the Mississippi–Atchafalaya River Basin owing to high agricultural activity in the US Corn Belt (Midwest United States), for example, has led to the eutrophication of downstream waterways and the Gulf of Mexico. The increased expansion or intensification of resource-intensive crop production such as corn or soy beans has already been detrimental to US water bodies (Donner 2003; Donner and Kucharik 2008; Nolan et al. 2002; Twomey et al. 2010; Ward et al. 2005).

Although less water-intensive (meaning lesser or no irrigation) biofuel crops exist, such as cellulosic biofuels, these biofuels are not yet available on a commercial scale (Mielke et al. 2010). Biofuels derived from agricultural or forest waste products (that are not otherwise utilized) might mitigate some water concerns, as these feedstocks typically do not require additional irrigation or chemical inputs (Cooper and Sehlke 2012). Cellulosic biofuels from perennial grasses such as switchgrass typically require no irrigation or chemicals and might actually improve water quality by providing a buffer between agricultural land and water sources (Zhuang et al. 2013). They can also be grown on marginal land that is not suitable for other crops, reducing competition between the food and fuel supply. However, biomass grows faster when applying water at its full evapotranspiration need, and marginal land is “marginal” for a reason. Thus, it is unclear whether biofuel feedstocks grown on marginal land would be irrigated or not in practice.

There is a lot of interest in producing biofuels from algae; however, to date, algal biofuels have not been economical compared to other liquid fuels. They are also often more water intensive than other fossil and renewable fuels with current cultivation and conversion technologies (Beal et al. 2012; Harto et al. 2010). However, algal biofuels offer potential benefits including carbon sequestration and the ability to utilize dirty water, rather than freshwater, for production. Furthermore, it is difficult to assess the energy–water trade-offs of algal biofuel production since commercial-scale technologies are not yet viable (King et al. 2013).

13.3 THE WATER IMPACTS OF FUEL TRANSPORTATION

The transportation of the nation’s energy supply and its national water resources are intimately linked. Globally, oil resources move by large tankers to markets around the world. Increasingly, natural gas is cooled into liquefied natural gas (LNG) and also traded globally by specialized ships that can accommodate the temperatures, effectively acting as large insulated container ships. The expense of liquefaction adds significant cost, thus hindering the economics of LNG shipments that usually go to countries with few or dwindling local fossil resources (e.g., Japan, South Korea). Coal resources produced in the United States are generally moved within the contiguous United States by railway or barge; however, the export of coal to the global market has increased as the United States continues to decrease coal-fired power generation because of its aging infrastructure and environmental priorities (Grubert et al. 2012). Low natural gas prices, combined with lower economic activity since the Great Recession, has since enabled natural gas–powered electricity to better compete with coal-fired power and promote the coal exports. It is unclear how long the United States will continue this small, but significant, shift to natural gas away from coal.

Coal produced in the United States is often moved on large rivers by barge to locations where it can be transferred to a railway. Moving coal by barge is generally the cheapest mode to move large quantities (Kelic et al. 2009). The Coast Guard is also considering allowing the transport of wastewater from hydraulic fracturing operations by barge on the Ohio River, since hydraulic fracturing operations in the Marcellus Shale have insufficient capacity for Class II wastewater disposal (Beaver 2014). However, this decision is contentious owing to fears over accidents that could lead to widespread water contamination. The movement of energy resources via barge is subject to weather and climatic variability such as drought and floods. Although large water corridors are often highly engineered with locks and can be dredged, severe drought can hinder the movement of energy resources via barge. The 2008 barge season on the Missouri River was nearly canceled because of the extreme drought that began in 2006 (Kelic et al. 2009).

In addition to moving energy resources by water, water is also used to test pipelines during a process referred to as hydrostatic testing (US Department of Energy 2006). During this process, pressurized water is pumped through new oil and gas pipelines to ensure that the pipeline has the integrity to transport liquid or gas resources. The water that is pumped through the pipelines ultimately has to be treated using energy-intensive processes to remove contaminants resulting from the tests (Kelic et al. 2009).

13.4 THE WATER IMPACTS OF ELECTRICITY GENERATION

After primary fuels are extracted and transported, some are used as feedstocks for electricity generation. There are several factors that influence the water required for power production, including fuel source, generation technology (i.e., prime mover), cooling system, ambient climate characteristics, and pollution controls (Sanders et al. 2014). The water trade-offs among these factors are discussed in the following sections.

13.4.1 Fuel Source and Prime Mover

The most water-thirsty electricity producers are typically thermoelectric generators. Thermoelectric power plants utilize heat to produce high-pressure steam as a working fluid that spins a steam turbine, such that mechanical energy is converted into electrical energy. The efficiency of a thermoelectric power plant is influenced by how effectively the hot working fluid exiting the turbine is cooled. Thus, most thermoelectric power facilities are cooled using large volumes of water and collectively represent 49% and 3%–4% of annual US water withdrawal and consumption, respectively (Kenny et al. 2005; Scolley et al. 1998). While some of this water is pumped through a heat exchanger and released back into its native reservoir, a subset is lost via evaporation. Water use is therefore distinguished into two categories including *withdrawals*, the total volume of water extracted from a reservoir, and *consumption*, the subset of withdrawals lost as evaporation.

Approximately 87% of US power generation requires water for cooling, which includes steam cycle and combined cycle facilities that represent 62% and 25% of total US generation, respectively (US Energy Information Administration 2014a). Typically only one-third of the electricity generated at combined cycled plants is produced via the steam turbines, with combustion turbines representing the remainder. Thus, combined cycle power plants have lower cooling water requirements compared to typical pure steam cycle plants. Conventional combustion turbines have negligible water requirements, although newer versions often require some water to prechill inlet air to increase net efficiency (Scanlon et al. 2013). However, these combustion units often have lower capacity factors because they are typically used for ancillary services and to maintain the reliable operation of the grid rather than for baseload operation (Sanders et al. 2014).

While the prime mover (e.g., steam turbine or combustion turbine, etc.) of a thermoelectric power generator influences the cooling water requirements of electricity generation, the fuel source also affects water use. Coal, natural gas, and nuclear power generators encompass the majority of steam and combined cycle thermoelectric power generation, representing 37%, 27%, and 19% of total 2012 US generation, respectively. Biomass, concentrating solar power (CSP), petroleum-fired, geothermal, and other miscellaneous fuel generation units that require cooling contributed a small percentage of total US power generation (collectively 2.5%) in 2012 (US Energy Information Administration 2014a).

Coal-fired power plants tend to require more water per unit of electric power generation than natural gas facilities of similar cooling technologies attributed, in part, to the nature of the fuel itself. Coal typically burns less efficiently than natural gas because of its combustion properties and high moisture content, which decrease the overall efficiency of the process (Sieber 2013). Furthermore, coal power plants typically have auxiliary systems such as pollution controls that often require electricity (and water) to run, also decreasing the net output of the unit (Grubert et al. 2012). Even with the increased requirements of shale gas in comparison to conventional natural gas, the life cycle water consumption of unconventional natural gas combined cycle units is more water lean than coal-fired generation (Grubert et al. 2012).

Nuclear and CSP power plants tend to be more water consumptive than natural gas– or coal-fired power generation units using similar cooling systems (Macknick et al. 2012a). CSP plants tend to operate with lower thermal efficiencies than similarly sized coal- or natural gas–fired plants, thereby requiring more circulating steam per unit of power output (Gerdes and Nichols 2009). Also, both nuclear and CSP have no flue gas outlet, which is a form of heat rejection in fossil fuel units (Förster and Lilliestam 2009).

Geothermal power generation units exploit natural hydrothermal gradients within subsurface hot rock to produce steam for electricity generation. While some geothermal resources are sufficient for natural steam production, typically geothermal resources are characterized by hot, dry rocks that do not have sufficient water to recover the naturally occurring thermal energy. In this case, enhanced geothermal processes can be utilized, where large volumes of water are injected into fractured rock to absorb heat that is utilized in the steam cycle (King et al. 2013). Enhanced geothermal electricity is still at the early stage of development, with only a handful of small (usually <1 MW) test or experimental operations in the United States.

Non-thermoelectric power generation requires no water for cooling. Wind turbines generally require no water at the point of generation. Solar photovoltaics (PV) requires some water for cleaning, but these water requirements are very low compared to wet-cooled thermoelectric power plants.

The water requirements of hydroelectric power plants are contentious (Bakken et al. 2013; Mukheibir 2013; Pfister et al. 2011). These plants require water for moving turbines; however, the majority of this water passes through and moves downstream. However, the presence of an impoundment can increase the surface area in comparison to the natural run-of-the-river, leading to increased evaporation. The rate of evaporation varies significantly on the basis of local climatic conditions but can be several times higher than the evaporative losses from thermoelectric power plants depending on the nature of the facility (King et al. 2013). However, dams often serve purposes other than electricity generation, such as flood control, water storage, recreation, and so on, making it difficult to attribute all increases in evaporation to hydropower (Mukheibir 2013).

13.4.2 COOLING TECHNOLOGIES

The cooling technology required for cooling thermoelectric power plant is a large factor in its net water requirements (King 2014). There are two pervasive types of cooling systems that are used in the vast majority of current power plants. The first type, once-through cooling, withdraws large amounts of water from a cooling reservoir (lake, reservoir, river, or ocean), uses it once to cool the hot steam loop exiting the back of the turbine, and returns the cooled water back into the environment. The second type withdraws water and recirculates it in cooling towers for multiple cooling cycles. Water is lost via evaporation and, to a lesser extent, through "blowdown," which is water that exceeds a critical threshold of TDS and is removed in order to decrease scaling and fouling in the condenser (Altman et al. 2012).

There are trade-offs in the water requirements of once-through and recirculating cooling tower systems. Once-through cooled (i.e., open-loop) systems have very large water withdrawals but lose lesser volumes of water to "forced" evaporation (50%–70% as compared to evaporation when using cooling towers). Nationwide, once-through cooled power plants represent approximately 43% of thermoelectric generating capacity, but represent nearly 90% of the power sector's water withdrawals (Feeley et al. 2008; Kenny et al. 2005). Recirculating cooling (i.e., closed-loop) systems that utilize cooling towers have much lower withdrawal requirements since water is recycled yet lose the majority of this water through evaporation from the cooling towers. Consequently, these systems represent approximately 42% of thermoelectric generating capacity but cause the majority of total water consumption in the power sector (Feeley et al. 2008; Macknick et al. 2012a).

A third type of system utilizes recirculating cooling ponds and represents approximately 14.5% of thermoelectric power capacity. These systems do not use cooling towers but recirculate water in reservoirs for subsequent cycles (Feeley et al. 2008). These systems are similar to once-through cooled systems in function and design but serve as somewhat of a hybrid between the two aforementioned systems in terms of water requirements. They typically withdraw less water but consume more than once-through cooled plants. Likewise, they typically withdraw more water but consume less than generation units with recirculating cooling towers (Baker et al. 2014). Because environmental reporting forms (e.g., EIA [Energy Information Administration] forms 860 and 923) rely on facility owners to categorize their cooling systems (e.g., as once-through vs. recirculating pond), the distinction is often arbitrary and difficult to make.

A small fraction (approximately 1%) of power plants utilize dry cooling systems that utilize air, rather than water, for removing heat from the power plant (Feeley et al. 2008). Since air does not have as favorable heat capacity characteristics for removing heat and electricity must be supplied to power air cooling fans that create necessary airflow through the cooling fins, these systems are more expensive to operate in comparison to wet-cooled systems. Furthermore, the capital cost of dry cooling systems is also typically three to four times higher than recirculating water cooling towers (Badr et al. 2012).

Efficiency losses of power plants with dry cooling systems are typically 1% for every 5°F–10°F increase in the condenser temperature. Power generation efficiency can, thus, be reduced 1%–3% for every increase in 1°F (King 2014; King et al. 2013), generally averaging 2% less efficient than wet-cooled systems (Badr et al. 2012). Because dry cooling systems require more surface area, compared to wet cooling towers, for airflow over cooling surfaces, they have significantly larger capital cost and land footprint per unit of generation (Keller et al. 2010). While dry-cooled systems are typically uneconomical because of low water prices and senior water rights, they might be the only alternative in water-scarce regions (King et al. 2013). A cooling water cost of \$3–\$6 per thousand gallons, typical of municipal water supply costs, is the range that would incentivize a power plant design to utilize dry cooling versus wet cooling (King 2014).

Hybrid wet–dry systems, which combine wet and dry cooling systems, offer flexibility when ambient temperatures reach levels that significantly decrease the efficiency of power generation. However, these systems typically require a large land footprint, since two types of cooling systems are combined, and are not often utilized in practice. Although hybrid systems offer the flexibility to switch to wet cooling when ambient temperatures are very high, these periods might coincide with times that are more water scarce in some climates (i.e., hot and arid), reducing the value of the flexible cooling system. These systems can be advantageous when dry-cooled power plants need to shed parasitic energy losses to achieve maximum output levels during times of high electricity demand and thus high electricity prices (King et al. 2013).

13.4.3 Policies

While once-through cooling systems were the most prevalent cooling systems before the 1970s, concerns over the environmental impacts of the large water withdrawals, utilization of the water rich locations, and discharges of cooling water from once-through cooling systems have led to the slow phasing out of the technology for new construction. Provision 316(a) and 316(b) of the US EPA's Clean Water Act (CWA) directly regulate the thermal impacts and the intake impacts (i.e., entrainment and entrapment) of power plant cooling systems and industrial facilities, respectively. The CWA 316(a) mandates that warmed cooling water discharged from power plants does not exceed a thermal threshold set by a state's National Pollution Discharge Elimination System (Madden et al. 2013). In the event that surface water is heated in excess of the thermal limit, the generation unit is typically required to curtail operation, thus discharging less heat into the environment to prevent an increase in ecosystem impacts. The CWA 316(b) provision was designed to reduce the ecosystem impacts of cooling system water intakes. Historically, the provision required that only new facilities reflect "the best technology available" to reduce environmental impacts (Barnthouse 2013). However, a 2014 extension of the rule now applies to existing facilities, creating a precedent for large-scale changes to cooling systems across the United States (US Environmental Protection Agency 2014).

In addition to the CWA 316 provisions, there are several policies that will affect the water intensity of the power sector moving forward. Increasing environmental controls in recent years such as the Cross-State Air Pollution Rule, Mercury and Air Toxics Standards, Coal Combustion Residuals, and the 2014 Clean Power Plan will likely reduce the share of power produced by coal-fired power facilities (North American Electric Reliability Corporation 2011). The reduction in coal-fired generation is likely to decrease the water intensity of the power sector in the future (Arent et al. 2014; Chandel et al. 2011). However, in the event of a large-scale expansion of Carbon Capture and Sequestration (CCS), which, to date, is uneconomical in comparison to other alternatives, the water intensity of coal-fired generation would increase (Dodder 2014; Macknick et al. 2012b; Webster et al. 2013). CCS requires water for the CO_2 scrubbers, and a considerable amount of energy from the input fuel must be diverted for internal processes. In the case of post-combustion capture designs, steam (for thermal cycling of the capture fluid) and gross electricity (for compressing CO_2 to supercritical state) reduce net electricity generation output (to consumers) by 20%–30% (Rochelle 2009). Current postcombustion CCS technologies double a typical coal plant's (with cooling towers) water requirements per unit of net electricity output (Zhai and Rubin 2010). However, because electricity will have a higher cost, because of overall less electricity output per fuel input, electricity prices will increase and consumers will purchase less electricity to some degree. It is therefore unclear how much *total thermoelectric water consumption* will increase (as compared to the water intensity in gallons per megawatt-hour at a power plant) if CCS is employed at large scale.

Renewable energy goals and incentives, as well as carbon legislation, will also incentivize the expansion of renewable energy technologies. The replacement of thermal power generation units with solar PV and wind, which both have low water requirements, will result in water resource benefits. However, some renewable electricity technologies (e.g., solar concentrating power and some types of geothermal) have high water requirements per unit of output.

13.4.4 CLIMATE CONCERNS

Climate change is anticipated to increase ambient air temperatures, increase rainfall variability in many regions of the United States, increase sea level, and increase the intensity of extreme events, which will affect the electricity generation sector (Cayan et al. 2010; Jaglom et al. 2014; Kopytko and Perkins 2011; Li et al. 2014; MacDonald 2010; Sathaye et al. 2013; Schaeffer et al. 2012; Sieber 2013; Vorosmarty 2000). Hydropower and thermoelectric power generation are particularly vulnerable to these changes, as both typically depend on ample water resources for operation. Low water resources in the Western United States caused by prolonged drought have already had appreciable impacts on hydropower generation (Edson 2014; Harto et al. 2011; US Energy Information Administration 2014c). Inadequate cooling water supplies have also threatened the shutdown or curtailment of thermoelectric power generators across the United States, most frequently owing to the exceedance of thermal discharge limits (Abrams and Hall 2010; AP 2014; Badr et al. 2012; Madden et al. 2013; Staletovich 2014).

Electricity distribution infrastructure is also vulnerable to climate change. Higher air temperatures can accelerate aging of transformers, decrease the carrying capacity of distribution lines, and reduce the reliability of transmission and distribution infrastructure. Increasing summer air temperatures will also result in increases in electricity demand in many regions, compounding stress on the grid (Sathaye et al. 2013).

13.5 THE ENERGY REQUIREMENTS OF WATER TREATMENT, DISTRIBUTION, AND USE

The US water sector consumes a lot of energy for the production and reliable distribution of clean water. Nationally, 12.6% of the country's annual primary energy consumption is for pumping, treating, distributing, and preparing water for end use (Sanders and Webber 2012). This energy use varies regionally according to the

- Characteristics of the source water (e.g., quality and elevation)
- Pumping and distribution system
- Water quality target and treatment practices
- End-use requirements (e.g., heated, chilled, pressurized, etc.)

States such as California that lean on energy-intensive practices such as long-distance pumping or desalination for its water supply have larger energy costs than states that have a local, abundant, and gravity-fed supply of freshwater.

13.5.1 Energy Impacts of Water Treatment and Distribution

The energy consumption for the public water supply in the United States varies with source water location and quality, water quality standards, distribution system characteristics, and ultimate use and location. Pumping groundwater from deep aquifers is typically more energy intensive than pumping surface water, as surface water sources are often gravity fed in a distribution system. Large elevation gradients such as hills, mountains, and tall buildings can also introduce energy costs when pumping against the force of gravity, especially in the case when water is pumped large distances.

Water treatment also requires energy, which varies according to the difference between the incoming and outgoing water quality. For example, cleaning heavily polluted water requires energy to remove contaminants that might require various treatment technologies to achieve the intended end-use quality. Similarly, treating water to an "ultrapure" standard often required for semiconductor manufacturing can require advanced, high-energy desalination processes. The majority of public water treatment facilities in the United States treat relatively clean surface water sources to potable drinking water quality (regardless of end use) and, thus, require only basic physical and chemical treatment processes that are not energy intensive (Sanders and Webber 2012).

As water-constrained regions shift to marginal water sources such as recycled water and desalination, the energy demands of water treatment will increase. Seawater desalination can be one to two orders of magnitude more energy intensive than clean groundwater or surface water sources. Desalination processes require energy to remove salt from water, most commonly via reverse osmosis treatment technology (e.g., in the United States and Israel). During reverse osmosis treatment, volumes of degraded water are pushed through a membrane such that water molecules can pass through and solids remain behind the membrane. Thus, large amounts of energy are required to overcome the osmotic pressure to separate water from contaminants (King et al. 2013). Additionally, the brine concentrate that is separated from the freshwater must be disposed of, which is expensive in the United States, because of stringent environmental regulations. Because of brine disposal costs (and population concentration), most desalination facilities worldwide are located along coasts. The largest inland desalination facility is in El Paso, Texas, and it utilizes an UIC well for brine disposal (El Paso Water Utilities 2014).

13.5.2 ENERGY IMPACTS OF WATER AT END USE

End use is typically the most energy-intensive stage of the water use cycle. End-use preparation might include heating, chilling, pressurization, pumping, or evaporation. Residential and commercial water heating is especially energy intensive, representing nearly 4% of total US primary energy consumption across all sectors (Sanders and Webber 2012). More than half the water used indoors in the United States is heated, making water heating an important target for energy conservation. Even in regions that depend on energy-intensive water sources such as desalination, end use is still the most energy-intensive part of the water cycle.

Some water uses at the point of use require negligible energy outside of initial pumping, treatment, and distribution. Outdoor water use, for example, generally requires little to no energy at the point of use. Half of the water delivered in the public supply is used outdoors (King et al. 2013). Toilet flushing also requires very little, if any, energy usage for water.

13.5.3 ENERGY IMPACTS OF WASTEWATER TREATMENT, PUMPING, AND RECYCLING

Municipal water that is not lost to the environment, via groundwater seepage, pipeline leakage, or evaporation (e.g., lawn watering), is typically returned to a wastewater treatment facility where it is treated to a standard acceptable for discharge to a receiving water body. Wastewater sanitation is critical to protecting human health and the environment and is mandated before water exiting the US public water supply can be discharged to the environment. Wastewater treatment is more energy intensive than conventional groundwater or surface water treatment facilities, since incoming water contains solid and liquid waste. Physical, biological, and chemical treatment processes are required to adequately remediate water to a quality that is in compliance with the EPA's CWA. As more sophisticated treatment technologies are developed and enable the removal of more advanced contaminants, the energy required for treatment generally increases. However, the implementation of anaerobic digestion and biosolid incineration could offer energy savings in the future if rolled out on the large scale (Stillwell et al. 2010).

In some regions, a fraction of water treated at publically owned treatment works is remediated such that it can be recycled for nonpotable purposes, typically through distribution by a "purple-pipe" network reserved for nonpotable water. Generally treated wastewater effluent goes through additional treatment to be suitable for indirect or direct reuse; however, reclaimed water quality standards are regulated by the states; hence, recycling practices vary regionally (Sanders and Webber 2012). Energy-intensive membrane technologies are typically utilized to treat water to a desired standard for reuse. Recycled water in the United States is typically limited to indirect (i.e., non-potable) uses such as irrigation, toilet flushing, and so on. (Direct potable reuse is generally not practiced in the United States, except in a few instances, such as in Wichita Falls, which began a direct reuse program in 2014 [Associated Press 2014].)

13.6 CURRENT TRENDS IN THE ENERGY–WATER NEXUS

There are several trends that suggest that the tension between energy and water resources is growing. Generally, as water supplies become constrained or degraded, finding alternatives or remediating contaminated reservoirs becomes increasingly energy intensive. Brackish water or seawater desalination requires advanced treatments that can be an order of magnitude higher in energy costs than baseline surface water supplies. Pumping water across long distances also incurs large energy costs. As groundwater sources become more depleted, more energy is required to lift water from deeper depths. All over the world, the cost of providing clean water is increasing as communities shift toward more marginal sources of water.

The energy sector will also endure changes in terms of its water requirements. However, the trends in the energy sector are not as clear as in the water sector. While some forms of energy expansion will be more water intensive (e.g., biofuels, concentrating solar power, nuclear power, etc.), other forms of energy will require less water than the baseline (e.g., solar PV, wind, natural gas combined cycle, dry-cooled power plants, etc.) (King et al. 2013). In the transportation sector, most alternative fuels are more water intensive than baseline petroleum fuels. First-generation biofuels, such as corn starch–based ethanol and soybean biodiesel, for example, require large volumes of water for irrigation. Advanced biofuels that are intended to reduce freshwater reliance are under development, but to date, there exist few water-lean substitutes for the transportation sector. In the power sector, the expansion of water-lean solar PV and wind reduce dependence on freshwater resources, which might result in the gradual lessening of tension between power generation and water availability. However, the large-scale deployment of low-carbon sources such as CCS and nuclear power could reverse this trend (Webster et al. 2013). Thus, it is important to consider the water impacts of energy fleet expansion, as well as the air quality and greenhouse gas impacts that often receive the majority of the policy attention.

The tension between energy and water resources continues to increase in many regions of the world, and in some regions, it has challenged the reliable distribution of energy and water services. Globally, 1.1 billion people lack access to a safe drinking water supply and 2.6 billion people lack adequate sanitation. For these populations, inadequate energy and water services can be life-threatening, especially to children, who are particularly susceptible to waterborne illness (Sanders et al. 2013). Oftentimes, these regions are also those that are most vulnerable to the effects of climate change (i.e., salinization of groundwater via sea level rise, increased air and water temperatures, increasing aridity, increased flooding, etc.), which will likely exacerbate existing water issues (Bollinger et al. 2013). In these cases, increasing the energy consumed for water services is essential for health and safety. However, expansion of energy and water services must be executed with balanced environmental and economic priorities. This expansion must also be done in a way that enables communities to take ownership of new infrastructure through local workforce training to empower self-sufficiency (Sanders et al. 2013).

These tensions are not isolated to developing regions. In 2003, the large heat wave that swept across Europe and was associated with thousands of casualties was largely an outcome of an energy–water nexus issue. At the time, France, which generates approximately 80% of its electricity with nuclear power facilities, was forced to reduce its nuclear power generation drastically because of insufficient cooling supplies. The heat wave resulted in high cooling water temperatures that constrained the cool capacity of the reactors, thus mandating the generation reduction. Consequently, France and other countries that relied on its nuclear power plant fleet only received a fraction of typical electricity output at a time of high demand because of increased cooling loads (Sovacool and Gilbert 2014). Casualties included the young, sick, and elderly who were particularly sensitive to the heat.

The 2003 European crisis was one of the most drastic crises that have faced the global community in terms of the energy–water nexus, but dozens of other examples punctuate a need for better coordination. In the United States, multiple coal and nuclear facilities have been at risk of or have exceeded thermal threshold limits set forth by CWA 316(b), threatening the curtailment of electricity generation (Madden et al. 2013). New thermoelectric facilities have been denied because of concerns over insufficient cooling water reservoirs (King et al. 2013). In California, regulations to phase out once-through cooled power plants have resulted in the retirement or repowering of power capacity along the coast. Repowered plants have installed dry cooling systems, potentially decreasing marine-ecosystem impacts, but slightly increasing the freshwater and carbon emission (as a result of decreased efficiency) impacts of these plants (Keller et al. 2010).

13.7 ISSUES REGARDING THE COORDINATION OF ENERGY AND WATER POLICIES AND TECHNOLOGIES

The world has effectively passed the time when optimal isolated solutions have minimal isolated impacts—environmentally, economically, and socially. Our contemporary and future energy and environmental problems cannot be solved by focusing on a single issue or variable. Because of the complex interactions between multiple energy and environmental objectives, we now live in a time and place where a single "optimal" solution cannot be defined, much less derived. Optimizing for one objective (e.g., cheap energy) does not necessarily also optimize other objectives (e.g., minimal water consumption, lower greenhouse gas emissions) (King 2013; King et al. 2013). Beneficial solutions must be defined as those that keep us from exceeding a "space" defined by critical boundaries and thresholds rather than finding the optimal location within the space (Rockström and Noone 2009). Where people and stakeholders disagree is in both the defining of these boundaries and the will to take actions that keep us from crossing those boundaries that do have accepted definitions.

Action within the energy–water(–food–climate) nexus inevitably requires tradeoffs for the inclusion of several energy technologies, management practices, and legal instruments that can be utilized to achieve one or more strategic objectives. These principles are organizational concepts that allow stakeholders to view how individual technologies and policies can be included in holistic solutions that practically have physical benefits and impacts in one location yet can also benefit people and ecosystems somewhere else. These principles are important for creating the necessary dialogue among energy and water industries, environmental stakeholders, the public, and regulators. This section presents some examples of coordination within the energy–water nexus.

13.7.1 Common Institutional Gaps That Impede Coordination between Energy and Water Policies

While it is difficult to generalize any situation, there are some broad institutional gaps, some identified by the OECD, that commonly compromise coordination efforts within governments (Charbit and Michalun 2009). Here, we provide a brief summary (largely from King et al. 2013).

Policy frameworks and agendas can hinder coordination. Differing political agendas, visibility concerns, and power rivalries across ministries and agencies at the federal level can focus too much effort on unproductive tasks not tuned to solving resource problems. Additionally, national ministries often dictate top-down vertical approaches to cross-sectoral policies that would benefit from co-design at the local level where more of the necessary knowledge is located.

Unclear and overlapping administrative roles and responsibilities among government ministries often do not correspond well with the economic, social, and physical boundaries of water and energy flows. Water issues are localized, while water basins cross political and administrative boundaries. There is an ongoing challenge in creating effective and accountable water-governing institutions across political lines, but some countries use these water boundaries to create agreements where few others exist.

Either a lack of capacity resources (knowledge, enforcement, and infrastructure), or asymmetry of those resources, within all levels of government can potentially leave no one in charge. Asymmetry of revenues and distribution of resources across ministries and levels of government can lead to certain ministries dominating the counter-balancing ministry or being in charge of its own regulation. An example exists when the ministry in charge of producing tax revenues from land leases is in charge of environmental regulation of those leases.

Data gaps and inconsistencies create informational challenges between and within the levels and ministries of government. Different schedules and deadlines between ministries and within election cycles create difficulty for engaging in strategic planning over appropriate time frames. Without evaluation, governance practices cannot be assessed, and very often feasibility is limited.

13.7.2 EXISTING MECHANISMS THAT FACILITATE ENERGY–WATER POLICY COORDINATION

The problem of simultaneously considering multiple constraints on energy and water can be stifling. The rest of this section describes examples and issues related to coordinating energy and water policy for mutually beneficial outcomes. Within the context and constraints of each region of the world, the best technologies and policies are likely to be different. Just as energy and water are intimately coupled, so too are policies and technologies that affect the energy–water nexus. Thus, while some technologies leverage policy changes, some policies encourage or need technology to be effective.

13.7.2.1 Examples of Technological Coordination of Energy–Water Nexus Issues

In general, it seems that many of our future low- and high-carbon energy options are more water intensive (e.g., higher water input, usually consumption, per energy output) than past energy supplies. Energy-related water withdrawal and consumption are expected to increase in business-as-usual scenarios, but likely more so for low-carbon fossil and biofuel-intensive scenarios.

While we consider the water impacts of energy production, we must recognize the context that the vast majority of worldwide water consumption (>75%) is for irrigating crops for food. In addition, the overall water balances for water basins are largely driven by the evapotranspiration of the vegetation. The more we tie vegetation to energy via biofuels, the more we integrate our land and water resources to our energy supply. Nonetheless, there are good examples where the energy sector has used technologies to consume less water and coordinate with other water users in the water basin.

Dry cooling technologies for thermoelectric power plants clearly reduce water consumption and withdrawal, but the local situation determines the circumstances in which they are appropriate. Historically, dry cooling was not used for cooling thermoelectric power plants because water was relatively abundant. Now, in places where water is scarce, coal is abundant, or population is high, dry cooling is becoming a more common option.

The locations with the most dry-cooled power plants are Australia, South Africa, and Western United States (King 2014). The Queensland Kogan Creek (750 MW) coal-fired power plant is perhaps the newest and most efficient coal-fired plant that uses dry cooling (an air-cooled condenser) (King 2014). Kogan Creek is situated in a dry region close to coal deposits near Chinchilla, 280 km northwest of Brisbane, Queensland (CS Energy 2008). The cooling system is supplemented with water sprays beneath the air-cooled condenser to operate in hot (>40°C) temperatures, and the water is sourced from a local aquifer (Siemens 2007, 2008). The Queensland government approved the power station based on the choice of dry cooling technology to reduce water consumption by 90% compared to wet cooling systems.

The South African state-owned electric utility Eskom operates one of the largest fleets of dry-cooled power plants in the world. Six of its 15 coal-fired power stations use dry cooling technologies because the power plants reside near the mines in dry regions of the country (King 2014).

Dry cooling is also used as a precautionary environmental or aesthetic mitigation measure in many cases where freshwater or saline water is in relative abundance (King 2014):

- The combined cycle power plants for the Aluar aluminum-producing company in Puerto Madryn were specified to use dry cooling instead of once-through design with seawater to ensure the security of whale habitat (during migration) and thus the subsequent tourism.
- Both the Carrington power plant in the United Kingdom and the Baudour/Saint Ghislain natural gas combined cycle power plant in Belgium installed dry cooling for aesthetic reasons, that is, to prevent the visible mist plumes arising from the wet cooling towers.

The energy sector has also begun to coordinate with the water sector to develop solutions. The use of alternative cooling supplies, such as treated wastewater effluent, for cooling towers is becoming increasingly economical. For example, the Palo Verde Nuclear plant purchases 90 million gallons of water per day from seven cities in the Phoenix, Arizona Metropolitan area to reduce freshwater tension in the region (Sovacool and Sovacool 2009a). Although the cost of recycled water is often less expensive than treated potable water, the increase in condenser fouling often increases the operation and maintenance costs of the cooling system (Sovacool and Gilbert 2014; Walker et al. 2012). Since reclaimed water quality standards vary by state, additional chemical or membrane treatment is often required to use reclaimed water in recirculating cooling systems (Sovacool and Gilbert 2014; Sovacool and Sovacool 2009b; Stillwell and Webber 2014). Despite the added costs, this practice is becoming common in water-scarce regions around the United States for the power and other water-intensive industries.

There are 100 GW of installed US hydropower capacity at approximately 200 locations generating 250–290 TWh/year (or 6%–7% of US electricity). Because much of the hydropower infrastructure is old, there is an opportunity to increase hydropower capacity while decreasing impacts to freshwater biodiversity. Today, existing fish-friendly hydropower turbines need investment to get past the development and demonstration phases. When the Low Impact Hydropower Institute considers hydro projects for certification, it evaluates impacts with respect to eight general criteria.* Many existing projects have passed these criteria and have been certified as "low impact" in the United States, and many more could qualify with the deployment of advanced technologies. After years of research, design, and demonstration of efficiency and decreased fish impacts (94%–100% fish passage), hydropower turbine retrofit projects at large scale are underway, for example, at Wanapum Dam (~1000 MW) that resides 415 miles upstream of the mouth of the Columbia River (Hogan et al. 2012). This Wanapum project is significant because the successful experimental retrofit of 1 of the 10 turbines indicated increased power efficiency without affecting the survival of salmon smolts passing through the unit—giving confidence to move forward in replacing all of the original 10 turbines.

While wind power and PV panels produce electricity with practically no water consumption, there is so far little evidence that their zero-to-low water consumption has been a significant factor in their choice for installation. However, the low water impact is often touted by wind and solar proponents.

In the realm of oil and gas extraction, technological progress continues on recycling flowback, produced, and process water as well as using brackish to saline water for hydraulic fracturing. For biofuels, technological advancement in use of no/low-irrigation, saline-tolerant, or drought-tolerant feedstocks (e.g., succulents, grasses) has not yet reached commercial viability. Nonetheless, those feedstocks are an attempt at a technological solution within the energy–water nexus to lower freshwater needs for biofuels.

13.7.2.2 Examples of Policy Coordination of Energy–Water Nexus Issues

While many of the interactions of the energy–water–carbon nexus are known on the individual facility and technology level, there is much less coordination at larger scales. This lack of coordination in energy–water policy leaves many uncertainties as to how federal energy and climate policies can affect local and regional actors (US GAO 2012a). Most of our future energy options have trade-offs for various strategic objectives: water security, energy security, carbon/greenhouse gas management, water quality, and biodiversity (King 2013; King et al. 2013). Creating solutions with benefits in all areas will necessitate government agencies to work alongside both for-profit and nonprofit nongovernmental organizations as well as academic institutions.

Table 13.1 presents a list of energy and water technologies, legal instruments, and management practices that are relevant to the energy–water–carbon–biodiversity nexus (for more details, see King 2013; King et al. 2013).

For each listed technology or management practice (left column), a relationship to the objectives is given as follows: an up arrow (↑) indicates that the technology helps achieve the strategic objective, a down arrow (↓) indicates that the technology hinders achievement of the objective, a level arrow (↔) indicates that the technology has

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* The Low Impact Hydropower Institute is a nonprofit 501(c)(3) organization dedicated to reducing the impacts of hydropower generation through the certification of hydropower projects that have avoided or reduced their environmental impacts pursuant to the Low Impact Hydropower Institute's criteria. The eight criteria are (1) river flows, (2) water quality, (3) fish passage and protection, (4) watershed protection, (5) threatened and endangered species protection, (6) cultural resources protection, (7) recreational use and access, and (8) recommendations for dam removal.

TABLE 13.1
Various Technologies and Practices Affect Water, Energy, and Environmental Objectives in Different Ways

			... Strategic Objectives...						... Policy Choices							
	Technologies and Management Practices...	... Can Be Used to Meet ...	Water Security	Energy Security	Water Quality	Carbon Mgmt.	Freshwater Biodiversity and Ecosystem Health	... With Help from...	Product Labeling or Certification	PR Campaign	Data Gathering	Mandate/ Regulation	Right Pricing	Subsidy	Financing	Public Works
Energy management	Energy-conserving appliances and buildings		↑	↑	—	↑	↑[a]		○	○	×	●	○	●	×	×
	Electricity peak shifting		↔	↔	↔	↔	↔		×	○	●	×	●	○	×	×
	Electricity peak shaving		↑	↑	↑	↑	↑		×	○	●	×	●	○	×	×
Electricity generation	Solar photovoltaics		↑	↑	—	↑	↑		×	×	×	●	●	●	●	○*
	Wind power		↑	↑	—	↑	↑		×	×	×	●	●	●	●	○*
	Concentrating solar power (steam cycle)		↓	↑	—	↑	↓		×	×	×	●	●	●	●	○*
	Freshwater wet-cooled power plants (steam cycle)		↓	↑	↔	—	↓		×	×	×	○	×	×	×	○*
	Seawater wet-cooled power plants (steam cycle)		↑	↑	↔	—	↑[b]		×	×	×	○	×	×	×	○*
	Dry-cooled power plants (steam cycle)		↑	↓	—	↔	↑		×	×	×	○	●	×	●	○*

(Continued)

TABLE 13.1 (CONTINUED)
Various Technologies and Practices Affect Water, Energy, and Environmental Objectives in Different Ways

			... Strategic Objectives...						... Policy Choices							
	Technologies and Management Practices...	... Can Be Used to Meet ...	Water Security	Energy Security	Water Quality	Carbon Mgmt.	Freshwater Biodiversity and Ecosystem Health	... With Help from...	Product Labeling or Certification	PR Campaign	Data Gathering	Mandate/ Regulation	Right Pricing	Subsidy	Financing	Public Works
	Gas combustion turbines		↑	↑	↑	↔	↑		×	×	×	×	×	×	×	×
	Carbon dioxide capture		↓	↔	↔	↑	↓ to ↔		×	×	●	●	●	●	●	○
	Combined heat and power		↑	↑	↑	↑	↑		×	×	×	●	○	●	○	○*
	Hydropower		↑	↑	↓	↑	↓		×	×	×	●	○	×	●	●
Energy resource extraction and waste injection	Conventional oil and gas extraction		↓	↑	↔	↓	↔		×	×	×	●	○	×	×	×
	Hydraulic fracturing		↓	↑	↔	↔	↔		×	×	×	●	○	×	×	×
	Mining (coal, uranium)		↓ to ↔	↑	↓ to ↔	↓	↓ to ↔		×	×	×	●	○	×	×	×
	Carbon dioxide sequestration		— to ↔	↔	— to ↔	↑	— to ↔		×	×	●	●	●	●	●	○
	US corn ethanol (Midwest)		↔	↔	↓	↔	↓ to ↔		×	×	●	●	●	●	×	×
	Brazilian (state of Sao Paulo) sugar cane ethanol		↔	↑	↔	↑	↓ to ↔		×	×	●	●	●	●	×	×
	Solar hot water heating		↑	↑	↑	↑	↑		○	○	×	●	●	●	○	×
	Geothermal heat pumps		↑	↑	↔ to ↑	↑	↑		○	○	×	●	●	●	○	×

(*Continued*)

TABLE 13.1 (CONTINUED)
Various Technologies and Practices Affect Water, Energy, and Environmental Objectives in Different Ways

			... Strategic Objectives...						... Policy Choices								
	Technologies and Management Practices...	... Can Be Used to Meet ...	Water Security	Energy Security	Water Quality	Carbon Mgmt.	Freshwater Biodiversity and Ecosystem Health	... With Help from...	Product Labeling or Certification	PR Campaign	Data Gathering	Mandate/ Regulation	Right Pricing	Subsidy	Financing	Public Works
	Municipal waste to energy		↑	↑	—	↑	↑		×	×	×	●	●	×	×	●
Water supply and management	Low-flow water fixtures		↑	↑	—	↑	↑[a]		○	○	×	●	○	●	×	×
	Distributed rainwater collection (nonpotable)		↑	↑	↑	↑	↔		×	○	×	●	○	●	×	×
	Distributed rainwater collection (potable)		↑	↓	↑	↓	↔		×	×	×	●	●	●	○	×
	Groundwater pumping		↔	↓	—	↓	↔		×	○	●	●	●	●	○	×
	Desalination		↑	↓	↓	↓	↔ to ↑		×	×	×	●	●	×	●	●
	Graywater and reclaimed water use		↑	↔	—	—	↑[a]		×	×	×	●	●	○	○	●
	Aquifer storage and recovery		↑	↓	↔	↓	↔		×	×	●	×	●	×	×	●

(*Continued*)

TABLE 13.1 (CONTINUED)

Various Technologies and Practices Affect Water, Energy, and Environmental Objectives in Different Ways

			... Strategic Objectives...						... Policy Choices							
	Technologies and Management Practices...	**... Can Be Used to Meet ...**	**Water Security**	**Energy Security**	**Water Quality**	**Carbon Mgmt.**	**Freshwater Biodiversity and Ecosystem Health**	**... With Help from...**	**Product Labeling or Certification**	**PR Campaign**	**Data Gathering**	**Mandate/ Regulation**	**Right Pricing**	**Subsidy**	**Financing**	**Public Works**
Legal instruments	Conservation easements		↔ to ↑	↓ to ↔	↔ to ↑	↔ to ↑	↔ to ↑		●	×	●	×	×	×	○	●
	Water rights and permits		↔	↔	↔	↔	↔		×	×	×	●	×	×	×	×
	Interbasin water transfer		↔	↓	—	↓	↓		×	×	●	×	●	×	×	●
System management practices	Integrated water resource management		↑	↔ to ↑	↔ to ↑	—	↔ to ↑		○	●	●	×	×	×	×	×
	Water funds		↑	—	↑	—	↑		○	×	●	×	●	×	●	×
	Nonpotable water use for energy		↑	↓ to ↔	↑	↔	↑		○	○	●	●	●	●	○	●

○* Because many cities and regions have electric grids operated by government-owned utilities, electric generation infrastructure projects are public works projects.
× Not likely effective.
○ Somewhat effective.
● Effective.

[a] Assuming in combination with ecologically based limits on further water withdrawals to ensure instream flows.

[b] There can be impacts to marine biodiversity.

choices and trade-offs that make its effect upon the objective site specific or unclear, and dashes (—) indicate that the technology has no appreciable impact on the strategic objective. In situations where a technology can be used for widely varying purposes (e.g., hydraulic fracturing, which can be used for accessing natural gas and geothermal resources), multiple arrows indicate that the outcome can be different depending on the application.

The (●) symbol indicates policy choices that can be effective in affecting increased or decreased use of a technology or practice, and the (○) symbol indicates policy choices that are only moderately effective. The effectiveness of a particular policy in promoting a technological solution is independent of whether that solution produces good or bad outcomes for the objectives. In other words, it is possible to craft a policy that is effective at creating a negative outcome for any one strategic objective.

To briefly summarize the takeaways from Table 13.1, several technologies show a "multiple win" scenario in terms of positively addressing more than three of the strategic objectives: low-flow fixtures, energy-efficient appliances and buildings, rainwater collection for nonpotable uses, solar hot water heating, geothermal heat pumps, electricity peak shaving as a demand response method, solar PV power, wind power, combined heat and power, hydropower, and converting municipal waste to energy. Other technologies have various trade-offs: biofuels development, groundwater pumping, electricity peak shifting for demand management, carbon capture and storage, graywater reuse for potable purposes, and interbasin water transfer.

The costs and benefits of many water management practices and legal instruments are dictated significantly by the individual context within the water basin or region. For example, integrated water resource management is largely meant to increase water security and quality, thus benefiting biodiversity, and could potentially ensure more reliable hydropower generation and drinking water supply that lowers the need for groundwater or desalination. The degree of achieving any objective varies tremendously across each case study.

It is important to point out that a "coordinated" policy might not achieve one or more strategic objectives important to one stakeholder group. For example, the exemption of hydraulic fracturing from the SDWA as part of the Energy Policy Act of 2005 was coordinated energy–water policy for the purpose of facilitating oil and natural gas production from shale (Tiemann and Vann 2013). While there are state and federal regulations aimed at protecting groundwater, and hydraulic fracturing water use and disposal are still regulated at the state level, the SDWA federal exemption has led some to fear that the government and industry are not taking all necessary steps to protect water quality and freshwater biodiversity.

This example of water and energy policy is an important aspect of future North American energy supply. Since 2005, the subsequent production of natural gas from shale has played a significant role in facilitating lower US CO_2 emissions from fossil fuel energy with respect to the peak emissions rate in 2007 (6023 million metric tons of CO_2 in 2007 and 5494 million metric tons of CO_2 in 2011; see Table 12.1 [US Energy Information Administration 2012]) because of the recent shift from coal- to gas-fired electricity. However, high oil prices and a sluggish economy since 2008 are also major reasons for less energy consumption and energy-related CO_2 emissions in the United States, and aggressive CO_2 mitigation goals cannot be met with a shift from coal to gas power without CO_2 capture. However, it is most likely that *increased* water consumption (albeit small) in oil and gas extraction during hydraulic fracturing has *reduced* overall water consumption for power generation (Grubert et al. 2012; Scanlon et al. 2013).

13.7.2.2.1 Coordination among Governmental Agencies

Because of the need for data on energy–water trends, the US federal government has shown keen interest in energy–water interdependencies (US GAO 2009a,b, 2012a,b), leading agencies to work together on data collection and management. For example, the US Energy Information Administration has made recent changes to its electric generator reporting forms (e.g., forms 860 and 923) in coordination with the United States Geological Survey that assesses water use more broadly across all economic sectors. These changes to forms include providing useful diagrams to obtain more meaningful and accurate water use information about power plants. Data collection mechanisms can better inform policy and technology solutions for energy–water challenges by using engineering-like diagrams to indicate where water is being consumed and withdrawn within the energy system.

Despite the stagnation in lawmaking from recent US Congresses, there is a core group of elected officials and staff among agencies that keeps the energy–water nexus on the legislative agenda. This focus on energy and water coordination is exemplified by a series of proposed bills that arise during each 2-year Congress (Bingaman 2009, 2011; Gordon 2009; Murkowski 2014).

A good example of coordinate efforts, largely focused on coordinating data collection on water needs for different purposes, is the recent Western Water Data Exchange (WaDE). This online data repository was developed by partnership among Department of Energy laboratories, universities, and state governments. WaDE stores both projected and current water use data for Western US water resources by an eight-digit hydrologic unit code (HUC8) and water end use, including uses for thermoelectric power and oil and gas development. By linking to state databases directly, WaDE prevents duplicative data-gathering efforts at the federal level such that more local state-based experts, rather than federal agencies, can inform the data sets.

13.7.2.2.2 Coordination among Energy and Water Utilities

Coordination among energy and water utilities is generally easier when the same governmental jurisdiction (e.g., city, county) oversees both utilities. More often than not, particularly in regions with deregulated wholesale electricity markets, this common jurisdiction has been broken. The Central Texas cities of Austin and San Antonio are examples of common water and electric utility governance.

For more than 40 years, since the mid-1960s, the City of San Antonio has been using reclaimed water for power plant cooling acting as one of the early pioneers in the use of reclaimed water for power generation (King 2014). After the 10 years of drought from 1947 to 1957, considered the driest period on record for Texas, leaders of City Public Service Board (later named CPS Energy) began to look for ways to conserve Edwards Aquifer water, which until 2002 was the sole source of drinking water for the City of San Antonio and surrounding counties. To meet the increasing energy demand of the growing city and to conserve water from the Edwards Aquifer for potable use, CPS Energy (San Antonio's gas and electric utility) planned the use of treated effluent discharged from the city's wastewater treatment plants into the San Antonio River as a source for cooling the city's future power plants. Because an adequate amount of storage is needed to stabilize the variability of flow discharged from the wastewater treatment plants and to ensure a consistent supply of water, in the late 1960s, Braunig and Calaveras Lakes were built on the southeast side of San Antonio to serve as cooling lakes for CPS Energy's newest generating units. Since the initial operations in 1966, approximately 308 billion gallons of Edwards Aquifer water have been saved. However, there is an environmental trade-off in that now less water flows down the San Antonio River to Texas' bay system because it is diverted and evaporated (both natural and forced evaporation) from the cooling ponds. Thus, the Edwards Aquifer water is conserved at the slight expense of freshwater inflows to the bay.

13.7.2.2.3 Coordination of Energy–Water Nexus Issues in Industry

Electric and water utilities are traditionally not sources of significant quantities of original research, technology, or funding for research and technology. Industry organizations such as the Electric Power Research Institute (EPRI), the Edison Electric Institute, and the American Water Resources Association do often work with government agencies and nongovernmental organizations to help sponsor and coordinate academic and industry research. One example is the EPRI coordinating with the National Science Foundation for a 2013 solicitation for proposals for "Advanced Dry Cooling for Power Plants." Another example of coordinated water–energy research effort is the Water Research Center (started in 2013) that is run by the Southern Research Institute in partnership with Georgia Power (a subsidiary of the electric utility company Southern Company) and the EPRI. This center researches various technologies to conserve and reuse water within thermoelectric power plants. These types of partnerships are needed to supplement government-funded research efforts.

13.7.2.2.4 Relevant Policies That Demonstrate Coordination

Australia presents an example of creating a framework that facilitates some trade of water during times of drought and that, in theory, can facilitate water (purchases from lower-value users) for power production (see Chapter 6 of King 2014 for more details). Under the 2004 Australian National Water Initiative, the federal and all state governments agreed that the volume of water allocated from each aquifer or river basin would be capped (Commonwealth of Australia et al. 2004). If fully implemented, all major water users would be required to hold tradable water rights that are a share of the available water resource. While substantially implemented in the agricultural sector with positive socioeconomic outcomes, in a number of instances, power producers remain outside the cap and trade water market system (NWC 2011).

South Africa also presents an example of coordinated water–energy policy (King 2014). South Africa's state-owned utility, Eskom, is the main electricity generating institution in Southern Africa. Power Generation (and by implication Eskom) is recognized by South Africa's National Water Act as a strategic water user and is granted water use at a 99.5% level of assurance (DWA South Africa 2013). Eskom uses approximately 1.5% to 2% of the total amount of water consumed in the country, mainly by its fleet of wet-cooled, coal-fired power stations. Eskom has implemented a dry cooling policy since the 1980s that recognizes the water scarcity in South Africa and Eskom's responsibility in this regard as a major water user. Six of its 15 coal-fired power stations use dry cooling.

13.7.2.3 Issues Relevant to Bridging Institutional Gaps

As societies experience new challenges, they require added complexity to solve these challenges (Tainter 1988; Tainter and Patzek 2012). The means for handling this increased complexity comes from either increased energy consumption, increased information processing, or both. More than increasingly efficient energy technologies and systems, what we need in the future are increasingly resilient organizations and social constructs that recognize the differences between our historical trajectory and future visions (Dearing et al. 2010; Rockström and Noone 2009; Westley et al. 2011). We can try to label our future visions as *transformative* or *sustainable pathways* and *resilient economies and societies*. However, a driving future characteristic is the need to have multiple stakeholders learn to work together in new ways rather than employ past solutions that were often in isolation. The world has effectively passed the time when optimal isolated solutions have minimal isolated impacts—environmentally, economically, and socially. Our contemporary and future energy and environmental problems cannot be solved by focusing on a single issue or variable. Because of the complex interactions between multiple energy and environmental objectives, we now live in a time and place where a single "optimal" solution cannot be defined, much less derived. Nonetheless, there are some concepts, discussed in this subsection, that help minimize conflict and facilitate the dialogues that lead to better and longer-lasting water allocation solutions (see King 2013; King et al. 2013 for a fuller discussion).

13.7.2.3.1 Water Pricing and Water Markets

Right pricing and *full-cost recovery* describe policies that ensure that energy and water tariffs (or charges) are sufficient to cover the full supply costs of energy and water. Included in this definition are concepts such as ecological zoning and carbon pricing as means to incorporate externalities. If water is not fully priced and consumers are not exposed to that price, then they will form habits that do not reflect the local scarcity and costs of fresh water supplies.

Water markets are also seen as one mechanism for effectively allocating water, particularly during times of water scarcity.

A severe drought in Texas during 2011 also forced Texas regulators (the Texas Commission on Environmental Quality) to subvert the prior appropriation of water rights because they would have otherwise cut off water to power generators in one of the hottest and driest summers on record (Texas Commission on Environmental Quality 2011, 2012, 2013). A small water market or river master (for basin planning) could help facilitate this type of situation, and a new water master has been proposed for one of the drought-stricken Texas basins (Brazos River basin).

13.7.2.3.2 Policy Mechanisms (Conservation, Subsidies, Financing, etc.)

Mandates and *regulations* encompass government laws and rules that consumers and businesses must follow to avoid civil and criminal penalties (e.g., building codes, efficiency standards, water rights). *Government subsidies (and taxes)* encompass targeted monetary incentives given by the government to specific projects, categories of projects, or industrial sectors. *Public works (and private partnership) projects* encompass public capital projects funded partly or entirely by the government via bonds or other public financing instruments. *Financing* as a policy includes options that enable private businesses and consumers to spread the capital costs of technology over time rather than paying 100% up-front.

13.7.2.3.3 Basin-Level Planning (Integrated Water Resource Management)

Integrated Water Resource Management (IWRM) is a collaborative engagement process with the goal to consider ecosystem health and biodiversity in tandem with other goals for freshwater use such that management of water resources is as fair and equitable as possible to all water users. Technically, no water use or impact is excluded within IWRM; practically, all uses and impacts will not be addressed to full satisfaction by all.

While often neglected historically in water planning, energy production systems should be an integral consideration. One of the most recent impacts has been that drought and high water temperatures are influencing the ability of thermoelectric power plants to fully operate or meet regulatory limits across the United States from Texas to the Midwest to Connecticut (AP 2014; Staletovich 2014; Wald 2012; Wald and Schwartz 2012). These factors also affect freshwater ecosystems, biodiversity, and trade (e.g., via barge traffic). The designs for nuclear and other thermoelectric generating stations did not account for the magnitude of some of the low-precipitation and high-temperature events between 2010 and 2013.

Ultimately, the electric power industry's product is of such high value that added economic value from consuming water is usually above the direct cost of water, and power generation often receives high priority access to water (e.g., South Africa planning and Texas 2011 drought response). This enables the electricity industry to afford higher water costs than most competing users (Smart and Aspinall 2009). Thus, the need for water security for cooling thermoelectric power plants provides the driver for water conservation efforts in that industry. On the other hand, economic sectors that rely on ecosystem services can have more incentive to keep sufficient freshwater flows than industry or agriculture. For example, it can very well be the case that fisherpersons are willing to pay a price for some additional stream flow that exceeds the price that farmers are willing to sell some of their water (as was estimated in 51 of 67 US river basins that have a significant level of irrigation [Hansen and Hallem 1991]).

Stakeholders can consider these water, energy, and other trade-offs during IWRM, including in state water planning processes. However, the different boundaries of electricity markets, water basins, and governmental boundaries (e.g., counties, states) create difficulty for holistic solutions.

The thermoelectric cooling anecdote exemplifies the future climate challenge. Air and water temperatures will increase. Drought frequency is predicted to increase in much of North America. All other energy systems that require water will run into increasingly competitive water situations with all other water stakeholders. Metrics for product life cycles, such as the water embodied in driving a vehicle (e.g., gallons of water per mile driven), can be useful for characterizing technology options, but these metrics must be correctly aggregated to total broader scales such as overall water consumption in a water basin (King et al. 2010, 2013). While we need to consider that our future energy supplies might need an increasing share of available water resources, it might not be best to put a water use limit on one product versus another (e.g., crops for food versus crops for biofuels). The IWRM process and the use of computational models can avoid such water allocation confusion, but the process is most effective if stakeholders understand and are part of model development such that they buy into the IWRM outcomes.

13.7.2.3.4 Research Efforts

Funding research is often critical to introduce new combinations of solutions, including both policies and technologies. Pure technology-focused research within the energy–water nexus can be facilitated via existing government, industry, and nongovernmental channels with targeted solicitations on concepts such as new biofuel crop development, fuel processing and refining, and power plant cooling. More difficult is the funding of regional initiatives that cross technology and policy boundaries to manage and document IWRM efforts with or without significant energy-related water demands. Via IWRM, stakeholders can learn about examples of combinations of policies and technologies that worked in various real-world cases from which to more quickly come to governance solutions in their own region.

13.7.2.3.5 Information/Data Gaps

Data gathering involves data collected on wider scales of cities and countries that can be used to create statistics for policy decisions and track whether policy decisions produce intended outcomes. There is almost always a desire for more data for scientific analysis. The challenge is in making decisions with the available data while also maintaining the flow and quality of existing data streams for tracking outcomes. When stakeholders understand the need for each type of data to create measureable metrics of accountability and progress, then they can agree to collect and maintain the data. Typical data relevant for water–energy nexus concepts are electricity generation output (from every minute to annual sums), water use quantities and sources for energy resource extraction (e.g., oil extraction) and conversion (e.g., electric power production), and water discharge quantities and qualities (e.g., temperature, salinity).

13.7.2.3.6 Public Awareness

Product labeling includes the dissemination of information regarding water, energy, and biodiversity life cycle impacts on consumer products. *Certification* for products and best management practices describes products and practices that comply with a predefined set of principles, characteristics, or technologies. Certification programs are often operated by third-party organizations specifically set up for the purpose (e.g., Forest Stewardship Council governing forest harvesting and management, Alliance for Water Stewardship governing freshwater resources, and Low Impact Hydropower Institute for hydropower). *Public relations (PR) campaigns (information dissemination)* encompass targeted educational and outreach activities, by governments, nongovernmental organizations, or private for-profit and nonprofit companies that inform consumers or persons who can take direct action upon learning about a topic of interest.

Each of these concepts listed in the previous paragraph can add value in terms of assessing products and business practices at proper scales. The value is in informing consumers on the impacts of their purchasing decisions. One major challenge is in creating product information that is reliable and that indicates a substantial rather than trivial difference in environmental (e.g., water resource). Water basins and resources present unique challenges because governments usually have ultimate authority over water allocation that is spread across many users (unlike timber harvesting by a single land or lease holder).

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14 Water, Energy, and Ecosystem Sustainability

Cindy Loeffler, Leslie D. Hartman,
and Daniel H. Chen

CONTENTS

> Water is life's matter and matrix, mother and medium. There is no life without water.
>
> **Albert Szent-Gyorgy, MD**
> *Discoverer of Vitamin C*

Water is essential to life. Every living thing on Earth requires freshwater to survive, yet access to freshwater is not a given. More than 96% of the Earth's water is in the form of seawater. Freshwater resources in the form of precipitation and water in lakes, rivers, streams, and aquifers make up the remaining 4%.* According to the United Nations, almost one-fifth of the world's population faces water scarcity today.† As the world's population increases (Figure 14.1) and the climate warms (Figure 14.2), water scarcity will pose an even greater challenge.

Water is also essential to support socioeconomic development and healthy ecosystems world-wide. Without an adequate freshwater supply, many basics of everyday life would not be possible. Food and energy production, transportation, waste disposal, industrial manufacturing, recreation, and, last but not least, human health and sanitation all depend on adequate water supplies (Gleick 2012).

Water, if carefully managed, is a renewable resource. If mismanaged, either through unsustainable development or pollution, water quickly becomes a limiting factor. It has been estimated that humans only use roughly approximately 12% of available freshwater worldwide (International Water Management Institute 2007) but problems arise when water is withdrawn from rivers, lakes, and aquifers at faster

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* https://water.usgs.gov/edu/earthhowmuch.html

† http://www.un.org/waterforlifedecade/scarcity.shtml

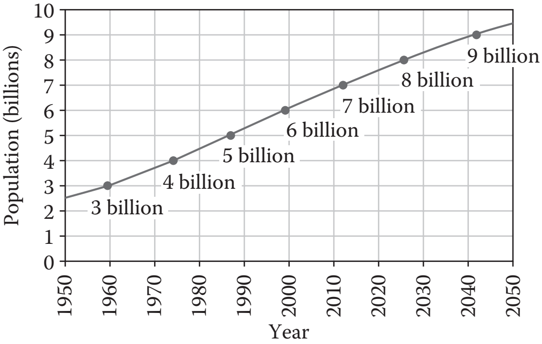


FIGURE 14.1 World population growth: 1950–2050 (http://www.census.gov/population/international/data/idb/worldpopgraph.php).

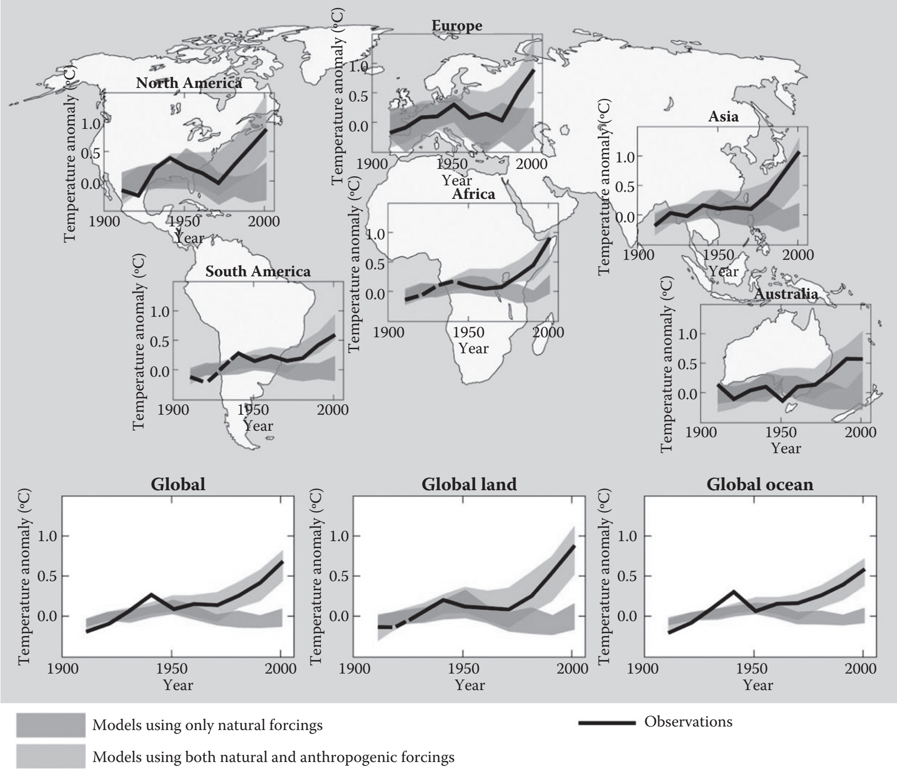


FIGURE 14.2 Global temperature anomalies. (IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.)

rates than it is replenished. A useful analogy when thinking about water sustainability is your personal checkbook (Richter 2014). To manage one's finances sustainably, it is important to not only be aware of how much money is deposited in the account but to also be aware of how much is remaining before additional withdrawals are made. If withdrawals exceed the balance at any given time, problems result. Aquatic ecosystems are no different. Impacts to freshwater ecosystems accrue when rivers and streams are depleted and flow regimes are altered. Additional environmental impacts occur from construction of dams, reservoirs, and other strategies related to the development of water (Table 14.1).

Discussions of sustainability are typically centered on economic interests, efficient use technologies, ecosystem health, and even ethics (Vucetich and Nelson 2010), yet these words are simply categories without agreed upon specifications. While educational efforts in the Galapagos (Bassi and Baer 2009) and in Africa (Barry et al. 2011) have shown some positive benefits, they are unlikely to yield lasting results as their control and influence end at their political boundary. Yet, ecosystem services are a single global component. While not precisely accurate, pragmatically the Earth could be viewed as a closed-loop system. Water is neither created nor destroyed but is simply converted into other formats such as vapor, biomass, saltwater, or even clean or unclean. As we consumptively use water, both the quality and quantity of water remaining for ecosystem services declines. The implications of ecosystem declines are far reaching.

14.1 ECOSYSTEM SERVICES

Ecosystem services, those benefits to humans provided by well-functioning watersheds, are also often overlooked. Ecosystem services fall into several categories: provisioning services, supporting services, cultural services, and regulating services (Millennium Ecosystem Assessment 2005). Food production and water supply are two examples of provisioning services. Supporting services include nutrient cycling, soil formation, and habitat for fish and wildlife. Cultural services include aesthetic, recreational, and spiritual benefits. Flood attenuation and water purification are examples of regulating services. Healthy aquatic ecosystems—rivers, streams, lakes, and estuaries—provide all of these benefits at no cost if managed carefully.

Different economic sectors use water in differing amounts for different purposes. Each sector extracts water from a lake, river, or aquifer, consuming a certain percentage and returning the remainder. For example, the agricultural sector uses water to irrigate crops used to produce food and fiber, the domestic sector uses water in and around the home, while the industrial sector uses water to produce and manufacture goods. In general, agricultural production extracts and consumes the largest percentage of water worldwide (Figure 14.3).

14.1.1 Water for Fish and Wildlife

Traditionally, water planning and management have focused on human uses of water. Water for fish and wildlife, if considered at all, was often a secondary concern. In some cases, consideration for fish and wildlife and other environmental water needs did not occur until water supplies were fully or even over-appropriated. Between

TABLE 14.1

Potential Environmental Impacts Associated with Water Development Strategies

Proposed Water Strategy	Potential Environmental Impacts	General Actions
On-channel reservoir	Direct impacts: inundation and loss of habitat types such as terrestrial, wetland, riverine, riparian, and bottomland hardwoods Indirect impacts: reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods Changes in water quality conditions Reduction and alteration of instream flows, overbanking flows, and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Changes to sediment transport processes Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Mitigation required to compensate for terrestrial wetland, riverine, and riparian habitats and bottomland hardwoods inundated by the reservoir and dam Mitigation required to compensate for terrestrial and wetland habitat lost or altered downstream of reservoir and dam Reservoir pass-throughs required to provide daily instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats, aquatic and terrestrial communities, and ecosystem processes Reservoir pass-throughs required to prevent degradation of water quality Overbanking flows recommended to maintain riparian and bottomland hardwood habitats and floodplain connectivity and seasonal channel maintenance flows recommended to maintain sediment transport and scouring processes
Off-channel reservoir	Direct impacts: inundation and loss of habitat types such as terrestrial, wetland, riverine, riparian and bottomland hardwoods Indirect impacts: reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods Changes in water quality conditions Reduction and alteration of instream flows, overbanking flows, and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events	Mitigation required to compensate for terrestrial wetland, riverine, and riparian habitats and bottomland hardwoods inundated by the reservoir and dam Mitigation required to compensate for terrestrial and wetland habitat lost or altered downstream of reservoir and dam Reservoir pass-throughs required to provide daily instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats, aquatic and terrestrial communities and ecosystem processes

(*Continued*)

TABLE 14.1 (CONTINUED)
Potential Environmental Impacts Associated with Water Development Strategies

Proposed Water Strategy	Potential Environmental Impacts	General Actions
	Changes to sediment transport processes Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Reservoir pass-throughs required to prevent degradation of water quality Overbanking flows recommended to maintain riparian and bottomland hardwood habitats and floodplain connectivity and channel maintenance flows recommended to maintain sediment transport and scouring processes
Chloride control	Reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods Changes in water quality conditions Reduction and alteration of instream flows, overbanking flows and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Brine disposal and contaminants issues Ecological changes in aquatic communities adapted to highly saline environment Changes to sediment transport processes Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Recommend studies to ensure survival of species dependent on physical and chemical conditions of the highly saline environment Brine disposal and contaminants rules and guidelines must be followed Contaminants monitoring or test wells may be required Mitigation required to compensate for terrestrial wetland, riverine, and riparian habitats and bottomland hardwoods inundated by the reservoir and dam Mitigation required to compensate for terrestrial and wetland habitat lost or altered downstream of reservoir and dam

(*Continued*)

TABLE 14.1 (CONTINUED)
Potential Environmental Impacts Associated with Water Development Strategies

Proposed Water Strategy	Potential Environmental Impacts	General Actions
Interbasin transfer	Reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods in both basin of origin and receiving basin Changes in water quality conditions in both basin of origin and receiving basin Reduction and alteration of instream flows, overbanking flows, and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Changes to sediment transport processes Possible transfer of exotic, nuisance, or atypical species to receiving basin Possible transfer of disease or parasites Possible hybridization of similar, but genetically distinct species Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Reservoir pass-throughs required to provide daily instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats, aquatic and terrestrial communities, and ecosystem processes Mitigation required to compensate for terrestrial and wetland habitat lost or altered downstream Overbanking flows recommended to maintain riparian and bottomland hardwood habitats and floodplain connectivity and channel maintenance flows recommended to maintain sediment transport and scouring processes Removal of exotic, nuisance, or atypical species through water treatment or other means Requirements to prevent degradation of water quality in basin of origin and receiving basin
New direct diversion	Reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods Changes to sediment transport processes Changes in water quality conditions Reduction and alteration of instream flows, overbanking flows, and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Diversion restrictions required to provide daily instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats and to maintain water quality standards and ecosystem processes Mitigation recommended to compensate for terrestrial and wetland habitat lost or altered downstream Overbanking flows recommended to maintain riparian and bottomland hardwood habitats and floodplain connectivity and channel maintenance flows recommended to maintain sediment transport and scouring processes

(Continued)

TABLE 14.1 (CONTINUED)
Potential Environmental Impacts Associated with Water Development Strategies

Proposed Water Strategy	Potential Environmental Impacts	General Actions
Groundwater pumping	Possible reduction, alteration, or cessation of springflow attributed to groundwater level decline Possible reduction in baseflows of rivers and streams that cross aquifer outcrop areas Subsidence with corresponding loss of shoreline, riparian and shallow water, nearshore habitat Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Pumping limits recommended to protect aquatic ecosystems Pumping limits may be required to protect endangered species Prevent subsidence by following subsidence district rules and regulations
Water marketing	Reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods Changes to sediment transport processes Changes in water quality conditions Reduction and alteration of instream flows, overbanking flows, and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Diversion restrictions required to provide daily instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats and to maintain water quality standards and ecosystem processes Mitigation recommended to compensate for terrestrial and wetland habitat lost or altered downstream Diversion limits required to prevent degradation of water quality Overbanking flows recommended to maintain riparian and bottomland hardwood and floodplain connectivity and channel maintenance flows recommended to maintain sediment transport and scouring processes

(*Continued*)

TABLE 14.1 (CONTINUED)
Potential Environmental Impacts Associated with Water Development Strategies

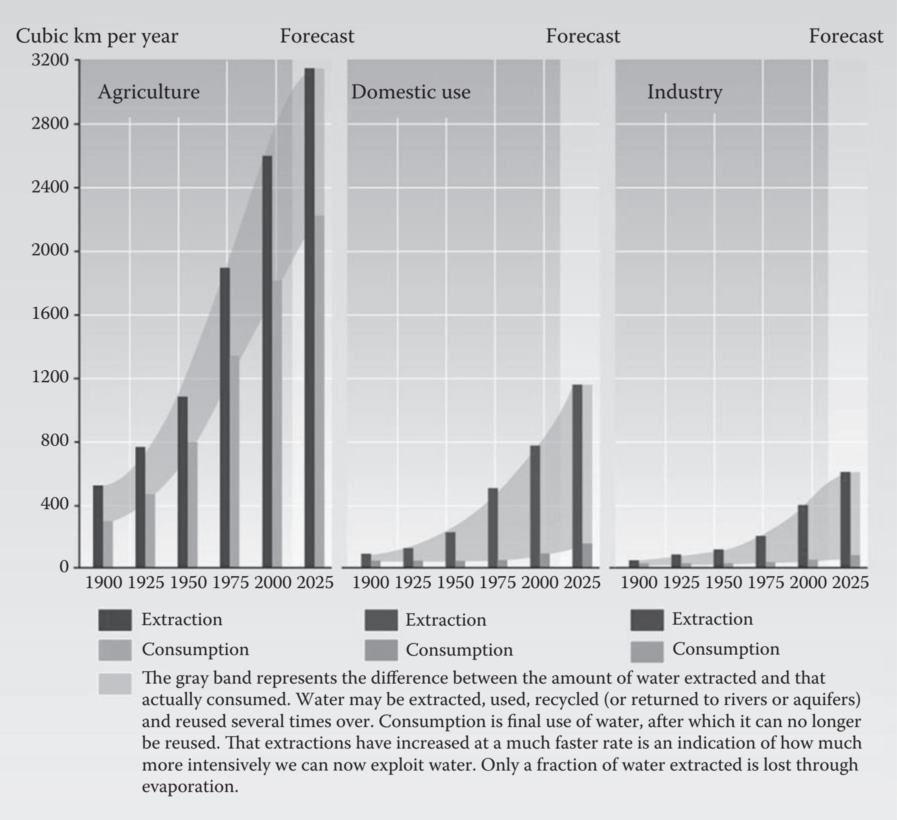
Proposed Water Strategy	Potential Environmental Impacts	General Actions
Rechannelization or in-channel brush control	Alteration or loss of instream and riparian habitat Changes to sediment transport processes Increased sediment runoff and erosion Reduction in groundwater discharge Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Consultation with TPWD recommended
Brush control	Alteration of terrestrial habitat Increased sediment runoff and erosion Impacts from chemical control measures Potential for increased groundwater recharge Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Consultation with TPWD recommended
Aquifer storage and recovery	Reduction or alteration of downstream habitat types such as riverine, estuarine, riparian, wetland, and bottomland hardwoods Changes to sediment transport processes Changes in water quality conditions Reduction and alteration of instream flows, overbanking flows and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Diversion restrictions required to provide daily instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats, to maintain water quality standards and ecosystem processes Mitigation recommended to compensate for terrestrial and wetland habitat lost or altered downstream Diversion limits required to prevent degradation of water quality Overbanking flows recommended to maintain riparian and bottomland hardwood habitats and floodplain connectivity and channel maintenance flows recommended to maintain sediment transport and scouring processes

(*Continued*)

TABLE 14.1 (CONTINUED)
Potential Environmental Impacts Associated with Water Development Strategies

Proposed Water Strategy	Potential Environmental Impacts	General Actions
Sediment removal from existing reservoirs	Resuspension of sediments and possible contaminants Disposal of potentially contaminated sediments Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Laboratory sediment analysis required before disposal of sediments
Desalinization	Alteration of brackish water habitat Brine disposal Alteration of water quality Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Brine disposal rules and guidelines must be followed Consultation with TPWD recommended
Reuse	Reduction and alteration of instream flows, overbanking flows, and freshwater inflows to bays and estuaries relative to magnitude, timing, and frequency of hydrologic events Changes to sediment transport processes Changes in water quality conditions Concentrations of salts, nutrients, and contaminants Impacts to aquatic and terrestrial communities and ecosystem processes Influence on energy and nutrient inputs and processing	Bed and banks permit restrictions required to provide instream flows and freshwater inflows on a seasonal or monthly basis to conserve and protect downstream habitats Permit restrictions required to prevent degradation of water quality and to maintain water quality standards
Water conservation	Positive impact	None required

Note: Environmental assessments to determine extent of impacts on threatened and endangered species, critical vegetation types, and water quality/quantity issues are required for major water development projects. Major project sponsors will also need to determine if instream flow or freshwater inflow study results are available. If study results are not available, environmental planning criteria may be used for planning, but detailed, site-specific studies will be required for permitting. Proposed project types are listed and ordered from projects that generally have more environmental impacts to those having the least environmental impacts.



The gray band represents the difference between the amount of water extracted and that actually consumed. Water may be extracted, used, recycled (or returned to rivers or aquifers) and reused several times over. Consumption is final use of water, after which it can no longer be reused. That extractions have increased at a much faster rate is an indication of how much more intensively we can now exploit water. Only a fraction of water extracted is lost through evaporation.

FIGURE 14.3 World water use by sector. (Igor A. Shiklomanov, State Hydrological Institute [SHI, St. Petersburg] and United Nations Educational, Scientific and Cultural Organisation [UNESCO, Paris], 1999.)

1970 and 2000, populations of freshwater aquatic species have declined by 55% worldwide.*

Water flowing in rivers and streams, also known as instream flows, supports a multitude of freshwater aquatic species and ecosystems. Variable flow regimes that include large and small pulses of flow as well as base and subsistence flows during dry times are necessary to support healthy freshwater ecosystems. Water that emerges from underground aquifers, also known as springs, often supports highly adapted rare and endemic aquatic species that depend on stable conditions associated with springs. The hydrologic stability of springs makes them an important contributor to baseflows in rivers and streams, especially during drought.

Freshwater inflows are a defining component of estuaries. Estuaries (or bays) are specifically defined as the zone where freshwater rivers and streams mix with ocean water in the coastal zone. Although influenced by the tides, estuaries are protected from the full force of ocean waves, winds, and storms by barrier islands, or fingers

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* UNWater.org Water and Biodiversity Fact sheet.

of land that surround them. The chemical and physical processes that accompany this mixing provide key nursery habitats to many economically important and ecologically characteristic fish and shellfish species. These intermediate salinity mixing zones provide food and cover to juvenile fish, shrimp, crabs, oysters, and other biota.

Anthropologic or natural reductions in freshwater inflow to estuaries lead to increased salinities, allowing for greater intrusion of marine predators, parasites, and disease. Reduced freshwater inflows also lead to diminished nutrient loads originating from upstream watersheds, which, in turn, leads to reduced productivity in the estuary. This loss of productivity eventually results in loss of economically important fish and shellfish species that depend on estuarine habitats as nursery areas for juvenile life stages. In addition, reduced freshwater inflows can also lead to decreased sediment loads, which, in turn, can cause erosion and loss of delta marsh habitat critical to many estuarine-dependent organisms (Longley 1994).

Additionally, freshwater inflows to estuaries have a seasonal component to which species are keyed. Peak spawning for many species is typically in the spring with a second, smaller spawn in the fall. With tens of thousands of species involved, spawning does occur in every month of the year, so each month has a critical value to estuarine health. Sustainable water management practices in South Africa, Australia, and Texas, USA, have adapted to mimic the seasonality of natural flows. External influences such as dams, droughts, and climate change may influence the success of such adaptive management techniques.

Estuarine species have variable salinity needs throughout their lifetime. Many species spawn nearshore, depending on water currents and hydrologic conditions to transport eggs and larvae into the bays where abundant habitat and food are available. The salinity needs of egg, larval, and adult stages differ during an individual's life, and each species' requirements also differ widely. For example, an adult threadfin shad (*Dorosoma petenense*) can sustain salinities near 20‰ but the eggs and larvae of this species require freshwater to develop. While in the same bay, spotted seatrout (*Cynoscion nebulosus*) eggs and larvae need salinities in the mid-teens and higher yet the juvenile seeks salinities of approximately 20‰ down to 8‰. If water is diverted from rivers at high rates, attempts to mimic natural flow regimes may be thwarted, preventing freshwater inflows from reaching the bays in sufficient quantities to provide for the lower salinity needs of many species. While drought is a naturally occurring, periodic episode that species can withstand, continuing chronic failures to access sufficient freshwater will affect species composition and estuarine carrying capacities within the bays. Equally, off-channel reservoir storage in flood years will reduce periodic scouring and flushing of the bay necessary to recharge nutrients that are foundational to the productivity of estuarine nurseries.

Desalination of seawater is becoming a more economically viable option for addressing increased water demand associated with population growth. While desalination can help reduce pressure on freshwater resources, there are still potential environmental impacts to consider. Environmental implications include direct impacts such as habitat loss from the plant itself, brine concentrate disposal, and impingement and entrainment of larval species. The cumulative effects of water development including desalination need to be considered in concert with the heterogeneous nature of the world's oceans. Globally, estuaries are the nursery area for a major portion of the world's fishes and marine invertebrates. Yet, given their proximity to land, estuaries are often viewed as the most cost-effective source of seawater for desalination plants. The ecosystem impact of a single desalination plant is sustainable as some eggs and larvae from up-current, offshore spawners will continue to provide a source for an impacted bay. Inclusion of a seasonal seawater diversion pattern to mitigate impacts during peak spawning season for estuarine spawners can help further reduce impacts. Cumulative effects from freshwater and estuarine diversion must also be considered to avoid long-term impact to spawning populations.

As estuarine health is affected, marine health follows. Anthropogenic causes such as nonpoint source runoff in the Mississippi River drainage in the United States have created a hypoxic "deadzone" in the Gulf of Mexico. Reductions in habitat availability have led to reduced species distribution, which inevitably leads to a reduction in overall populations. Other human-induced impacts such as the global plastic gyre[*] and oil spills affect marine ecosystem health in international waters. Yet, it is algae biomass in these waters that provide the globe with upward of 75%[†] of the Earth's oxygen. Any discussion of sustainability must recognize the global impact of the world ocean, on weather and associated food production and on oxygen production itself. Local sustainability efforts are not operating in a vacuum and deleterious impacts are global impacts.

14.2 CLIMATE CHANGE/DROUGHT

The global climate is not static; short-term and long-term changes do occur. Global oscillations such as El Niño and La Niña produce shifts in weather patterns, yielding localized flood and drought extremes. Climate change is expected to further exacerbate these extremes. Such shifts are already occurring globally. Climate-induced drought in Syria has already been implicated as a contributing factor in armed conflict (Gleick 2014) as drought conditions drive famine in areas like East Africa and additional conflicts are likely to occur. While armed conflict is an extreme result of climate change, impacts in areas such as Texas have already resulted in some community fracturing with no user group feeling adequately served.

Currently, Texas is in the midst of a historic drought, the second worst in historical record statewide, behind the drought of the 1950s.[‡] Hydrologists use the drought of the 1950s as a benchmark for water planning. The assumption is that if water projects like reservoirs are designed to provide through a repeat of the "Drought of Record," then we will have adequate supplies going forward. Although we have had a bit of relief since 2011, the driest single year on record, many areas of the state are still suffering from lack of precipitation, leading experts to wonder if we are experiencing a new Drought of Record. The outlook for drought relief is not promising. Most climate model simulations suggest that our warmer temperatures may be the "new normal" for Texas.[§]

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[*] http://marinedebris.noaa.gov/learn-basics/movement

[†] http://www.ecology.com/2011/09/12/important-organism/

[‡] Personal communication, Texas State Climatologist, Dr. John Nielsen-Gammon.

[§] Personal communication, Dr. Gerald North, Texas A&M University.

Precipitation projections through 2100 for Texas are highly uncertain. Some models show increased precipitation over parts of the state, but other models project more arid conditions like those we are experiencing presently. It is likely that future precipitation patterns will differ either seasonally or geographically from historical patterns. What is certain is that Texas bay waters have warmed by an average of nearly 3°F over the past 25 years, primarily as a result of warmer winters. In addition, Texas coastal sea level is rising. At a continued subsidence rate of 4 inches per century, Gulf coast sea levels could be 17 inches higher by 2100. This will mean more frequent and longer flooding of marshes that could convert to open water.

Higher temperatures in lakes, wetlands, and rivers will likely result in lower dissolved oxygen, which could mean more fish kills. Rates of decay will accelerate, possibly leading indirectly to eutrophication and more frequent blooms of harmful algae such as golden alga and red tide.

Changes in the seasonality of river flows, and in the amount and distribution of rainfall, could alter the magnitude, timing, and rate of river flow, which could adversely affect river, estuary, and riparian species adapted to specific flow regimes for spawning cues or other life needs.

The consequences of this drought have been to pit agricultural producers against urban dwellers, and ecological needs versus economic viability. Discussion rarely includes the ecological needs of estuaries and focuses on use for additional expansion. Water as a limiting factor is affecting societal cohesion. While cognizant of the ecological impacts and need for sustainability, short-term planning tends to overwhelm possible long-term consequences.

14.3 ENERGY–WATER NEXUS

It takes water to make energy and it takes energy to make water useable. This paradigm is known as the *energy–water nexus*. Approximately 157,000 million gallons of water annually are consumed for cooling power plants in Texas (Stillwell et al. 2009). In addition, approximately 0.8%–1.3% of electricity generated in Texas goes to the treatment, transportation, and heating of water. While these numbers may not seem alarming today, water and energy experts are planning ahead. The population of Texas is expected to nearly double by 2060 from the current 25.4 million to approximately 46 million people. Along with increasing population comes increasing demand for water and electricity. By 2060, the Texas Water Development Board (TWDB) predicts that 7.4% of our water supply will be needed to generate electricity. They also predict that existing water supplies will not be enough to meet the growing overall water demand.

Competition for limited water supplies is heating up, especially during drought. In some cases, water supplies are overcommitted, risking the potential for economic loss and ecosystem damage. Water planning at the state, regional, and local level helps address the conflicts, but when drought intensifies, planning assumptions might not hold.

The TWDB reports that statewide reservoirs are only 73% full. Since many of these reservoirs serve as cooling water for thermoelectric power plants, which account for 85% to 90% of Texas' power generation, this is cause for concern. In

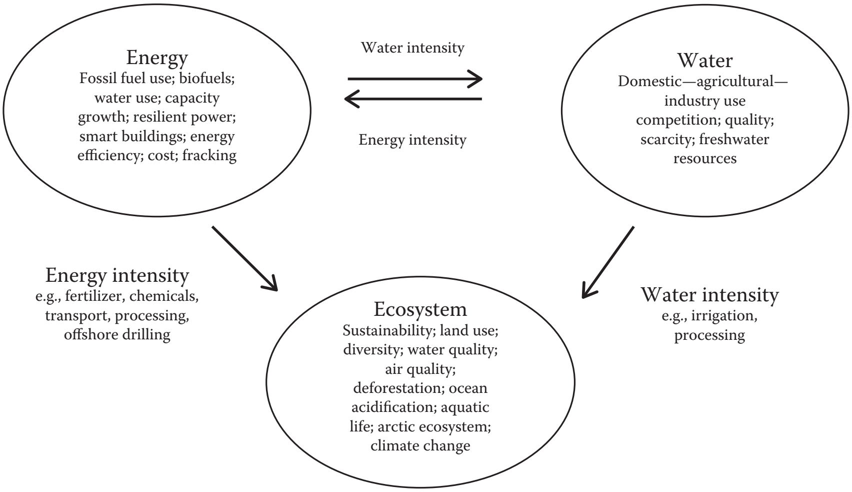

FIGURE 14.4 Energy–water–ecosystem nexus. (Adapted from Google images [https://www.google.com/search?biw=1024&bih=540&noj=1&tbm=isch&sa=1&q=energy+water+food+nexus&oq=energy+water+food+nexus&gs_l=img.12..0.14175.15017.0.16805.11.5.0.0.0.0.43.61.2.2.0.ernk_zc...0...1.1.64.img..10.1.43.REkZoLausA8].)

addition, if “cooling” water reservoirs are hot as a result of record heat as experienced in 2012, power plants have to work harder to generate electricity.

Thermal power plants—those that use fuels such as biomass, coal, oil, natural gas, or uranium to generate heat that drives turbines that spin generators that make electricity—often use water for cooling. Doing so improves their performance and efficiency. However, that means the water has to be available. Drought-induced water scarcity or temperature means water might not be available or effective as a coolant. That means the power sector is vulnerable to water constraints.*

During the summer of 2011, demand for electricity in Texas was so great that the Electric Reliability Council of Texas issued consumer warnings, asking users to raise their thermostats and otherwise limit electricity use, because our demand was exceeding the state’s electrical grid capacity. Fortunately, Texas consumers responded, conditions moderated, and the crisis was averted.

Even though renewable energy sources like wind and solar need much less water to generate electricity when compared to conventional fuels, they do require water to manufacture turbine blades and solar panels. In fact, every product we consume requires water and energy to produce. This concept, when applied to every product we consume, is known as the “water footprint.” The interrelated nature of water and energy, including impacts to ecosystems, is depicted in Figure 14.4.

Tackling the energy–water nexus may seem like a daunting, even impossible challenge, but there’s a positive side: saving water saves energy and saving energy saves water. Individuals can conserve energy by turning off appliances that are not being

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* Personal communication, Dr. Michael E. Webber, associate professor of mechanical engineering at the University of Texas.

used and installing a programmable thermostat. Saving electricity in turn saves water that could benefit lakes, rivers, and aquifer. Most local utilities offer energy audits and other services to help homeowners identify and target inefficiency problems at home. Individuals can also consider using alternative energy as a means to reducing their water footprint. Texas leads the nation in wind energy production. Wind energy is a low carbon source of dependable energy that has a low water footprint. Individuals can reduce their water footprint by choosing locally produced item whenever possible. Since a substantial percentage of Texas' water supply is used outdoors during summer months to water landscapes and fill swimming pools, outdoor water conservation is something most homeowners can undertake. Individual homeowners can save water, and help wildlife in the process, by creating drought-tolerant, native plant-based "wildscapes" at home. Texas is fortunate to have a wide variety of attractive native and climate-adapted plants that need less supplemental water and provide benefits to wildlife. Rainwater collection systems have the added benefit of reducing energy needs since water does not have to be pumped from far away. Using collected rainwater to water plants also eliminates the need for treatment, again saving energy. With natives, you can also forgo fertilizer, which also requires water and energy to produce. Less lawn watering and fertilizing equals less mowing, in turn saving water and energy. Saving water delays the need for building new water supply projects that may also affect fish and wildlife habitat.

14.4 WATER PLANNING FOR A SUSTAINABLE FUTURE

Water sustainability is key to our future. Thoughtful planning and careful water management are critical to water sustainability. Seven principles for sustainable water management (Richter 2014) are as follows:

1. Build a shared vision for your community's water future.
2. Set limits on total consumptive water use.
3. Allocate a specific volume for each user, then monitor and enforce.
4. Invest in water conservation to its maximum potential.
5. Enable trading of water entitlements.
6. If too much water is being consumptively used, subsidize reductions in consumption.
7. Learn from mistakes or better ideas, and adjust as you go.

The challenge for implementing a global sustainable water strategy is for each nation to find the method and emphases that are most appropriate. Australia and South Africa are already forerunners in sustainability, with other areas such as Texas moving toward a more sustainable water future. For example, in Texas, water planning is now decentralized, conducted at a regional level. Regional water plans, developed every 5 years to address water needs by decade for the next 50 years, are compiled into one state water plan. These regional water plans are created by local stakeholder committees composed of a variety of interests, including environmental interests. Step 1 of the water planning process is to determine expected population growth and water supply needed by that population. The most recent State Water

Plan released in 2012 envisions that nearly a quarter of Texas' future water needs will be met by conservation. If water reuse is added to the equation, the percentage is even greater. Surface water rights, granted by the state, may be bought and sold or retired to protect environmental flows. In the Edwards Aquifer region of Texas, agricultural irrigators may voluntarily elect to suspend irrigation during dry seasons and be compensated monetarily as a means to protect spring flows upon which endangered species depend. Since water plans are developed every 5 years, they may be adjusted to incorporate more up-to-date information and better strategies for meeting water needs.

14.5 CONCLUSION

Various water-sustainability scenarios are seen on every continent. Youth education and pragmatic, economic applications are particularly effective yet local conservation efforts will have limited success if each drop saved supports only human needs. Ecosystem needs must also be a part of the equation. Population growth and associated agricultural and industrial needs are already increasing at a rate that may exceed affordable freshwater supplies despite new technologies. Equally, human sustainability in our closed-loop Earth is directly linked to ecosystem sustainability. All food, fuel, oxygen, and any other human material good is at its origins a product of the planet. Thus, the choice is not between sustainable development and nonsustainable development, the choice is between a long-term, thriving population and a reduced population.

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15 Optimum, Sustainable, and Integrated Water Management

Tapas K. Das

CONTENTS

15.1 WHAT IS WATER SUSTAINABILITY?

Water sustainability means that we take care of our water and water systems to meet our current needs in ways that ensure that an adequate quantity of good quality water is available and accessible for future generations. It is based on the concept that an economy can only exist in the context of a society and, in turn, a society exists within an environment that both supplies resources and provides an acceptable place to live and work and play. The key elements of sustainability include the following:

Resilience: Ensuring that our natural water systems (watersheds, groundwater, lakes, rivers, and wetlands) and the systems we have built to manage, clean, and deliver water are able to tolerate disturbance, restore balance, and adapt to change.

Equity: Ensuring that ecological needs and human needs are both met so that all systems can thrive without impairing the ability of future generations to enjoy the same opportunities and benefits.

Affordability: Ensuring that water is available at an affordable cost to meet the needs of individuals while supporting healthy communities and vibrant economies.

Stewardship: Promoting the use and management of water by individuals, communities, businesses, and organizations in a manner that protects the quality and resilience of our water and water systems for the long term.

Sustainability is about ensuring that water and sanitation services continue to work over time. It is about developing the skills of communities, governments, and local service providers to manage finance and maintain services, and it is also about creating permanent changes in hygiene practices through hygiene promotion programs.

Water and sanitation services are under threat when there is insufficient money and skill available to maintain them on an ongoing basis. In addition, climate variability, climate change, disasters, and increasing pressure on water and land resources from growing populations, all affect the sustainability of water and sanitation services.

First, sustainability means selecting the right technology for the local situation. There is no point, for example, in installing a water pump in a remote rural village if the pump requires lots of spare parts that are only produced in another country and are expensive to buy. As soon as something breaks, it is likely to fall into disrepair.

To ensure that the most appropriate technology is used, we work with local partners and local people to carry out an assessment of the area and then agree on the best ways to meet the water and sanitation needs of the community. We also make sure we build the skills and capability of local governments, service providers, and our local partners so they can carry on the work in the longer term.

Second, it means involving local communities every step of the way—from project planning right through to training and maintenance. If the local people who are going to use the new facilities are not involved, they are less likely to feel ownership of the project and the chances of failure are much higher.

This is also true when a project is aiming for "behavior change"—for example, to stop people defecating in the open. If everyone is to change their behavior permanently, the whole community has to understand the benefits and support the process from the start.

Finally, improving the sustainability of water and sanitation services is about making solutions more effective through development and innovation. We are exploring new ways of working, such as focusing on ways to improve surface water storage. Basic technologies, such as sand dams and rainwater harvesting, for example, can help ensure that when it does rain, more water is stored in a safe way for drinking later.

15.1.1 SUSTAINABLE SUPPLY OF CLEAN WATER AND THE SOLUTIONS

Billions of people around the world are facing shortages of clean water. At least 80 countries already have water shortages that threaten human health and economic activity. Almost 1 billion people lack reliable access to clean drinking water, and the situation may worsen with population growth and global climate change.

15.2 SUSTAINABILITY

15.2.1 What Is Sustainability?

The traditional definition of sustainability calls for policies and strategies that meet society's present economic, social, and environmental needs without compromising the ability of future generations to meet their own needs.

In ecology, sustainability is how biological systems remain diverse and productive. Long-lived and healthy wetlands and forests are examples of sustainable biological systems. In more general terms, sustainability is the endurance of systems and processes. The organizing principle for sustainability is sustainable development, which includes the following four interconnected domains: ecology, economics, politics, and culture. Sustainability science is the study of sustainable development and environmental science.

Healthy ecosystems and environments are necessary to the survival of humans and other organisms. Ways of reducing negative human impact are environmentally friendly chemical engineering, environmental resources management, and environmental protection. Information is gained from green chemistry, earth science, environmental science, and conservation biology. Ecological economics studies the fields of academic research that aim to address human economies and natural ecosystems.

Moving toward sustainability is also a social challenge that entails international and national law, urban planning and transport, local and individual lifestyles, and ethical consumerism. Ways of living more sustainably can take many forms, from reorganizing living conditions (e.g., ecovillages, eco-municipalities, and sustainable cities), reappraising economic sectors (permaculture, green building, sustainable agriculture), or work practices (sustainable architecture), using science to develop new technologies (green technologies, renewable energy, and sustainable fission and fusion power), to adjustments in individual lifestyles that conserve natural resources.

Despite the increased popularity of the use of the term *sustainability*, the possibility that human societies will achieve environmental sustainability has been, and continues to be, questioned—in light of environmental degradation, climate change, overconsumption, and societies' pursuit of indefinite economic growth in a closed system.

15.2.2 Three Pillars of Sustainability

A diagram is shown in Figure 15.1 indicating the relationship between the "three pillars of sustainability," in which both economy and society are constrained by environmental limits.

Sustainable development consists of balancing local and global efforts to meet basic human needs without destroying or degrading the natural environment. The question then becomes how to represent the relationship between those needs and the environment.

A study from 2005 pointed out that environmental justice is as important as is sustainable development. Ecological economist Herman Daly asked, "what use is a sawmill without a forest?" From this perspective, the economy is a subsystem of human society, which is itself a subsystem of the biosphere, and a gain in one sector

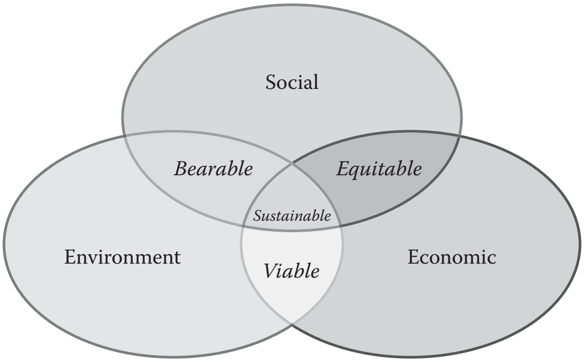


FIGURE 15.1 Three pillars of sustainability.

is a loss from another. This perspective led to the nested circles figure of "economics" inside "society" inside the "environment."

The simple definition that sustainability is something that improves "the quality of human life while living within the carrying capacity of supporting eco-systems," though vague, conveys the idea of sustainability having quantifiable limits. But sustainability is also a call to action, a task in progress or "journey" and therefore a political process, so some definitions set out common goals and values. The Earth Charter (2000) speaks of "a sustainable global society founded on respect for nature, universal human rights, economic justice, and a culture of peace." This suggested a more complex figure of sustainability, which included the importance of the domain of "politics."

More than that, sustainability implies responsible and proactive decision making and innovation that minimizes negative impact and maintains balance between ecological resilience, economic prosperity, political justice, and cultural vibrancy to ensure a desirable planet for all species now and in the future. Specific types of sustainability include sustainable agriculture, sustainable architecture, or ecological economics (Costanza and Patten 1995; Liam et al. 2013). Understanding sustainable development is important, but without clear targets, it is an unfocused term like *liberty* or *justice*. It has also been described as a "dialogue of values that challenge the sociology of development" (Blewitt 2008; Ratner 2004).

15.2.3 SOCIAL SUSTAINABILITY

Sustainability issues are being expressed in scientific, environment, economic, and business terms, as well as in ethical terms of stewardship, but implementing change is a social challenge that entails, among other things, national and international law, urban planning and transport, local and individual lifestyles, and ethical consumerisms. The relationships between human rights and human development, between corporate power and environmental justice, and between global poverty and citizen action suggest that responsible global citizenship is an inescapable element of what may at first glance seem to be simply a matter of personal consumer and moral choice (Blewitt 2008).

According to the Western Australia Council of Social Services (Sen 2000):

> Social sustainability occurs when the formal and informal processes; systems; structures; and relationships actively support the capacity of current and future generations to create healthy and livable communities. Socially sustainable communities are equitable, diverse, connected and democratic and provide a good quality of life.

It has the following dimensions (Anand and Sen 1996):

- **Equity**—the community provides equitable opportunities and outcomes for all its members, particularly the poorest and most vulnerable members of the community.
- **Diversity**—the community promotes and encourages diversity.
- **Interconnected/Social cohesions**—the community provides processes, systems, and structures that promote connectedness within and outside the community at the formal, informal, and institutional level.
- **Quality of life**—the community ensures that basic needs are met and fosters a good quality of life for all members at the individual, group, and community level (e.g., health, housing, education, employment, and safety).
- **Democracy and governance**—the community provides democratic processes and open and accountable governance structures.
- **Maturity**—the individual accepts the responsibility of consistent growth and improvement through broader social attributes (e.g., communication styles, behavioral patterns, indirect education, and philosophical explorations).

Figure 15.2 portrays the major pathways in building sustainable development in an emerging green economy in which the social sustainability is one of the essential components, along with economical, ethical, environmental, efficient, and equitable sustainability.

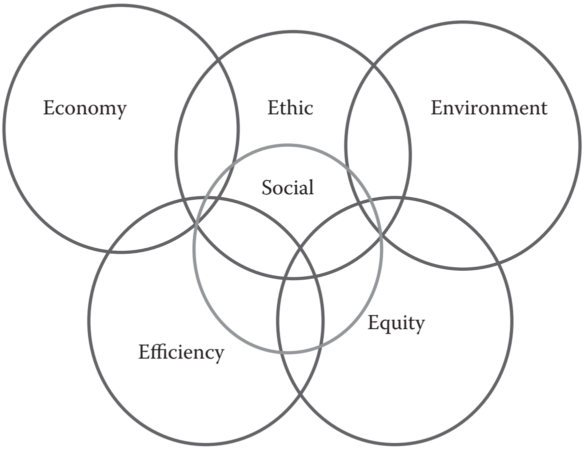


FIGURE 15.2 Major pathways in building sustainable development.

15.3 WATER RESOURCES

Water resources are sources of water that are useful or potentially useful. Uses of water include agricultural, industrial, household, recreational, and environmental activities. The majority of human uses require freshwater.

Ninety-seven percent of the water on Earth is saltwater and only 3% is freshwater; slightly more than two-thirds of this is frozen in glaciers and polar ice caps. The remaining unfrozen freshwater is found mainly as groundwater, with only a small fraction present aboveground or in the air.

Freshwater is a renewable resource, yet the world's supply of groundwater is steadily decreasing, with depletion occurring most prominently in Asia and North America, although it is still unclear how much natural renewal balances this usage, and whether ecosystems are threatened. The framework for allocating water resources to water users (where such a framework exists) is known as water rights.

15.3.1 FRESHWATER AND OCEANS

Water covers 71% of the Earth's surface. Of this, 97.5% is the salty water of the oceans and only 2.5% is freshwater, most of which is locked up in the Antarctic ice sheet. The remaining freshwater is found in glaciers, lakes, rivers, wetlands, the soil, aquifers, and atmosphere (Figure 15.3). Because of the water cycle, freshwater supply is continually replenished by precipitation; however, there is still a limited amount necessitating management of this resource. Awareness of the global importance of preserving water for ecosystem services has only recently emerged as, during the 20th century, more than half the world's wetlands have been lost along with their valuable environmental services. Increasing urbanization pollutes clean water supplies and much of the world still does not have access to clean, safe water. Greater emphasis is now being placed on the improved management of blue (harvestable) and green (soil water available for plant use) water, and this applies at all scales of water management.

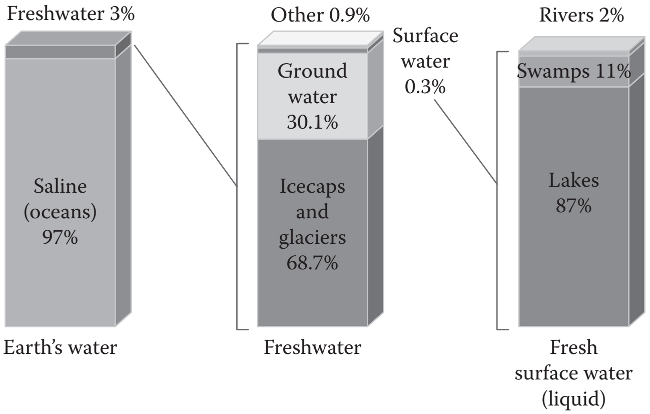


FIGURE 15.3 Distribution of Earth's water.

Ocean circulation patterns have a strong influence on climate and weather and, in turn, the food supply of both humans and other organisms. Scientists have warned of the possibility, under the influence of climate change, of a sudden alteration in circulation patterns of ocean currents that could drastically alter the climate in some regions of the globe. Ten percent of the world's population—approximately 600 million people—live in low-lying areas vulnerable to sea level rise.

Water security and food security are inextricably linked. In the decade 1951–1960, human water withdrawals were four times greater than the previous decade. This rapid increase resulted from scientific and technological developments affecting through the economy—especially the increase in irrigated land, growth in industrial and power sectors, and intensive dam construction on all continents. This altered the water cycle of rivers and lakes, affected their water quality, and had a significant impact on the global water cycle. Currently, toward 35% of human water use is unsustainable, drawing on diminishing aquifers and reducing the flows of major rivers: this percentage is likely to increase if climate change impacts become more severe, populations increase, aquifers become progressively depleted, and supplies become polluted and unsanitary. From 1961 to 2001, water demand doubled—agricultural use increased by 75%, industrial use by more than 200%, and domestic use by more than 400%. In the 1990s, it was estimated that humans were using 40%–50% of the globally available freshwater in the approximate proportion of 70% for agriculture, 22% for industry, and 8% for domestic purposes with total use progressively increasing.

Water efficiency is being improved on a global scale by increased demand management, improved infrastructure, improved water productivity of agriculture, minimizing the water intensity (embodied water) of goods and services, addressing shortages in the nonindustrialized world, concentrating food production in areas of high productivity, and planning for climate change. At the local level, people are becoming more self-sufficient by harvesting rainwater and reducing use of mains water (Hoekstra 2006; Hoekstra and Chapagain 2007; Shiklomanov 1998).

15.4 WATER–ENERGY NEXUS

Present-day water and energy systems are tightly intertwined. Water is used in all phases of energy production and electricity generation. Energy is required to extract, convey, and deliver water of appropriate quality for diverse human uses and then again to treat wastewaters prior to their return to the environment. Historically, interactions between energy and water have been considered on a regional or technology-by-technology basis. At the national and international levels, energy and water systems have been developed, managed, and regulated independently. Water and energy are critical, mutually dependent resources—the production of energy requires large volumes of water and water infrastructure requires large amounts of energy.

Water is required to generate energy: Thermoelectric cooling, hydropower, energy mineral extraction and mining, fuel production (including fossil fuels, biofuels, and other nonconventional fuels), and emission controls all rely on large amounts of water. In the United States, the thermoelectric generating industry is the largest withdrawal user of water. According to the United States Geological Survey, 349 billion gallons of freshwater were withdrawn per day in the United States in the year 2005. The largest use, thermoelectric, accounted for 41% of freshwater withdrawn at 143 billion gallons per day. However, freshwater consumption for thermoelectric purposes is low (only 3%) when compared to other use categories such as irrigation, which was responsible for 81% of water consumed.

- **Water withdrawal**: The total volume removed from a water source such as a lake or river. Often, a large portion of this water is returned to the source and is available to be used again.
- **Water consumption**: The amount of water removed for use and not returned to its source.

Water supply also requires energy use. A large amount of energy is needed to extract, convey, treat, and deliver potable water. Additionally, energy is required to collect, treat, and dispose of wastewater. In 2010, the US water system consumed more than 600 billion kWh, or approximately 12.6% of the nation's energy according to a study by researchers at the University of Texas at Austin. The study found that water systems use about 25% more energy than is used for residential or commercial lighting in the United States.

Water and energy are both multifaceted issues with many variables affecting their supply, demand, and management. Lawmakers should consider the following variables, which add complexity to the management of water and energy:

- **Growing population**: According to a 2012 United States Census Bureau projection, the US population could reach 400 million people by 2051. Population growth affects energy use through increases in housing, commercial floor space, transportation, and economic activity. The US Energy Information Administration estimates that total electricity consumption will grow from 3841 billion kWh in 2011 to 4930 billion kWh in 2040, an average annual rate of 0.9%. With a higher generating capacity, the United States will require additional water withdrawals.
- **Agriculture**: Feeding a growing population may require greater agricultural water use. Agriculture accounts for approximately 37% of total freshwater withdrawals in the United States, and 81% of water consumption.
- **Geographical water demand**: Water supply and demand are not geographically linked. From 1990 to 2010, the second largest regional population growth, 13.8%, occurred in the West, which is one of the most water-deficient regions in the United States. Additionally, water consumption in the western United States is much higher than that in other regions because of agricultural demands. It is estimated that it takes more than 1 million gallons of water a year to irrigate 1 acre of farmland in arid conditions. In other words, approximately 86% of irrigation water withdrawals were in western states in 2000.

- **Climate change**: Climate change could affect water supply and electricity use. Warmer or colder weather patterns could result in increases or decreases in energy use. Changes in precipitation in a region could increase or decrease the ability to store water, agricultural production and water use, and overall water supply.

States are beginning to assess their energy options and promote policies that allocate financial support to a diverse range of technologies to encourage responsible, sustainable energy production. States are also becoming aware of the limitations to accessible water, and as our energy demands grow, competition for water among municipalities, farmers, industrial, and power suppliers will increase. Water and energy are linked at both the supply side (electric generation and water/wastewater facilities) and the end-use side (residential, commercial, industrial, and agriculture sectors) (Figure 15.4). In order to sustain energy production and a dependable water supply, the United States must gain a detailed understanding of the interdependencies of water and energy systems and balance the needs of all users. State lawmakers and constituents will be critical in this process given their responsibility formulating policy, convening stakeholders, facilitating negotiations, and ratifying reached agreements.

Flows of energy and water are intrinsically interconnected, in large part owing to the characteristics and properties of water that make it so useful for producing energy and the energy requirements to treat and distribute water for human use. This

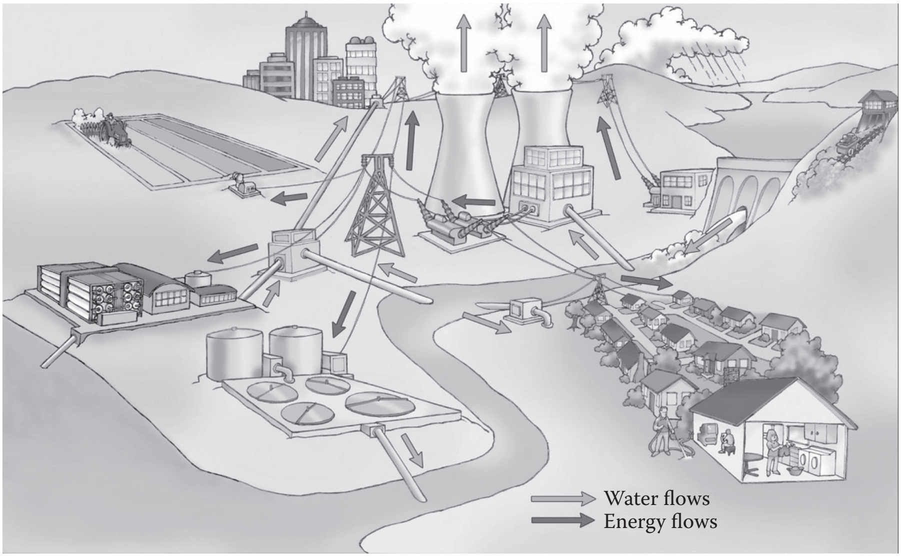


FIGURE 15.4 Examples of interrelationships between water and energy (US DOE 2014). (Adapted from *Energy Demands on Water Resources*. U.S. DOE Report to Congress on the interdependency of energy and water.)

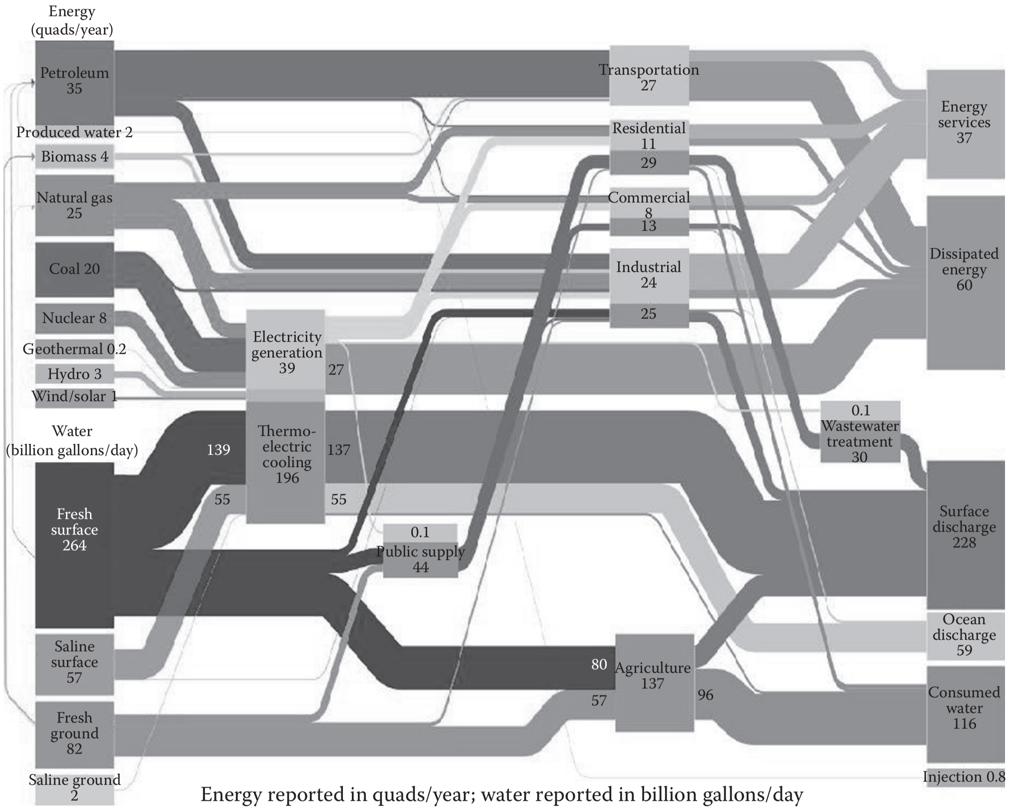
interconnectivity is illustrated in the Sankey diagram in Figure 15.5, which captures the magnitude of energy and water flows in the United States on a national scale. As shown in the diagram, thermoelectric power generation withdraws large quantities of water for cooling and dissipates tremendous quantities of primary energy attributed to inefficiencies in converting thermal energy to electricity. The intensity of water use and energy dissipated varies with generation and cooling technology.

As the largest single consumer of water, agriculture competes directly with the energy sector for water resources. However, agriculture also contributes indirectly to the energy sector via production of biofuels. Both connections will be strained by increasing concerns over water availability and quality. In addition, water treatment and distribution for drinking water supply and municipal wastewater also require energy.

Significant aspects of water and energy flows do not appear in Figure 15.5. First, flows will change over time, and anticipated changes in flows are important to consider when prioritizing investment in technology and other solutions. Increased deployment of some energy technologies in the future, such as carbon capture and sequestration, could lead to increases in the energy system's water intensity, whereas deployment of other technologies, such as wind and solar photovoltaics could lower it. In addition, there is significant regional variability in the water and energy systems, their interactions, and resulting vulnerabilities. For example, producing oil and natural gas through horizontal drilling and hydraulic fracturing has the potential for localized water quantity and quality impacts that can be mitigated through fluid life cycle management. Large volumes of water produced from oil and gas operations in general present both localized management challenges and potential opportunities for beneficial reuse. The energy requirements for water systems also have regional variability, based on the quality of water sources and pumping needs.

Water availability will affect the future of the water–energy nexus. While there is significant uncertainty regarding the magnitude of effects, water availability and predictability may be altered by changing temperatures, shifting precipitation patterns, increasing variability, and more extreme weather. Shifts in precipitation and temperature patterns—including changes in snowmelt—will likely lead to more regional variation in water availability for hydropower, biofeedstock production, thermoelectric generation, and other energy needs. Rising temperatures have the potential to increase the demand for electricity for cooling and decrease the efficiency of thermoelectric generation, as well as increase water consumption for agricultural crops and domestic use. These changes and variations pose challenges for energy infrastructure resilience.

Water and energy needs will also be shaped by population growth and migration patterns, as well as changes in fuels used and energy technologies deployed. For example, projected population growth in the arid Southwest will amplify pressure on water and energy systems in that region. Increased production of oil and gas may increase both localized demand for water and generation of produced water that requires management. According to Energy Information Administration data, planned retirements and additions of electricity generation units and cooling systems will likely decrease water withdrawals, increase water consumption, and increase the diversity of water sources used. While many of the forces affecting the water–energy nexus are out of the federal government's direct control, the future of the



Energy reported in quads/year; water reported in billion gallons/day

FIGURE 15.5 Hybrid Sankey diagram of 2011 US interconnected water and energy flows. (From DOE (U.S. Department of Energy) (2014). The Water–Energy Nexus: Challenges and Opportunities. June 2014.)

nexus hinges on a number of factors that are within the DOE's scope of influence, including technology options, location of energy activities, and energy mix.

The decision-making landscape for the nexus is shaped by political, regulatory, economic, environmental, and social factors, as well as available technologies. The landscape is fragmented, complex, and changing; the incentive structures are overlapping but not necessarily consistent. Water is inherently a multijurisdictional management issue and is primarily a state and local responsibility. States and localities vary in philosophies regarding water rights. There is also variation across states in relevant energy policies, including renewable portfolio standards, regulation of oil and gas development activities, and regulation of thermoelectric water intake and discharge. Regulations for both oil and gas development and thermoelectric water use are currently undergoing substantial change. Energy for water is also the subject of policy activity at multiple scales, from appliance standards to municipal water treatment funding mechanisms. A more integrated approach to the interconnected energy and water challenges could stimulate the development and deployment of solutions that address objectives in both domains (Table 15.1; AGU 2012; Clark and Veil 2009; DOE 2013a,b; EPRI 2011).

TABLE 15.1
Comparison of the Water Withdrawal and Water Consumption Factors (in Gallons per MWh) for Fuel-Based Electricity Generating Technologies

Fuel Type	Cooling	Technology	Median Withdrawal	Median Consumption
Nuclear	Tower	Generic	1101	672
	Once-through	Generic	44,350	269
	Pond	Generic	7050	610
Natural gas	Tower	Combined cycle	225	205
		Steam	1203	826
		Combined cycle with CCS	506	393
	Once-through	Combined cycle	11,380	100
		Steam	35,000	240
	Pond	Combined cycle	5950	240
	Dry	Combined cycle	2	2
Coal	Tower	Generic	1005	687
		Supercritical	634	493
		IGCC	393	380
		Supercritical with CCS	1147	846
		IGCC with CCS	642	549
	Once-through	Generic	36,350	250
		Supercritical	15,046	103
	Pond	Generic	12,225	545
		Supercritical	15,046	42
Biopower	Tower	Steam	878	553

Source: National Renewable Energy Laboratory (NREL). (2011). A review of operational water consumption and withdrawal factors for electricity generating technologies.

15.4.1 TECHNOLOGY ROADMAPS AND R&D

There are a number of technologies that support water-efficient energy systems or energy-efficient water systems. These technologies are at various stages of research, development, demonstration, and deployment. Figure 15.6 illustrates a range of technologies optimizing water use for energy in waste heat recovery, cooling, alternate fluids, and process water efficiency.

Cooling for thermoelectric generation is an important target for water efficiency because it withdraws large quantities of water for cooling and dissipates tremendous amounts of primary energy. One approach to reduce thermoelectric and other cooling requirements, along with associated water use, is to reduce the generation of waste heat through more efficient power cycles (e.g., the recompression closed-loop Brayton cycle). Another option is to increase the productive use of the waste heat, such as through thermoelectric materials, enhancements in heat exchanger technologies, or low-temperature coproduced geothermal power. A third approach to improve the water efficiency of cooling systems is through advancements in technologies, including air flow designs, water recovery systems, hybrid or dry cooling, and treatment of water from blowdown.

Opportunities to optimize water use also exist in other parts of the overall energy system. With further research, alternative fluids may replace freshwater in hydraulic fracturing, geothermal operations, and power cycles. Process freshwater efficiency

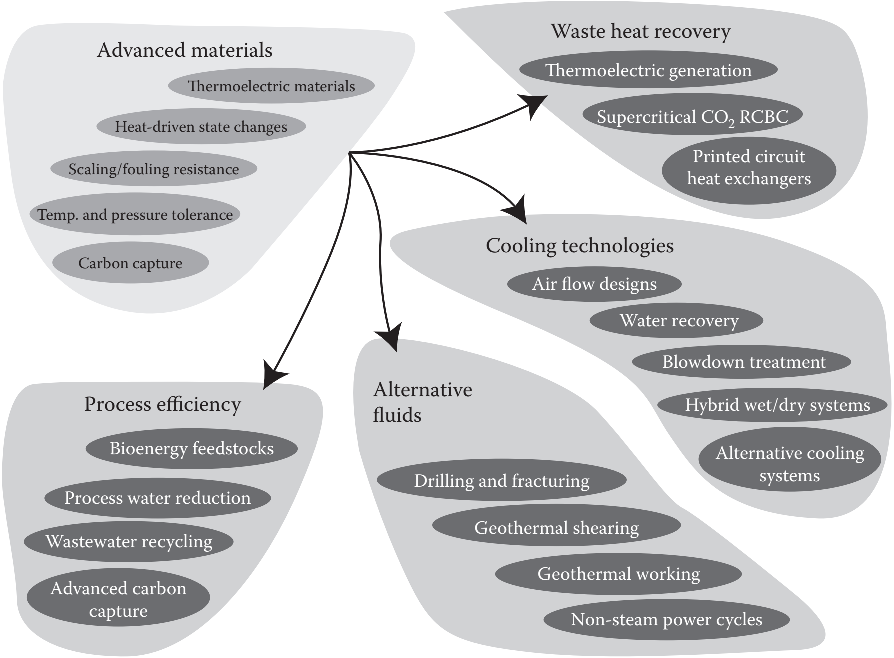


FIGURE 15.6 Representative problem/opportunity spaces in water for energy. (From DOE (U.S. Department of Energy) (2014). The Water–Energy Nexus: Challenges and Opportunities. June 2014.)

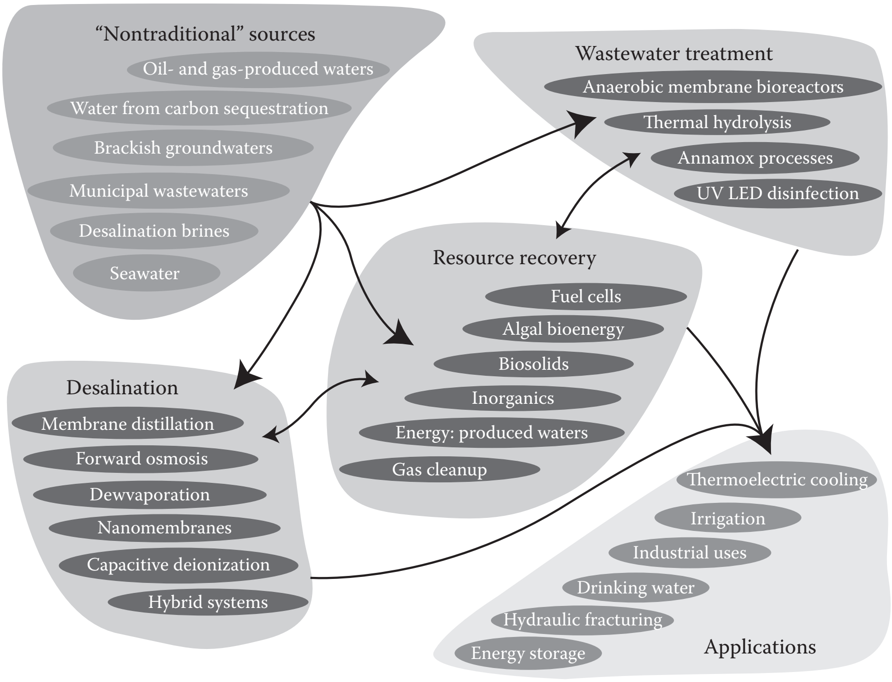


FIGURE 15.7 Representative problem/opportunity spaces in energy for and from water. (From DOE (U.S. Department of Energy) (2014). The Water–Energy Nexus: Challenges and Opportunities. June 2014.)

can be improved in carbon capture, bioenergy feedstock production, and industrial processes. Many of the technologies that improve water efficiency are enhanced by advances in materials, including thermoelectric properties, heat-driven state change, scaling/fouling resistance, and temperature and pressure tolerance.

Figure 15.7 shows water treatment technologies that can potentially enhance energy efficiency of water systems and enable the productive, economical, and safe use of nontraditional water resources for energy and nonenergy applications. Such improvements in water treatment and management have particular use for treating oil- and gas-produced waters, as well as saline aquifers, brackish groundwater, brines, seawater, and municipal wastewater. For saline sources, promising water treatment technologies include membrane distillation, forward osmosis, dewvaporation, nanomembranes, and capacitive deionization. For municipal wastewater, treatment technologies include anammox systems, anaerobic pretreatments, and anaerobic membrane bioreactors. In addition, the biosolids contained in wastewater can be a source of methane energy.

15.5 LIFE CYCLE ASSESSMENT AS APPLIED TO WATER RECLAMATION AND REUSE

The increasing scarcity of water coupled with the escalating cost of freshwater and its treatment has prompted industry to think of water conservation, reuse, and recycling. Incorporating advanced technologies such as reverse osmosis, nanofiltration, and so on would result in reclamation and reuse of water and less environmental damage, but to what degree, and with what trade-offs? To answer these questions, this chapter will present a number of life cycle assessments (LCAs) on industrial and municipal wastewater systems, with a focus on short-term or long-term effects and benefits of reusing and recycling waters on economics (life cycle cost), energy, public health, environment, and water ecology. Some streamlined LCA case studies will be presented on water reuse/recycling practices in pulp and paper, food processing, pharmaceutical, power generating industries, ultraviolet disinfection for wastewater reuse, agricultural and land applications of reclaimed water, and water augmentation to creeks and rivers during summer low flow (Das 2005a,b, 2015).

Life cycle cost analyses were performed for the tertiary treatment systems studied experimentally and for several other treatment options. A public domain conceptual costing tool (LC^3 model) was developed for this purpose. Municipal wastewater (MWW) sand filtration (lime softening and sand filtration) and MWW nanofiltration were the most cost-effective treatment options among the tertiary treatment alternatives considered because of the higher effluent quality with moderate infrastructure costs and the relatively low doses of conditioning chemicals required (Dzombak 2013).

15.6 OPTIMUM, SUSTAINABLE, AND INTEGRATED WATER RESOURCES MANAGEMENT

Water is a key driver of economic and social development while it also has a basic function in maintaining the integrity of the natural environment. However, water is only one of a number of vital natural resources and it is imperative that water issues are not considered in isolation.

Managers, whether in the government or private sectors, have to make difficult decisions on water allocation. More and more they have to apportion diminishing supplies between ever-increasing demands. Drivers such as demographic and climatic changes further increase the stress on water resources. The traditional fragmented approach is no longer viable and a more holistic approach to water management is essential.

This is the rationale for the Optimum, Sustainable, Integrated Water Management (OSIWM) approach that has now been accepted internationally as the way forward for efficient, equitable, and sustainable development and management of the world's limited water resources and for coping with conflicting demands. OSIWM is a process that promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

There are great differences in water availability from region to region—from the extremes of deserts to tropical forests. In addition, there is variability of supply through time as a result of both seasonal variation and interannual variation. All too often, the magnitude of variability and the timing and duration of periods of high and low supply are not predictable; this equates to unreliability of the resource, which poses great challenges to water managers in particular and to societies as a whole. Most developed countries have, in large measure, artificially overcome natural variability by supply-side infrastructure to assure reliable supply and reduce risks, albeit at high cost and often with negative impacts on the environment and sometimes on human health and livelihoods. Many less developed countries, and some developed countries, are now finding that supply-side solutions alone are not adequate to address the ever-increasing demands from demographic, economic, and climatic pressures; wastewater treatment, water recycling, and demand management measures are being introduced to counter the challenges of inadequate supply (OSIWM).

In addition to problems of water quantity, there are also problems of water quality. Pollution of water sources is posing major problems for water users as well as for maintaining natural ecosystems.

In many regions, the availability of water in both quantity and quality is being severely affected by climate variability and climate change, with more or less precipitation in different regions and more extreme weather events. In many regions, too, demand is increasing as a result of population growth and other demographic changes (in particular urbanization) and agricultural and industrial expansion following changes in consumption and production patterns. As a result, some regions are now in a perpetual state of demand outstripping supply, and in many more regions, that is the case at critical times of the year or in years of low water availability.

15.6.1 IMPLEMENTATION

Operationally, integrated water resources management (IWRM) approaches involve applying knowledge from various disciplines as well as the insights from diverse stakeholders to devise and implement efficient, equitable, and sustainable solutions to water and development problems. As such, IWRM is a comprehensive, participatory planning and implementation tool for managing and developing water resources in a way that balances social and economic needs and that ensures the protection of ecosystems for future generations. Water's many different uses—for agriculture, for healthy ecosystems, for people and livelihoods—demand coordinated action. An IWRM approach is consequently cross-sectoral, aiming to be an open, flexible process, and bringing all stakeholders to the table to set policy and make sound, balanced decisions in response to specific water challenges faced. An IWRM approach focuses on three basic pillars and explicitly aims at avoiding a fragmented approach of water resources management by considering the following aspects:

1. Through an Enabling Environment: A proper enabling environment is essential to both ensure the rights and assets of all stakeholders (individuals as well as public and private sector organizations and companies) and also to protect public assets such as intrinsic environmental values.
2. Through the Roles of Institutions: Institutional development is critical to the formulation and implementation of IWRM policies and programs. Failure to match responsibilities, authority, and capacities for action are all major sources of difficulty with implementing IWRM.
3. Through Management Instruments: The management instruments for IWRM are the tools and methods that enable and help decision-makers to make rational and informed choices between alternative actions.

Some of the cross-cutting conditions that are also important to consider when implementing IWRM are as follows:

- Political will and commitment
- Capacity development
- Adequate investment, financial stability, and sustainable cost recovery
- Comprehensive monitoring and evaluation

IWRM should be viewed as a process and not as a one-shot approach—one that is long term and forward moving but iterative rather than linear in nature. As a process of change that seeks to shift water development and management systems from their currently unsustainable forms, IWRM has no fixed beginnings or endings. Furthermore, there is not one correct administrative model. The art of IWRM lies in selecting, adjusting, and applying the right mix of these tools for a given situation (Biswas et al. 2005; Rahaman and Varis 2005; Rahaman et al. 2004).

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