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Sediment Dynamics upon Dam Removal

ASCE

EWRI ENVIRONMENTAL & WATER RESOURCES INSTITUTE

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Sediment Dynamics upon Dam Removal

Prepared by
the Task Committee on Sediment Dynamics Post-Dam Removal of
the Environmental and Water Resources Institute of
the American Society of Civil Engineers

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PREFACE

With the growing concern over adverse environmental impacts of dams on ecosystems and fish populations, the number of dam removals is rapidly increasing. Questions regarding sediment behavior and overall stream geomorphology when a dam is removed have thus come to the fore. It has therefore become essential that guidance and documentation of experience in dam removal be made available to the river management and engineering community. This manual contains several chapters covering numerical and physical modeling and field experience regarding dam removal and its modeling, and is intended to be of use to watershed and river agencies and their consultants as well as researchers in their continued efforts to enable people to live in a healthy balance within their environments.

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CONTENTS

PART I: SUMMARY AND REVIEW

CHAPTER 1

SEDIMENT DYNAMICS POST-DAM REMOVAL: STATE OF THE SCIENCE AND PRACTICE

Athanasios (Thanos) N. Papanicolaou, Brian D. Barkdoll, Laura Wildman, Cassie C. Klumpp, Blair Greimann, James G. MacBroom, and Mohamed Elhakeem

1.1 PROBLEM STATEMENT

There are more than 80,000 dams listed in the U.S. Army Corps of Engineers (USACE) National Inventory of Dams (NID) database. However, the NID limits its listings to dams with the following characteristics: (1) dams that are greater than 1.8 m (6 ft) in height with a storage volume greater than 61,700 m^3 (50 acre-ft); (2) dams that are greater than 7.5 m (25 ft) in height with a storage volume greater than 18,500 m^3 (15 acre-ft); and (3) dams of any size that can "pose significant threat to human lives or property." There are roughly 2 million dams estimated by the National Research Council (NRC 1992) that are not listed in the NID.

Dams were once considered long-term, permanent landscape structures (or, interchangeably, infrastructure) that provide for water supply, irrigation, flood control, hydropower generation, pollution control, navigation, or recreation (ASDSO 2005). Dams were once seen as sources of clean energy that did not require the burning of coal and, therefore, negated "raping" of the land through strip mining and the production of acid rain. In addition, dams helped make possible the migration of new settlers in the western part of the United States. In North America, 3,123 dams were completed in 1960, the greatest number of dams completed in one year (WWF 2009) and more than 200 major dams were completed each year between 1962 and 1968 (Beaumont 1978).

However, dams have also changed the ecology of thousands of rivers, disrupted native populations of fish and wildlife, and adversely affected

A B

Figure 1-1. Dam removal. (A) Smelt Hill Dam removal in 2002, Presumpscot River, Maine (photo courtesy of Friends of the Presumpscot River); (B) Embrey Dam removal in 2006, the Rappahannock River, Virginia (photo courtesy of the U.S. Dept. of Defense, Integration and Application Network, Image Library, http://ian.umces.edu/imagelibrary).

many local economies and communities (Babbitt 2002). Trade-offs between the dams' benefits and detrimental impacts have led to a reconsideration of the value of many dams in the nation. According to Hart et al. (2002), in the United States dam removal is "no longer considered a fringe radical approach for river restoration," especially when the operational costs and environmental impacts outweigh the benefits, or when the dam no longer serves any useful purpose. Over the past two decades there has been a clear shift toward the removal (or breaching) of structurally outdated, ecologically damaging dams from river systems (ASCE 1997). Such removals include not only small, obsolete dams (Fig. 1-1A), but also midsize and large dams such as Embrey Dam (Fig. 1-1B), which has caused great ecological damage to the Rappahannock River in Virginia (American Rivers 2002).

This struggle to balance the perceived needs of humans and those of wildlife and ecology have come to a head. The number of dams being built is declining (Fig. 1-2) (partly due to awareness of environmental effects and partly due to the lack of new appropriate dam sites), while the concurrent number of dams being removed is increasing exponentially. On average, ten dams were removed per year between 1940 and 1970, whereas the average number of dams removed per year in the 1980s and 1990s was 90 and 180, respectively (AR/FE/TU 1999). The number of dam removals, however, is still small compared to the number of dams built. If these trends continue, the number of dams removed each year will surpass the number of dams being built.

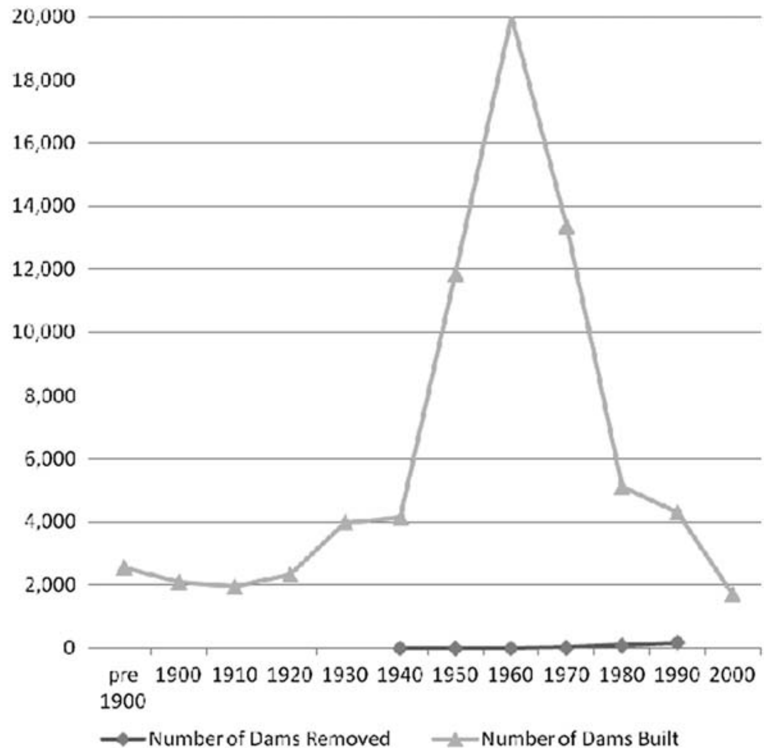

Figure 1-2. Dams removed in the United States. Source: AR/FE/TU (1999); Doyle et al. (2000); USACE (2009).

1.2 THE FUTURE OF DAM REMOVAL

Improved understanding and appreciation for the many societal values of healthy rivers and fisheries has increased the interest in dam removal as a means of river restoration (Aspen Institute 2002). Multiple factors motivate dam removal, including economic and social effects (AR/FE/TU 1999), but the primary reason for dam removal is to remediate the disruption of ecosystems and restore the functionality of rivers (Bednarek 2001). However, dam removal can have as significant effects on ecosystems at both reach and watershed scales as does dam construction. Also, this river restoration approach adds new challenges for watershed and riverine management to find nonstructural alternatives for water storage, flood mitigation, irrigation, and power generation. Although removal of small dams can be inexpensive and the assessment of the rivers' response to restoration can be relatively straightforward, decisions about removal of large dams are complex—due in no small part to the substantial time and costs associated with removing a large dam, and to great scientific uncertainty (or lack of site-specific knowledge) about the potential environmental impacts of the removal option (Wik 1995). Also, in most cases, many of these dams still serve their original, or perhaps somewhat modified, purposes.

To determine the most appropriate future for a dam, the positive and negative impacts resulting from its removal—from both short- and long-term perspectives—must be evaluated based on scientifically valid criteria. It is difficult to predict the many changes (biological, chemical, physical, spatial, and temporal) in post-dam-removal conditions, and this has implications for decisions about removal appropriateness and methodology (Babbitt 2002). More data on river responses to dam removal are required, including changes in hydrologic conditions due to the drastic shift in subsurface/surface flow stage caused by the reservoir removal; sediment releases and transport rates of mixed fine and coarse material upstream and downstream of the removed dam; degradation rates of reach habitat conditions for fish and other organisms through the altered reach of the river; and water quality trends during and after the removal.

More importantly, a scientific framework is needed for examining how rivers potentially respond to dam removal and altered watershed characteristics. This scientific basis, when established, can help in dam removal/retention decision making and can direct the local community to optimal use of funding (Heinz Center 2002). A first step toward the development of a science-based framework is the collection and documentation of studies and findings related to the impacts of dam removal, which is the goal of this manual.

An example of the development of such a framework is the integrative environmental assessment performed for the 2008 Chiloquim Dam removal on the Sprague River in southern Oregon. The dam was removed in order to expand the spawning habitat of endangered suckers in Upper Klamath Lake. The National Research Council (with support from the U.S. Bureau of Indian Affairs and the U.S. Fish and Wildlife Service) recommended the removal of the dam to potentially enhance the population of both the Lost River Sucker (*Deltistes luxatus*) and the Shortnose Sucker (*Chasmistes brevirostris*). Figure 1-3 demonstrates the site prior to and after the Chiloquim Dam removal. Extensive environmental assessments included documentation of land use changes; water quality (geomorphology, hydrology, and sediment transport); ecology; threatened and endangered species and critical habitats; archaeological and historic resources; air quality socioeconomics; public health and safety; aesthetics; noise; and traffic (Hay-Hoffert 2008).

Figure 1-3. Restoration of the Sprague River, Oregon, after the Chiloquim Dam removal. These two photographs were taken by a time-lapse camera that Tim Randle and Mike Neuman of the U.S. Bureau of Reclamation set up during the summer of 2008.

1.3 SCOPE

From past experience with dam construction, researchers have learned a great deal about the adverse effects dams have on river ecosystems. Also, considerable knowledge has been gained pertinent to the removal of dams, especially small ones. These experiences can collectively guide and improve fundamental knowledge regarding future dam removal, and can create opportunities for advancing the sciences of ecology, hydrology, and geomorphology. In recent years, many studies have been conducted in the field of dam removal and there is thus a definite need to disseminate reports on these research efforts and encourage the scientific community to evaluate the pertinent theories and practices. Some of the ecological impacts related to dam removal, mainly on fish and other aquatic species, were documented in a landmark issue of *BioScience*, which is published by the American Institute of Biological Sciences (AIBS) (AIBS 2002). In comparison, this manual primarily focuses on the geomorphologic impacts associated with dam removal, including the effects of sediment transport, aggradation, and degradation on the physical characteristics of rivers.

The organization of this manual is based on the different topics presented by the contributors and the feedback provided by the ASCE/EWRI Task Committee on Sediment Dynamics Post Dam Removal. In July 2005, this ASCE/EWRI Task Committee, led by Laura Wildman, Chair, Glastonbury, Connecticut; Cassie Klumpp, Vice Chair, Denver, Colorado; Blair Greimann, Secretary, Denver, Colorado; and James MacBroom, Committee Member, Cheshire, Connecticut, brought together many national experts, both in research and practice, on the specific topic of sediment dynamics post-dam removal. The authors represented federal agencies, universities, consulting firms, environmental nonprofit organizations, federal and academic research laboratories, as well as state agencies; they included engineers, geomorphologists, academic researchers, hydraulic/hydrologic modelers, model developers, ecologists, and fisheries biologists. The ultimate goal of the ASCE/EWRI Task Committee was a state-of-the-art publication including invited papers on dam removal compiled to a manual.

The papers were peer-reviewed and reflect the many and various regional and project-specific perspectives related to this topic. Subjects covered included physical models, numerical simulations, specific case studies, decision-making processes, individual dam issues, geomorphic changes, channel bed evolution, downstream sediment transport, ecological implications, lessons learned from case studies, and sediment quality. Further, these papers encompassed wide variety in sediment composition, hydrologic region, and project scale. This manual is a compilation of the most relevant and innovative papers on dam removal, and thus presents the many national ongoing efforts and the state-of-the-science/practice in the field of sedimentation as it relates to river dynamics post-dam removal.

1.4 KEY DAM REMOVAL SEDIMENT ISSUES ADDRESSED IN THE MANUAL

Streams and rivers collect and convey surface water runoff as well as varying amounts of sediment and dissolved materials. Riverine sediments consist of silt, clay, and sometimes sand suspended in the water column, plus bed load of coarse-grain material that is mobilized and rolled, dragged, or pushed along the river bed periodically, mostly during flood events. Many reservoirs have accumulated sediment deposits within their pools, ranging from thin, fine-grain bottom materials to massive deltas of coarse-grain bed material. In some cases, such as the Matilija and San Clemente dams in California, sediments have filled virtually the entire pool, leaving little usable water storage capacity.

Dam removal projects must address many sediment issues, ranging from estimating how much sediment may erode from the pool to the downstream channel and overbank deposition; flooding; poor water quality; burial of benthic species such as mussels; and long-term ecological impacts. Several large dams that have substantial quantities of sediment are being studied for possible removal, including Elwha, Glines Canyon, Matilija, and Savage Rapids (refer to Chapter 4, Bureau of Reclamation Case Studies of Dam Removal).

Direct observations of small dam removal projects and post-removal inspections have provided valuable information on channel erosion and sediment transport from reservoirs. Contrary to popular perception, many dams do not have significant deposits (Hart et al. 2002; also refer to Chapter 5, Channel Evolution Upstream of Dam Removal Sites). Some forested watersheds have low sediment yields; some dams are protected from sediment by upstream dams; and run-of-river dams may have low trap efficiency for some sediment sizes. Chapter 5 provides extensive observations based on small dam removals and lessons learned.

The behavior of sediment deposits at low-head dams has varied. In Chapter 3, Stream Ecosystem Response to Small Dam Removals, Doyle and Stanley report on uncontrolled Midwestern dam removal sites where post-dam channels developed similar to channel evolution models with classic headcutting in the upstream direction, followed by bank collapse and widening. They found that downstream sediment transport magnitude and timing were largely controlled by the rate of headcut migration in the upstream reservoir and what sediment deposits were accessed by the headcut. In Chapter 6, The Geomorphic Effects of Existing Dams and Historic Dam Removals in the U.S. Mid-Atlantic Region, Skalak, Pizzuto, Egan, and Allmendinger report their research on three dams in the mid-Atlantic that were removed 6, 31, and 70 years ago; the sediments of those dams were removed by vertical incision but the process was relatively slow, with a "half-life" in the range of a decade.

1.4.1 Forecasting the Effects of Dam Removal

Several techniques are currently being used to forecast sediment response at the removal of large dams and/or large sediment masses in the western United States. Sediment transport forecasting techniques include use of geomorphic channel evolution processes, conceptual models, physical models (e.g., flumes), and computer models. Analysis of sediment transport during and after the removal of a dam should reflect each project's unique conditions and be commensurate with the scope and scale of the individual project. Levels of analyses may vary with dam size, dam use, flood control capabilities, condition of the dam, type and size of the impoundment, quantity of impounded sediment, sediment chemical content, sediment grain size, environmental sensitivity, project budget, type of river system, and the level of controversy surrounding the project. Because there is no standard analysis that would apply to every dam removal project, there is considerable judgment is left to the project engineer to assess what level of analysis is needed. Erosion of sediments from a dam impoundment, and their downstream transport and deposition, is a complicated process that involves scientific uncertainty due to current technology limitations and limited availability of case studies.

1.4.2 Reservoir Sediment Deposits

The type and form of reservoir sediment deposits have been discussed extensively in the literature and are directly related to post-dam-removal erosion and channel evolution. The classic delta sediment model of deposits in large reservoirs, which has upstream coarse delta sediments at the influent rivers and fine-grain (bottomset) lakebed deposits extending toward the dam, is presented by Randle and Bountry in Chapter 10, Guidelines for Numerical Modeling of Dam Removals.

Sediment deposits in reservoirs may contain substantial barriers that interrupt channel evolution and expected sediment transport. Pre-removal field studies at South Batavia Dam in Illinois and Carbonton Dam in North Carolina found original construction cofferdams buried in sediment upstream of the dams, altering post-dam-removal flow and transport patterns. Dam removal studies and field investigations at the Veazie and Great Works dams in Maine, and Rocky Glen Dam in Connecticut, found portions of old full-scale, nineteenth-century dams abandoned and submerged in the pools created by the newer downstream dams (refer to Chapter 5).

Many exceptions and variations of the classic delta sediment model have been observed by Morris and Fan (1998) and are described by MacBroom in Chapter 5. Narrow impoundments with high longitudinal flow velocities have been observed to lack fine-grain bottomset deposits, while numerous run-of-river dams have bed load deposits forming a wedge against the back side of the dam. Some deltas extend for the width of the pool, while others form a long, central bar that splits inflow to both sides. Watersheds and rivers with minimal bed load may not have any delta. Thus, as a first approximation, the project engineer may determine the expected reservoir sedimentation based on the surrounding geology, the sequence of dams in the river, and the type and management history of the dam of interest. In humid climates, sediment deposits have been found to contain large trees and woody debris that reinforce the mass. At urban dams, cars, lumber, tires, oil drums, shopping carts, and mattresses are also found mixed with sediment deposits. Reservoir sediments often are non-uniform, with horizontal and vertical variations in grain size, density, and cohesion. Sediments may contain random cobbles or small boulders from hillside slides or ice. Sanitary sewer pipes, gas mains, or water mains may be buried in the post-dam sediments, under the sediments, or in adjacent river banks; these require protection or relocation.

In small reservoirs, sediments can be explored using manual probes or augers. In larger reservoirs, barge-mounted mechanical boring equipment is necessary to reach and penetrate deep and thick sediments. Recent studies have begun to develop other methods of combining coring, probing, and depth profiling to establish the quantity and texture of sediment deposits, and some of these methods allow rapid and economical methods of identifying sediment characteristics. Continuous samples are desirable to identify stratification and pre-dam bottom material. It is always desirable to locate the pre-dam channel and assess its natural substrate.

1.4.3 Sediment Quality Assessment and Management

The Massachusetts Assessment Model by Rathbun et al. (2005) helps to guide investigations of the extent and magnitude of contamination, including sample locations and number, sampling collection, laboratory tests, and desired quality criteria. Sediment assessment contributes to the decision process with regard to five potential management options:

1. Complete dam removal followed by natural erosion and deposition
2. Staged dam removal followed by natural erosion and deposition
3. Sediment containment or capping
4. Partial sediment removal of "hot spots"[1]
5. Full sediment removal

Final decisions on dam removal and sediment management are often influenced by individual and regional approaches. These philosophical approaches address habitat benefits versus risk, project risk and uncertainty, and cost risks. Sediment management-related risks include habitat impacts, flood increases, and duration of impacts. Removal of a dam should consider the potential impacts of sediment loads on downstream aquatic biota, although there can be substantial variability in impacts and ecological resistance to such disturbances (refer to Chapter 3). Also, local, state, and federal regulatory programs have a major influence on dam removal and sediment management decisions.

1.4.4 Sediment Erosion and Channel Evolution

In Chapter 3 Doyle and Stanley describe the observed erosion process at two Wisconsin dams and present a conceptual six-step model with vertical erosion followed by mass wasting of the banks and channel widening. In Chapter 10, Randle and Bountry describe how portions of eroded sediment may redeposit as a new delta farther downstream within a reservoir, and similar processes have been observed in flume studies, as reported by Bromley, Randle, Grant, and Thorne in Chapter 7.

[1] "Hot spots" are defined as areas that most affect water quality.

In Chapter 5, MacBroom reports on a wide variety of upstream channel evolution processes at small dam removal sites, and on channel formation during reservoir drawdowns and dam failures; he also comments on behavior of large glacial lakes. He describes a generalized channel evolution model that considers sediment gradation, presence of a thalweg, pool width, and type or extent of sediment deposits. It was found that some channels with erodible sandy sediments or steep gradients enlarge by vertical progressive bed erosion, while others advance by retrogressive headcuts. Observed channel patterns include straight single stems, meandering, braided, and anabranched. At Bunnels Pond Dam, the eroded channel changed alignment in sediments that were thinner than the bankfull water depth.

Bromley, Cantelli, and Wooster have developed a numerical model for the evolution of a channel during and after removal of a dam, which is presented in Chapter 2. The most important new feature of the model is that it captures a phenomenon they observed in experiments on dam removal: "erosional narrowing," a narrowing of a channel due to preferential erosion along the channel centerline and consequent flow restriction and spatial acceleration. The narrowing tendency is counterbalanced by the well-known tendency of a channel to widen due to bank erosion. The interplay of these two effects can lead to, among other things, upstream propagation of waves of incision and sedimentation. The onset of narrowing is sensitive to the rate of fall of baselevel, controlled in the dam-removal case by the rate of draining of the reservoir.

1.4.5 Sediment Stability and Transport Analysis

Analytical techniques are becoming increasingly useful for evaluating dam removals, ranging from simple allowable velocity and shear stress applications to advanced evaluation of unsteady flow and continuous simulation of sediment transport. Computer models are increasingly able to integrate the analysis of hydraulic flow and sediment transport using interactive loops to adjust the channel dimensions to obtain sediment equilibrium conditions. Some of the uncertainties of computer modeling include the armoring of the bed; the effects of bank vegetation, variable substrate layers, cohesive soils, and biochemical processes; and determining initial and optimum channel widths, meander patterns, and profile features such as pools and riffles (ASCE Task Committee 1997). Nevertheless, flow and sediment transport computer models can still be useful in answering complex project questions such as emerged in the Elwha Dam removal project in Washington State (U.S. Geological Survey 2006b).

1.4.6 Computer Analysis Examples

Continuous simulation computer models are being used to predict sediment transport at proposed large dam removal projects using mobile bed or mobile boundary analysis. The models presented here are all derived from traditional open-channel hydraulic and sediment transport models, and are now being applied to dam removal projects.

Predicting the sediment impacts is critical to ensure that the dam is removed in a safe, controlled manner and the downstream mitigation or protective measures can be appropriately designed. However, because of limited data and still-inadequate models, quantification of sediment impacts is subject to great uncertainty (refer to Chapter 9). None of the currently available models has been extensively field-verified with dam removal data. Consequently, it is essential that pending projects be carefully monitored and provide data for future model calibration

1.4.6.1 HEC-6T Model Examples. The computer program *Sedimentation in Stream Networks* (HEC-6T) is a proprietary program developed by Thomas and described in Chapter 11, Sedimentation Studies for Dam Removal Using HEC-6T. It is an updated version of the USACE program *Scour in Rivers and Reservoirs* (HEC-6), which Thomas also developed. HEC-6T contains features that facilitate the computation of sedimentation processes following the removal of a dam, and its application is illustrated in three proposed dam removal projects.

HEC-6T has several features that facilitate dam removal studies: erosion limits can be set separately from deposition limits in the cross section; special input concepts allow the width of the channel bed and the channel pattern (which are determined outside of the program) to be coded into the input data file; the program will fail the channel banks if bed erosion produces excessive heights; Bed roughness can be separated from bank roughness and computed using bed roughness equations; roughness can be modeled as a function of depth of water or depth of sediment deposits; the dam can be placed at an internal cross section in the model, and the computations will simulate processes both upstream and downstream in a continuous simulation; the entire dam can be removed instantly, or it can be removed in stages by notching; wash-off from the land surface can be coded as lateral inflows; and the model can contain a network of tributaries, enabling it to compute the flow distribution around islands, and the network can have two outlets.

HEC-6T is not an expert system. It is a generalized computer program that allows competent engineers and scientists to study a host of sediment problems. These studies can be for dam removal as well as for many other issues dealing with river systems.

"Back of the envelope" evaluations similar to those presented in this manual may be conducted for other dam removal projects prior to resource-intensive field data collections. The general methodology could be applied to other projects, but the parameters to be evaluated and degree of accuracy depend on the objectives of the project, the specific site characteristics, and existing field data. For different objectives it may be more appropriate to use a best-case scenario evaluation. For example, if the most pressing issue is suspended sediment concentration, and initial evaluation indicates that suspended sediment concentration will be high enough to cause unacceptable ecological consequences, it may be worthwhile to examine whether sufficient data exist to evaluate the suspended sediment concentration under a best-case scenario. Under such a best-case scenario assumption, parameters with considerable uncertainty would be chosen at values so as to minimize the likelihood of sediment suspension. If such an evaluation is possible and its results indicate that the suspended sediment level is indeed unacceptable even under the best-case scenario conditions, it would be safe to conclude that release of the sediment is not an option and different alternatives should be examined. If such a best-case-scenario evaluation cannot be conducted or its results indicate that there would not be a suspended sediment problem, more field data would need to be collected to reduce uncertainty so that a more accurate evaluation can be conducted.

1.4.6.2 Bureau of Reclamation Diffusive Wave Model. A diffusive wave model of downstream aggradation is presented that may simplify the analysis of deposition of coarse material downstream. The diffusive wave model is tested against two sets of laboratory data and a one-dimensional (1-D) sediment transport model (Greimann, Chapter 9, Movement of Sediment Accumulations). If the proper constant sediment transport rate is prescribed, the model accurately predicts the downstream diffusion of sediment in these cases. Further work should be done to develop predictive relationships for the sediment transport rates of the accumulation. Presently, it is assumed that relationships derived for uniform bed conditions apply.

The analytical diffusive wave model was also compared against the results of GSTAR-1D, a 1-D hydraulic and sediment transport model. The analytical diffusive wave model generally agrees with the results of GSTAR-1D except for where bedrock or hydraulic controls are present. The diffusive wave model requires that the sediment transport rates are specified. In addition, the sediment in the accumulation that is expected to travel as suspended or wash load should not be included in the volume estimates used as initial conditions in the model. The diffusive wave model can be used in cases where detailed deposition information is not required, or it can be used as an initial assessment tool.

1.5 BUREAU OF RECLAMATION EXPERIENCES

The U.S. Department of the Interior, Bureau of Reclamation is involved in many dam decommissioning projects in the western United States. These projects involve complete to partial dam removal. The Bureau of Reclamation has analyzed the sediment impacts of several dam decommissioning projects: Battle Creek Dams in California, Matilija Dam in California, and Savage Rapids Dam in Oregon. The dams range from small to large and the impacts also span a large range. The major components of these projects and specific lessons learned are summarized by Klumpp in Chapter 4, Bureau of Reclamation Case Studies of Dam Removal.

Three case studies of dam decommissioning were examined. The case studies were of different-sized dams with different physical settings, using two different models. The smaller dams (Savage Rapids Dam, South and Coleman Dams) are predicted to have a fairly rapid return to pre-dam conditions with deposition in downstream pools based on the sediment transport models. The relative volume of sediment stored in these dams is no more than 1 to 3 years of sediment supply. Nearly all of the sediments would be eroded and contaminants or metals would not be present in the sediments. Sediment concentrations would increase initially, but they would quickly return to pre-dam conditions.

Matilija Dam is a much larger dam under consideration for removal. Its removal would result in very high sediment concentrations and somewhat large bed changes downstream. It would require a long time period to return to pre-dam conditions. Extensive monitoring of the sediment concentrations and bed changes should be included in the dam decommissioning plan. Sediment released downstream would deposit somewhere because of decreasing channel slopes, or the river would enter a lake or ocean. Depositional effects must be carefully studied to determine whether the effects from the sediment management alternative are acceptable. Monitoring is essential during reservoir drawdown to validate the model predictions and prevent large short- or long-term impacts (Randle 2003).

One-dimensional sediment transport models were utilized to predict sediment transport rates, bed change, and grain size change. These models are most useful to predict reach average results for bed changes, sediment transport rates, and grain size change. Conceptual models of incised channels can also be useful in determining channel change after dam removal (Pizzuto 2002).

1.6 COMPUTER MODEL VERIFICATION AND FIELD TESTS

There has been very limited field verification of sediment transport models at actual dam removal projects; thus, there is uncertainty about their performance. The ongoing small dam removal projects can and should be used to test and further develop analytical techniques.

The MIKE 11 1-D dynamic computer model was used by Granata, Cheng, Zika, Gillenwater, and Tomsic (Chapter 8, Modeling and Measuring Bed Adjustments for River Restoration and Dam Removal: A Step toward Habitat Modeling) to simulate flow and river bed changes in the Sandusky River in Ohio pertaining to two potential dam removal sites. The model was tested by comparing predicted river bed elevations with measured elevations following removal of St. Johns Dam. The model can simulate unsteady flow, sediment transport, and changes in bed elevation due to degradation or aggradation, but it does not represent bank erosion or recession. St. Johns Dam is a run-of-river structure, 2.2 m high and 40 m crest length, with an impoundment extending 13 km upstream. The MIKE 11 model was used to simulate water levels, velocity, sediment transport, and channel bed elevations. The predicted bed elevations were generally within 10% of measured elevations, except at three sections with up to 27% differences in meanders. The predicted bed elevation in the meanders does not account for local 2-D secondary flow or bend scour.

1.6.1 Physical Models

Physical models constructed in laboratories are a classic method of performing both hydraulic and sediment transport research. They have been used extensively by federal agencies (USACE, Bureau of Reclamation), as well as academic institutions to replicate complex site conditions. Bromley, Randle, Grant, and Thorne (Chapter 7, Physical Modeling of the Removal of Glines Canyon Dam and Lake Mills from the Elwha River, Washington) constructed a scaled physical model of Glines Canyon Dam in a flume at the St. Anthony Falls Laboratory (University of Minnesota) using media to represent mixed-grain sediment. The physical model was used to evaluate alternate dam removal breach elevations and rates with respect to upstream sediment erosion and downstream deposition. The model boundaries were based upon 1926 pre-dam topography at a horizontal scale of 1:310 with some amount of vertical distortion. The results found that the eroded sediment volume increased as the dam breach is adjusted to the center and as the vertical drop increases, representing staged removal.

1.6.2 Monitored Dam Removals

The increasing number of documented case studies and monitoring of dam removal sites is providing valuable information on physical and ecological impacts of dam removal. Recent studies of dam removals have revealed the limited scientific understanding of the environmental effects and the need to address dam removal, and debates about how small dam removal may inform decisions on large dam removal. In Chapter 3, Stream Ecosystem Response to Small Dam Removals, Doyle and Stanley report on monitoring several small dam removal sites in Wisconsin. The new channels that formed across the former impoundments were found to follow classic channel evaluation models with headcuts and the impoundment areas rapidly regenerated. Fish and macroinvertebrates were found to rapidly re-establish their presence; however, there was high mortality among mussels. The results suggest that ecosystems may follow at least two separate paths to post-dam recovery. Some ecosystems may return to pre-dam conditions, but the rate of return could be variable and may be at such a slow rate as to appear static. Other ecosystems may never return to pre-dam conditions due to irreversible impacts or watershed changes. Doyle and Stanley indicate that the potential for full or potential ecosystem recovery could be dependent on the sensitivity of specific organisms, dam characteristics, and geomorphic conditions. They recommend that management agencies assess the recovery potential and identify critical species prior to dam removal.

Skalak, Pizzuto, Egan, and Allmendinger (Chapter 6, The Geomorphic Effects of Existing Dams and Historic Dam Removals in the U.S. Mid-Atlantic Region) document three separate dam removal monitoring programs, including Manatawney Dam, three historic dam removals on Muddy Creek in southeastern Pennsylvania, and the effects of dams on 15 additional sites in Pennsylvania and Maryland. The Manatawny was a non-engineered dam removal with no active management plan. The channel has slowly degraded and continues to adjust its slope. The downstream channel has aggraded over 4 years and the site has not yet stabilized; the recovery period is continuing. An additional three historic (1933, 1972, 1997) dam removal sites were subject to a post-removal assessment. Reservoir sediment deposits still form terraces at all three sites with only partial sediment removal. The two older sites have had complete vertical sediment incision, which has not been completed yet at the 1997 removal site. These limited data suggest that complete channel morphology recovery could take several decades after dam removal.

Skalak et al. also investigated channels at 15 existing dam sites. They found that the upstream channels had finer sediment than the corresponding downstream channels but that upstream and downstream channels had similar slopes and widths. The lack of morphologic change suggests that post-dam channels in these humid, low-sediment-yield watersheds will be relatively unchanged. These regional observations may vary in other climate zones.

Additional water quality parameters that can be used to monitor the effects of dam removal include water temperature, turbidity, nutrients, total suspended solids, and dissolved oxygen. Doyle and Stanley (Chapter 3) have monitored the ecosystem response at dam removal sites by assessing macroinvertebrates, mussels, riparian vegetation, and fish communities.

1.7 CURRENT AND ONGOING RESEARCH

There has been some additional work since the preparation of this manual; we provide short descriptions of these works here. There is a growing database of monitored dam removals that will prove valuable in designing future dam removals.

Ashley et al. (2006) monitored the redistribution of sedimentary contaminants after the two-stage removal of the 2.5-m-high Manatawny Dam described above. Pre- and post-removal monitoring was performed for a variety of sedimentary contaminants (PCBs, PAHs, Cd, Cr, Cu, Ni, Pb, Zn). While in this case it was concluded that the dam removal did not have an adverse effect, the authors recommend similar monitoring for other removals as needed.

Cantelli et al. (2007) analyzed the experiments of Cantelli et al. (2004) where lab-scale experiments of sudden dam removal were performed. They developed a morphodynamic model of channel incision and channel widening that explained the processes observed in the experiments. The model was focused on the upstream erosion processes that occur upstream of the dam after removal. They identified the "erosional narrowing" processes that may occur during the initial channel incision if the rate of incision is faster than the rate at which it can be supplied to the bed by transverse movement.

Lisle (2007) identified the complex relationships between transport, storage, and sediment sorting, and demonstrated these using the laboratory data of B. J. Smith's 2004 Master's thesis, "Relations between Bed Material Transport and Storage during Aggradation and Degradation in a Gravel Bed Channel (Humboldt State University, Arcata, California). Lisle re-emphasized the predominance of dispersion over advection in the movement of sediment waves, but he also suggested that the variations in bed geometry and bed particle size play important roles in the movement of sediment waves. There is most often a non-unique relationship between flow and sediment transport following dam removal. The flow will alternately erode and deposit sediment in storage areas along the river. The transport rate of will vary with changes in channel morphology and sediment texture.

Rumschlag and Peck (2007) monitored the changes to Munroe Falls Dam in Summit County, Ohio. After removal of the 3.8-m dam, they recorded a bed-material coarsening upstream of the dam, a bed-material fining downstream of the dam, and approximately 1 m of bed aggradation just downstream of the dam. Upstream of the dam, the dam quickly incised to the pre-dam elevation. Once the pre-dam thalweg elevation was reached, channel widening became the primary channel response.

A special publication of the *Journal of Great Lakes Research*, Vol. 33, Issue SP2 in September 2007 had several articles on sediment aspects of dam removals in the Great Lakes region. Evans (2007) monitored the 1994 failure of IVEX Dam on the Chagrin River in northeast Ohio. He extended the channel evolution model of Doyle et al. (2003) to include (1) a new Stage A2 that represents pre-dam failure sediment erosion, including channeling and longitudinal scours in the reservoir sediments; (2) an extensively modified Stage B representing development of an early-breach drainage network that cross-cut earlier features; and (3) an extensively modified Stage E representing lateral channel migration and incision, resulting in channel backfilling (terraces and point bars). Tukerman and Zawiski (2007) and Rumschlag and Peck (2007) monitored the sediment and water quality effects of modifying Kent Dam in 2004 and removing Munroe Falls Dam in 2005 on the Cuyahoga River in Ohio. The monitoring data of Tukerman and Zawiski (2007) showed marked improvements of the fish community less than 1 year after dam modifications of Kent Dam and improved dissolved oxygen concentrations after the Munroe Falls dam removal. Rumschlag and Peck (2007) monitored the sediment transport and morphologic response of the channel to the removal of the 3.66-m Munroe Falls Dam. Within 2 months, the channel incised to the pre-dam substrate and, subsequently, channel widening became the dominant channel response. The downstream channel aggraded approximately 1 m immediately downstream of the dam. They expected the river channel to take years or decades to equilibrate to its new characteristics. More details can be found in J. H. Rumschlag's 2007 Master's thesis, "The Sediment and Morphologic Response of the Cuyahoga River to the Removal of the Munroe Falls Dam, Summit County, Ohio" (Dept. of Geology, University of Akron, Akron Ohio).

Granata et al. (2008) monitored the discharge and suspended sediment transport during the removal of 2.2-m-high St. Johns Dam on the Sandusky River in Ohio in 2003. The dam was first breached in March 2003 by removing a small section of the dam. They determined that there was no discernable increase in discharge and suspended sediment concentrations due to the partial breach. In November 2003 removal of the remainder of the dam began. The intention had been to slowly remove the dam over a period of 1 day, but the initial removal operation caused the deteriorating concrete on the east bank to fail and the dam was washed out in a period of 2 h. During the removal the suspended sediment concentrations increased approximately three-fold and then decreased to background levels within 8 h. The resulting floodwave had a peak discharge of 33.5 m^3/s, which attenuated by 50% over a channel distance of 53 km.

Kosky et al. (2004) and the U.S. Geological Survey (USGS 2006a) document the collection of suspended sediment, dissolved oxygen, and geomorphic conditions before and after the gradual removal of an approximately 2-m-high dam in 2003 on Brewster Creek in Illinois. The dam was removed in five 12- to 18-in. increments over a 9-month period. They stated that preliminary results indicate that the notching system employed to lower the dam had a moderating effect on sediment behavior in relation to the incoming sediment load, but had little effect on dissolved oxygen concentrations in Brewster Creek.

Major et al. (2008) document some initial channel bathymetry and sediment load measurements taken before and after the Marmot Dam removal on the Sandy River in Oregon. Marmot Dam was originally a timber crib structure built in 1913, and was replaced by a 14-m-high, 50-m-wide concrete dam in 1989. It was breached in October 2007 and the 40- to 50-m^3/s flow rapidly incised through the sand and gravel reservoir deposits. Preliminary analyses of photographs indicate that approximately 100,000 m^3 of sediment was eroded upstream of the dam in the first 48 h. The sediment concentrations downstream of the dam immediately after removal were more than 100 times higher than upstream of the reservoir deposit. However, within a few hours the sediment concentrations decreased to 10 times higher than upstream of the reservoir deposit. The deposition downstream of the dam rapidly modified the channel morphology in a 2-km reach downstream of the dam. Approximately 4 m of deposition occurred immediately below the dam in the first 66 h. Additional monitoring of sediment impacts of the dam removal is planned.

Riggsbee et al. (2007) collected total suspended solids (TSS), dissolved organic carbon (DOC), and total dissolved nitrogen (TDN) loads during the dewatering phase and after removal of Lowell Mill Dam on the Little River in North Carolina. During the dewatering phase of the project, the TSS, DOC, and TDN levels were less than those occurring at comparable discharges on the river. After dam removal, the TSS, DOC, and TDN levels were 1.2 to 1.75 times greater than those occurring at comparable discharges on the river. They also compared their measured increases in TSS, DOC, and TDN levels to other dam removals in different regions.

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CHAPTER 2

SUMMARY AND SYNTHESIS OF EXPERIMENTAL RESEARCH ON STORED SEDIMENT RESPONSE TO DAM REMOVAL

Chris Bromley, Alessandro Cantelli, and John Wooster

2.1 INTRODUCTION

The rate of dam removal has accelerated dramatically in the United States, and, with an estimated 2 million dams on the nation's rivers in 1996 (Graf 1996), the total number of dams removed over the coming decades will continue to increase. While dam removal has the potential to rehabilitate river systems, it is nevertheless a disturbance to the fluvial system (Stanley and Doyle 2003) that is currently taking place without a thorough scientific understanding of the potential impacts. Collection of field data from dam removals is urgently required, but invaluable information can be learned from laboratory physical models of dam removals to help assess the impacts of future dam removals.

For the engineer or geomorphologist working on issues of dam removal, one of the fundamental problems lies in understanding the morphodynamic response of a reservoir that is partially or completely filled with sediment once the baselevel is altered by removing the dam. This response will be governed by a suite of key variables that includes reservoir deposit geometry, deposit sedimentology, hydrology, and the timing, rate, and magnitude of baselevel change. Erosion of the sediment deposit will typically exhibit many of the form–process interactions commonly found in incising channels, such as knickpoint/knickzone migration (e.g., Holland and Pickup 1976; Schumm et al. 1984) and bank erosion through mass wasting and fluvial erosion (e.g., ASCE 1998). The behavior of incising channel systems is traditionally conceptualized using channel evolution models (CEMs), such as those of Schumm et al. (1984) and Simon and Hupp (1986), but these only describe in general terms the evolutionary sequence through which incising channels progress as they respond to a disturbance. While some or all of these stages can be applicable to a reservoir-area channel during dam removal (Doyle et al. 2002), they do not describe in detail any of the mechanisms by which incising channels adjust. Their use in understanding channel responses within the reservoir area to dam removal is thus limited, as is their ability to guide the development of predictive models. A new generation of conceptual models is thus required to form the basis on which our understanding of dam removal can progress (Pizzuto 2002) and which will help to guide the development of predictive models.

The National Center for Earth-surface Dynamics (NCED), housed at the University of Minnesota's St. Anthony Falls Laboratory (SAFL), has developed an ongoing research program in order to contribute to the understanding of the physical responses associated with dam removal. This chapter presents a summary and synthesis of the findings from three sets of experiments performed at SAFL (Cantelli et al. 2004; Wooster et al., in press; and C. Bromley's unpublished Ph.D. dissertation, "The Morphodynamics of Sediment Movement through a Reservoir during Dam Removal," University of Nottingham, Nottingham, UK, 2007, hereafter referred to as "Bromley 2007, unpublished data") that investigated some of the geomorphic responses related to dam removal, with a view to improving our conceptual understanding of some of these process–form interactions.

2.2 DAM REMOVAL EXPERIMENTS AT ST. ANTHONY FALLS, MINNESOTA

2.2.1 Experiments on Upstream-Migrating Bed and Bank Erosion Induced by Dam Removal

2.2.1.1 Background. The first set of experiments (Cantelli et al. 2004) was performed in a rectangular flume 15 m long, 0.61 m wide, and 0.48 m high, set at a slope of 1.8%. The reservoir deposit was 9 m long and consisted of noncohesive sand with a specific gravity of 2.67, a D_{50} of 0.80 mm, and a geometric standard deviation (σ_g) of 1.71. The dam was put in place 9 m downstream from the inlet and the deposit was grown by feeding sediment into the inlet at a constant rate of 1.4×10^{-2} kg/s until it reached the dam (Table 2-1). Ten experimental runs were performed in which the pre-dam-removal delta progradation and post-dam-removal delta erosion were studied. The goal of the work was to investigate the mechanisms of delta formation due to dam installation (Phase I) and the morphodynamic evolution of the deltaic deposit following dam removal (Phase II). Only data describing the evolution of the bed and water surface longitudinal profiles, the sediment discharge downstream from the dam, and the rate of bank erosion during Phase II evolution are reported here (Fig. 2-1).

Table 2-1. Experimental Parameters of Dam Removal Experiments at St. Anthony Falls, Minnesota

Run	Q_w (m^3/s)	Q_s (kg/s)	D_{50} (mm)
1	0.0015	0.014	0.8
2	0.0015	0.014	0.8
3	0.001	0.096	0.8
4	0.0005	0.041	0.8
5	0.0005	0.02	0.8
6	0.0005	0.02	0.8
7	0.0003	0.02	0.8
8	0.0003	0.032	0.33
9	0.0003	0.02	0.8
10	0.0003	0.02	0.8

Q_w, water discharge; Q_s, sediment discharge.
Source: Cantelli et al. (2004).

2.2.1.2 Results. Immediately following dam removal, the sediment discharge through the dam site reached a concentration of the same order of magnitude as the flow rate, followed by a gradual decrease toward the upstream supply rate (Fig. 2-1C). In the first stage of the erosional process, the channel incised into the deposit immediately upstream from the dam after the failure of the leading front of the sediment deposit. This initial incision was accompanied by erosional narrowing, which caused the channel width to decrease to below that of the pre-removal channel. The incision and narrowing propagated upstream relatively quickly, but decreased in intensity as they did so (Fig. 2-1B). While these effects were migrating upstream, however, the depositional contribution from the side slopes at the dam site eventually balanced and surpassed the flow's transport capacity, thus slowing and halting the erosional narrowing and causing the channel to widen toward a new equilibrium state with a lower streamwise slope (Fig. 2-1A). This widening phase also migrated upstream, albeit more gradually than the initial incision and narrowing, until the entire deposit had adjusted to essentially the same width (Fig. 2-1B).

The phenomenon of erosional narrowing observed by Cantelli et al. (2004) following the "blow and go" method of dam removal can be explained theoretically in terms of a competition between rapid bed degradation, which enhances narrowing, and the input of eroded sediment from the sidewalls, which suppresses it. More specifically, the narrowing is hypothesized to occur as a result of the lateral variation of the boundary shear stress from a higher value at the channel center to a lower value along the banks. Under conditions of sufficiently rapid degradation, the

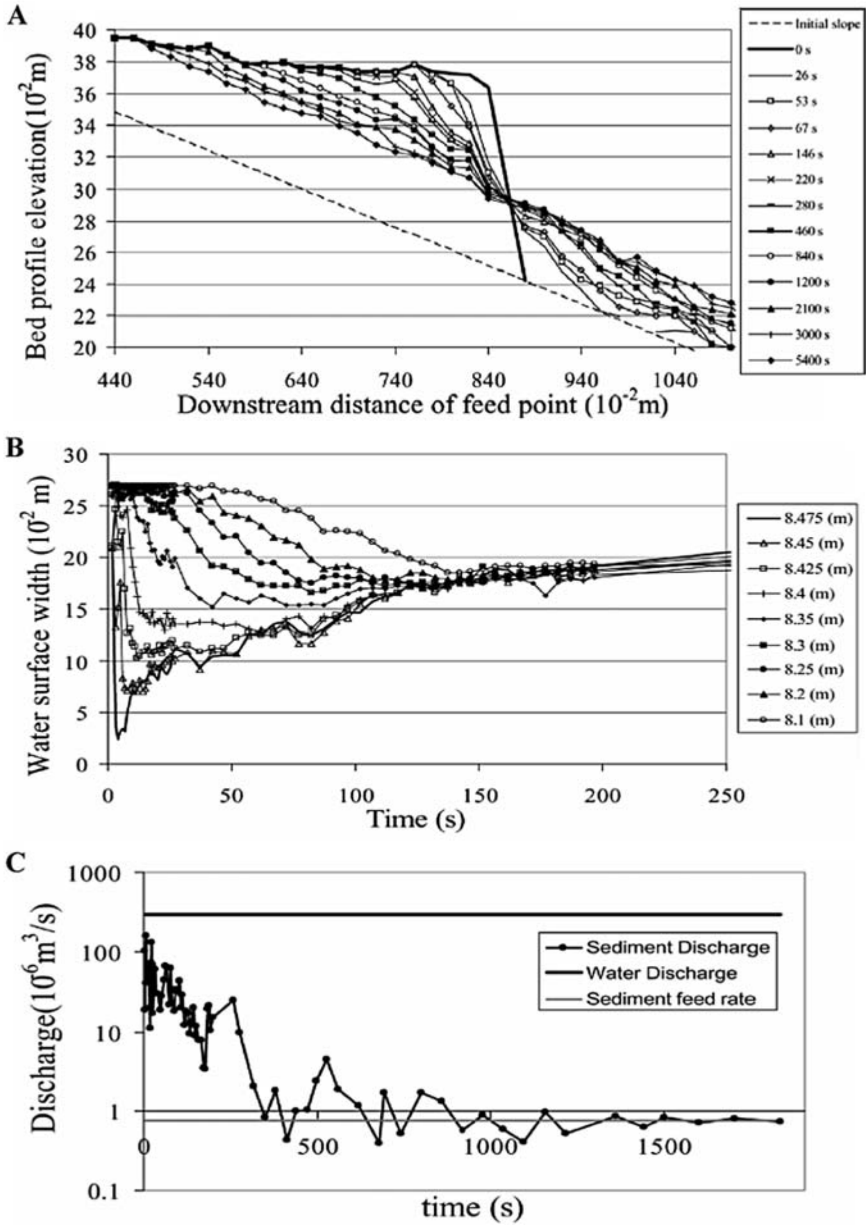

Figure 2-1. Experimental data from Run 6. (A) Evolution of the bed profile along the channel center during the erosion of the front. Dam is located at 9 m downstream of the feed point. (B) Time evolution of the channel's water surface width at various points upstream of the dam after removal. Each line corresponds to a different section along the deposit. (C) Sediment discharge at the dam site. Source: Cantelli et al. (2004). © 2004 American Geophysical Union. Reproduced by permission of American Geophysical Union.

contribution of sediment from the sidewalls cannot keep up with bed degradation and the channel narrows. As the rate of degradation drops, the volume of sediment from the sidewalls begins to exceed the volume eroded from the bed, and channel narrowing gives way to channel widening (Cantelli et al. 2004). This process is consistent with a simple one-dimensional (1-D) numerical model capable of simulating the phenomenon (Cantelli et al. 2007; Wong et al. 2004).

2.2.2 Physical Models of Dam Removal with a Mixed Sand and Gravel Reservoir Deposit

2.2.2.1 Background. The second set of experiments was conducted using the same flume as Cantelli et al. (2004) and Wooster et al. (in press). Sediment deposits trapped behind dams often have mixed or bimodal grain size distributions (Sambrook-Smith 1996), and how the interaction of the fine and coarse layers influences channel evolution and the release of sediment following dam removal remains a key uncertainty. The primary objective of these experiments was to investigate the role of different ratios of fine to coarse sediment in the initial reservoir deposit on channel evolution upstream from the dam, the downstream channel response, and the sediment transport rates.

The main variable used in this set of experiments was the ratio of sand (D_{50} of 0.6 mm and σ_g of 2.1) to gravel (D_{50} of 4.2 mm and σ_g of 2.6) in the sediment mixture used to create the reservoir deposit and for the sediment feed post-dam removal. The percentages of sand in the sediment mixtures used for the flume runs were 89%, 80%, and 73%; flume runs were named according to sand content: S89, S80, and S73 (Table 2-2). The initial channel bed was composed entirely of the gravel mix, was set to a 1% slope, and was immobile at the experimental discharges. Each run was started by filling the reservoir with sediment using constant sediment and flow feed

Table 2-2. Summary Statistics for Experimental Sediments and Set-Up Parameters Used for Physical Models of Dam Removal

Experiment	D_{50} (mm)	D_{84} (mm)	σ_g	Post-Dam Removal Q_W (m^3/s)	Post-Dam Removal Q_S (kg/s)	Initial Gavel Bed Slope
S89	0.68	1.66	2.14	0.00234	0.008	0.01
S80	0.76	2.38	2.48	0.00234	0.007	0.01
S73	0.77	3.55	2.84	0.00234	0.006	0.01

σ_g, geometric standard deviation; Q_w, water discharge; Q_s, sediment discharge.
Source: Wooster et al. (in press).

rates at the upstream end of the model. This allowed the delta to prograde and to stratify naturally behind the dam. For each run the dam was completely removed in one stage.

2.2.2.2 Results. The experiments using coarser sediments (runs S80 and S73) evolved in a similar progression with channel evolution upstream of the dam coupled with downstream channel responses occurring in four phases:

Phase I: Immediately after dam removal, a knickzone rapidly migrated upstream from the former dam site (Fig. 2-2).

Phase II: After the knickzone migrated upstream from a channel segment, the dominant erosional process changed from vertical incision to channel widening at that section. The amount of channel widening decreased with increasing distance upstream from the dam, which is attributed in part to an upstream coarsening stratigrfaphy of the initial deposit.

Phase III: After the channel attained its maximum width, the system developed a multi-thread channel planform due to the deposition of mid-channel bars. As the upstream areas continued to degrade, one of the channels captured the majority of flow and the system transitioned back to a narrow, single-thread channel, which resulted in a secondary knickzone propagating upstream.

Phase IV: The channel along the entire flume length (upstream and downstream of the former dam) degraded synchronously until reaching a stable profile.

Cycles of aggradation and degradation in the downstream channel fluctuated in response to the upstream erosional phases and the associated sediment supply. The sediment pulse released in Phase I deposited as a large wedge with a stationary apex of maximum depth and volume directly downstream of the dam (Fig. 2-2). The sediment wedge deposited below the dam did not translate farther downstream and primarily dispersed in-situ (Lisle et al. 1997; 2001). Downstream aggradation and bed-load transport rates reached peak levels as the upstream channel attained its maximum width at the end of Phase II. Bed-load samples taken immediately after the dam was removed contained more gravel than at any other time during the experiment, which may have been due to the mobilization of the initial downstream gravel bed by the influx of sand from upstream (Wilcock et al. 2001). During the transitional period at the beginning of Phase III, the upstream sediment supply declined, which produced a sustained drop in bed-load transport rates (Fig. 2-3). The downstream channel also began to incise into the sediment wedge deposited below the

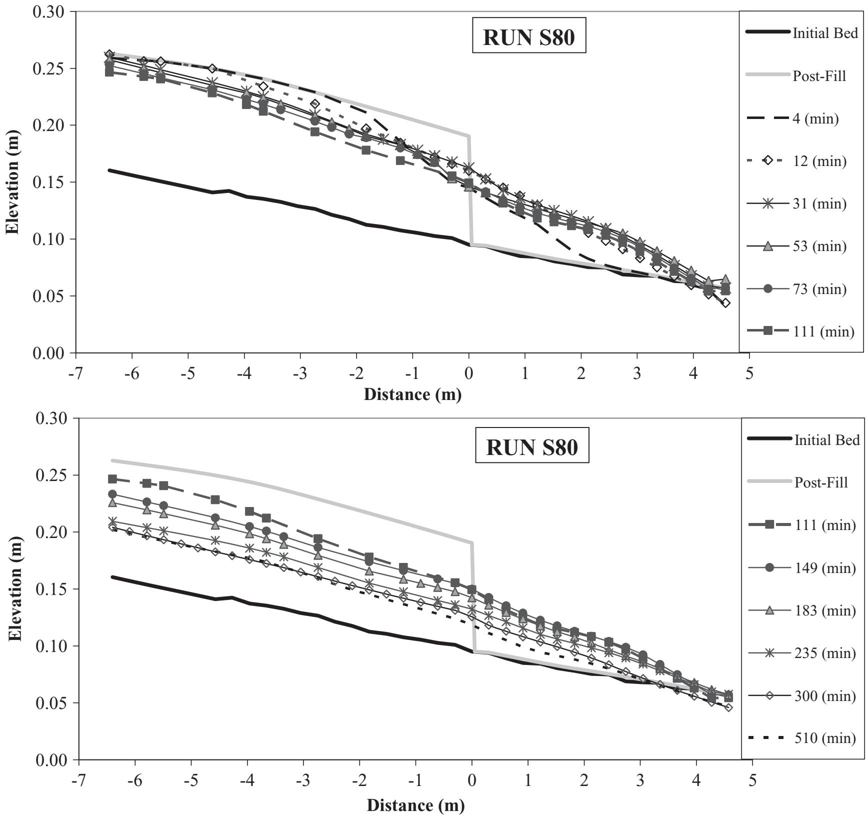

Figure 2-2. Longitudinal profiles for dam removal run S80 depicting sediment deposit evolution where the profile "Post-Fill" reflects sediment storage at time of dam removal (i.e., t = 0) and distance = 0 m is the location of dam. The top frame illustrates profile adjustments immediately following dam removal and the bottom frame depicts adjustments as the profile approached quasi-equilibrium. Source: Cantelli et al. (2004).

former dam. Bed-load transport rates returned to peak levels as the sediment pulse from Phase III reached the flume outlet, then asymptotically declined during Phase IV to the sediment feed rate as a stable bed profile was achieved. By the end of the experiment the downstream channel thalweg eroded to pre-dam-removal bed elevations.

The initial responses following dam removal with the finer reservoir deposit (S89) were similar to the other experiments: knickzone

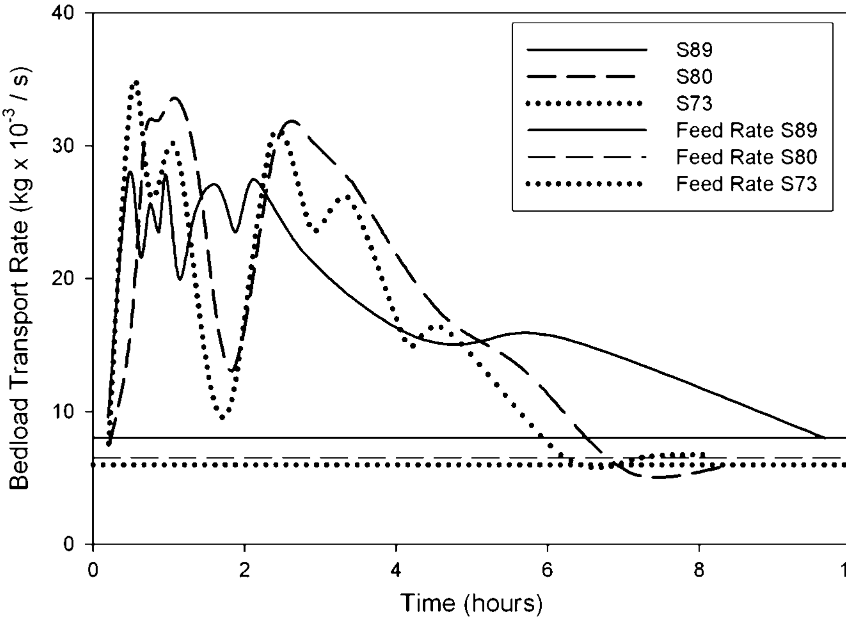

Figure 2-3. Bed-load transport rates for three experimental runs investigating different ratios of sand to gravel in the initial reservoir deposit. Dam removal occurs for all runs at t = 0. Source: Wooster et al. (in press).

propagation upstream from the dam and a sediment wedge depositing downstream from the dam. However, in the subsequent evolution phases, run S89 evolved in a different progression than the coarser-sediment experiments. These differences were: (1) there was no transition to a multi-thread channel; (2) there were no distinct vertical and lateral phases of adjustment post-Phase I, as both processes were evident throughout the experiment; and (3) the channel widened to nearly the full flume width along the entire length of the deposit, which is attributed to a lack of an upstream coarsening stratigraphy in the finer reservoir deposit. By experiment completion, nearly the entire reservoir deposit had been eroded in the S89, whereas significant sediment volumes remained stored along the channel margins in the upstream portions of the sediment reservoir in the coarser-sediment experiments where channel widening did not occur. Bed-load transport rates increased rapidly shortly after dam removal and fluctuated near peak levels without a distinct drop and second peak, before decreasing asymptotically toward the feed rate (Fig. 2-3).

2.2.3 Scaled Physical Modeling of the Removal of Glines Canyon Dam and Lake Mills from the Elwha River, Washington

2.2.3.1 Background. Glines Canyon Dam and Lake Mills are being decommissioned to allow anadromids to migrate upstream to spawn. However, Lake Mills impounds about 11.85 million m^3 of sediment, which has the potential to damage the ecosystem downstream from the dam as well as human infrastructure. A primary goal during deconstruction of Glines Canyon Dam is thus to minimize the total volume and rate at which sediment enters the downstream system during and after dam removal. This will be done by retaining as much sediment as possible within the reservoir area, while keeping it distributed throughout this area in a manner that promotes the effective dewatering, consolidation, and stabilization by vegetation.

To help identify how best to achieve these sediment management objectives, a physical model of the Glines Canyon Dam and Lake Mills area was constructed. The model had a horizontal scale of 1:310 and a vertical scale of 1:81.7, and was designed to achieve similitude of the Froude and Shields numbers in the delivery channel upstream from the original delta area according to standard modeling practices (ASCE 2000). The original delta was defined as the area occupied by the undisturbed delta deposit prior to any dam removal activity; it extended over one-quarter of the reservoir's length, which corresponded to the dimensions of the prototype reservoir delta in 2002. Each model run was started by growing the original delta using an accelerated sediment feed to ensure that the sediment was hydraulically sorted. The model dam was composed of 21 × 0.028-m-high[1] wooden blocks and each experiment examined the effects of removing the entire dam in increments of the same overall number of dam pieces, but with the number of dam pieces per baselevel lowering increment varying between runs. In addition, the starting position of the incising channel on the delta surface varied between the right, left, and center of the topset[2] surface (Table 2-3). A more detailed description of the experimental methodology can be found in Bromley (2007, unpublished data).

2.2.3.2 Results. The results show that, in general, as the initial position of the incising channel at the onset of dam removal moved from delta left or delta right (marginal runs) to delta center (central runs), and as the

[1] Each block scaled to the 2.29-m increments in which the prototype Glines Canyon Dam would be cut down.

[2] The "topset" is the uppermost surface of the delta deposit. The term "bottomset" refers to the fine sediments that deposit across the reservoir bed downstream from the original delta.

Table 2-3. Results Summary of Experimental Parameters: Physical Model of the Glines Canyon Dam and Lake Mills Area

Run Name[a]	2xR	3xR	1xL	3xL	3xC	6xC[b]	12xC[b]	21xC[c]
No. of dam pieces removed per increment of dam removal	2	3	1	3	3	6	12	21
Delta surface channel position at start of run	Right	Right	Left	Left	Center	Center	Center	Center
Model sediment mixture (mm)	Not sampled	D_{16} = 0.15 D_{50} = 0.42 D_{84} = 1.30	D_{16} = 0.19 D_{50} = 0.40 D_{84} = 1.38	Not sampled	Not sampled	D_{16} = 0.16 D_{50} = 0.43 D_{84} = 1.33	D_{16} = 0.14 D_{50} = 0.43 D_{84} = 1.33	D_{16} = 0.16 D_{50} = 0.5 D_{84} = 1.51
Discharge during dam removal (m^3/s)	0.00026	0.00026	0.00026	0.00026	0.00026	0.00026	0.00026	0.00026
Recurrence interval of flood flows[d]	No floods	1st flood = 2-yr 2nd flood = 2-yr 3rd flood = 5-yr	1st flood = 2-yr 2nd flood = 2-yr 3rd flood = 5-yr	1st flood = 2-yr	1st flood = 2-yr	No floods	No floods	No floods
Original delta volume eroded at end of dam removal (%)[e]	46.8	36.7	38.9	45.4	69.3	49.0[f]	53.3[f]	30.9[c]
Total volume of reservoir sediment passing downstream of dam at end of dam removal (%)[g]	13.8	2.4	7.8	13.9	25.1	No sediment downstream	No sediment downstream	No sed iment downstream

[a] The number in each run name refers to the number of dam pieces removed per increment of removal, while the letters R, L, and C refer to Right, Left, and Center—the initial position of the incising channel on the topset surface at the start of the run.
[b] Partial runs: only a total of 12 dam pieces removed.
[c] Run only performed for 330 min, the time taken for the baselevel to drop the equivalent of 21 dam pieces.
[d] The channel position is assigned looking downstream from the upstream end of the delta.
[e] Volumes normalized by the total original delta volume at the start of the run.
[f] Original delta volume eroded after the removal of 12 dam pieces [modified from Bromley et al. (2010)].
[g] Volumes normalized by total reservoir sediment volume (original delta volume plus bottomset deposit) at the start of the run.

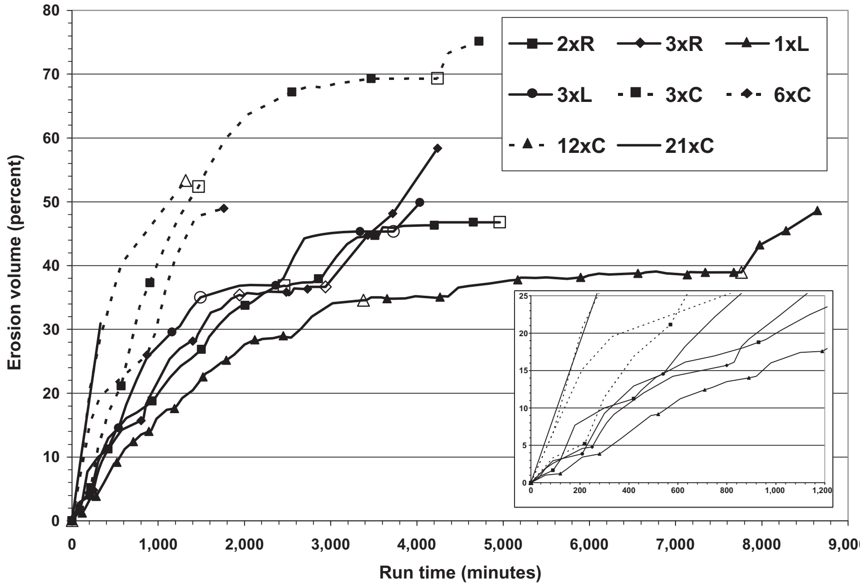

Figure 2-4. Original delta volumes eroded during selected experimental runs by Bromley et al. (2010). The insert graph provides an expanded view of the area of the main graph close to the origin. Source: Modified from Bromley et al. (2011).

magnitude of the removed dam increment increased from one to three pieces, the percentage of the original delta that eroded and subsequently prograded into the reservoir increased significantly from 38.9% (Run 1xL) to 69.3% (Run 3xC) by the 21-piece equilibrium[3] (Fig. 2-4, Table 2-3). Runs 2xR, 3xR, and 3xL show no clear relationship between the magnitude of baselevel drop, the initial channel position, and the volume of original delta eroded. These runs eroded 46.8%, 36.7%, and 45.4%, respectively, of the original delta by the 21-piece equilibrium (Fig. 2-4, Table 2-3). These variations occurred largely because of the varying degree of interaction of the incising channel with the highly asymmetrical reservoir boundary (Fig. 2-5A). In the central runs, the incising channels were largely unaffected by the basin boundary, particularly in the early stages of each run, and were able to move freely across virtually the entire delta surface. This led to the formation of a meander loop through the original delta area

[3] "21-piece equilibrium" describes the point in time at which the delta system reached a static equilibrium condition following the removal of the 21st dam piece (i.e., the entire dam). Similar short-hand terms are used to describe other points in the runs.

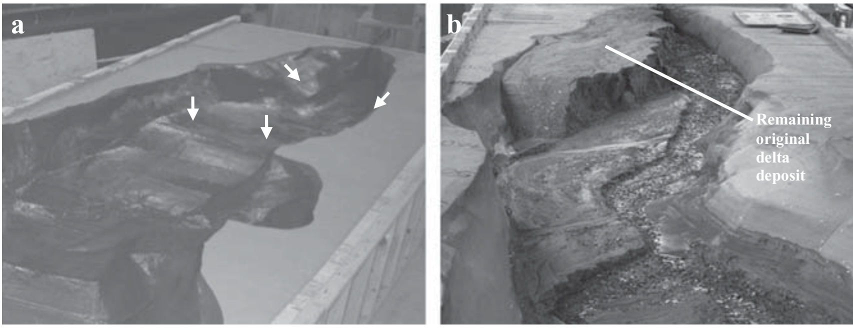

Figure 2-5. (A). View looking upstream at the empty basin in the original delta area. Arrows indicate features of the basin geometry that influenced original delta erosion under the different removal scenarios. (B). Example of the leftward curvature of the left side of the basin preventing the incising channel from eroding almost any of the right half of the original delta by the end of dam removal (Run 3xL). Source: Modified from Bromley et al. (2011).

whose belt width was about the same as that of the delta deposit, which was able to erode substantial portions of the original delta as the individual bends extended and migrated downstream. In the marginal runs, a greater proportion of the channel length through the original delta area was in contact with the basin boundary, and this lateral constraint prevented the formation of such well-developed bends. Erosion was thus restricted to the side of the original delta on which the incising channel developed at the onset of dam removal (e.g., Fig. 2-5B).

Similarly, the pattern of response was not straightforward when comparing runs 3xC, 6xC, and 12xC (Fig. 2-4). Runs 6xC and 12xC were only partial runs but, by the 12-piece equilibrium (the last point at which the three runs were directly comparable), 52.4%, 49%, and 53.3%, respectively, of the original delta had been eroded. This shows that there was not a clear and continuous increase in the volume of original delta eroded as the magnitude of drop in baselevel continued to increase beyond the 3x increment (Bromley et al. 2011).

By the 21-piece equilibrium, the total reservoir sediment volumes[4] that passed downstream were, in decreasing order, 25.1% (run 3xC), 13.9% (run 3xL), 13.8% (run 2xR), 7.8% (run 1xL), and 2.4% (run 3xR) (Table 2-3). This pattern of decrease is identical to that for the decrease in the volume of the original delta sediment eroded by the static equilibrium at the end

[4] The total reservoir sediment volume is the original delta volume plus the bottomset deposit that was laid down during the period of accelerated delta growth.

of dam removal (Table 2-3), which suggests that the more sediment is eroded from the original delta, the more sediment will eventually pass downstream once the entire dam has been removed (Bromley et al. 2011).

2.3 DISCUSSION

A number of important observations concerning the morphodynamic response of sediment stored upstream from a dam following dam removal can be made by comparing the results of these three suites of experiments. One key observation is that the available reservoir storage capacity in the experiments of Bromley et al. (2011) acted as a buffer between the original delta and the area downstream from the dam, within which the eroded original delta sediments were deposited. In the experiments of Cantelli et al. (2004) and Wooster et al. (in press), this buffer was not present and the eroded original delta sediment was immediately transported to the channel reaches downstream from the dam.

Common to all three suites of experiments was the characteristic upstream migration of incision and channel widening of a noncohesive alluvial channel responding to a drop in baselevel (Schumm et al. 1987; Simon 1992). However, within this broadly similar morphological response there were important differences that shed light on the influence of the variables discussed in the Introduction. The experiments of Cantelli et al. (2004) and Wooster et al. (in press) both involved the complete removal of the dam at one time, thus introducing a large erosive potential to the flow over the deposits' surface. But while the runs of Cantelli et al. produced strong erosional narrowing, those of Wooster et al. only experienced weak erosional narrowing. Cantelli et al. performed their experiments using an almost uniform mixture of medium sand, while Wooster et al. used a mixture of slightly finer sand and gravel ranging from 11% to 27% by volume. Qualitative observations from the experiments of Bromley (2007, unpublished data), which generally involved smaller and stepped drops in baselevel, only reported mild erosional narrowing during the upstream migration of the most intensively developed knickzones and only when the alluvium being incised was almost entirely sand. A large and rapid drop in baselevel therefore appears to be a prerequisite for erosional narrowing. In addition, the ability of channel beds formed in heterogeneous sediment to armor may suppress erosional narrowing.

The conditions under which erosional narrowing occurred in Cantelli et al. (2004) and those during the early stages of run 21xC (Bromley 2007, unpublished data) reveal some important characteristics of the roles played by the magnitude and rate of baselevel drop and the grain size distribution of the sediment deposit. In both cases, a large amount of potential energy was introduced to the deposit in a short time period, although more rapidly in the experiments of Cantelli et al. (2004) than in those of Bromley (2007, unpublished data). In both cases, the incising channel remained essentially straight over the full length of the deposit during the early stages of the response to dam removal, because the large energy slopes over the delta surface kept the streamlines running predominantly from upstream to downstream. This precluded significant energy dissipation by the formation of a sinuous channel planform (e.g., Leopold et al. 1960), which resulted in more energy dissipation through channel incision and widening. This also enabled these process–form interactions to migrate to the upstream-most reaches of the delta deposit more rapidly and more extensively than if a sinuous channel planform had developed. Another prerequisite for this upstream migration appeared to be the rapid evacuation of sediment away from the locus of its generation, since this prevented a reduction of the energy slope that would greatly slow the rate of incision. In this respect, the upstream progression of erosional narrowing or intense fluvial entrainment is similar to one of the rate-controlling factors of knickpoint migration; research by Bennett (1999) indicates that there is a positive correlation between the rate of sediment evacuation from the scour pool and the rate of knickpoint migration. Clearly, the further upstream a zone of erosion is able to migrate, the greater the proportion of the deposit the incising channel is potentially able to access and erode.

The coarser-mixture runs (S73 and S80) of Wooster et al. (in press) and the marginal runs (1xL, 3xL, 2xR, 3xR) of Bromley et al. (2011) both showed a decrease in the final incised channel width with increasing distance upstream on completion of the adjustments related to dam removal, irrespective of whether the dam was removed at one time or in increments. In addition, runs S73 and S80 showed a reduced intensity of erosional narrowing. The reduction in channel widening probably occurred in the runs of Wooster et al. due to increased thresholds of bank and bed stability imposed by the coarser nature of the upstream ends of the sediment deposit (Morris and Fan 1998). This also occurred in the laboratory experiments of Wolman and Brush (1961) and during the prototype drawdown of Lake Mills in 1994 (USGS 2000). In the experiments of Bromley et al. (2011), the reduction occurred because of the interaction of the incising channel with the reservoir's non-erodible boundary (frequently bedrock in the prototype), which restricted lateral channel movements, and because of the coarser sediments at the upstream end of the deposit. In contrast, there was very little or no upstream coarsening in the reservoir deposit in Wooster et al.'s run S89, nor in Cantelli et al.'s (2004) runs, and the channel widened to the same width along the full length of the deposit. Where the channel was laterally unconstrained at the start of dam removal (Bromley et al.'s runs 3xC, 6xC, 12xC and 21xC), the channel did erode laterally across the full width of the basin, which resulted in the largest original delta erosion volumes (Table 2-3).

The coarser sediment mixture runs (S73 and S80) of Wooster et al. (in press) and all the runs of Bromley (2007, unpublished data) experienced planform transitions from a single-thread channel to a braided system and back to a single-thread in a manner that conforms to Hey's (1979) picture of a damped oscillatory response. In runs S73 and S80 these transitions occurred during Phase III, once the channel cross section attained its maximum width and became incompetent to transport the sediment being eroded by Phase II channel widening further upstream. In the runs of Bromley (2007, unpublished data), these transitions generally occurred one or several times per dam increment removed. In both cases, rapid channel widening (mostly by mass wasting) generated more sediment than the single-thread channel was competent to transport, causing sediment deposition, bar formation, and additional channel widening, which provided a positive feedback to further decrease transport capacity. This drop in sediment transport through the wider channel reach was manifested as lower bed-load transport rates at the flume outlet in runs S73 and S80, and as drastically reduced rates of delta progradation in the runs of Bromley (2007, unpublished data). Eventually, the supply of sediment from upstream decreased sufficiently to allow a single-thread channel to re-form. While these process–form interactions appear to be primarily a function of sediment supply and transport capacity, the absence of a multi-thread planform in run S89 suggests that a sufficient supply of coarse sediment may also be required to either armor the bed or initiate and stabilize the formation of mid-channel bars.

2.4 CONCLUSIONS

The results presented herein reveal some of the complex interactions between the magnitude and rate of baselevel drop, the sediment deposit's grain size distribution, and the position of the incising channel on the deposit's surface at the start of dam removal. Also shown are how these variables interact to control the volumes of sediment eroded from a reservoir deposit and subsequently prograded further into the reservoir or transported to the downstream system. The results suggest that there are significant differences between incising sand-bedded channels and channels with a more heterogeneous boundary composition—which is to be expected—and that these differences exert a strong influence on the extent to which incision and channel widening are able to migrate upstream. The results suggest that, all other factors being equal, a drop in baselevel of a given magnitude and rate may be able to erode a greater proportion of a relatively homogenous sand deposit than can a more heterogeneous deposit whose channel can develop an armor layer. This hypothesis clearly requires further testing, however. In particular, research should be directed toward understanding the range of values of basin geometry, especially the width of the deposit relative to channel width, through which differences in deposit sedimentology and the regime of baselevel change are able to effect significant differences in the volume and rate at which sediment is eroded. More research is also needed to understand the dynamics of armor layer formation and destruction in an actively incising channel.

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PART II: FIELD STUDIES

CHAPTER 3

STREAM ECOSYSTEM RESPONSE TO SMALL DAM REMOVALS

Martin W. Doyle and Emily H. Stanley

3.1 INTRODUCTION

In this chapter a series of small dam removal studies are synthesized to examine how changes in channel form can affect riparian vegetation, fish, macroinvertebrates, mussels, and nutrient dynamics. Results suggest that ecosystems may follow two trajectories of recovery following dam removal. First, ecosystems may fully recover to pre-dam conditions, although this may be unlikely in many cases. Even if full recovery occurs, the time scales over which different attributes recover will vary greatly and the ecosystems may be perceived by the public or management agencies as not recovering at all. Second, ecosystems may only partially recover to pre-dam conditions because the legacy of environmental damage of long-term dam presence may not be reversible or because other watershed changes inhibit full recovery. The potential for full or partial recovery is likely driven by the sensitivity of particular organisms, the characteristics of the dam removed, and the local geomorphic conditions of the watershed. Scientists and management agencies should assess the potential for full or partial recovery prior to dam removal and should identify those species or groups of species that are likely to not recover to pre-dam conditions.

3.2 DAMS AND GEOMORPHOLOGY

3.2.1 Small Dam Removal

The dramatic rise in the number of dam removals nationwide has captured the attention of hydraulic engineers, stream ecologists, and geomorphologists. Recent studies of dam removal have revealed several issues, including (1) the lack of fundamental scientific understanding of the environmental effects of these structures; (2) the impending need to address dam removal because of the large number of dams nearing the end of their design lives or license periods; and (3) debates about how small dam removal can or cannot inform decisions for large dam removal. These issues are combined with the well-known impact of small dams—many of which are more than 100 years old—on rivers throughout the United States, and particularly Wisconsin (Gebken et al. 1995). Collectively, these trends indicate that there is still much to be learned about how the diversity of small dams may influence rivers, and that removal of small dams can have substantial but as yet only sparsely studied effects on fluvial systems.

3.2.2 The Geomorphic Context of Small Dam Removal

Despite the fact that numerous dams have been removed in the United States over the past few decades, little information exists on how channels will respond to dam removal. Geomorphic response to dam removal will likely be governed by the quantity of sediment stored in the reservoir and the ability of the fluvial system to adjust. The upstream erosion of reservoir sediment will drive the rate and magnitude of downstream geomorphic response to dam removal. Presumably, systems with greater energy via higher discharge or higher slope will adjust more quickly than those with lower energy. Further, sediment texture should drive the potential time scales of response following dam removal in that fine-sediment transport should occur at greater temporal rates than coarse-sediment transport (Doyle and Harbor 2003). Another important consideration is the spatial scale of geomorphic adjustments (i.e., how far upstream and downstream the impacts of dam removal are evident). Unfortunately, there are few studies on which to base qualitative predictions.

In Wisconsin, impoundments have typically filled, at least partially, with sediment because of their age and history of upstream agricultural development. Removing these dams causes erosion of the impounded sediment, which is then transported and deposited downstream. Surprisingly little is known about the quantity of sediment that is eroded at these dam removal sites, the rate at which the erosion occurs, and how far downstream the sediment will be transported.

To test some of these general qualitative predictions, Doyle et al. (2003b) studied two small dam removals in Wisconsin and described the geomorphic response in terms of a channel evolution model. The model describes the changes in geomorphology as six sequential stages and highlights (1) the similarities between adjustments associated with dam removal and other events that lower the local channel baselevel, and (2) the role

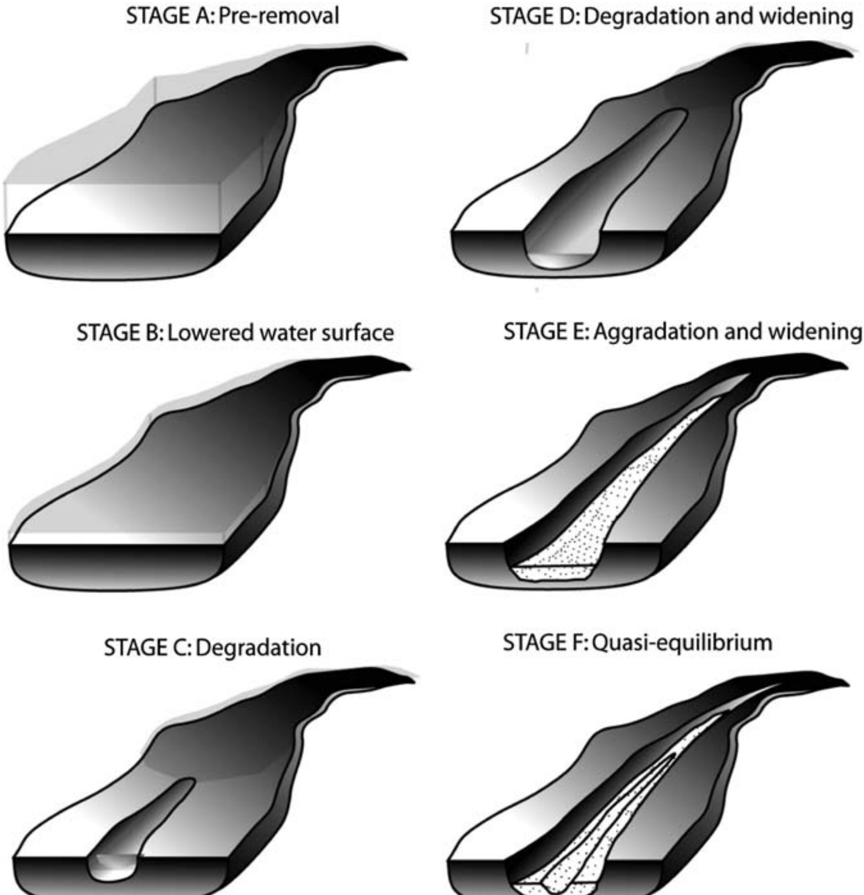

Figure 3-1. Conceptual channel evolution model for river response to dam removal. Source: Adapted from Doyle et al. (2003b).

of reservoir sediment characteristics (particle size, cohesion) in controlling the rates and mechanisms of sediment movement and channel adjustment (Fig. 3-1). At both study sites, channels developed in the reservoir sediment through bed degradation, channel widening, and aggradation.

Upstream channel development and evolution were strongly controlled by the character of the reservoir sediment, in that a reservoir (Baraboo River) that was dewatered regularly and had relatively little consolidated or coarse sediment progressed rapidly through the evolution sequence, with erosion occurring throughout the reservoir immediately following dam removal. In contrast, a second site (Koshkonong River) with consolidated fine reservoir sediment progressed much more slowly through the stages because of the limited migration of a headcut, which controlled subsequent channel development.

At both sites, a large amount of fine sediment was exported from the reservoirs immediately following dam removal. However, subsequent erosion of reservoir sediment, and thus subsequent downstream sedimentation, was strongly controlled by the rate and magnitude of channel development and evolution within the reservoir. At the site where erosion occurred along the entire length of the reservoir (Baraboo River), sand was transported through the reservoir and into downstream reaches. Downstream aggradation, however, was temporary. At the other site (Koshkonong River), little downstream sedimentation occurred through time because of the limited reservoir sediment erosion.

The results of this and other studies of small dam removals (Stanley et al. 2002) highlight the potential for widely varying rates of both upstream erosion and corresponding downstream sedimentation. Because upstream erosion and downstream sedimentation have impacts on ecosystem processes, there is also the potential for widely varying ecological changes immediately after the removal, as well as on the rate and trajectory of change in the weeks, months, and years after the dam has been removed. It is important to note that the dams studied in Wisconsin were run-of-river dams and thus did not affect the downstream hydrologic regime. Potential impacts of such changes are beyond the scope of these studies.

3.3 ECOLOGICAL RESPONSE TO DAM REMOVAL

3.3.1 Riparian Vegetation

To examine the effects of dam removal on vegetation, Orr and Stanley (2006) surveyed multiple sites in Wisconsin that represented a range of years since removal, rather than following a single site through time. Thirteen former impoundment sites were surveyed, ranging from sites where the dam had been removed as recently as 1 year earlier, to others where removal had occurred more than 30 years earlier. These researchers found that vegetation established quickly following dam removal and that bare sediment was extremely rare (<1% of all sampled areas), even at recent removal sites. Plant composition differed among recent and older sites because newer sites were dominated by a combination of grasses and small or early successional forbs, and riparian trees were common at sites more than 30 years post-removal. Nevertheless, while older sites were different from younger ones, predictable patterns of replacement of one growth form by another were not apparent. Species diversity was also highly variable among sites within their first 10 years post-removal, with some sites being solely dominated by a few aggressive species while others contained a variable number of additional species. Diversity was consistently high for the oldest dam removal sites.

Based on these results, Orr and Stanley (2006) suggested that (1) persistence of exposed sediment for an extended period of time following dam removal is unlikely; and (2) plant communities are likely to continue to develop over time and not become arrested in an early successional stage.

3.3.2 Fish

The response of fish communities to dam removal in Wisconsin was documented by Kanehl et al. (1997) following the extraction of Woolen Mills Dam on the Milwaukee River. The dam was 4.3 m high, with an impoundment of 27 ha extending 2.3 km upstream. Removal occurred in 1988, although the impoundment was dewatered for long periods from 1979 to 1988. Sediment in the former impoundment was stabilized using vegetation and stone immediately after removal, and some of the channel was modified in 1989 to improve habitat quality for smallmouth bass.

Kanehl et al. (1997) established five study reaches around Woolen Mills Dam, with each reach being ~1.0 km in length, including a reference reach in a nearby river. Each of the five reaches was sampled to estimate quantitative habitat characteristics and relative abundance and size structure of fish once per year, particularly for smallmouth bass. Smallmouth bass are a highly desirable species for anglers and also are indicative of good habitat and water quality [see Kanehl et al. (1997) for justification of indicator species]. Using the fish assemblage data, biotic integrity of the site was estimated using a version of the Index of Biotic Integrity (IBI) developed for Wisconsin streams.

Removal of Woolen Mills Dam resulted in rapid geomorphic changes in the impoundment, including increases in sediment size, thalweg depth variability, and increased cover for fish (Kanehl et al. 1997). Cumulatively, these changes were reflected in increased habitat scores for the formerly impounded reaches and evident changes in fish assemblages following dam removal (Fig. 3-2). Carp, a ubiquitous and destructive non-native species, decreased in the impoundment site, while smallmouth bass increased. Interestingly, there appeared to be a ~3-year lag between dam removal and smallmouth bass recovery, whereas the effect of removal on carp was immediate. Cumulatively, IBI based on fish assemblage showed modest gains following dam removal, approaching but not reaching values for the reference reach. Worth noting is that the fish populations of interest here were limited not by the dam's presence as a migratory barrier, but because of the habitat changes induced by the dam. This is further discussed in Section 3.3.4.1.

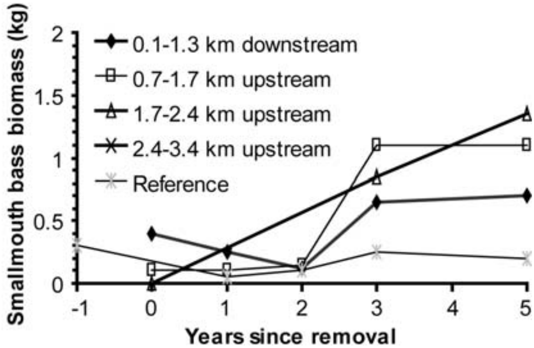

Figure 3-2. Changes in smallmouth bass biomass following dam removal. Source: Kanehl et al. (1997).

3.3.3 Macroinvertebrates

Stanley et al. (2002) examined responses of macroinvertebrates to the removal of two dams in the Baraboo River, Wisconsin. Three dams were removed between December 1997 and October 2001, during which time these researchers surveyed cross sections and collected benthic macroinvertebrate samples in multiple study and reference reaches before and after the removal.

Dam removal decreased cross-sectional area in the former impoundment as flow velocity increased and a channel incised into the reservoir sediment, although channel form in other reaches did not change. Fine, loose sediment was transported out of the impoundment reach and into downstream reaches. A flood in June 2000 (5 months post-removal) further widened the channel through the former impoundment and transported sediment farther downstream, out of the reach immediately downstream of the former dam site.

One year after the removal, macroinvertebrate assemblages in formerly impounded reaches were indistinguishable from those in the upstream reference site and in downstream unimpounded reaches (Fig. 3-3). Regardless of their impoundment history, all unimpounded reaches had macroinvertebrate assemblages comparable to those in natural streams. These results showed that, similar to fish response in the study by Kanehl et al. (1997), macroinvertebrate assemblage structure in the Baraboo River study was determined by habitat availability. Given the relative mobility and short life cycle of macroinvertebrates, it is reasonable to expect that assemblages have the potential for rapid response to dam removal and that changes will be constrained by the rate of geomorphic adjustment following removal. Recovery within 1 year or less in the Baraboo River

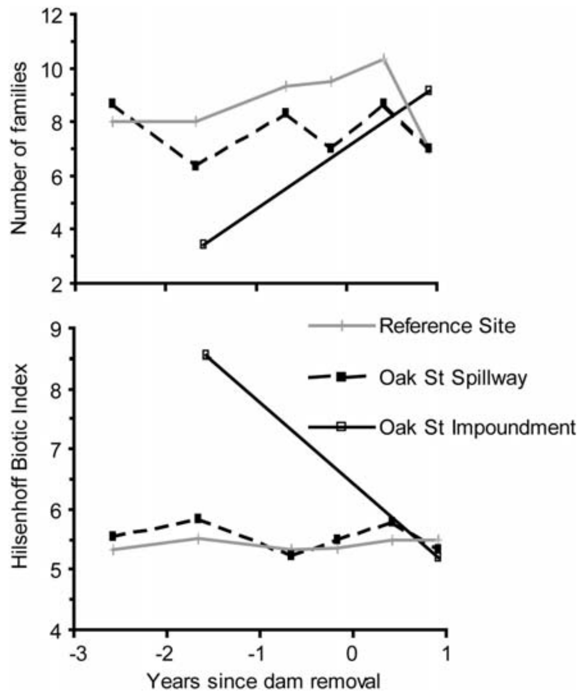

Figure 3-3. Changes in macroinvertebrate communities following dam removal. Source: Stanley et al. (2002).

may have been partly be due to the limited geomorphic disturbance caused by the dam's presence, and because the flood 5 months after removal increased the rate of geomorphic adjustment to dam removal and, presumably, the rate of habitat recovery.

3.3.4 Unionid Mussels

In an effort to gain a preliminary understanding of potential effects of dam removal on mussels, Sethi et al. (2004) conducted a post-removal survey of mussels within the impoundment and downstream following the removal of Rockdale Dam on the Koshkonong River. Within the former reservoir, mortality rates of mussels following dam removal were extremely high (95%) due to desiccation and exposure. Mussel densities in a bed 0.5 km downstream from the dam declined from 3.80 ± 0.56 mussels/m^2 in the fall of 2000 (immediately after dam removal) to 2.60 ± 0.48 mussels/m^2 by the summer of 2003. One rare species, *Quadrula* *pustulosa*, was completely lost from the community over the time of the study. Mortality of mussels buried in deposited silt was also observed at a site 1.7 km below the dam. Silt and sand substrate increased from 16.8% and 1.1%, respectively, of total area sampled in the fall of 2000 to 30.4% and 15.9%, respectively, in the summer of 2003. Total suspended sediment concentrations in the water column were always higher downstream from the reservoir than upstream. This transport and deposition of reservoir-born sediments likely contributed to downstream mussel mortality.

Overall, the physical changes caused by dam removal (lowered water surface, sediment transport to downstream) caused significant declines in mussel densities within the reservoir and downstream. Further, the absence of mussels in the newly formed channel since dam removal emphasizes the slow recovery of this group compared to the rate of recovery of fish and macroinvertebrates. Establishment in this newly created habitat requires persistence of viable downstream or upstream populations that act as propagule sources; fish colonization (because mussel larvae disperse to new sites by piggy-backing on fish); development of suitable habitat for mussels; and time (because mussels are long-lived, slow-growing organisms).

3.3.4.1 Nutrient Dynamics. To explore the potential linkages between dynamic channel morphology and nutrient retention, Doyle et al. (2003c) examined retention of soluble reactive phosphorus (SRP) through time at the Rockdale Dam removal site (described above) using both pre- and post-removal data and simulation modeling. Five time periods representing five geomorphically different conditions (Fig. 3-1) were modeled assuming steady-state nutrient uptake parameters, an incoming nutrient concentration of 0.15 mg/L, and a discharge of 2.7 m^3/s, which approximates the conditions for SRP on November 11, 2000. They also examined the effect of higher discharges by simulating retention at a discharge of 5.7 m^3/s.

Removal of Rockdale Dam on the Koshkonong River caused upstream-progressing erosion in the form of a discrete headcut, and subsequent geomorphic adjustments well-described by the conceptual model presented earlier (Doyle et al. 2003b). Changes in channel morphology were particularly pronounced downstream of the headcut as it migrated upstream. Eleven months after the removal, the headcut was located approximately 400 m upstream of the dam. Upstream of this point, the flow area was still relatively high, while downstream it was greatly reduced. Final equilibrium conditions had reduced flow area throughout the reservoir reach.

In the simulation results, pre-removal conditions represent the dam still in place, creating backwater conditions upstream (Stage A in Fig. 3-1).

Post-removal conditions represent the removal of the dam but prior to any geomorphic adjustments within the reservoir (Stage B). Eight months and 11 months after removal represent a transitional geomorphic condition when the reservoir is actively eroding reservoir sediment, and a channel is beginning to form in the downstream part of the reservoir (Stages D and E). For estimating final, long-term equilibrium conditions (Stage F, decades after dam removal), the channel geometry at an upstream channel cross section (4,180 m upstream of the dam) was extrapolated through the reservoir at a uniform slope between that cross section and the base of the dam.

The simulated SRP concentration showed that the backwater conditions created by the dam greatly enhanced nutrient retention and thus, as the free-flowing water progressed through the reservoir, there was a downstream reduction in nutrient concentration (Fig. 3-4). The greatest retention occurred in the final 500 m of the impoundment, where flow was the most stagnant and thus conducive to nutrient retention. Removal of the dam and formation of a narrow channel in the lower impoundment worked to greatly increase flow velocity, reducing the potential for nutrient retention. However, upstream of the headcut, the reservoir remained mostly unaffected by the dam removal, and so the nutrient retention trends are similar to when the dam was still in place. Final equilibrium conditions showed decreased, although still persistent, nutrient retention. These simulation results suggest that changes in channel morphology following dam removal can cause large changes in nutrient retention patterns within a stream.

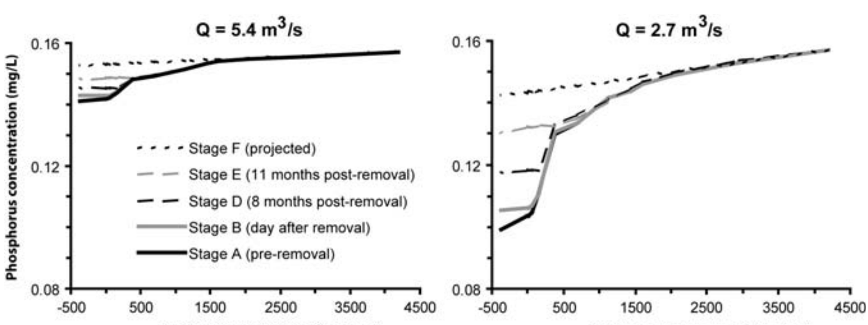

Figure 3-4. Simulated changes in phosphorus retention (SRP concentration) following dam removal. Q, water discharge. Source: Doyle et al. (2003a).

3.4 DISCUSSION

3.4.1 Synthesis

In this review of case studies from Wisconsin, we show that dam removal can affect stream ecosystems at multiple trophic levels, and, in each case, ecological changes could be related to geomorphic changes. Using the available geomorphic and ecological data presented above, a simplified conceptual model of ecosystem response to dam removal is suggested that considers the degree to which the river returns to a pre-dam state (Fig. 3-5). A single synthetic parameter is used to represent channel

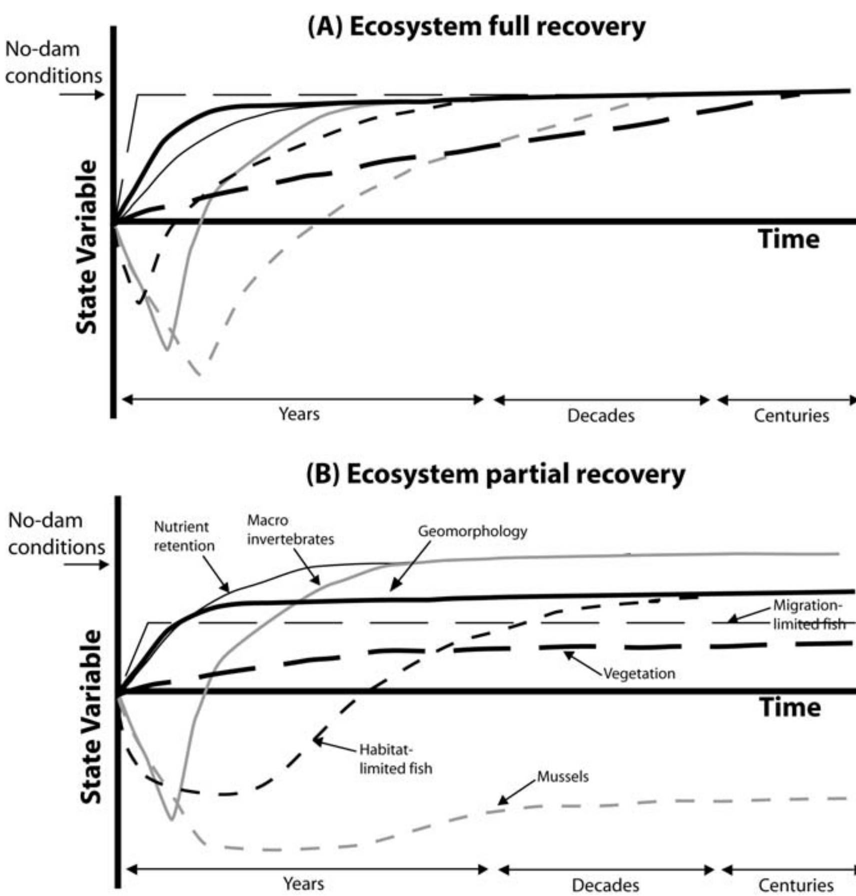

Figure 3-5. Conceptual framework for ecosystem recovery following removal of a small dam. Source: Adapted from Doyle et al. (2005).

morphology and single parameters are also used for each of the ecological attributes examined earlier. We have assumed that both physical and ecological changes through time are asymptotic toward an equilibrium or steady state, although alternative recovery trajectories are possible. In our first scenario (Fig. 3-5A), we assume that channel morphology as well as all components of the stream ecosystem will recover to a previous no-dam condition. In the second scenario (Fig. 3-5B), we assume full recovery of some components of the system but only partial recovery or alternative states for other components.

3.4.2 Conceptual Framework A: Ecosystem Full Recovery

An inherent assumption often exists that dam removal will result in the return to pre-dam conditions in many rivers. Even if all components fully recover following dam removal, recovery is likely to progress at disparate rates, just as is the case for natural disturbances such as flooding. Variability in response rates is important because, if changes in a monitored species or taxa are particularly slow, then a dam removal project may be perceived an ecological failure simply because the benefits of removal have yet to be realized.

Because many organisms are limited by habitat availability, much of the ecological recovery should be controlled by the rate of geomorphic recovery because geomorphic recovery is a necessary precursor to the development of natural stream habitat. Our observations suggest that the bulk of channel adjustments will occur within the first year after removal for small dams. The periphyton community, reflected by the nutrient retention modeling, is likely to recover rapidly following dam removal and should essentially move toward equilibrium at the same rate as channel morphology. Both fish and macroinvertebrate communities are expected to decline initially due to the disturbance of dam removal. Sediment movement in the former reservoir, downstream deposition, and elevated suspended loads should degrade habitat of fish and macroinvertebrates. Although we did not examine short-term mortality from sediment movement at our sites, others have reported substantial fish and invertebrate mortality in such circumstances (Doeg and Koehn 1994). However, results from the Baraboo River for macroinvertebrates and the Milwaukee River for fish suggest that both fish and macroinvertebrates have the ability to recover to no-dam equilibrium conditions, provided suitable habitat is created by geomorphic adjustments. Invertebrate recovery is likely to be slightly faster due to the shorter life-span of these organisms—an expectation supported by the 3-year lag in recovery of smallmouth bass in the Milwaukee River study. Because of their habitat needs, fish and macroinvertebrate recovery rates should not exceed geomorphic recovery rates but will follow closely behind. In contrast, if fish communities are limited by the dam as a migratory barrier rather than as a habitat disturbance, the simple act of removing the dam—although initially detrimental—may be sufficient to restore upstream fish communities, and thus recovery will essentially be instant.

The two ecosystem components considered in our overview that are expected to require the longest period of time to recover are vegetation and mussels. Vegetation showed surprisingly variable patterns with respect to time since dam removal, and apparently many decades may be required for the development of tree assemblages characteristic of riparian areas in Wisconsin. The rate of native vegetation establishment may be increased through active planting of the floodplain, although studies confirming this prediction have yet to be undertaken.

Of all the ecosystem components, our observations suggested that mussel communities in Midwestern streams were affected most severely by dam removal and did not become established in the downstream channel within 3 years after dam removal. Because mussel reproduction and colonization are dependent on fish, mussel recovery requires, at a minimum, the geomorphic adjustments necessary for fish recovery as well as those needed for the mussels themselves. Further, should a situation exist in which downstream source populations are significantly reduced following removal, recovery could be delayed simply by reduction of source populations. Recent studies have suggested that mussels do recover following catastrophic disturbance, but recovery may be on the order of decades (Sietman et al. 2001).

3.4.3 Conceptual Framework B: Ecosystem Partial Recovery and Loss

Removing a dam cannot be assumed to completely return the local ecosystem to pre-dam conditions. Indeed, removing a dam may instead cause permanent, irreversible ecological changes. Variable recovery scenarios are critical to consider because dam removals may be declared successful ecological restorations because of the return of a few notable large species or taxa (e.g., fish), while other less-notable taxa do not recover. This necessitates careful consideration of how to define successes or failures in dam removal projects (Doyle et al. 2003d). Weighing such costs and benefits of dam removal is important prior to undertaking large-scale dam removal plans. Numerous alternative scenarios of partial ecosystem recovery exist, and only a few are presented here as possibilities.

In this second conceptual model scenario, we assume that nutrient retention and macroinvertebrate communities recover to pre-dam conditions due to the bulk of geomorphic adjustments allowing these parameters to approach pre-dam conditions (Fig. 3-5B). However, we also assume that channel morphology recovers toward pre-dam conditions but morphologic conditions identical to pre-dam are not attainable. Such causes for this partial recovery could be that dam-induced incision is irreversible, or that upstream sediment loads are very different from pre-dam conditions due to land use changes and are sufficient to cause post-removal morphology to be substantially different from that prior to dam construction. Due to the relatively low recovery of channel morphology in this scenario, habitat-limited fish would not recover completely to pre-dam conditions.

Despite not being limited by habitat within the former reservoir, it is possible that migration-limited fish species travel upstream following dam removal only to find degraded habitat, poor water quality, or aggressive competitors and predators. Thus, the ability to migrate upstream will not necessarily restore pre-dam fish populations. For habitat-limited fish, downstream populations may be so heavily decimated by elevated suspended sediment loads immediately following dam removal that longer periods of time are needed before they are able to reproduce and establish viable populations.

For vegetation, C. H. Orr suggested that initial conditions at the time of dam removal are critical in determining the trajectory of vegetation change through time (unpublished M.S. thesis, "Patterns of Removal and Ecological Response: A Study of Small Dams in Wisconsin," University of Wisconsin, Madison, 2002). While occurrence of tree species increased through time, Orr noted that exotic species now common in the region were less prevalent at the time of removal for older sites, particularly reed canary grass (*Phalaris arundinace*). Thus, succession of plant communities is currently occurring under very different conditions than existed at the time of dam construction. How the presence of aggressive exotic species alters rates and patterns of vegetative change at removal sites remains to be determined.

As with riparian plant communities, the long-term effect of dam removal on mussels in the midwestern United States is unknown. Mussels, or any other acutely sensitive group of species, may be vulnerable to any change in the river system attributes. That is, regardless of the long-term benefits, the drastic short-term changes may be sufficient to reduce local populations below a threshold, restricting further recovery, as may be the case for *Quadrula pustulosa* on the Koshkonong River. If this scenario is correct, then dam removal poses a dilemma for management and recovery of mussel populations. Existence of dams is a major contributor to long-term declines in this group, but dam removal may push this weakened group over a threshold beyond which recovery of local populations is no longer possible.

3.4.4 Variability in Ecosystem Responses

In this review we have examined only sites within Wisconsin, so our results by no means represent all potential dam removal scenarios. Great regional variability is likely to exist in the types of dams and their effects on local ecosystems, and thus the potential changes to local ecosystems caused by their removal. For instance, two concerns in Wisconsin (nutrient loading and mussel communities) may not be relevant in other areas that are nutrient-limited, and thus would benefit greatly from dam removal, or in areas lacking downstream mussel populations. Further, areas with limited sediment loading to streams may have very little reservoir sediment accumulation, and thus removal would constitute a fairly insignificant disturbance. However, we expect that in all cases there will be some benefits and some ecological costs to removing a dam, and these should be explicitly identified for each case.

3.4.5 Management Implications

Dam removal represents a very significant opportunity to restore geomorphic and ecological functioning in previously disturbed stream ecosystems. While certain aspects of stream ecosystems will undoubtedly return to pre-dam or near-pre-dam conditions rapidly after dam removal (e.g., Stanley et al. 2002), the assumption that removing a dam will rapidly reverse the cumulative effect of years of environmental degradation caused by the dam's presence for all components of the stream ecosystem is unrealistic (Stanley and Doyle 2002). The very real possibility exists that environmental restoration associated with dam removal will not be evident for years, or even decades, after a dam is removed, and this will likely vary between components of the ecosystem. In fact, decision makers must consider the potential for dam removal to cause irreversible degradation to specific ecosystem attributes. However, the benefits of dam removal are likely to be substantial, and thus dam removal represents a very powerful tool for restoring streams to more natural conditions.

The goal of management agencies responsible for removing dams should be to minimize the negative impacts of a removal as well as to maximize the rate of recovery of the physical and ecological systems. Thus, a primary goal should be to identify those species or taxa that are particularly sensitive to disturbance, and mitigate the potential impacts of dam removal. This will likely increase the cost of many small dam removals. Further, because channel morphology and channel adjustments control many of the subsequent attributes of the stream ecosystem, management agencies should focus on maximizing the rate of physical recovery following dam removal. This may involve channel manipulation, stabilization, or bioengineering. Currently there is very little basis from which to approach a channel design in a former impoundment, but tools are available with which to begin such a project (ASCE 1997).

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CHAPTER 4

BUREAU OF RECLAMATION CASE STUDIES OF DAM REMOVAL

Cassie C. Klumpp

4.1 INTRODUCTION

Of the estimated more than 2 million dams in the United States, more than 25% are older than 50 years; the primary reason for dam removal is exceeded design life. Dams also cause significant riverine environmental problems. More than 75,000 dams greater than 5 ft tall are found in the United States, and 50,000 dams greater than 50 ft tall can be found worldwide (National Research Council 1992). Hydropower operations harm fish and other biota by causing irregular flow patterns and negatively affecting water temperatures. Operations have been adjusted for some dams to mitigate these effects. For example, operations were changed at Flaming Gorge Dam on the Green River in Utah to protect endangered species; spring flooding was allowed to occur and daily flow fluctuations were changed to protect fisheries (Bednarek 2002).

Sediment transport is also altered by dams. Storage dams slow river velocities, causing sediment to settle as flow enters the reservoir, and aggradation of the streambed upstream. Because of sediment deposition upstream of the dam, clear water is released from the dam, resulting in channel erosion downstream (Bednarek 2002). The downstream channel may become armored, resulting in channel incisement, bank erosion, and the loss of riparian habitat.

However, dams provide vital functions to mankind, including water supply for irrigation, municipal and industrial use, navigation, recreation, and hydroelectricity. Dams may reach a point where it is necessary to decommission them based on economics, dam safety, or ecosystem restoration. In some instances, dams are either reaching their capacity or are having adverse effects on downstream river systems, including blockage of fish movement, collection of sediment and debris, and alteration of temperature and river system characteristics (Aspen Institute 2002)

Prior to dam removal, it is important to predict the equilibrium channel upstream post-removal. Because the reservoir area alters sediment and vegetation from their natural states, undisturbed reaches can be a starting point for determining pre-removal channel width and depth (Pizzuto 2002), but prediction of eventual channel width and depth can be difficult. Models of channel evolution for incised channels can help identify width changes associated with dam removal, and these conceptual ideas may help to improve sediment transport models that are used in dam removal analysis. The objective of this chapter is to describe the Bureau of Reclamation's (hereafter, Reclamation) current dam removal projects, and to identify deficiencies and successes in prediction of sediment dynamics in dam removal by application of one-dimensional (1-D) sediment transport models.

Three case studies of dam removal projects will be presented. These case studies are Savage Rapids Dam on the Rogue River in Oregon, Matilija Dam on the Ventura River in California, and Coleman and South Dams on Battle Creek in California. Each project will be described in terms of sediment characteristics and dam removal options.

4.2 CASE STUDIES

4.2.1 Savage Rapids Dam

Savage Rapids Dam is located on the Rogue River in Oregon at River Kilometer 175.5 (Table 4-1) (Bountry and Randle 2001). A permanent pool extends upstream ~0.8 km. Although Savage Rapids Dam has fish ladders, they are old and do not meet current fisheries criteria, and dam removal has been proposed to restore fish habitat to natural conditions.

Sediment has deposited behind the dam and filled up the permanent pool. The reservoir pool is very small and probably filled to capacity during its earliest years. Approximately 153,000 m^3 of sediment is stored

Table 4-1. General Characteristics of the Studied Dams

Dam	Height (m)	Reservoir Volume (m^3)
Savage Rapids	3.75	153,000
Matilija	58	6,000,000
Coleman	13	30,000
South Diversion	30	30,000

in the permanent reservoir pool, mainly consisting of sand and gravel (Bountry and Randle 2001). This sediment volume is equivalent to 2 years of sediment transported by the Rogue River at Grants Pass. The majority of coarse sediment (sand and gravel) is transported during periods of high flow on the Rogue River, mainly during winter floods

Complete removal of Savage Rapids Dam has been proposed, with the construction of a pumping plant to deliver water to irrigation canals. The HEC-6T computer model (Thomas 2001) was applied to predict the volume of sediment eroded from the reservoir. The model uses Yang's sediment transport equation (Yang 1984; 1973) to determine the rates of erosion and sediment delivery to the downstream river channel and the temporary downstream deposition. Model inputs included channel cross-section data, flow hydrographs, water slope, friction resistance, upstream sediment supply, sediment bed composition, and thickness of the bed sediment.

Another key component of any dam removal analysis is the timing and magnitude of river flows (Bountry and Randle 2001). The magnitude and duration of peak flows during and immediately following dam decommissioning can affect the flux of stored sediment. For the decommissioning of Savage Rapids Dam, two hydrologic modeling sequences were considered based on historical discharge data: dam removal followed by a period of relatively dry years with very few winter flood peaks, and dam removal followed by many wet years with several flood events. Complete removal of the dam was simulated with erosion occurring initially.

The model results indicated that following dam removal, about three-fourths of the reservoir sediment would be eroded within the first year and transported downstream, and would be independent of the hydrology. Virtually all of the remaining reservoir sediment would be eroded during subsequent high flows. The reservoir sediments would be transported at least 12.5 miles downstream past the next major tributary in a period of 1 to 10 years, depending on the magnitude and frequency of high flows (Bountry and Randle 2001). The eroded sediment would temporarily deposit in downstream river pools during low-flow periods, with maximum deposition ranging from 1 to 8 ft. However, sediment was not predicted to deposit in riffles or rapids (hydraulic controls), and therefore dam removal is not expected to increase downstream flood stages.

4.2.2 Matilija Dam

Matilija Dam (Table 4-1) is located the on a tributary of the Ventura River in southern California, 26 km from the Pacific ocean (USACE 2002). The Ventura River watershed is a 360-km^2 coastal watershed that includes rugged mountains in the upper basin; about 75% of the basin is rangeland covered with brush and shrubs (USACE 2002). The rangeland area produces the largest amount of sediment in the watershed.

Initially, Matilija Dam provided necessary water supply to the region, but problems with the dam have been evident since its construction in 1948. This includes large volumes of sediment deposition behind the dam, loss of water supply availability, obstruction of fish passage, and loss of riparian and wildlife corridors (USACE 2002). According to the U.S. Army Corps of Engineers (USACE) (2002), it is estimated that 4.6 million m^3 of sediment is deposited behind the dam, and approximately 50% of the sediment is sand and gravel. Release of this sediment would benefit the ocean beaches near Ventura. The dam now has only 616,000 m^3 (7%) of its reservoir capacity available. Prior to the construction of Matilija Dam, the Ventura River system allowed the annual spawning of 4,000 to 5,000 steelhead trout, an endangered migratory trout (USACE 2002). Construction of the dam resulted in a loss of 50% of the prime habitat for these fish.

The dam has weakened in its upper portions due to alkali–concrete reactions. A feasibility study of Matilija Dam is now being conducted to determine the future effects if the dam is left in place, and additional studies are being conducted to determine the effects of partial and complete dam removal. Portions of the dam were removed in 1965, 1979, and 2000, resulting in a current dam height of 36 m (USACE 2002). Reclamation has evaluated three areas behind the dam (Greimann 2003): the reservoir pool, which stores approximately 1.6 million m^3 of sediment (mostly silts and clays); the delta of the reservoir, which extends approximately 0.45 km upstream and stores approximately 1.9 million m^3 of silty-sand material; and the upstream channel, which stores about 1.0 million m^3 of sands, gravels, and cobbles. If the dam remains in place, sediments will continue to deposit behind the dam for the next 35 years, with an additional 7 million m^3 of sediment depositing behind the dam. The storage capacity of the dam will then be only 1% of its original capacity.

The 1-D Sedimentation and River Hydraulics (SRH) Model (Yang et al. 2003) was used to model sediment transport for different scenarios for the removal of Matilija Dam. According to Greimann (2003), this used the Meyer-Peter and Muller (1948) formula for gravel load and the Engelund and Hansen (1972) formula for sand load. The three scenarios included (1) complete dam removal in one notch, (2) partial removal of the dam to an elevation of 317 m, and (3) no dam removal (Table 4-2). The scenarios were modeled with a peak discharge of 396 m^3/s based on a 1998 storm, or an approximately 20-year-return-period flood.

For complete dam removal, approximately 60% of the sediment material (520,000 m^3 of silt and clay) would be removed. Approximately 0.7 million m^3 of material would have eroded prior to dam removal because of the creation of the notched channel to start the dam removal process

Table 4-2. Matilija Dam: Summary Table for the ~20-Year Flood

Scenario	Erosion from Reservoir (m^3)	Maximum Elevation Increase (m)	Maximum Sediment Concentration (mg/L)	Ending Sediment Concentration (mg/L)
1: Complete dam removal in one notch	520,000	1.5	400,000	20,000
2: Partial removal of the dam to an elevation of 317 m	275,000	1.2	400,000	20,000
3: No dam removal	–382,000	0.9	30,000	2,000

Source: Greimann (2003).

(Greimann 2003). This means that approximately 25% of the material would be removed after the 1998 storm. It is expected that future storms would remove less material but the material size would be coarser. The sediment concentrations for complete and partial dam removal (400,000 mg/L) are predicted to be much higher than normal riverine conditions (20,000 mg/L) after such a storm has passed.

4.2.3 South and Coleman Dams

Battle Creek, a cold-water mountain stream located west of Lassen Peak in northern California, joins the Sacramento River about halfway between Redding and Red Bluff near the Coleman National Fish Hatchery. Battle Creek is known as one of the three remaining Sacramento River tributaries in which spring-run and winter-run Chinook salmon and steelhead trout continue to exist. Its long, deep-shaded canyons provide productive habitat for salmon.

The Battle Creek drainage is an alternating pool-and-riffle-sequence stream that repeats every five to seven channel widths. The pools contain finer bed material; riffles are shallower with coarser bed material. The river has a large range of material (from sand to boulder size) available for transport (Greimann 2001). Periodic bars also exist that store significant amounts of sediment.

The South Fork of Battle Creek is very steep, especially in the upper reaches (slope > 0.03). Large bed material sizes are D_{50} = 200 mm. Below the confluence with the North Fork of Battle Creek, the river slope decreases to less than 0.01, and near the confluence with the Sacramento River the river slope decreases to only 0.0015 (Greimann 2001).

In the early 1900s the Northern California Power Company constructed five diversion dams on the North Fork and three diversion dams on the South Fork, along with a complex canal system, to generate hydroelectric power at five power plants. Pacific Gas and Electric (PG&E) has owned and operated the Battle Creek Hydroelectric Project since 1919.

Declining salmonid populations in the Sacramento River have resulted in increased restoration efforts to preserve and enhance current fish populations. Numerous studies have identified restoration of fish passage in Battle Creek as a top priority. Studies are presently being conducted to improve water quality concerns at the Coleman National Fish Hatchery and to improve anadromous fish populations within Battle Creek. The California Department of Water Resources (DWR) developed designs for fish ladder and fish screen locations to improve upstream fish passage for adult salmon and steelhead, and downstream passage of juvenile fish. Reclamation developed plans for removal of one diversion dam on the North Fork and two diversion dams on the South Fork of Battle Creek to improve the fishery.

The sediment material located behind Coleman Dam (Table 4-1) is approximately 30% of the annual volume. Estimates of the amount of sediment stored in bars downstream approximately (3,800 m^3/km) suggest that 13 km of stream store the equivalent amount of sediment stored behind Coleman Dam. Utilizing the 1-D SRH sediment transport model (Yang et al. 2003) with Yang's sediment transport equation (Yang 1984; 1973) and assuming complete removal of Coleman Dam and the formation of a typical pre-dam channel, slightly more than one-third of the material stored behind Coleman Dam (9,000 to 10,000 m^3) would be transported in an average or wet year, and no more than 10% of the sediment would be transported in a dry year. With a series of average or wet years, the reservoir channel would quickly return to pre-dam conditions in less than 6 years. A series of dry years would take longer than six years to return the bed profile to pre-dam conditions, but little sediment would be deposited downstream. Bed material sizes in the first mile downstream would tend to become slightly finer but would not significantly alter the channel characteristics such that they would affect the fishery (Greimann 2001).

South Diversion Dam (Table 4-1) is in a steeper reach of the South Battle Creek drainage. Removal of this dam could result in mobilization of no more than 25% of the material stored behind the dam in the first year for an average or wet year scenario. Much of the material would not be mobilized because of the large cobble and boulder material stored behind South Dam. The volume of sediment stored in bars downstream from South Dam is estimated at approximately 1,500 m^3/km. Most of the

Table 4-3. Volume and Depth of Sediment Trapped behind Dams Scheduled for Removal

	South Diversion	Coleman Diversion
Trapped sediment volume (m^3)	23,000	22,000
Maximum depth of sediment (m)	7	4

additional material transported from South Dam would be stored in bars downstream of the dam. As with Coleman Dam, little fining of the bed material downstream would be evident based on the analysis. The bed profile would quickly return to pre-dam conditions, resulting in few effects on the anadramous fishery.

The volume and depth of sediment trapped in South and Coleman Dams are given in Table 4-3.

4.3 CONCLUSIONS

Three case studies of potential dam decommissioning were examined, involving dams of different sizes and physical settings. The smaller dams (Savage Rapids, South, and Coleman Dams) are predicted to have a fairly rapid return to pre-dam conditions because the relative volume of sediment stored in these dams is no more than 1 to 3 years of sediment supply. Sediment concentrations would increase initially, but would quickly return to pre-dam conditions. The estimated impact of the smaller dams on the environment following removal would be small.

Matilija Dam is a much larger dam and its removal would result in very high sediment concentrations and somewhat large bed changes downstream. It would require a period of 7 to 10 years to return to pre-dam conditions. Extensive monitoring of the sediment concentrations and bed changes should be included in the dam decommissioning plan. Any sediment released downstream would deposit somewhere because of decreasing channel slopes, or the river would enter a lake or ocean. Depositional effects must be carefully studied to determine whether the effects from any sediment management alternative are acceptable. Monitoring would be essential during reservoir drawdown to validate model predictions and prevent large short- or long-term environmental harm (Randle 2003).

1-D sediment transport models were successfully applied to predict average sediment transport rates, bed change, and grain size changes. Accurate prediction of sediment transport is not as critical for smaller dam removal projects, such as those presented herein, as for larger-scale projects. Improvement in prediction techniques will continue with the collection of field data on sediment transport, sediment volume, and bed changes from actual dam removals to help calibrate predictive models. 1- and 2-D sediment transport models may be applied in future dam removal cases to understand the physical conditions that will occur regarding sediment during dam removal. It is important to improve the current useful 1-D models to be able to determine hydraulic and geomorphic processes after dam removal (Pizzuto 2002). Monitoring of morphological processes following dam removal should help improve numerical models for use in predicting sediment transport and morphology for future dam removal projects.

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CHAPTER 5

CHANNEL EVOLUTION UPSTREAM OF DAM REMOVAL SITES

James G. MacBroom

5.1 INTRODUCTION

The removal of obsolete, unsafe, and environmentally harmful dams has become increasingly frequent in the past decade due to their increasing age and deterioration, favorable economics for removal, and environmental impact. Among the key technical issues are the fate of impounded sediments, aquatic habitat, water quality, risk of downstream channel aggradation, and uncertainty about the formation of a channel upstream of the dam through the impoundment area.

It is important to establish specific goals for channels and sediments upstream of dam removal sites so there is a clear understanding of and consensus on the river management approach. The goals vary from site to site and could include providing fish passage, minimizing sediment erosion, achieving channel alignment stability, grade control, and improving recreation, water quality, and safety. Post-dam fish passage and habitat restoration requires that the channel through the breach and across the impounded area has flow depths, velocities, substrate, and features appropriate for the targeted fish species. Coordination with regulatory agencies and aquatic biologists is essential to identify the desired aquatic species and their habitat characteristics. Sediment management may include stabilization-in-place, allowing its natural erosion, on-site relocation, or off-site relocation via partial or full dredging. There is a popular but erroneous perception that dam removal will always release impounded sediments and create problems. While this has occurred at some sites, most notably the Hudson River's Fort Edwards Dam, sediment release is not a universal problem. A typical evaluation of upstream conditions includes the following procedural steps:

1. Assess pre-dam channel conditions, hydrology, and morphology.
2. Evaluate impounded sediment formations, gradation, cohesion, and density.
3. Sample and test sediments for contamination.
4. Study sediment stability and channel evolution.
5. Determine whether uncontrolled channel evolution is acceptable.
6. Develop a channel and sediment management strategy.

The ability to anticipate future channel response is summarized by Pizzuto (2002), who states "[G]eomorphologists remain unable to forecast stream channel changes caused by the removal of specific dams." The review of dam removal analogies, however, along with channel evolution models and increasing observations of dam removals helps to identify channel evolution trends.

The purpose of this chapter is to assess the wide variety of channel types that evolve after dam removal and to develop an empirical model to help predict post-dam channel evolution. This model is already being used to screen and prioritize potential dam removal projects.

5.2 BACKGROUND

5.2.1 Impounded Sediment Formations

Channels that form after dam removal are dependent upon the watershed hydrology, pool bathymetry, and the characteristics of sediments in the impoundment. These materials affect the channel's slope, width, depth, stability, substrate grain size, rate of erosion, and location. The classic deposition pattern in an impoundment has often been described as a three-part sequence. The heaviest particles entering the impoundment settle fastest and are found near to the inflow point, creating a delta. As material accumulates, particles are transported to the downstream end of previous deposits before settling, forming a foreset deposit with a steep face. Smaller particles that settle slowly are transported beyond the coarse deposits, gradually accumulating as bottomset deposits spread over the base of the impoundment, or are transported past the dam. The upper surface of the delta deposit may aggrade to the pool level and become a floodplain or island, receiving topset deposits from later flood flows.

Morris and Fan (1998) and White (2001) studied sedimentation processes in reservoirs and discuss potential deposition patterns. In addition to deltas, wedge-shaped deposits may fill deep-water areas behind the dam and become thinner in the upstream direction. This is attributed to high-density turbidity currents that carry sediments across the reservoir bottom, and also can occur in large reservoirs operated with low water levels. Uniform bottom deposits may occur when sediment loads are comprised of fine materials or when water levels fluctuate over a broad vertical range.

Studies of sediments in temporary glacial lakes in New England have identified seven types of depositional patterns called morphosequences (Stone et al. 1998), with three types of deposits consisting of fluvial, deltaic, and lake bottom. The drained glacial lakes allow direct observation of these deposits, which is seldom possible in active impoundments.

5.2.2 Channel Initiation

Channel erosion into impounded sediments after dam removal may be initiated in several different locations, starting at the delta face, dam site, inflow source, or by general progressive degradation. Breaching or removing a dam at the downstream end of impounded sediment creates a steep hydraulic gradient with high velocities and often high turbulence. This creates opportunities for local scour and creation of headcuts that migrate upstream, removing sediment at the exposed face and at the sides of the scoured channel as the banks become higher and steeper, ultimately leading to collapse. The migratory direction of the headcut will be influenced by gradients, flow velocities, and sediment characteristics, with headcuts typically extending upgradient following the highest velocities.

Redeposition may occur within the pool area or downstream of the dam if sediment transport capacity is less than the rate at which sediment is supplied from upstream. Channels that are carved into shallow deposits may quickly reach tough pre-dam soils, bedrock, or old channel armor that limits incision (Morris and Fan 1998). These conditions promote earlier channel widening or even increased sinuosity.

5.2.3 Sediment Control

Numerous methods are available to control the impounded sediments at dam removal sites. The intent of this approach is to retain the bulk of the sediment in place by controlling the channel's bed elevation; it is appropriate when the slope of the pool's sediment surface is suitable for an equilibrium regime channel and when the sediment thickness at the dam allows for a reasonable transition length between the downstream channel bed and the new upstream channel bed. Grade control methods include timber or steel sheeting, check dams, boulder sills, concrete drop structures, created riffles, and riprap channel sections. Their primary limitation, of course, is that vertical grade controls may block fish passage. Examples of grade control systems are the steep riprap channel installed at the Lake Switzerland Dam site in the Catskill Mountains of New York, and the cobble-lined channel at Zemko Dam in Eightmile River at Salem, Connecticut. In both cases, little sediment was released during and after dam removal.

Other sediment control measures at low dams include mass excavation, sediment relocation, preemptive channel excavation, partial dam removal, and bypass channels. During the 2006 removal of Ballou Dam from the Ballou Pond River in Berkshire County, Massachusetts, sand and gravel sediments were excavated to form a new step pool channel before they could erode. Cohesive contaminated sediments were excavated from Mill Pond Dam (Norwalk, Connecticut) during construction to prevent the release of mercury into downstream waters, and channel controls were used to prevent sediment releases from channel incision at the Billington Street Dam (Town Brook, Massachusetts) removal project. The Lowell (Johnson County, North Carolina) and South Batavia (Batavia, Illinois) Dams were only partially removed in order to retain asymmetric sediment deposits in place.

5.3 METHODS

5.3.1 Empirical Channel Evolution Forecasts

Several techniques are available to forecast future channel evolution upstream and downstream of dam removal projects. Empirical methods include the study of completed dam removal projects and review of similar phenomena. The writer has completed dam removal site investigations and feasibility studies at more than 60 sites and completed the removal of 15 low dams that are being informally monitored. Several analogies have also been considered to indirectly study the impact of dams and dam removals (Poff and Hart 2002). Natural analogs include debris dams, beaver dams, landslides, waterfalls, and lake outlets. The writer has considered four additional analogies (reservoir drawdowns, reservoir flushing, glacial dams and lake sites, and dam failures) to help define physical sediment deposits and channel evolution processes. Analytical methods are based upon hydraulic analysis of flow velocities, shear stress, and sediment transport with rigid or mobile boundaries. Analytical methods should be supplemented with empirical and historic data to help verify possible channel behavior.

5.3.2 Field Observations and Discussion

The initial factors affecting post-dam channels are whether the impoundment has sediment and the presence of a pre-existing channel or thalweg across its bed. At the Cuddebackville Dam on the Neversink

River in New York, a low run-of-the-river dam site, there was no appreciable sediment and the post-removal flow simply reverted back to the pre-dam channel without new incision or widening of any kind. At the Chase Brass Dam on the Naugatuck River in Connecticut, there was a uniform veneer of thin bottom deposits across the impoundment that did not fill the old channel, and the post-dam flow simply reverted to the pre-dam channel with few geomorphic changes or sediment transport. Unconsolidated sediment in the pre-existing channel is likely to be rapidly removed with minimal channel migration.

Coarse, poorly graded sediments, often found at run-of-the-river dams or in steep watersheds with high bed loads, encourage wide, shallow channels that may form an armored bed. The Platts Mill (Spartansburg, Pennsylvania) and Anaconda (Tooele, Utah) dams fall into this category. Channels that form on fine sediments tend to initially degrade vertically, with periodic mass bank failures as the steep banks become too high for cohesive materials. The depth of incision will be limited by the channel's baselevel, equilibrium slope, or non-erodible materials. This condition was observed at Bunnells Pond Dam (Bridgeport, Connecticut) and Norwalk Mill Pond (Norwalk, Connecticut).

Another type of channel evolution occurs where a delta of coarse sediment extends part-way into an impoundment, creating a subaqueous mound that longitudinally bisects the impoundment. When water levels were drawn down at MacKenzie Reservoir (Connecticut) and at Red Cedar Lake (Lebanon, Connecticut) for dam repairs, the incoming flows split across the delta, much like an alluvial fan, resulting in an anabranched condition. This resembles braiding but is created by degradation rather than deposition. Another example of this scenario is the site of the former Jenkins Dam on the Neponset River in Boston. Following its removal (about 1960) in response to a flood, the river became anabranched around the delta with one channel following each bank, leaving the old pond sediments as islands, which still remain more than 50 years later.

Concern has been expressed about channel degradation or headcutting upstream of dams that have been removed. In many cases, rivers in upland areas are naturally degrading and headcuts are quite common. Headcuts at dams will release previously stored sediments that will be transported downstream. This process is harmful where it causes excessive environmental damage such as burial of benthic species or spawning sites, or causes water quality problems such as high turbidity. Excess sediment can also aggrade channels, obstruct bridges or culverts, and raise flood water levels.

Upstream channel degradation has not been a major problem at low dam removal sites. It is either limited due to shallow sediments or intentionally controlled before it develops. Control methods include the construction of boulder ramps (Platts Mill Dam), created riffles, and vortex weirs (Billington Dam, Plymouth, Massachusetts). Shallow headcuts with minimal channel damage are being allowed to run out at the Anaconda and Union City (Pennsylvania) dams. The 1979 failure of Community Lake Dam on the Quinnipiac River in Wallingford, Connecticut initiated a 3-ft-high knickpoint that migrated 1 mile upstream to the head of the original pool, where it had to be controlled by a concrete sill installed at a sanitary sewer crossing that was in danger of being undermined.

5.3.3 Sediment Presence

One should not assume that all dams have sediment. Many of the nation's dams are low run-of-the river structures with short retention times, and some of these have limited sediment accumulation. The removal of the 6-ft-high, 220-ft-long Good Hope Mill Dam in Pennsylvania exemplifies this class. Removed in 2001 for fish passage, only traces of sediment over a bedrock and gravel bottom were found, and no significant cross section changes occurred (Chaplin 2003). Subsequent inspections by this writer found no mass bank erosion, little reduction in waterway width, and no downstream deposition. Similar conditions were present at Freight Street Dam on the Naugatuck River in Connecticut, removed in 1999. The 158-ft-long low concrete dam had little upstream sediment and no changes in morphology (Wildman and MacBroom 2000). Seven years after removal, the dam site is indistinguishable from upstream and downstream river reaches.

Pre-removal studies of the 25-ft-high, 917-ft-long Edwards Dam in Maine found little sediment in its 15-mile-long but narrow impoundment, in part due to frequent flood flows and upstream dams (Dudley 1999). The through-flow velocity was sufficient to minimize settlement of fine-grain sediments, and coarse sediment was forecast to remain in place (Oak Ridge National Laboratory 1997). The post-dam river has rapidly returned to free-flow conditions, with documented fish returns to upstream areas. A similar lack of sediment was found during dam removal studies at the Veazie, Great Works, and Howland hydroelectric dams in the Penobscot River basin in Maine (Milone & MacBroom 2003).

5.3.4 Submerged Barriers

It is not unusual to find substantial objects that are submerged in dam impoundments or buried in sediment, which modify channel evolution after dam removal. The water drawdown to inspect Sandy Hook Dam (Connecticut) exposed an old, undocumented timber crib structure retaining sediment upstream of the modern concrete dam, and our bathymetric surveys of the Veazie and Great Works dams in Maine found partial remains of nineteenth-century submerged dams. The sediments at

Carbonton Dam (North Carolina), removed in 2005, were held in place by a submerged log jam that had to be removed. Channel evolution at other sites has been affected by buried automobiles, boats, tires, trees, stumps, barrels, head races, and shopping push-carts.

5.3.4.1 Narrow Impoundments. Narrow impoundments occur where dams were built in confined valleys with significant cross-section side slopes, or at run-of-the-river dams whose pools are largely contained in the original banks. Dams constructed across previously incised channels, such as gorges, fall within this category. The post-dam channels across narrow impoundments have limited opportunity for lateral expansion or meandering and often revert to their original alignment.

Narrow impoundments with thin sediment deposits pose few problems due to limited volumes. The channel alignment has little flexibility due to the lateral constraints, and thin sediments do little to inhibit its return to the original thalweg. Sediment management could include no intervention (due to small sediment quantities), or sediment removal if there are contaminants or water quality concerns. With narrow impoundments and thin sediments, there is little need to preform the future channel's alignment, width, and depth. Narrow impoundments with high dams could have substantial sediment thicknesses. The post-dam channel will have a constrained alignment but could become incised, resulting in banks that could exceed critical heights for stability. The degree of incision will be influenced by the potential channel gradient, velocity, and substrate, while the channel width is influenced by the strength of the banks.

5.3.4.2 Wide Impoundments. Wide impoundments are defined here as those with a width (at the water surface) more than three times the width of the meander belt of the subsequent channel. The channel is not laterally constrained and is able to have lateral movement and a sinuous alignment. The relatively large width of wide impoundments also means that the subsequent self-formed channel may not revert to its pre-dam alignment, and may change alignment as it evolves.

The behavior of the Poquannock River at Bunnells Pond Dam in Bridgeport, Connecticut is an example of channel realignment. During dam repairs in 2001 and 2002, the wide impoundment was drained, exposing a flat sediment plain. The initial channel was near the left (east) bank of the impoundment, formed by a combination of vertical incisions and headcuts. Following floods and temporary overbank flows, an alternate channel evolved closer to the right bank and captured all flow. Within 1 year, the latter channel quickly developed into a stable, straight equilibrium alluvial channel with an armored bed and no lateral meandering or subsequent degradation.

Observations indicate subsequent channels in wide impoundments with fine-grain sediments can degrade by either vertical incision or headcuts that migrate upstream. The incised channels retain relatively straight alignments until reaching vertical non-erodible controls that limit upstream gradients; then meandering begins. The Connecticut River at post-glacial Lake Hitchcock at Wethersfield, Connecticut and above Holyoke, Massachusetts behaved in this manner, as well as Six Mile Creek in Tomkins County, New York. The incision of subsequent channels at wide glacial lakes removed only a small part of the total available lakebed sediments.

5.3.5 Channel Pattern

Channel planform patterns are related to discharge, slope, and sediment size, with meandering rivers common on mild slopes found on depositional floodplains and less-sinuous channels common on steeper gradients. The initial bed gradient of a channel is based on the sediment's top slope, which may vary from very flat over bottomset deposits to steep on foreset delta deposits. Observations at sites where low dams have been removed indicate that channel degradation to an equilibrium bed slope occurs initially by rapid incision, and that the steep gradient creates a low-sinuosity channel. The reach downstream of the headcut then adjusts its pattern to fit its flow, sediment load, gradation, and slope. Straight channels developed after removing the Union City and Anaconda dams, both of which had fairly steep pre-dam channels.

Recent studies (Milone & MacBroom 2003) of Six Mile Creek near Ithaca, New York found that the channel incised into fine-grain glacial lake bed sediments until an equilibrium slope was reached, and then sinuosity increased with lateral movement into legacy sediments. The 25-ft-high Mad River Dam in Waterbury, Connecticut was notched in 1999 to draw down water levels. The spillway was subsequently removed and a new channel was dredged; it then immediately widened and increased sinuosity, but did not degrade. The meandering channel movement led to considerable sediment removal.

5.4 DAM REMOVAL ANALOGIES

5.4.1 Reservoir Drawdowns

Sediment deposits and channels that evolve after reservoir water levels are drawn down are similar to conditions that occur during dam removal, but over a long time scale. Direct observation of sediment deposits has been an invaluable aid in interpreting subaqueous deposits that are not visible. Water level reductions at the Lake Whitney and MacKenzie reservoirs in Connecticut both revealed coarse-grain sediment deltas where the inflowing rivers entered impoundments in broad, low-gradient valleys, with an impoundment far wider than the river channel. At both sites there was no evidence of pre-dam channels across the impoundment, as they were totally filled with sediment. During the drawdowns, the waters of the inflowing streams split around the sides of the deltas, creating bifurcated channels. This type of delta condition with split flow was a major factor in planning the Cuddebackville Dam removal project in New York, where a delta exposed by removing flashboards became a vegetated island. In contrast to the above deltas, drawdowns at the narrow Woodtick and Saugatuck reservoirs in Connecticut exposed fan-shaped deltas across the full width of the impoundments. The river inflow on the exposed full-width deltas rapidly incised single-stem, slightly sinuous channels.

Permanent reservoir drawdowns have occurred when dams are partially drained by removing gates or by lowering the spillway crest elevation for safety purposes. Spillway modifications at four aging dams along the Kalamazoo River in Michigan have exposed the impounded sediments, most of which have become revegetated. The river has carved a new channel through these materials and remains fairly stable with most original sediments still in place. However, the erosion of even minor sediment quantities affects water quality due to polychlorinated biphenyl (PCB) contaminants.

5.4.2 Reservoir Sediment Flushing

Impoundments with low velocities and long retention times trap a portion of their sediment inflow and gradually lose water storage capacity. Sediment deposits interfere with navigation, reduce pool area, and raise upstream water levels. It is increasingly common practice, particularly on water storage reservoirs, to manage impoundments for long-term sustainable use by flushing excess sediment.

Sediment flushing consists of periodically opening low-level gates to discharge water that erodes impounded sediment. Large-scale sediment flushing begins to create through-flow that temporarily approaches the impact of dam removal. A free-flowing channel beginning at the dam and extending across the sediments can be created by repeated flushing with full reservoir drawdown (Morris and Fan 1998). Rates of sediment flushing depend on discharge rates, water surface or bed slope, and channel width. In fine sediments, the flushing channel will tend to revert to pre-dam channel conditions; in coarse sediment, it may meander or braid. Empirical data on new flushing channel widths has been developed to estimate the volume of sediment eroded (White 2001). Large sediment volumes are removed when the flushing channel develops flatter banks.

5.4.3 Glacial Lake Sediments and Channels

A close analogy to the dam removal channel evolution process is channel formation across beds of glacial lakes. Ice and debris dammed preglacial channels, creating temporary lakes lasting hundreds to thousands of years. Sediment accumulated in glacial lakes until they subsequently drained. Postglacial runoff scoured new channels and created floodplains and terraces that we still see today. Excellent examples of post-dam channel incision, sediment removal, and floodplain formation are found in glaciated terrain of New England and New York, where Ice Age debris dams formed and then breached, releasing water and sediment. Our modern dam removals are similar to these historic geologic processes described by Flint (1930), Jahns (1947), and Von Engeln (1961). Von Engeln describes in detail the glacial lake and channel processes in upstate New York, following proglacial deltas formed in the Finger Lakes, and the general stream incision that occurred after breaching glacial-era dams.

The Connecticut River near Hartford now meanders across the bottom of an old glacial lake bed, demonstrating that post-dam channels can have lateral migration.

5.4.4 Dam Failures

Channels that form upstream of dam failure sites have physical processes similar to dam removal projects, but at a rapid time scale. The former Community Lake Dam on the Quinnipiac River in Wallingford, Connecticut is an example of channel formation following dam failure. The 10-ft-high by 80-ft-long spillway was built in 1872 and failed in 1979, draining the 100-acre lake. Average water depth prior to failure was only 3 ft due to sediment accumulation that eliminated the pre-dam channel thalweg. After failure, an alluvial channel formed with a measured width of 60 to 80 ft, compared to a regime width prediction of 88 ft. The measured slope of 0.001 ft/ft is in the predicted range for a meandering channel, which has, in fact, formed. The meander length and radii are as expected. An important observation is that the width of the meander belt is only about one-fourth the former pool width; most sediments have remained in place for 25 years and have become a vegetated floodplain. This channel has clearly evolved in conformance with empirical hydraulic geometry relationships and removed only a small portion of available sediment.

5.5 CHANNEL INCISION AND EVOLUTION MODELS

Numerous models have been developed to describe sequential steps in channel evolution. Powell (1875) described how channels became incised by vertical erosion until a low gradient is reached, reducing further vertical cuts, followed by subsequent channel widening and bank failures that contribute loose sediment for floodplain deposits. Brigham (1903) linked channel and valley deepening with the recession of waterfalls as found in the incised gorges of New York and the subsequent valley widening by meanders that graze the valley sides. The formation of floodplains was recognized as being a deposition process. Czaya (1981) presents information on channel and valley widening following incision, pointing out that erosion-resistant layers affect side slopes. Rapid incision tends to correspond with steep side slopes that have not had time to flatten, and permeability affects seepage rates that alter side slope stability. Seven types of cross-section shapes are depicted by Czaya, representing geologic forms. A five-stage evolution model is presented, introducing the temporal sequence of progressive deepening and widening. Schumm et al. (1984) conducted extensive research on incised channels and gully formation, and the characteristics of knickpoints. A conceptual model describing evolution of an incised river was developed identifying five stages of channel cross-section development from upstream to downstream as a headcut migrates upstream. Stanley and Doyle (2002) present a conceptual six-stage model based on the channel incision model developed by Simon and Hupp (1987). The primary difference is that the first stage (A) has a deep water impoundment rather than a stable channel, and stage B reflects the lowered water surface in the impoundment at the start of the dam removal process.

The Union City and Anaconda dams on the Naugatuck River in Connecticut had largely filled with sediment prior to removal, but with granular sand and gravel, unlike the fine-grain deposits in Wisconsin dams studied by Doyle. The primary post-removal channel at Anaconda Dam generally followed the Schumm et al. (1984) and Simon (1989) type of incision model, but the coarse-grain banks lacked mass failures or corresponding critical heights. Islands (former deltas) created bifurcated flow, and the right channel had limited progressive degradation without a headcut. It was eventually abandoned as the left channel captured its flow. The final channel width and depth closely matched pre-removal predictions based upon the regime relationships (Wildman and MacBroom 2005).

5.6 RESULTS: THE CHANNEL EVOLUTION MODEL UPSTREAM OF DAMS (CEMUD)

Erosion of sediments from dam impoundments and subsequent evolution of a channel between the dam and upstream areas is a complicated process with many variables. At this time, we cannot reliably predict the precise spatial and temporal facets of upstream channel response. The available quantitative geomorphic and analytical models are helpful but represent very specific conditions. However, qualitative information from recent dam removals, reservoir drawdowns, and glacial lake processes help to extend our knowledge of channel behavior.

A broad conceptual model (Channel Evolution Model Upstream of Dams; CEMUD) has been developed to help forecast the various trends (refer to Fig. 5-1). The model is based on a combination of reservoir and substrate factors, although it does not yet incorporate all reasonably related parameters. It is apparent that channel evolution via sediment scour, transport, and redeposition will be a function of numerous internal variables within the impoundment, along with external variables in the adjacent river segments. Several physical reservoir characteristics affect post-dam-removal channel morphology that are readily observed and interpreted. They include:

- Ratio of reservoir width to upstream river width
- Impoundment retention period
- Length-to-width ratio
- Thalweg sediment thickness
- Sediment type and distribution
- Delta size
- Location of delta foreset face
- Inflow rates
- Longitudinal sediment gradient
- Pre-dam channel gradient
- Ratio of sediment thickness to bank-full flow depth
- Sediment properties
- Sediment angle of repose
- Presence of low-level or multiple outlets
- Presence of sediment against back of dam
- Dam breach location and depth

CEMUD depicts six types of sediment deposits with nine impounded conditions. The initial questions are whether the pool has significant sediment present, and then whether a submerged channel thalweg still exists. If sediment is present, the model leads to selecting one or more condition for coarse granular sediments, fine or cohesive sediments, or for steep delta and wedge-type deposits.

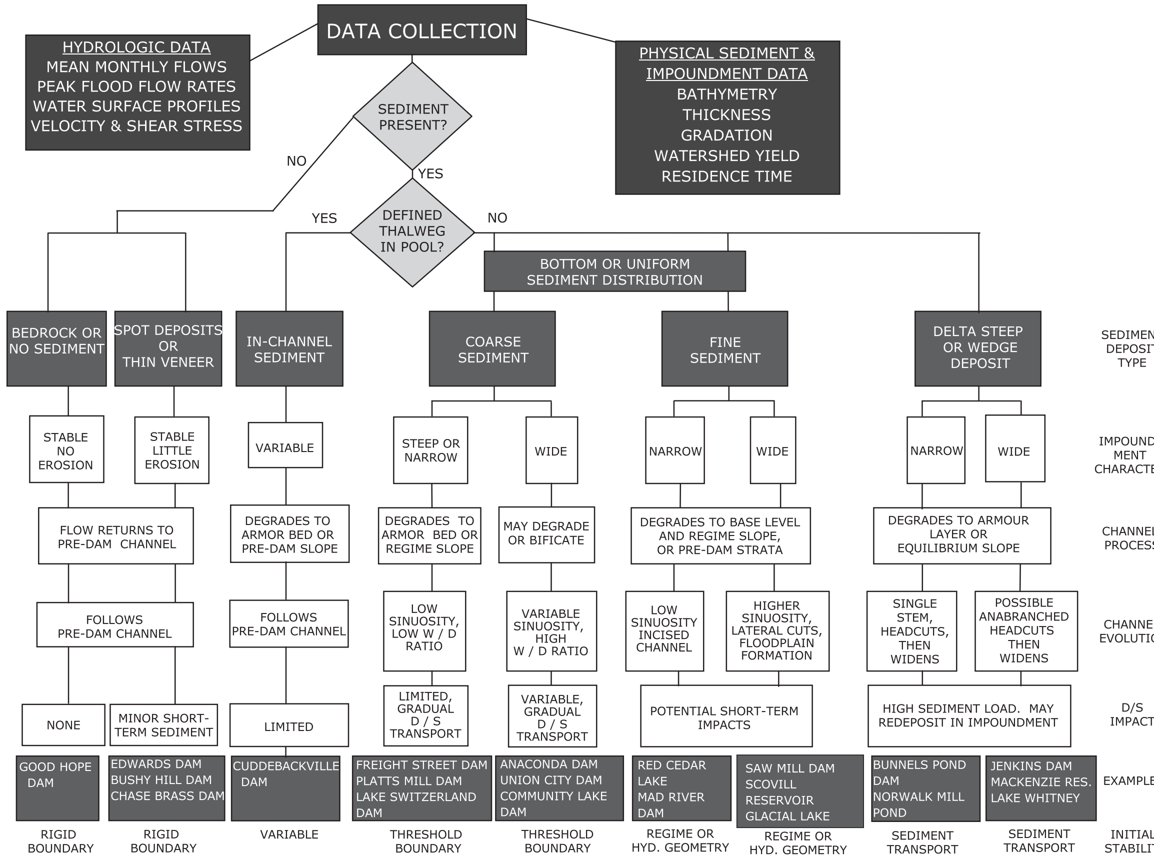

Figure 5-1. Channel Evolution Model Upstream of Dams (CEMUD). Source: Modified from MacBroom (2005).

The nine channel evolution types used in the model represent all scenarios found so far, but there may be more. Each evolution type leads to the anticipated type of channel and recommended types of stability analysis.

5.7 CONCLUSION

Channel evolution models, surrogate dam removal scenarios (glacial lakes, dam failures, reservoir drawdowns), and observations of low dam removals provide empirical information on the behavior of upstream channels and sediment transport. This creates a preliminary screening tool for the initial evaluation of dam removal impacts and for identifying sites that warrant further detailed studies.

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CHAPTER 6

THE GEOMORPHIC EFFECTS OF EXISTING DAMS AND HISTORIC DAM REMOVALS IN THE U.S. MID-ATLANTIC REGION

Katherine Skalak, James Pizzuto, Jennifer Egan, and Nicholas Allmendinger

6.1 INTRODUCTION

Dams have had a substantial impact on the Earth's water resources. Approximately 800,000 dams have been constructed worldwide (Friedl and Wuest 2002; Gleick 1999), and river damming has increased the residence time of river waters from 16 days to 47 days. Human-constructed dams have increased the world's standing water more than 700% (Friedl and Wuest 2002).

There are more than 75,000 major dams in the United States, most of which are relatively old and 90% of which are privately owned. A "major" dam is one taller than 7.6 m or impounding more than 61,650 m^3 (Evans et al. 2002). These dams have a design life expectancy that can be extended by regular maintenance. However, many times this is not done. The Federal Emergency Management Agency (FEMA) found that about 9,200 dams in the United States are classified as "high hazard" due to inadequate maintenance, lack of spillways, and lack of sediment management. About 35% of these dams have not had safety inspections in more than a decade (Doyle et al. 2000; Evans et al. 2002; FEMA 2002). Repairing older dams is often more expensive than removing them, making removal an attractive alternative.

Apart from maintenance problems, many proposed removals are based entirely on the environmental impacts of dams (Shuman 1995). The National Research Council (1992) has deemed research for the rehabilitation and restoration of aquatic ecosystems a priority for rivers in the United States. While dams have provided valuable services such as irrigation, hydroelectric power, navigation, flood protection, and recreational opportunities (Collier et al. 2000; Graf 1999), they have had a dramatic impact on rivers and streams. Flow regimes, channel morphology, sediment transport, and various ecological parameters such as the quality of riparian and aquatic habitats have all been influenced by dams (Heinz Center 2002). Dams have also increased soil salinity and flooding, impeded or eliminated fisheries, and produced unnatural nutrient loading (Shuman 1995).

Although as many as 450 smaller dams have already been removed in the United States, few detailed studies of existing dams or dam removal have been conducted (AR/FE/TU 1999), and therefore a paucity of data exists for predicting the geomorphic effects of dam removal. Due to the complex nature and prolonged duration of many fluvial processes, many predictions regarding the effects of dam removal remain provisional and uncertain (Pizzuto 2002).

The effects of dam removal will vary for each site depending on dam and watershed characteristics (Poff and Hart 2002). The different flow-release policies in a variety of dams and reservoirs introduce changes to the hydrological regime that will vary from dam to dam (Brandt 2000).

Although the effects of a dam and its removal differ with site characteristics, there are common outcomes for all dam removals. The dams in this study varied in height, width, storage capacity, and operation. Moreover, the dams occurred on streams of different sizes, with different topographic and hydrologic characteristics, and a myriad of human impacts and disturbances. These factors have important direct and indirect environmental impacts on a riparian system, which can make it difficult to forecast the effect of dam removal (Poff and Hart 2002). However, we have found that by examining the geomorphic responses to existing dams and dam removals in streams in the U.S. mid-Atlantic region, some general trends regarding the long-term effects of dam removal begin to emerge.

This chapter describes three studies conducted on streams in the mid-Atlantic region of the United States (Fig. 6-1). The first is a dam removal that occurred on the Manatawny Creek in Pottstown, Pennsylvania. The second describes three historic dam removals on Muddy Creek in southeastern Pennsylvania. The final study provides estimates of the long-term effects of dam removal by assessing the effects of existing dams on 13 sites in Pennsylvania and 2 sites in Maryland. By examining data from regional sites at various stages in the dam-removal process, we can create conceptual models and ultimately predictions of channel response to dam removal.

To assess the channel response to dam removal on relatively short time scales, we analyzed data from the Manatawny Creek in Pottstown, Pennsylvania. Manatawny Dam, 2.5 m high, 2 m thick, and 30 m in length, created an impoundment that stretched approximately 800 m upstream from the dam. The impoundment was dredged twice since 1750, with the last dredging occurring around 1970 (Egan 2001). Thus, the impoundment was relatively sediment-starved when the dam was

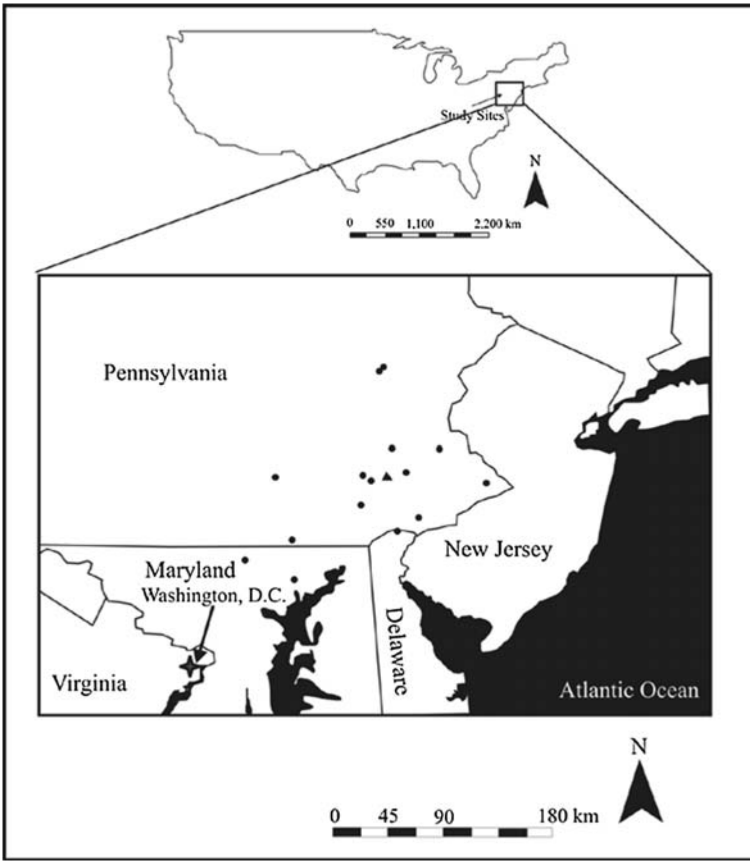

Figure 6-1. Location of study sites. The Manatawny Creek site is shown as a triangle. The 15 sites used in the analysis of the long-term effects of dam removal are shown as circles.

removed. Below the dam, Manatawny Creek joins the Schuylkill River after flowing only about 500 m.

Our measurement program included surveys of the impoundment, and we also surveyed the stream channel below the dam and at a control reach located approximately 2.4 km upstream of the dam.

6.2 THE TRANSIENT EFFECTS OF DAM REMOVAL: MANATAWNY DAM REMOVAL

Manatawny Dam was removed in two phases. In August 2000, a V-notch was cut into the dam and the impoundment was drained. Then

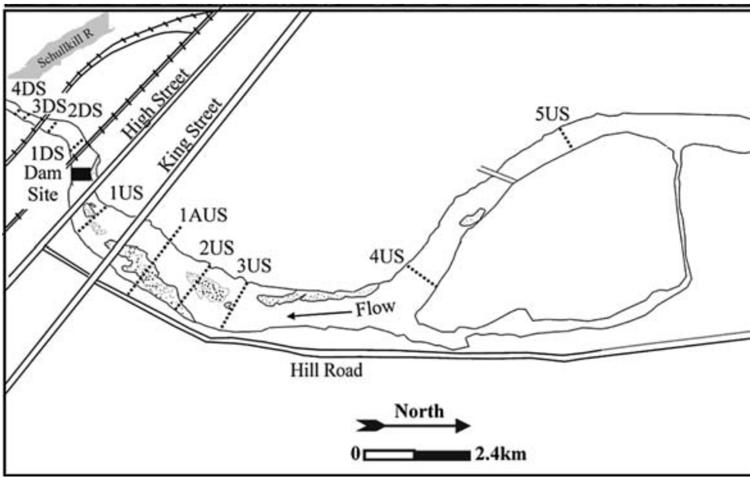

Figure 6-2. Sketch map of Manatawny Creek indicating cross-section locations and former dam site. Cross-sections are numbered consecutively with increasing distances upstream (US) and downstream (DS) of the former dam site. Source: After Egan (2001).

the top portion of the dam was removed. Subsequent surveys indicated that 0.5 m of dam debris remained, so a second removal was completed in November of that year.

Surveys of the channel and pebble counts were conducted both pre- and post-dam removal. Sediment data reflected little change after the August 2000 removal. Grain size data obtained at 0.5-m intervals reflect a coarsening trend at cross sections 1 and 2 (upstream) after the November 2000 dam removal from, initially, sand and mud to coarse sand and gravel (Bushaw-Newton et al. 2002) (Fig. 6-2). Pebble count data obtained at riffles and runs downstream from the dam showed that the sediment at these sites appears to have become significantly finer-grained following dam removal (Fig. 6-3).

The cross-sectional shape of the channel also changed little after the August 2000 removal (Bushaw-Newton et al. 2002). Cross sections taken several months after the second period of removal reflected the formation of large, transient bars in the former impoundment. Lateral bars formed on both sides of the channel, approximately 1 m high and 10 m or more wide. They were comprised primarily of loosely consolidated gravel and coarse sand. Figure 6-4 shows cross-section data taken at 1A US shown in Fig. 6-2. It can be seen in Fig. 6-4 that the initial survey before dam removal shows no evidence of lateral bars. However, the survey conducted several

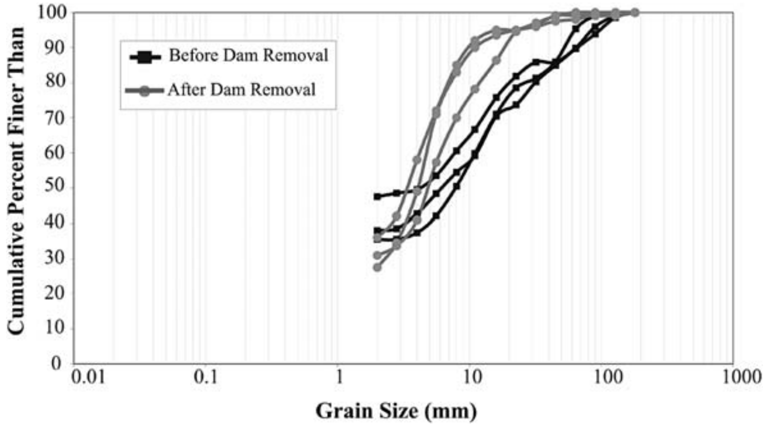

Figure 6-3. Grain size distribution before and after dam removal at cross-section 4 downstream of the former dam site on Manatawny Creek, Pennsylvania. Source: After Egan (2001) and Patrick Center for Environmental Research (2006).

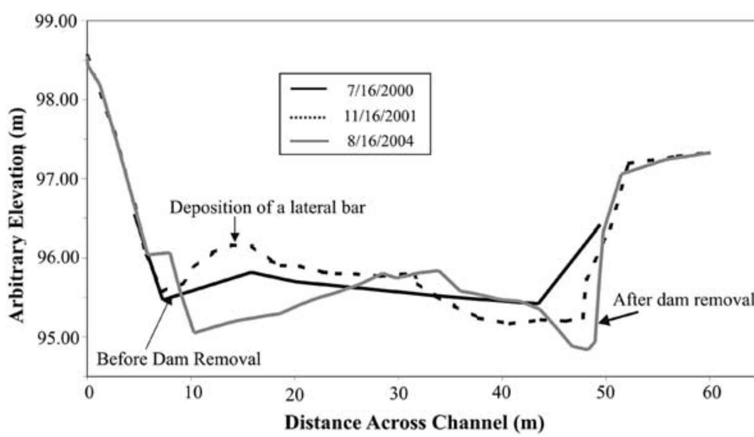

Figure 6-4. Cross sections of the channel upstream of former dam site on Manatawny Creek, Pennsylvania. This cross section corresponds with 1A US in Fig. 6-2.

months after dam removal indicated significant deposition on the left side of the channel. Figure 6-4 shows that 4 years after the dam was removed, there was no evidence of these lateral features remaining, which indicates that the channel upstream has degraded in recent years (Patrick Center for Environmental Research 2006).

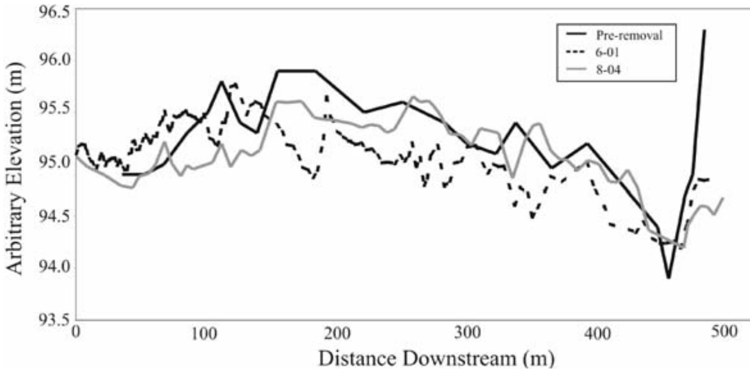

Figure 6-5. Longitudinal profiles of the former impoundment at Manatawny Creek at various stages of dam removal.

Longitudinal profiles upstream and downstream from the dam and in the control reach document changes in slope and pools and riffles. The bed of the impoundment, prior to dam removal, had a positive slope of 0.00015, which indicated an increase in elevation with increasing distance downstream toward the dam. After dam removal, the impoundment had a downstream slope of 0.00147, which indicated a decrease in elevation with increasing distance downstream toward the dam. The longitudinal profile data collected in 2004 in the former impoundment indicate that the channel continues to adjust its slope (Fig. 6-5). The slope of the channel downstream of the dam was 0.0022 before dam removal, close to that of the control reach of 0.0021 (Egan 2001). The slope in the downstream reach of the channel has remained stable.

Pools and riffles developed in the impoundment after removal in August 2000, but were closely spaced and shallow compared to the pools and riffles in the control reach. The downstream reach also exhibits pools and riffles with a spacing of 47 m and an average depth of 0.5 m, which corresponds to a pool riffle spacing of 2 channel widths.

The initial response of Manatawny Creek to the August 2000 removal was greatly subdued due to the 0.5 m of dam debris left in the channel. Additionally, the sand, gravel, and cobble-sized material could have remained in the impoundment because the flows during the months of August to November 2000 were not significant enough to initiate motion. The discharge in December 2000, however, was due to a 2.5-year storm that caused significant changes in the channel. However, this flow occurred after the contractor removed the additional dam debris. Consequently, the observed changes upstream and downstream from the dam resulted from the combined effects of the complete removal of the dam and the 2.5-year storm. In the years since the dam has been removed, there have been several large storm events that continue to stimulate channel adjustment.

Extensive changes continue to occur in the channel, although 4 years have passed since the dam was removed. Surveys of the longitudinal profile demonstrate that the channel is slowly cutting into the remaining rubble left at the dam site (Fig. 6-5). As this baselevel becomes lower, erosion continues at cross sections upstream. In downstream reaches, sand and pebbles have continued to replace the preexisting cobble-sized bed material. Thus, the recovery of Manatawny Creek appears to be an ongoing process 4 years following the removal of the dam.

6.3 ESTIMATING TIME SCALES OF CHANNEL RECOVERY FROM HISTORIC DAM REMOVALS

To determine the time scales of channel recovery time following dam removal, we studied three historic dam removal sites along Muddy Creek in southeastern Pennsylvania. Garthridge Dam, 12.2 m high and located the farthest downstream, was breached and removed in 1933. Highrock Dam, 1.8 m high and located the farthest upstream, was breached and removed in 1972. Castle Finn Dam, 3.1 m high, was removed in 1997. We surveyed the longitudinal profile and channel cross sections upstream of the former dam site. We also sampled the bed material and mapped floodplain and channel deposits. Undammed reaches far upstream were used as controls.

At all sites, laminated muddy reservoir deposits are still preserved as terraces up to 5 m high bordering the channel (Fig. 6-6). These deposits are very cohesive and will likely remain in place for decades. At Castle Finn, laminated muddy reservoir deposits underlie the channel bed, indicating that the channel has not incised to its pre-dam elevation after 6 years. At the other sites, vertical incision has completely removed fine-grained reservoir deposits from beneath the channel, though lateral migration has preserved some dam fill deposits on the left side of the channel at the former site of High Rock Dam. Bed material is finer-grained near the former dam site than at the control reaches at all the sites, and the water surface slope is higher near the former dam site than at the control reaches. These data suggest that, even after many years, channels above locations of removed dams are noticeably different from nearby control reaches, possibly indicating that complete recovery from dam removal may require decades.

Figure 6-7 shows the thickness (or depth) of the remaining dam fill deposits relative to the thickness of the initial reservoir deposits at each of the three sites. To obtain an initial fill thickness, we assumed that the trap efficiency of each dam was 100% and that the reservoir sediments

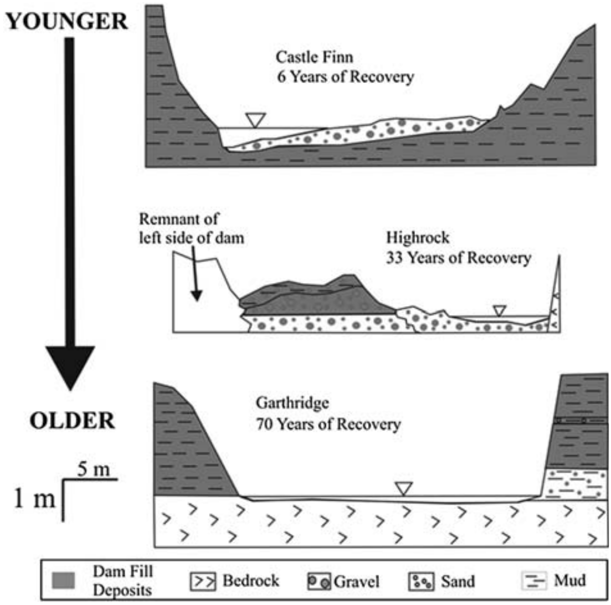

Figure 6-6. Geologic cross section upstream of three historic dam removal sites in southeastern Pennsylvania.

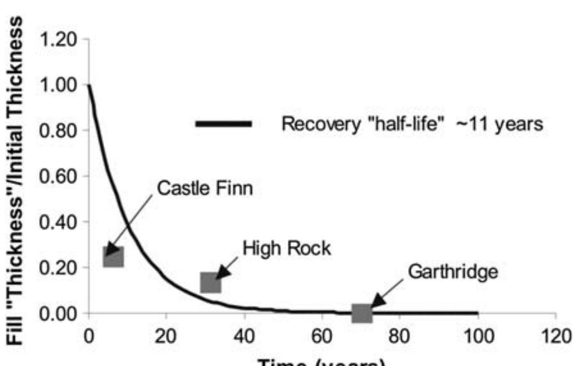

Figure 6-7. Channel recovery rate based on relative dam fill thickness through time. Fill "thickness" on the y-axis specifically refers to the vertical depth of former impoundment fill.

reached the initial height of the dam. By plotting the ratio of initial depth of impoundment fill (i.e., height of the dam) to depth of impoundment fill remaining (based on geologic cross sections in Fig. 6-6) versus the time since dam removal, we obtained an exponential decay function to describe removal of reservoir sediment through time. According to this curve, the process of channel recovery has a "half-life" of approximately 11 years (though the precision of this estimate is limited by the small number of observations). These results suggest that complete recovery from dam removal may take several decades.

6.4 LONG-TERM EFFECTS OF DAM REMOVAL: STUDIES IN PENNSYLVANIA AND MARYLAND

To investigate long-term effects of dam removal, we studied streams at 15 existing dams in Pennsylvania and Maryland. Our experimental design was based on the hypothesis that following dam removal the channel would ultimately recover completely to pre-dam conditions. Although no previous research has supported this hypothesis directly, in the absence of long-term monitoring data (which presently do not exist), the authors believe this is a reasonable assumption which provides a conceptual framework for analyzing long-term effects of dam removal on channel form and process.

The reference condition that was used to measure the effect of dam removal was a reach upstream that was unaffected by existing dams. Upstream reaches were assumed to represent the condition of the stream below the dam before dam construction (as discussed in J. Skalak's unpublished M.S. thesis, "The Effects of Dam Removal on Streams in PA and MD: Assessing the Potential Consequences of Dam Removal," University of Delaware, 2004, which is hereafter cited as Skalak 2004, unpublished). We measured the geomorphic characteristics upstream and downstream of the dam to determine the effects of the dam, and this comparison also allowed us to estimate the condition of the stream that would ultimately develop decades after dam removal. We surveyed a mid-channel longitudinal profile and three cross sections at upstream and downstream reaches. We also analyzed bed-material grain sizes at 10 cross sections in each reach at each study site.

Results from the grain size analysis indicate that the upstream reach is significantly finer than the downstream reach (Fig. 6-8): percentiles less than D_{50} (the 50th-percentile grain size) are significantly greater in the upstream reach than in the downstream reach. These results suggest that the dam has a significant effect on the finer half of the bed-material grain size distribution. The dam traps a significant portion of the upstream fine sediment supply, which results in a downstream coarsening of the bed. The coarsest fraction of bed material, as represented by the $D_{84,}$ is similar upstream and downstream of the dam. These results indicate that decades after dam removal, once the channel has established equilibrium, the downstream reach will become finer-grained.

The results from the channel surveys and longitudinal profiles indicate that there are few significant differences in stream morphology between

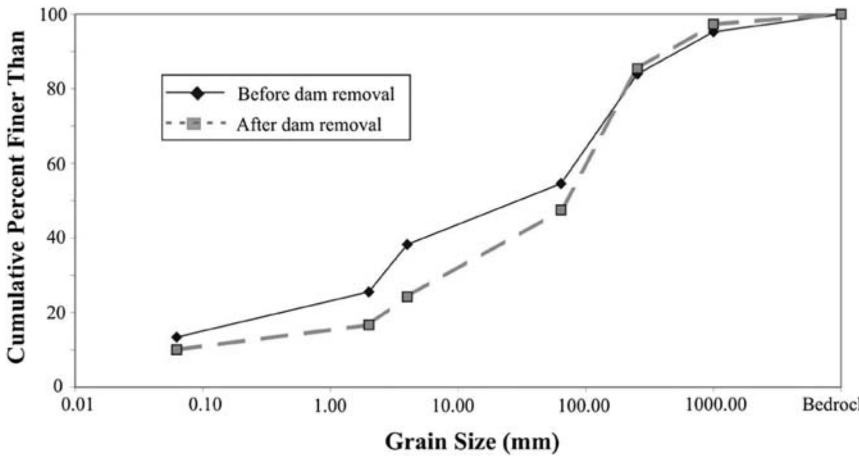

Figure 6-8. Cumulative grain-size distributions showing the long-term effect of dam removal. The curve labeled "Before dam removal" was obtained by averaging the upstream data for all 15 sites. The curve labeled "After dam removal" was obtained by averaging the downstream data for all 15 sites.

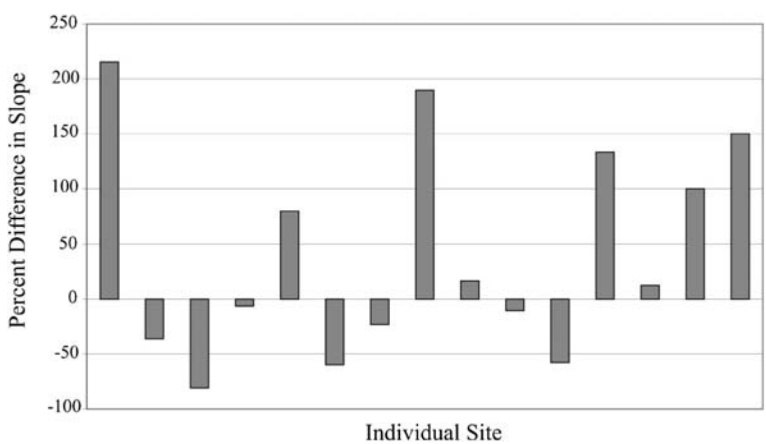

Figure 6-9. Percent difference in slope between upstream and downstream reaches for all 15 sites. Percent difference is calculated using the following formula: 100((downstream slope—upstream slope)/upstream slope).

the upstream and downstream reaches. There are no observable, consistent changes in slope when comparing the reaches upstream and downstream of the dam at each site (Fig. 6-9). Statistical analyses (Wilcoxon signed-rank test, SPSS version 13.0, $p = 0.91$) support this. Once width data are normalized by the square root of the drainage basin area, widths

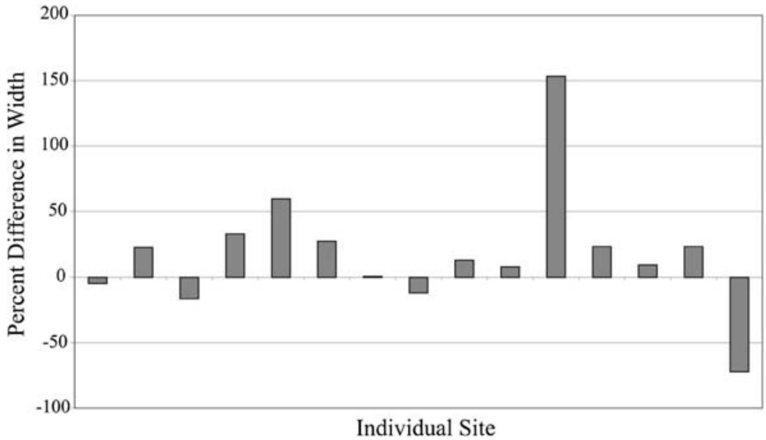

Figure 6-10. Percent difference in normalized width between upstream and downstream reaches for all 15 sites. Percent difference was calculated using the method presented in the caption of Fig. 6-9.

upstream and downstream do not appear to be significantly different (Fig. 6-10). The same statistical analyses ($p = 0.078$) support this, although this marginal p-value indicates the effects on channel width are more complex. However, if we take into account the within-site variability in channel width when interpreting this result, it is clear that dam effects on channel width are less significant than within-site variations in channel width (Skalak et al. 2009).

The lack of morphological change can be attributed to (1) pervasive bedrock influence on streams in this region; (2) low regional sediment supply, so upstream reaches unaffected by dams are sediment-starved (similar to downstream reaches) and thus little sediment is available below dams to affect channel morphological change through deposition; and (3) highly vegetated and cohesive banks that are difficult to erode, limiting possible width adjustment. These results indicate that after a channel has achieved equilibrium following dam removal, the morphology of the stream below the dam will remain relatively unchanged in terms of width and slope.

6.4.1 General Trends Regarding the Effect of Dam Removal on Mid-Atlantic Streams

By examining the geomorphic responses to existing dams and historic dam removals of differing ages in streams in the mid-Atlantic region, some general trends regarding the long-term effects of dam removal begin to emerge. A response curve based on dam size can be developed, as

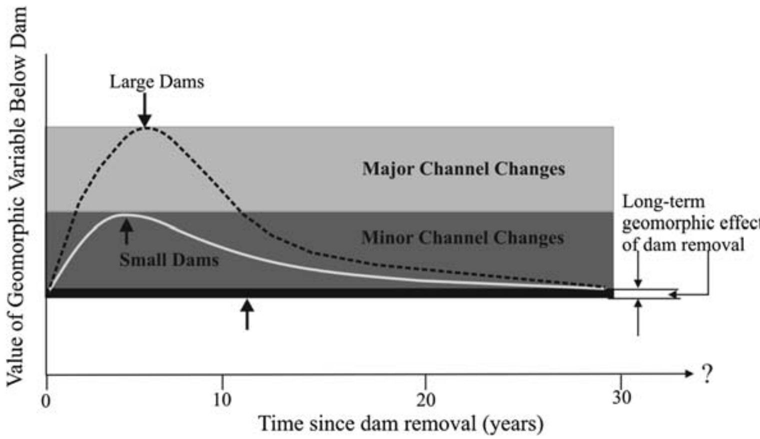

Figure 6-11. Expected channel response magnitude and duration based on dam size for streams in the mid-Atlantic region.

shown in Fig. 6-11. This response curve is applicable to the reach downstream of a dam. The baseline behavior or the initial condition of the stream can be defined as the downstream condition prior to dam removal. Width data are normalized by the square root of the drainage area.

Two discrete zones of geomorphic change are defined: major and minor changes. Major changes include significant aggradation or degradation of the bed, slope adjustments, channel width adjustments, changes in channel planform, formation of stable channel bars, and changes in stream type. Minor changes include textural adjustments of the bed, slight modifications of slope and width, and the formation of ephemeral bars. The response curves have also been classified according to dam size, with the expectation that reaches below larger dams will initially experience more significant changes downstream following dam removal. This expectation is based on the assumption that larger dams have a higher trap efficiency and impose a more substantial impact on the downstream hydrological regime. Channels with small dams are expected to undergo minor channel changes before recovering from dam removal.

As is evident by the thin region highlighted in black in Fig. 6-11, the ultimate magnitude of geomorphic change resulting from dam removal, when compared to the initial pre-removal channel, is expected to be small. That is, the final channel configuration after recovery downstream will not be significantly different from the initial condition. The magnitude and timing of channel response is based on the previously mentioned predictions of long-term channel recovery following dam removal (Figs. 6-5 through 6-7). Furthermore, because we could not observe any influence of dam size in the data of Figs. 6-5 through 6-7 [results related to dam size are not presented here but are thoroughly documented by Skalak (2004, unpublished)], we speculate that although dam size may be important during the initial response, both curves reach recovered state at about the same time. According to the response curves presented here, channel recovery following dam removal is expected to take several decades to complete.

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PART III: PHYSICAL MODELING

CHAPTER 7

PHYSICAL MODELING OF THE REMOVAL OF GLINES CANYON DAM AND LAKE MILLS FROM THE ELWHA RIVER, WASHINGTON

Chris Bromley, Timothy J. Randle, Gordon Grant, and Colin Thorne

7.1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) National Inventory of Dams (NID) lists about 80,000 dams in the United States but, including the smaller structures that do not meet the criteria for entry into this database, this number may actually be more than 2 million (Graf 1996). This infrastructure is aging rapidly, leading to problems of obsolescence, safety, high maintenance costs, and loss of functionality (ASCE 1997). Increasingly, these problems are causing dams to be removed; 579 documented removals had occurred by 2003 (AR/FE/TU 1999; see also www.americanrivers.org). The rate of removal is increasing and the large estimated number of dams in the United States suggests that the final number of dams removed could be very large.

While dam removal has the potential to successfully rehabilitate many miles of degraded river channel by re-establishing hydrological, sedimentological, and biological connectivity, it is nevertheless a disturbance to the fluvial system (Stanley and Doyle 2003). As such, it also has the potential to cause a great deal of physical and biological damage through the release of pollutants, the increased mobility of invasive species, and the remobilization of large volumes of reservoir sediment.

An example of the latter is the proposed removal of the Elwha and Glines Canyon dams from the Elwha River on Washington's Olympic Peninsula (Fig. 7-1). Both dams were built without fish passage facilities and they will be removed to achieve "the complete rehabilitation of the Elwha River system and its native anadromous fisheries" (National Park Service 1995), which is called for and authorized by the Elwha River Ecosystem and Fisheries Restoration Act (1992). The two reservoirs

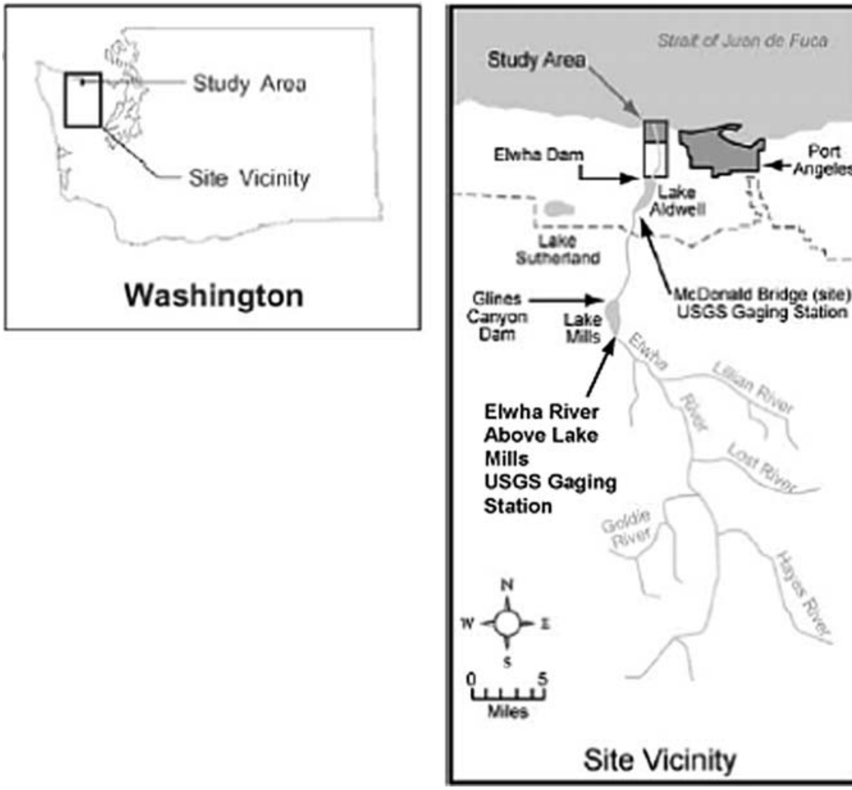


Figure 7-1. Site location. Source: Modified from National Park Service (2005).

impound 14.85 million m^3 of sediment, of which about 11.85 million m^3 is stored in Lake Mills behind Glines Canyon Dam. The sediment management objectives are to erode as much of the original delta as possible, but to distribute throughout and retain within the reservoir area as much of this eroded material as possible so that it can dewater, consolidate, and become stabilized over the medium to long term by recolonizing vegetation.

A series of physical modeling experiments was performed to investigate the morphodynamics of sediment movement through the reservoir area and into the downstream system in response to different magnitudes of drop in water surface elevation (baselevel) during dam removal, and to different initial channel positions on the delta surface. It was hypothesized that the greater the magnitude of drop in baselevel, the greater the volume of the original delta that would be eroded and prograded into the reservoir. In these experiments, the original delta was defined as the body of sediment enclosed between the topset and foreset[1] delta surfaces and the reservoir boundary prior to the onset of dam removal. It did not include the bottomset deposits produced during the period of accelerated delta growth.

7.2 METHODS

The Lake Mills Basin was shaped using the 1926 pre-dam valley topography (Bureau of Reclamation 1995) and was designed to approximate the Froude and Shields numbers in the upstream delivery channel, according to standard modeling practice (e.g., ASCE 2000). The model was built with a horizontal scale of 1 : 310 and a vertical scale of 1 : 81.7, which made it vertically distorted by a factor of 3.79. While vertical distortion is not ideal, it is an accepted practice in physical modeling and the degree of distortion here is well within the maximum upper limits found in the literature, i.e., ≤10 (Chanson 1999); ≤6 (ASCE 2000). This model had the added benefit of increasing flow depths and therefore the flow's hydraulic roughness, thus reducing the extent to which viscous effects could affect sediment transport.

Glines Canyon Dam is to be removed by cutting it down in 7.5-ft (2.29-m)-high sections, which scales to 0.028 m in the model. The model dam was thus composed of 21 0.028-m-high wooden blocks; each experiment examined the effects of removing the dam in increments of the same number of dam pieces, with the number of dam pieces per increment varying from run to run (Table 7-1, Fig. 7-2).

The delta at the start of each run was grown to the extent of the 2002 prototype[2] delta using an accelerated sediment feed. The silicate sediment mixture used was substantially coarser than required by the scaling calculations (Fig. 7-3) in order to avoid cohesive scale effects and the formation of ripples or dunes on the bed of the model channel, neither of which were present during a drawdown experiment of the prototype Lake Mills in 1994 (USGS 2000). Although lower-density sediments such as coal dust (Cazanacli et al. 2002), crushed walnut shells, or plastic grains (Larsen 1990) could have been used to scale the finer prototype sediments, Whipple et al. (1998) have shown that mixed-density models are subject to scale

[1] The topset surface is the near horizontal surface over which the incising channel flows. The foreset surface slopes steeply downwards from the downstream end of the topset surface to the bed of the reservoir. The bottomset deposits are the finest sediments spread across the reservoir's bed, between the original delta and the dam.

[2] The term "prototype" in modeling parlance refers to the real-world object or phenomenon being modeled.

Table 7-1. Glines Canyon Dam Removal: Experimental Parameters for Selected Model Runs

Run Name	2xR	3xR	1xL	3xL	3xC	6xC[c]	12xC[c]
No. of dam pieces removed per increment of dam removal	2	3	1	3	3	6	12
Delta surface channel position at start of run[a]	Right	Right	Left	Left	Center	Center	Center
Model sediment mixture (mm)	Not sampled	$D_{16} = 0.15$ $D_{50} = 0.42$ $D_{84} = 1.30$	$D_{16} = 0.19$ $D_{50} = 0.40$ $D_{84} = 1.38$	Not sampled	Not sampled	$D_{16} = 0.16$ $D_{50} = 0.43$ $D_{84} = 1.33$	$D_{16} = 0.14$ $D_{50} = 0.43$ $D_{84} = 1.33$
Discharge during dam removal (L/min)	15.57	15.57	15.57	15.57	15.57	15.57	15.57
Recurrence interval of flood flows[b]	No floods	1st flood = 2-yr 2nd flood = 2-yr 3rd flood = 5-yr	1st flood = 2-yr 2nd flood = 2-yr 3rd flood = 5-yr	1st flood = 2-yr	1st flood = 2-yr	No floods	No floods

[a]The channel position is assigned looking downstream from the upstream end of the delta.
[b]Flood flows listed in the order they were run through the model.
[c]Partial runs: a total of 12 dam pieces removed.

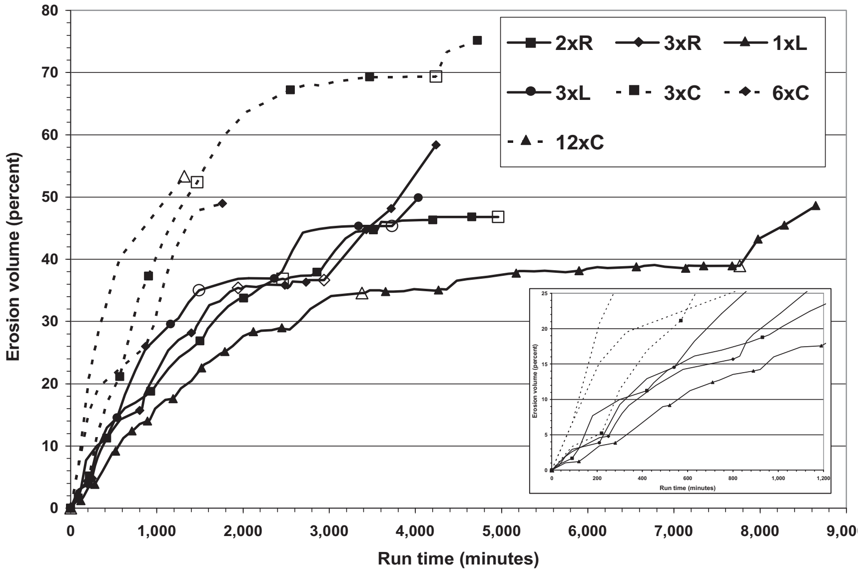


Figure 7-2. Original delta erosion volumes. The solid data markers denote the static equilibrium condition following the removal of one increment of dam, while the first and second empty data markers denote the 12- and 21-piece equilibrium conditions, respectively. The solid markers following the second empty marker denote the static equilibrium following the first two-year, the second two-year, and the five-year flood flows, respectively. The inset graph provides an expanded view of the area of the main graph enclosed between the black lines and the axes. Source: Modified from Bromley (2007; unpublished data).

effects that can complicate the interpretation of the model's results at the prototype scale. Given that the model was already subject to scale effects from the vertical distortion, it was thought prudent to avoid an additional layer of complexity that might further complicate the interpretation of the results. A thin layer of the modeling sediment mixture was stuck to the sides of the basin in order to roughen them prior to performing the experimental runs.

Each run was performed with a constant discharge of 15.57 L/min and a constant baselevel fall rate of 2.8 cm/15 min. Once the dam was completely removed, a series of flood flows were run through the reservoir as indicated in Table 7-1. For each increment of removal, the run was stopped after 1.5, 3.5, 5.5, and 9.5 h of run time, and sometimes at additional intervals in between, in order to scan the delta surface using a Keyence LK-500 laser. A final scan was also made once the system reached

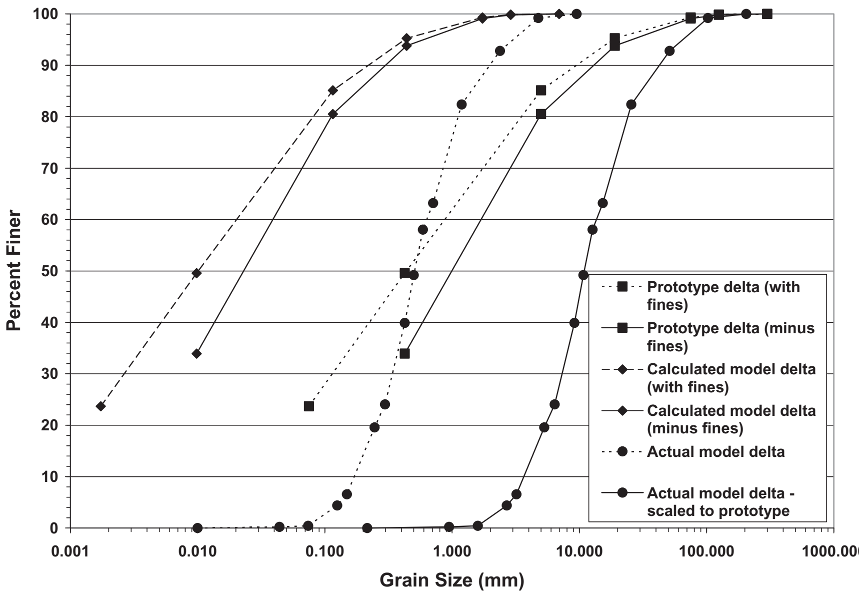


Figure 7-3. Key grain size distributions.

static equilibrium. All runs reported herein were allowed to reach a static equilibrium condition after each increment of dam removal except run 3xC, which was inadvertently performed with an accelerated rate of incremental removal. Cross sections were spaced longitudinally at 5-cm intervals. Delta surface elevation was measured across each section at 0.5-cm intervals and with sub-millimeter vertical accuracy. Additional cross sections were scanned to capture details of breaks in slope and bank line where these fell in between the 5-cm cross sections in order to accurately record the deposit's topography.

7.3 RESULTS AND ANALYSIS

7.3.1 Original Delta Volumes Eroded during Dam Removal

The laser data were used to create digital elevation models (DEMs) of the delta surface for each scan interval (Figs. 7-4 through 7-7). Cut-fill analyses were performed in ArcGIS version 9.0 to estimate the volumes of sediment eroded and deposited during each interval of run time. These estimates were corrected to account as much as possible for errors associated with overhanging banks and terraces and for slight variations in reservoir basin geometry, which were introduced into the DEMs by

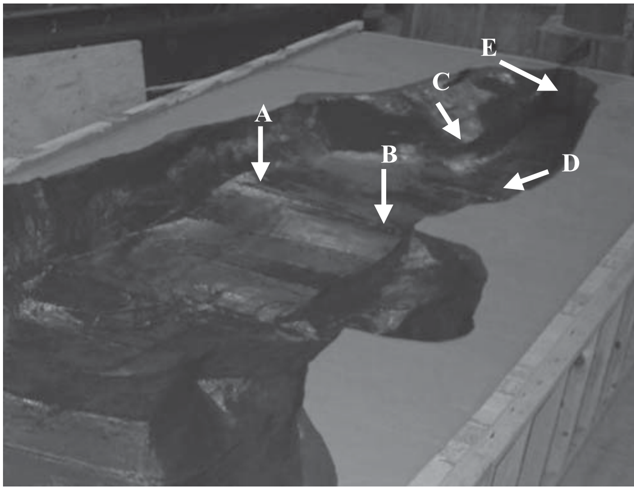


Figure 7-4. View looking upstream at the empty basin in the vicinity of the original delta. Arrows denote important topographical features.

changes in the number and position of the additional cross sections from time step to time step (as discussed in C. Bromley's unpublished Ph.D. dissertation, "The Morphodynamics of Sediment Movement through a Reservoir during Dam Removal," University of Nottingham, Nottingham, UK, 2007, which is hereafter cited as Bromley 2007, unpublished data). In reporting these results, reference is made below to the distal, medial, and proximal original delta areas, which refer to the delta surface sections from 0 to 100 cm, 100 to 200 cm, and 200 to 300 cm, respectively (Fig. 7-5). Reference is also made to central runs, in which the channel at the start of dam removal was located along the center of the original delta topset, and to marginal runs, in which the incising channel started along either the left or right side of the original delta topset.

The results show that, in general, as the position of the incising channel at the onset of dam removal moved from delta left or delta right to delta center, and as the magnitude of the removed dam increment increased from one to three pieces, the percentage of the original delta eroded and prograded into the reservoir increased significantly from 38.9% (run 1xL) to 69.3% (run 3xC) by the time the entire dam had been removed (Fig. 7-2; Table 7-2, Section A).

For runs 2xR, 3xR, and 3xL the pattern of response was not quite so simple. These runs eroded 46.8%, 36.7%, and 45.4%, respectively, of the original delta by the time the entire dam had been removed (Fig. 7-2; Table 7-2, Section A). These variations occurred largely because of the incising

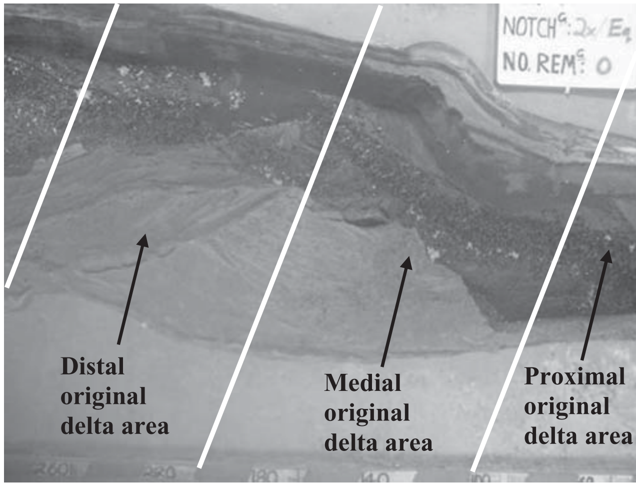


Figure 7-5. View of the original delta area in run 2xR at the static equilibrium following complete dam removal. Flow is from right to left.

channel's interactions with the highly asymmetrical reservoir boundary in the original delta area (Fig. 7-4). By the time the entire dam had been removed in run 2xR, the incising channel had pulled away from the less steeply sloping right reservoir wall (Fig. 7-4, arrow C) and eroded across the full width of the proximal original delta (Fig. 7-5). By the same stage in run 3xR, the incising channel remained against this more gentle slope and was unable to erode the sediment in the left half of the proximal original delta (Fig. 7-6). Although a greater width of the delta appears to have been eroded in run 2xR (Fig. 7-5) than in run 3xL (Fig. 7-7), both runs eroded almost exactly the same volume of original delta (Fig. 7-2; Table 7-2, Section A). This is because the transverse slope from a higher to a lower basin bed elevation (Fig. 7-4, arrows A to B) resulted in a greater depth of sediment through which the channel could incise along the left half of the delta, downstream from about 100 cm (refer to the numbers on the flat model top in Fig. 7-7). Conversely, the left-hand curvature of the left basin boundary (Fig. 7-4, arrow D) tended to guide the incising channel away from the main body of the original delta, thus reducing the amount of lateral original delta erosion.

The pattern of response was also less straightforward among the central runs. Runs 6xC and 12xC were only partial runs but, by the static equilibrium following the removal of the 12th dam piece, at the last point at which runs 3xC, 6xC and 12xC were directly comparable, 52.4%, 49%, and 53.3%, respectively, of the original delta had been eroded (Fig. 7-2; Table 7-2, Section A). This suggests that removing the next dam increment before the system had fully equilibrated to the effects of the previous

Table 7-2. Glines Canyon Dam Removal: Modeled Changes in Reservoir Sediment Volume

(A)	Original Delta Volume Eroded during… (as % of Original Delta Volume)				
Run	Dam Removal	1st 2-Year Flood Flow	2nd 2-Year Flood Flow	5-Year Flood Flow	(C) Total Volume Passing Downstream
2xR	46.8	—	—	—	46.8
3xR	36.7	8.1	3.3	10.3	58.4
1xL	38.9	4.3	2.3	3.1	48.6
3xL	45.4	4.5	—	—	49.9
3xC	69.3	5.8	—	—	75.1
(B)	**Volume Passing Downstream during… (as % of Total Reservoir Sediment Volume)**				
Run	**Dam Removal**	**1st 2-Year Flood Flow**	**2nd 2-Year Flood Flow**	**5-Year Flood Flow**	**(C) Total Volume Passing Downstream**
2xR	13.8	—	—	—	13.8
3xR	2.4	7.6	5.1	9.7	24.8
1xL	7.8	4.3	8.1	5.3	25.3
3xL	13.9	10.8	—	—	24.7
3xC	25.1	9.8	—	—	34.9

Section A: Original delta volume as proportion of initial original delta volume. Section B: Total reservoir sediment. Section C: Sediment volume passing downstream as a proportion of total reservoir sediment volume.

baselevel drop was able to generate a greater amount of original delta erosion than a baselevel drop of twice the magnitude, but in which the system was allowed to fully equilibrate. Furthermore, the relatively small difference in erosion volumes between runs 6xC and 12xC suggests that there may be an exponential decrease in the additional erosion volumes generated by large increases in the magnitude of baselevel drop. In turn, this suggests that there may be an upper limit to the magnitude of baselevel below which very little further increases in erosion volume can be realized. This possibility merits further investigation.

7.3.2 Original Delta Volumes Eroded by Storm Flows Post-Dam Removal

The discrepancy in the volumes eroded by the first 2-year flood flows between run 3xR and the other runs, and between the 5-year flood flows

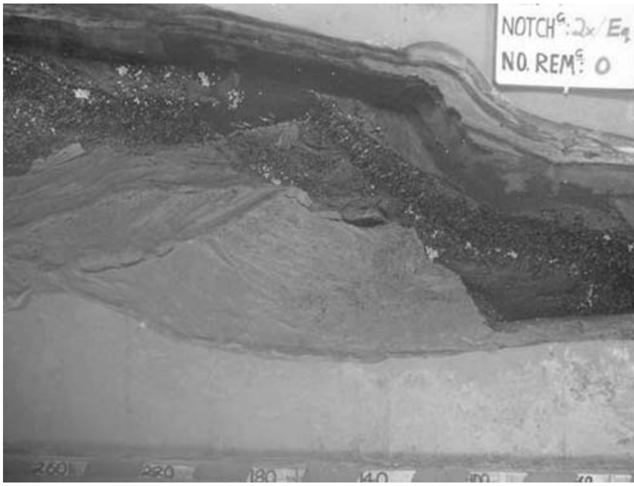


Figure 7-6. View of the original delta area in run 3xR at the static equilibrium following complete dam removal.

Figure 7-7. View of the original delta area in run 3xL at the static equilibrium following complete dam removal.

for runs 1xL and 3xR (Table 7-2, Section A), was probably due to the asymmetry of the reservoir basin. In run 1xL there was only a small amount of mass wasting of the right terrace at the upstream end of the delta after the 5-year flood flow (Fig. 7-8D), while during run 3xR the floods were able to erode large sections of the entire length of the left terrace (Fig. 7-9).

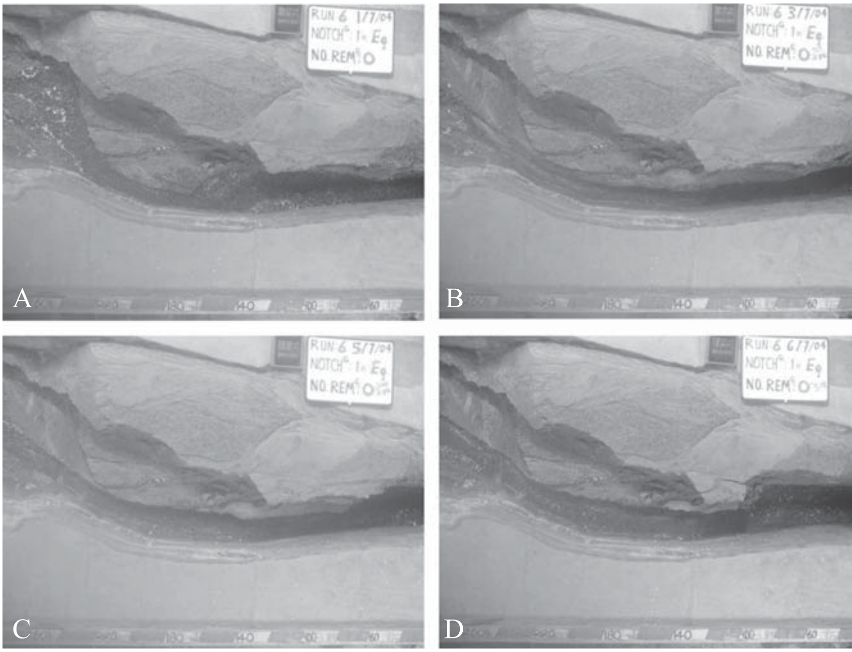


Figure 7-8. Original delta area in run 1xL at static equilibriums after (A) complete dam removal; (B) first 2-year flow; (C) second 2-year flow; (D) 5-year flow.

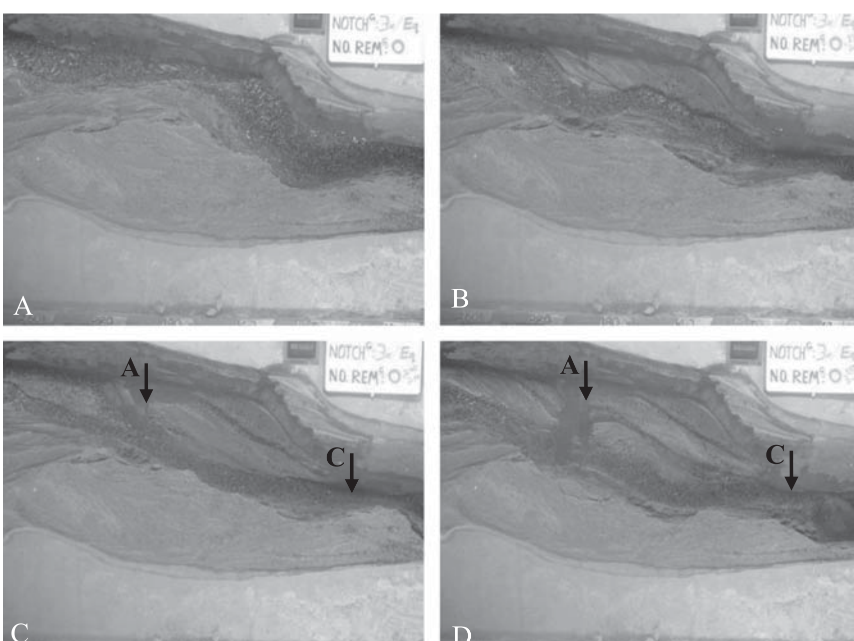


Figure 7-9. Original delta area in run 3xR at static equilibrium after (A) complete dam removal; (B) first 2-year flow; (C) second 2-year flow; (D) 5-year flow.

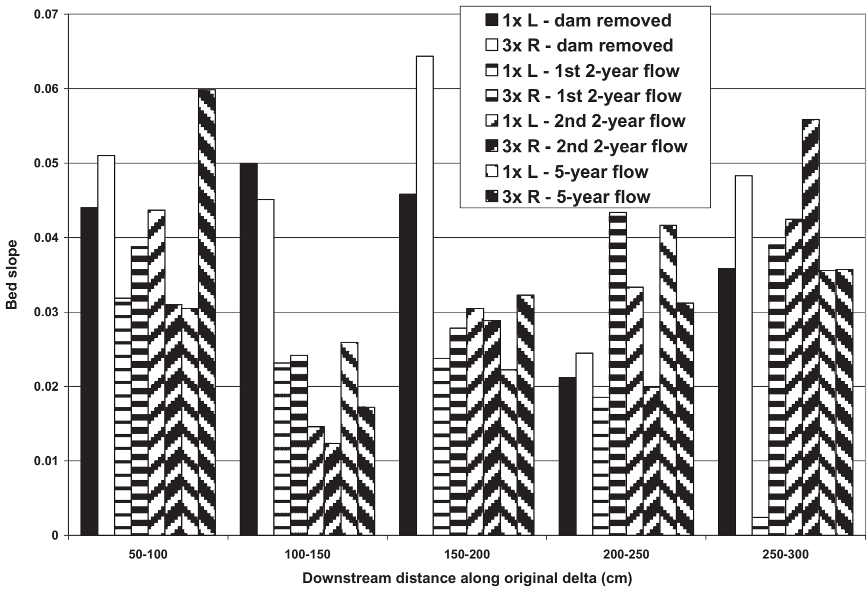


Figure 7-10. Thalweg slopes in the original delta area after flood flows.

While the channel became fixed against the bed of the basin boundary during the dam removal phase in run 3xR (Figs. 7-4 and 7-9, arrows A and C), thus reducing the erosion volume during that period, the higher discharge enabled it to move into the left side of the deposit. In both runs there was a rapid reduction in slope from 50 cm to 200 cm along the delta surface following the first 2-year flood flow (Fig. 7-10). In run 1xL this constituted the bulk of the volumetric adjustment, while in run 3xR the lateral adjustments were responsible for the bulk of the erosion.

7.3.2.1 Sediment Transport into the Downstream System. More sediment was transported through the dam site by the end of the dam removal phase of run 3xC (25.1%) than at any stage of any other run except run 1xL, in which 25.3% was transported by the end of the 5-year flood (Table 7-2, Section B; Fig. 7-11).

Following the 2-year flood in run 3xC, an additional 9.8% of the total reservoir sediment volume was transported through the dam site. The ranking of the runs in order of decreasing total sediment volume transported through the dam site corresponds almost perfectly with their ranking in order of decreasing original delta erosion volume (Table 7-2, Section B), which suggests that as more sediment was eroded from the original delta, more sediment was able to pass downstream once the entire dam had been removed (Bromley 2007; unpublished data).

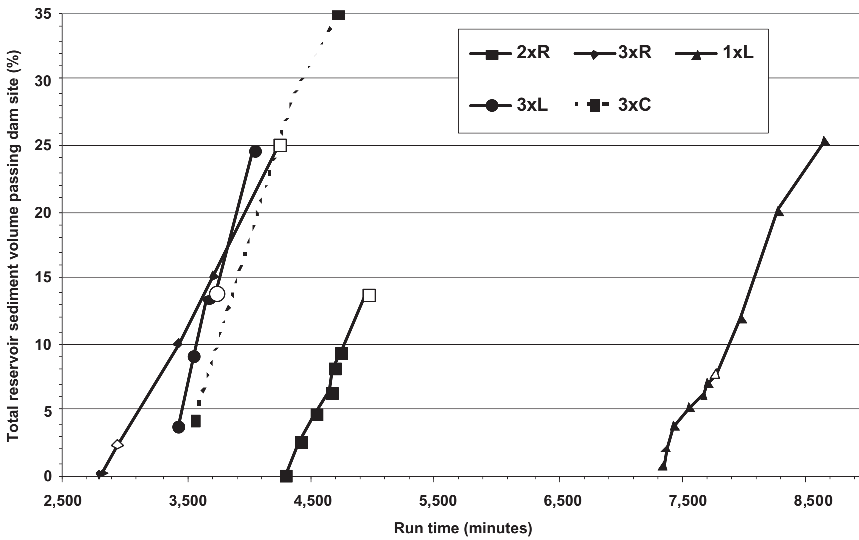


Figure 7-11. Total reservoir sediment passing downstream. The empty markers indicate the static equilibriums at the end of dam removal (Table 7-1).

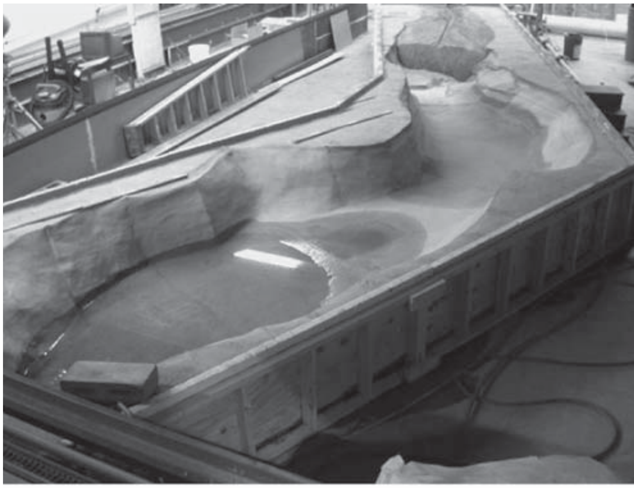
7.4 DISCUSSION

The results show that there was a general tendency for an increase in the magnitude of the drop in baselevel to lead to an increase in the volume of original delta erosion, but only up to a certain magnitude of drop. They also show that this tendency was moderated by the interaction of the incising channel with the reservoir boundary. A noncohesive alluvial channel responding to a drop in baselevel will widen in response to the upstream migration of incision (Schumm et al. 1984; Schumm et al. 1987; Simon 1989; 1992). This widening occurs through a combination of the banks exceeding their critical height for stability due to incision, and the development of sinuous flow paths that lead to channel meandering. Where the reservoir boundary prevented this sinuosity from developing in one direction (e.g., to the left in Fig. 7-8A–D), it also prevented the sinuosity from fully developing in the opposite direction in the next (incipient) bend downstream, thus restricting the extent to which the entire channel could move laterally. In the same way, the reservoir boundary also controlled the extent to which flood flows were able to erode the remaining terrace deposits (Figs. 7-8 and 7-9).

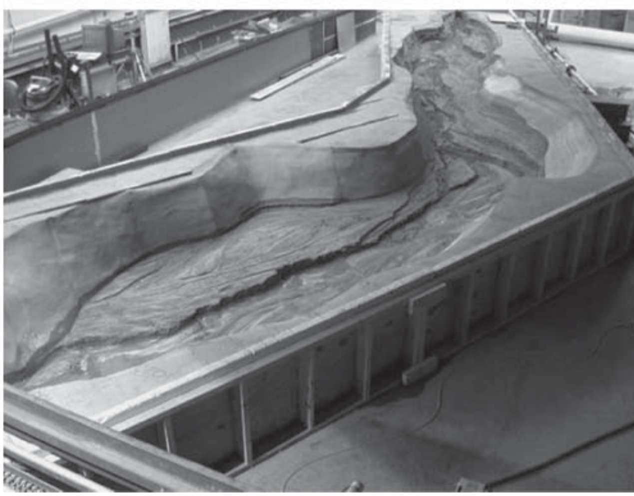
The influence of the reservoir boundary on delta erosion is one specific manifestation of the more general observation that the width of the reservoir sediment deposit relative to that of the river channel will have a significant effect on the proportion of reservoir sediment mobilized during dam removal. In the context of reservoir flushing to recover lost storage capacity, Annandale and Morris (1998) noted that most of the reservoir sediment deposit will be mobilized when it is of a similar width to the river channel. While the sediment management objectives during flushing and dam removal may be quite different, this principle remains the same. The relevant variables to the precise proportion of sediment that will be mobilized will be the deposit's grain size distribution and stratification, the discharge during removal (and specifically the capacity of this discharge to mobilize and transport this grain size distribution), the shape of the basin downstream from the original delta (for cases where the reservoir is not full of sediment); and the magnitude and rate of drop in baselevel. The interactions between some of these variables have been highlighted and discussed by Bromley et al. (2011) and by Bromley (2007; unpublished data).

Runs 3xC, 6xC, and 12xC eroded and redistributed the greatest volumes of original delta sediment throughout the reservoir area (Fig. 7-12). The greatest total reservoir sediment volume passing downstream both at the end of dam removal and after the first 2-year flood flow occurred during run 3xC. If runs 6xC and 12xC had been completed, it is possible that they would have seen similarly large volumes passing downstream. Thus, the central runs were the most effective at redistributing delta sediment throughout the reservoir area (thereby minimizing the ratio of the total reservoir sediment volume to sediment volume within the root zone of recolonizing vegetation). Paradoxically, they were also the most effective at introducing large volumes of sediment into the downstream system in the short-term following dam removal. That the accelerated incremental dam removal in run 3xC was able to generate erosion volumes very similar to those of magnitudes of baselevel drop four times greater is potentially of great practical utility. However, it indicates that the range of erosive behaviors obtained with a wide range of magnitudes of drop can also be obtained with much smaller drops that are more realistically attainable in the field, simply by manipulating the rate of baselevel drop.

These sediment volumes represent many years' worth of natural sediment transport and they will undoubtedly affect the physical and biological fabric of the downstream system. The extent to which they will do so remains unclear, however, and will depend on a number of factors, including the absolute quantities of fine (silt and clay) and coarse (sand and gravel) sediment released; the extent to which the fines are flushed through the system or deposited on and within the bed; the volume of coarse material deposited in pools, channel margins, riffles and, in the case of sand, within the bed; and the extent to which these deposits can be flushed out by higher flows. The adaptive management strategy that has



A



B

Figure 7-12. (A) Original delta at start of run 3xC. (B) Original delta sediment distributed throughout the reservoir by the static equilibrium at the end of dam removal. Compare the extent of original delta erosion here to that at the end of dam removal in the runs whose channels start in left or right delta positions (Figs. 7-5, 7-7, 7-8A, 7-9A).

been developed for sediment management during dam removal reflects this uncertainty (National Park Service 2005).

Over the medium to long term, however, vegetation within the reservoir area will form a well-developed root architecture that will stabilize some or all of the remaining reservoir sediment. If the prototype Glines

Canyon Dam is removed under a central channel removal scenario, the downstream sediment releases may be higher in the short term than under a marginal removal scenario. If the dam is removed under a marginal channel removal scenario, however, it is hypothesized that the sediment releases to the downstream system will be smaller in the short term but will persist at elevated levels over the medium to long term, due to the episodic mass wasting of high, unvegetated, and unstable terrace deposits within the original delta area (Figs. 7-5 through 7-9).

7.5 CONCLUSIONS

The morphodynamic behavior outlined above has not previously been reported for dam removal work. The results presented here do need to be treated with caution, however, since they are based on a limited amount of experimental data. Probably the greatest overall weakness of this study is the lack of replication of any of the experimental runs. This was not possible given the length of time required to complete each run (one month on average), and therefore it is impossible to quantify the natural variability inherent in each removal scenario examined. While such variability is unlikely to invalidate the large erosion volume differences between runs 1xL and 3xC, the same cannot be said for the much smaller erosion volume differences that exist between runs 1xL, 3xL, 2xR, and 3xR, and between 3xC, 6xC, and 12xC.

Also, the model is necessarily a simplification of reality. The bottomset deposits of the prototype were not present; the model was run with a constant discharge; and there was a drop between the mouth of the inlet channel and the channel bed once it began to incise (Fig. 7-4, arrow E). This drop was present because there was insufficient space on the laboratory floor to extend the inlet channel upstream at the correct slope and from the correct elevation on the reservoir base. This drop created an entrance effect in the model that reduced flow velocities at the upstream end of the delta and thus probably decreased the flow's erosivity.

Finally, the model was subject to scale effects from the vertical distortion and the coarse model sediment mixture. The latter may have decreased the erodibility of the original delta, thus leading to potential underestimation of the volume of sediment entering the downstream system.

Despite their shortcomings, the results highlight issues that are of importance to both the Elwha River project and to other dam removal projects. The variables discussed here and those presented in Bromley et al. (2011) merit further field and laboratory investigation in order to more thoroughly understand the dynamics of their interactions. In turn, this will help to clarify the roles of the fundamental factors that control the morphodynamic response of a mass of sediment impounded in a reservoir to dam removal.

ACKNOWLEDGMENTS

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PART IV: NUMERICAL MODELING

CHAPTER 8

MODELING AND MEASURING BED ADJUSTMENTS FOR RIVER RESTORATION AND DAM REMOVAL: A STEP TOWARD HABITAT MODELING

Timothy C. Granata, Fang Cheng, Ulrike Zika, Daniel Gillenwater, and Christopher Tomsic

8.1 INTRODUCTION

While dams provide many desirable benefits to society, they also are a major hydro-modification to ecosystems, can be safety and boating hazards, and may degrade water quality of the river. In the Great Lakes District, dams that exceed a height of 6 ft (2 m) and a pool volume 50 ac-ft (6.2×10^4 m^3) are inspected and require a state permit to ensure they are properly maintained. For dams that fail inspections, dam owners are faced with four options: (1) do nothing; (2) modify the dam to such an extent that it is not subject to the regulations; (3) rehabilitate the dam to meet the regulatory guidelines of the permit; and (4) remove the dam. The chosen option often depends on the outcome, its economics, and the environmental and political pressures associated with the option. For example, the "do nothing" option may carry a regulatory penalty and liability for a catastrophic failure that causes loss of life and property. If the dam is modified or removed, the fate of changing water levels and sediments loads downstream of the reservoir, immediately after removal and over time, will be a concern to residents along the river. Thus, dam owners need tools to assess the outcomes of the various options applied to their situation.

A cost-effective approach for dam removal planning and decision making is to combine a one-dimensional (1-D) mathematical model of the river hydraulics with a sediment transport model (Cheng and Granata 2007; Doyle and Stanley 2003). Although an extensive body of engineering literature has been amassed on dam failures using models such as

HEC-RAS, DamBreak, and FloodWave to predict water levels (e.g., Fread and Harbaugh 1973), these do not account for sediment transport or changes in bed morphology.

Models such as GSTARS 2.0 (Rathburn and Wohl 2001), DREAM (Cui et al. 2006), Fluvial-12 (Chang Consultants 2006), CONCEPTS (Langendoen 2007), and 3ST1D (Papanicolaou et al. 2004) have been used to simulate sediment loads after dam removal. However, HEC-6, developed by the U.S. Army Corp of Engineers (USACE), has been the preferred 1-D model (Rathburn and Wohl 2001; Thomas 2011; Williams 1977), probably because it is in the public domain and thus widely available. One major limitation of HEC-6 is that it simulates flooding as a series of steady-state water levels, when in fact the process is unsteady.

Another approach is the use of a dynamic model to simulate unsteady flow and sediment transport for assessing options. MIKE 11 is a suite of river modeling software developed by the Danish Hydraulic Institute and sold commercially. This chapter documents the results of studies and simulations using MIKE 11 to address the problem of dam removal and river restoration (Cheng et al. 2006; Gillenwater et al. 2006; Tomsic et al. 2007). MIKE 11 was used not only because it simulated unsteady flow but also integrated modules for dam break, sediment transport, and bed morphology. While the importance of higher-order models was recognized for simulating complex river morphology, such as bank erosion and channel incision (Randle and Bountry 2011), erosion at the study sites described in this chapter was predominantly from bed incision—a process that is adequately modeled by MIKE 11. Further, a more sophisticated model may not give more reliable results because of the data uncertainties (Vreugdenhil 2002). The goal of the MIKE 11 modeling was to achieve reasonable simulations of water and bed levels, within the limits of the data available for calibration and boundary conditions, as input for habitat models, and to assess the overall restoration success of the dam removals.

In this chapter, MIKE 11 is used to simulate operation and removal options for a low-head dam and a high-head dam on the Sandusky River. This entailed coupling the Hydraulic module to predict water levels, a Dam Break module to simulate unsteady breach conditions, and a Non-Cohesive Sediment Transport module of total load to estimate bed elevations. The results and an assessment of the model's usefulness for restoration studies are discussed. Examples of how habitat models are used to predict restoration for target species based on MIKE 11 output are also presented.

8.2 STUDY SITES

The Sandusky River, located in northern Ohio, is 190 km long and flows northeast into Sandusky Bay and then Lake Erie (Fig. 8-1). It

Figure 8-1. Map of the major tributaries in the Sandusky River watershed (northern Ohio). Also noted are the locations of the USGS gaging stations and nearby cities.

constitutes an important coastal watershed in the Great Lakes District. The river has a bedrock base that is exposed in some sections, although the majority (>80%) of the bed is composed of mixtures of sand, gravel, and cobbles. The Sandusky River drains a 3,637-km^2 area, 83% of which is in agricultural land use. In the upper watershed, south of the city of Tiffin, Ohio, the river is designated a State Scenic River. In the lower watershed, from the city of Fremont, Ohio, to the coast, the river supports the last vestiges of the spawning grounds for walleye in Ohio.

The first dam on the Sandusky River is Ballville Dam, located 29 km upstream of the river mouth and situated south of Fremont (Fig. 8-1). Built in 1911 and rebuilt in 1914 after it was damaged by a 100-year flood, the concrete superstructure stands 10.5 m high and 120 m wide (Fig. 8-2A). The dam has a 5-km-long impoundment with an average depth of less than 2 m, and an estimated storage volume of 0.5×10^6 m^3 (Table 8-1). Flow at Ballville Dam accounts for 92% of the drainage of the entire

Table 8-1. Characteristics of the Two Northern Ohio Dams Studied

	Ballville Dam	St. Johns Dam
Dam class	Class I	Class IV
Dam height (m)	10	2.2
Cities downstream	Fremont	Tiffin, Fremont
Use	Water supply	Water supply
Channel slope (m/m)	10^{-3}	10^{-4}
Backwater length (km)	5	13
Reservoir volume (m^3)	1.7×10^{6}[a]	0.56×10^{6}[a]
Sediment storage (m^3)	0.73×10^{6}[a]	0.20×10^{6}
Structural condition	Poor	Poor, prior breach
Ecological condition	Inaccessible upstream habitat	13 km of recovering habitat
Fate	Scheduled for removal in 2011	Removed in 2003

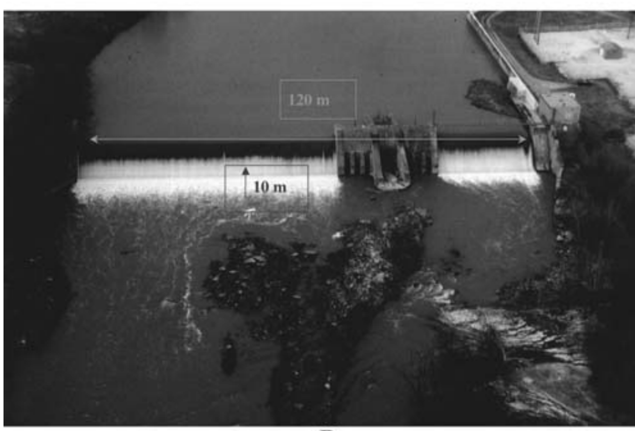
[a]Based on Evans et al. (2002).

watershed. Currently, the impoundment is a water supply reservoir for the city of Fremont. In 1980, USACE classified Ballville Dam as a high hazard potential because a sudden failure of the dam may cause a discharge overtopping the protective dikes. In 2005, the Dam Safety Division of the Ohio Department of Natural Resources found the dam to be in violation of its permit. Currently, the city of Fremont is looking at removing the dam and building an off-site reservoir as a water supply (Granata and Zika 2007).

St. Johns Dam is located 51 km upstream of Ballville Dam and south of the city of Tiffin (Figs. 8-1 and 8-2). At this site the Sandusky River drains an area in the upper watershed of 1,974 km^2. St. Johns Dam was a 2.2-m-high, 40-m-wide structure built in the 1930s as a water supply reservoir (Fig. 8-2B). The impoundment extended 13 km upstream of the dam, with an average width of 30 m and a total storage of approximately 0.56×10^6 m^3 (Table 8-1).

St. Johns Dam was removed by the Ohio Scenic Rivers Program (Ohio Department of Natural Resources) and the Ohio Department of Transportation (ODOT) in November 2003. As part of the removal, ODOT is receiving primary mitigation credit for draining the impoundment and secondary credit when fish and invertebrate habitat are restored. Impoundments upstream of both dams (Ballville and St. Johns) have accumulations of sediments composed of gravel to fine sands. Table 8-1 lists the various characteristics of the two dams.

A



B

Figure 8-2. Images of (A) Ballville Dam and (B) St. Johns Dam.

8.3 MODEL AND METHODS

Prior to the dam removals, a one-dimensional (1-D) hydrodynamic model of the Sandusky River was constructed using the commercial software package MIKE 11 (Danish Hydraulic Institute/USA, Portland, Oregon). The Hydrodynamic module simulated water level and mean velocity at specified cross sections, including spawning habitats. Sediment transport was modeled as total load with the Acker and White equation using the MIKE 11 Sediment Transport module in the morphological mode, where shear is dynamically linked to changing bed elevation based on sediment continuity and bed resistance. For each cross section, sediment was modeled as an average grain size and the standard deviation of the particle size distribution.

Rather than model the entire watershed with two dams, the model domains were divided into two overlapping networks for each dam (Fig. 8-3). For St. Johns Dam, the network was defined from 12 km upstream of the backwater of the impoundment (chainage 0 km) to a USGS gaging station 61 km downstream and south of Ballville Dam (Fig. 8-3A). For Ballville Dam, the network extended from north of Tiffin (chainage 0 km) to Sandusky Bay (chainage 65 km; Fig. 8-3B). More than 50 cross sections were used for each network, some of which were provided by the Federal Emergency Management Agency (FEMA) and others were surveyed with

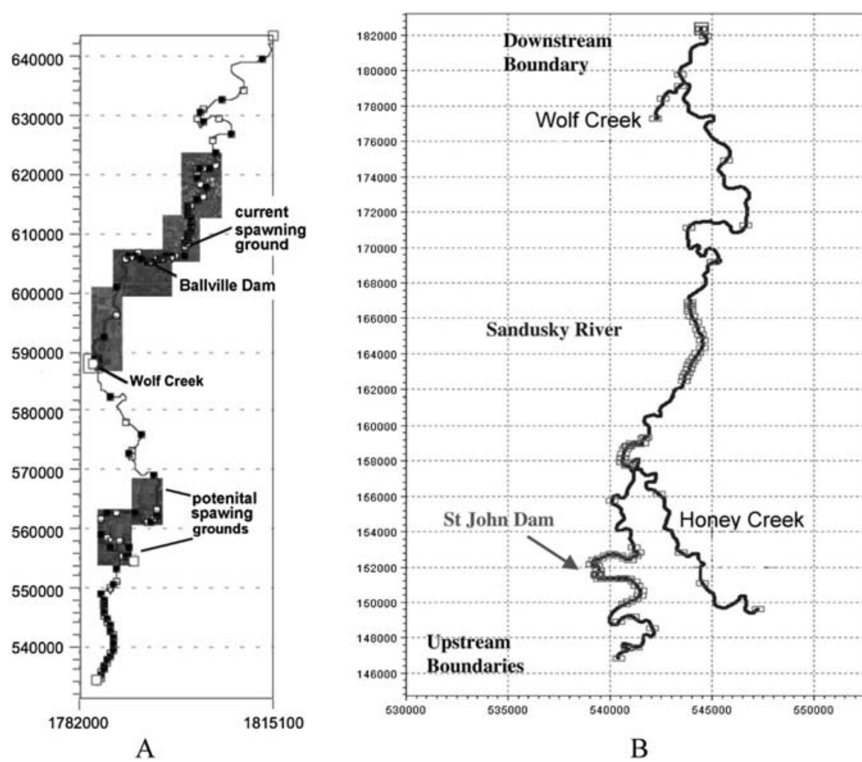


Figure 8-3. Model network of Sandusky River for the (A) Ballville Dam in the lower watershed and (B) St. Johns Dam in the upper watershed. Symbols indicate the chainages (i.e., nodes) in the models.

a remote GPS unit (Trimble 5700) or a total station (Sokkia). Cross sections were not evenly spaced over the model domain, but rather were concentrated upstream and downstream of the dams and over key habitat areas to provide better spatial resolution and higher accuracy there. To construct the river network, geo-referenced aerial photographs were used to resolve the channel, and the photos were overlaid with the chainages (i.e., computational nodes), spaced roughly 0.1 km apart.

The dam operation was simulated using the MIKE 11 Structures module interfaced to the Hydrodynamic module. The dams were modeled as cross sections with broad, crested weirs and operated with a discharge–water level (*Q–H*) relationship. The dams were breached using a 10-min time step over the duration of the break. For Ballville Dam, the catastrophic, instantaneous breach was from bank to bank. In contrast, the controlled removals had a duration of 2 days and were limited to a 40-m-wide section of the dam at the channel thalweg. The Ballville Dam simulations were run for high and low lake river flows and lake levels to determine the difference in sediment transport and water levels after the catastrophic failure and dam removals. For St. Johns Dam, the break duration was based on field observations of the removal (Granata et al. 2008).

The boundary condition upstream of Ballville Dam was the daily time series of discharge from the USGS gage at Fremont. The downstream boundary was based on daily water level data in Sandusky Bay from the CO-OPS National Water Level Observation Network (NWLON) database. Since the Fremont gage station was not located at the upstream boundary, flow was adjusted by subtracting inflows from tributaries between Tiffin and the gaging station, assuming the discharge was linearly proportional to the drainage area of the tributaries. Using the lake level as the downstream boundary was justified because the water level in Sandusky Bay was dominated by changes in lake level, which affected the river stage to within 5 km of the dam.

For the St. Johns Dam network, a daily time series of weighted discharge at 0 km was the upstream boundary and a *Q–H* relationship downstream at the Fremont gage (USGS 04198000, 1923–present, available at http://waterdata.usgs.gov/nwis/uv?04198000). The weighted discharge at the upstream boundary was the sum of two gages located outside of the network (Tymochtee Creek, USGS 04196800, 1922–present and Upper Sandusky, USGS 04196500, 1964–present; all are available at http://waterdata.usgs.gov/nwis/uv?04198000). Discharge data were weighted to the percent of watershed area between the gages and the upper boundary and were not modeled to account for any overland flow. This discharge relationship was verified by measurements using an acoustic Doppler profiler (Cheng and Granata 2007).

The simulation for St. Johns Dam was from November 2002 to September 2004, encompassing 1 year prior to and 1 year after the removal of the dam, and used a 1-sec time step. The dam removal was modeled as a 2-h breach across the width of the channel with 10-min time steps and occurred at low flow conditions ($<5\ m^3/s$). Time series of water level, obtained 200 m downstream of the dam using a pressure transducer (YSI, Yellow Springs, Ohio), were used to calibrate the hydraulic model to a breach event that occurred prior to removal (Granata et al. 2008). The calibration reproduced measured water levels to within 5%. The initial water level for the model was based on a hot start using the time series from pre-removal conditions in 2002.

Sediment load was measured by collecting sediment in pit traps over several weeks in 2003 and 2004 (Cheng and Granata 2007). Materials were sorted into size classes using sieves and were weighed. Three pit traps were located upstream and three downstream of the dam. Sediment distributions were determined from spatial maps resolved to 2 m × 2 m and provided by the Geological Survey of the Ohio Department of Natural Resources. Based on these maps and particle size distributions, the Sediment Transport module was initialized with fine sand ($D_{35} = 0.5$ mm) in the impoundment and had an active (i.e., movable) layer of 5 m. The exceptions were cross sections at the dam to 0.6 km upstream of it, which were exposed bedrock and thus were defined as a 0-m active layer. Finally, no sediment input was assumed at the upstream boundary for this time period, which was reasonable considering that the incoming load was small (3×10^{-3} kg/s) relative to the average release of sediment stored in the impoundment (3×10^{-1} kg/s) (Cheng and Granata 2007).

For the Ballville simulations, time series of water level from 1957 to 1978 were used to calibrate the model with the dam intact. Calibration errors in water level were less than 5% of field measurements and FEMA model results. Because the lake level regulated water levels downstream of the dam, four dam break scenarios were run for the removal option. These were high lake level for high and low discharges, and low lake level for high and low discharges, where "high" was $>500\ m^3/s$ and "low" was $<50\ m^3/s$. All simulations for Ballville Dam were run from January 1, 1978 to September 30, 1993 with 1-sec time steps. In the case of catastrophic failure, the dam break coincided with a high discharge event ($600\ m^3/s$) in 1979 and terminated 2 days after the breach. Initial conditions for the Ballville model were a hot start from the 1978 to 1983 simulation but without the dam removal. Based on available sediment data (Evans et al. 2002), the initial sediment conditions were coarse sand ($D_{35} = 1$ mm) in the impoundment with an active (i.e., movable) layer of 5 m. Because of the higher sediment loading in the lower watershed (1 kg/s), daily time series of suspended load collected at the gage was used as the upstream boundary in the Sediment Transport module.

8.4 RESULTS

8.4.1 St. Johns Dam Removal

The simulation accurately predicted the timing and magnitude of the water level for the 2-h removal (i.e., an abrupt breach). Water levels were within 5% of actual water level measured 200 m below the dam and reproduced the attenuation of the floodwave past the Fremont gage.

Compared to pre-removal conditions, bed elevation 10 months after the removal showed both erosion and deposition within the former reservoir. Modeled bed elevations in the thalweg of the impoundment differed from pre-removal conditions by 0.05 m to 1.5 m. Generally, the modeled bed elevations were <10% of the measured bed elevations except at three locations upstream of the dam site at distances of 1.2 km, 2.8 km, and 3.2 km (Fig. 8-4). At these locations, bed elevations differed by as much as 27% from pre- to post-dam removal. Further, these chainages were locations of meanders in the river network (Fig. 8-4, top). Erosion occurred upstream of the dam site from 3.2 to 4.5 km and from 1.2 to 2.5 km, while deposition occurred between 2.5 and 3.2 km.

The region from the dam to 0.6 km upstream of the dam was a zone of no scour, (i.e., no erosion or deposition occurred) (Fig. 8-4), which was defined as bedrock in the initial conditions. Erosion upstream of the reservoir was evident at distances from 5.5 to 12 km upstream of the dam (Fig. 8-5). Downstream of the dam, deposition occurred over a region of roughly 2 km. Overall, there was a net export of 5×10^3 m^3 of sediment from the reservoir, accounting for only 2.5% of the sediment stored in the reservoir.

8.4.2 Ballville Dam Options

For the catastrophic dam break, the crest of the floodwave after the breach was masked by the river stage during the high discharge (not shown). The catastrophic failure produced an abrupt discharge of sediment downstream with high deposition over downstream spawning habitat (Fig. 8-6A). In the first 48 h after the breach, the model predicted a maximum depositional zone located 2 km downstream of the dam (at node 37 km) with sediments >6 m deep over a 4-km reach. Sediments were also spread downstream of the maximum depositional zone.

For the timed (controlled) removals, water levels during the high discharge masked the crest of the floodwave for both high and low lake levels (Cheng et al. 2006). In contrast, the floodwave was a predominant feature of the breach during the low discharge, with peak water levels of 1.5 m and 2.0 m above the river stage for low and high lake levels, respectively. For all flow conditions during the timed removal, the bed elevation increased less than 0.05 m from the pre-removal condition (Fig. 8-6B).

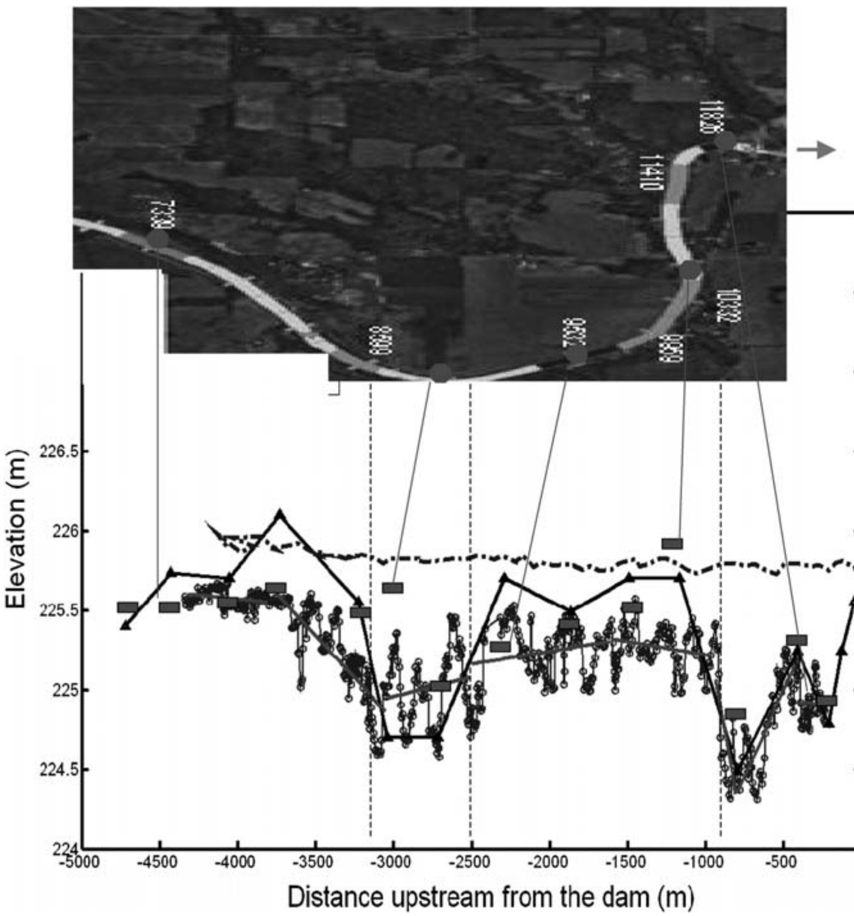


Figure 8-4. Measured (open circles) and modeled (filled rectangles) bed elevations relative to pre-dam removal bed elevation (filled triangles). Negative numbers are distances (m) upstream of the dam. The gray line passing through the open circles is a moving average of the measured bed elevation. The stippled line represents the water level during the measurements, while the solid line at 227.8 m is the pre-dam-removal water level. Channel morphology (top) shows the location of the modeled bed levels. The gray arrow indicates the direction of flow.

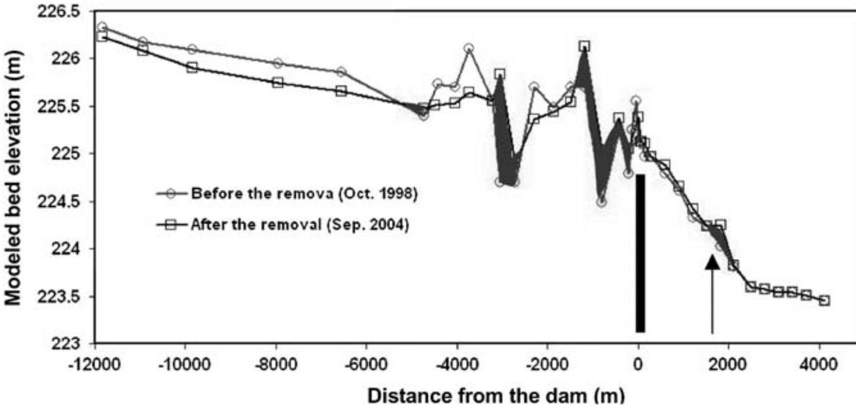


Figure 8-5. The longitudinal profile of modeled bed elevation (m) after the removal (open squares) and prior to removal (open circles) of St. Johns Dam. Filled areas between pre- and post-removal trends represent regions of sediment deposition. The bar at 0 m represents the location of the dam and the arrow at 1.8 km illustrates the extent of the depositional zone downstream of the dam.

Most importantly, the spawning habitat downstream of the dam experienced no sediment deposition even during bank-full water levels.

8.5 DISCUSSION

Post-removal bed elevations upstream and downstream of St. Johns Dam were adequately modeled using only a calibration of the Hydrodynamic module to Manning's roughness. The model performed well in simulating bed elevations in the river glides and runs, but overestimated and underestimated bed elevations in the meanders. In one case (1.2 km upstream of the dam site), the model had higher net erosion of the bed in the meanders compared to measurements, while in two other cases it had lower rates than expected (2.3 and 3.5 km upstream of the dam site). Part of this discrepancy may be that the 1-D model does not account for centrifugal acceleration of the flow in the meanders, secondary (i.e., cross-channel) currents, or size sorting on the concave and convex banks. Despite these errors in bed elevations, the model gave a realistic profile of the bed upstream and downstream of the former dam.

However, total sediment loads were overestimated by up to 300-fold over measured values (Cheng and Granata 2007). Measurements of load from the pit traps could have been in error because the traps collected bed load, as well as the heaviest fraction of the suspended load near the bed, but not the suspended load in the upper water column. In this case, the

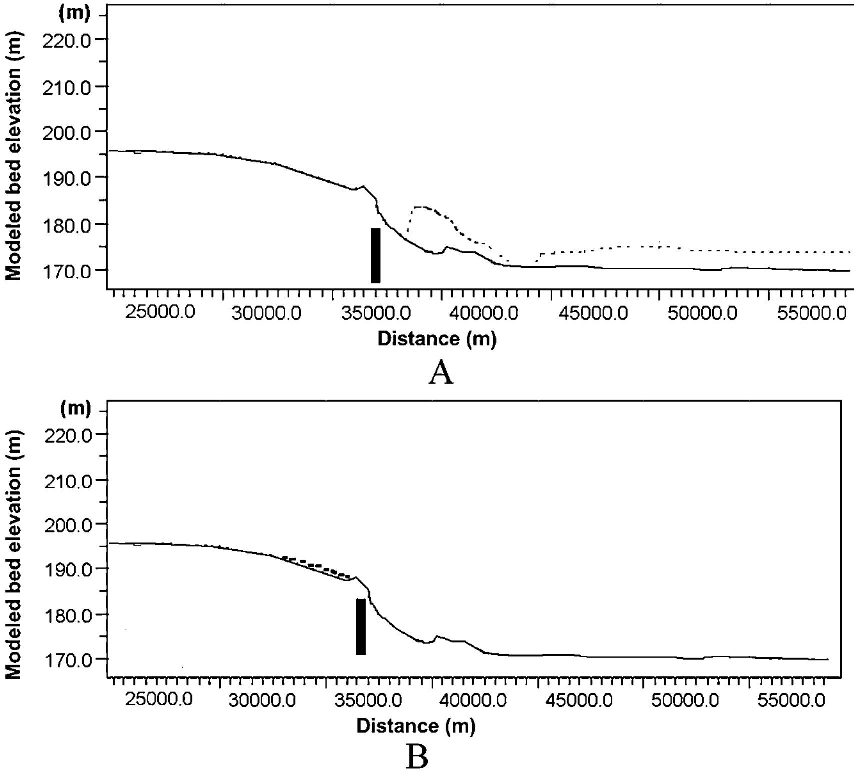


Figure 8-6. The longitudinal profile of the modeled bed elevations relative to pre-removal conditions (solid line) and for (A) a catastrophic failure during high discharge (dashed line) and (B) a 2-day removal during low discharge (dashed line indicates negligible change in bed elevation). The solid bar indicates the location of the dam.

field measurements would have underestimated suspended load, and thus total load, which is the sum of bed load and suspended load. Even accounting for a 50% error in measured load does not reconcile the predictions of the model. Rathburn and Wohl (2001) also found that sediment load was overestimated by up to two orders of magnitude for various sediment transport equations in HEC-6 simulations of a sediment pulse from a reservoir. Havis et al. (1996) found that HEC-6 overestimated sediment transport in a gravel bed for low flows but underestimated it for high flows. Our results are different from those of Wohl and Canderelli (2000), who describe filling of pools downstream of a reservoir. In their study, the upstream supply of sand was depleted, whereas sand was plentiful in the former St. Johns Reservoir. Our results are similar to studies of pool filling from mining spoils (Wohl 2001).

The results of the Ballville Dam simulations were not verified since the dam has not yet been removed and, thus, no data are available for either the catastrophic failure or timed (controlled) removals. The simulations of the timed removals produced minor depositional zones in the impoundment and negligible change in bed level downstream over the existing spawning habitat. Deposition in the impoundment probably resulted from sedimentation of the incoming load behind the outcropping of bedrock at the site.

The "do nothing" option that produced an abrupt dam break was the worst-case scenario for Ballville Dam and would be a highly destructive event for the city of Fremont and for walleye spawning grounds downstream of the dam. The catastrophic simulation predicted a deposition of sediment up to 6 m deep at a distance 2 km downstream of the dam—which is a prime habitat area—but only a minor bed level change in the upstream reaches of the former impoundment. The latter effect could be the result of the higher sediment load filling the impoundment after it was scoured. It appears that the bedrock outcropping, which forms a natural pool in the impoundment, has a significant influence on the distribution of sediments at the Ballville site.

Using a simple shear-stress model, Evans et al. (2002) concluded that flows from mean daily average (4 m^3/s) to bank-full (370 m^3/s) would transport 90% of the fill from the Ballville reservoir after the dam removal. This result is comparable to our catastrophic failure, except that we predict sediment being deposited downstream of the dam. Their result is drastically different from our timed removal simulations in that more sediment is transported in their model. An additional complication is that none of these models predicts increased scour in the outer bend of the Ballville reservoir. Nevertheless, the MIKE 11 simulations give a general view of sediment transport with different removal options.

In terms of flooding from controlled removal of Ballville Dam, only the low flow during high and low lake levels showed a floodwave progressing downstream. Thus, from the perspective of downstream residents, the minor effects of the breach would be noticed only during low flow conditions. We suggest that it would be advantageous to remove the dam during low flow and low lake level conditions, not only because this would produce the lowest water levels in the city of Fremont but also to prove to the public that the removal would not cause flooding. This would be more difficult to prove during high discharges since the higher river stage could be blamed on the breach.

8.6 CONCLUSION

Overall, the models of the St. Johns and Ballville dams removals predicted a reduction of bed slope in the former reservoirs. In the case of Ballville Dam, the slope varied little, while for St. Johns Dam it was reduced by approximately 30%. The latter was caused by fine sand filling pools in the former impoundment with little deposition downstream. For all options, except the catastrophic failure of Ballville Dam, spawning habitats were preserved downstream of the dams and were augmented upstream.

The fact that the integrated model produced estimates of bed elevation, velocity, and depth over habitat areas makes it ideal to use for predicting ecological outcomes of restoration in the Sandusky River. For example, output from MIKE 11 has been used with substrate (sediment) distributions to determine habitat suitability of target fish species in the Sandusky River (Cheng et al. 2006; Gillenwater et al. 2006; Tomsic et al. 2007).

By interfacing a GIS habitat model with MIKE 11 velocity and depth data every 0.3 km, Tomsic et al. (2007) predicted an increase in suitable habitat for the endangered Redhorse in the vicinity of St. Johns Dam (Fig. 8-7). This suitable habitat was defined on optimal water depths,

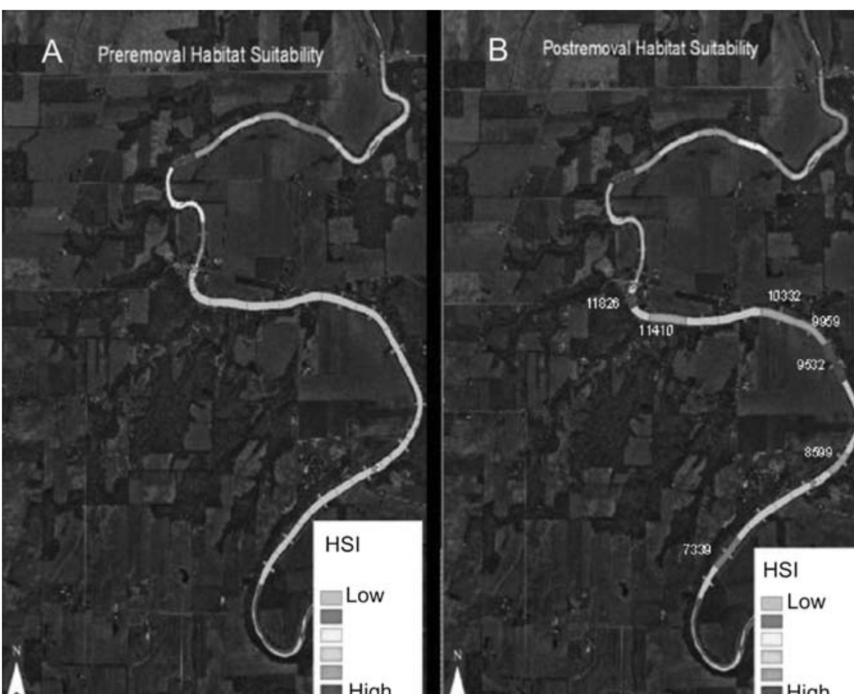


Figure 8-7. A habitat suitability index (HSI) at the St. Johns Dam site showing the percent suitable spawning ground of the Greater Redhorse (A) before dam removal and (B) 10 months after dam removal (right). Numbers are chainages in the model. Source: Adapted from Tomsic et al. (2007).

velocities, and substrates that are known to support Redhorse spawning. Gillenwater et al. (2006) have developed and calibrated a 2-D ecohydraulic model for walleye spawning habitat downstream of Ballville Dam (Fig. 8-8), which predicted spatial shifts in spawning areas for different flow conditions. The goal of these studies was to extend the assessment of dam

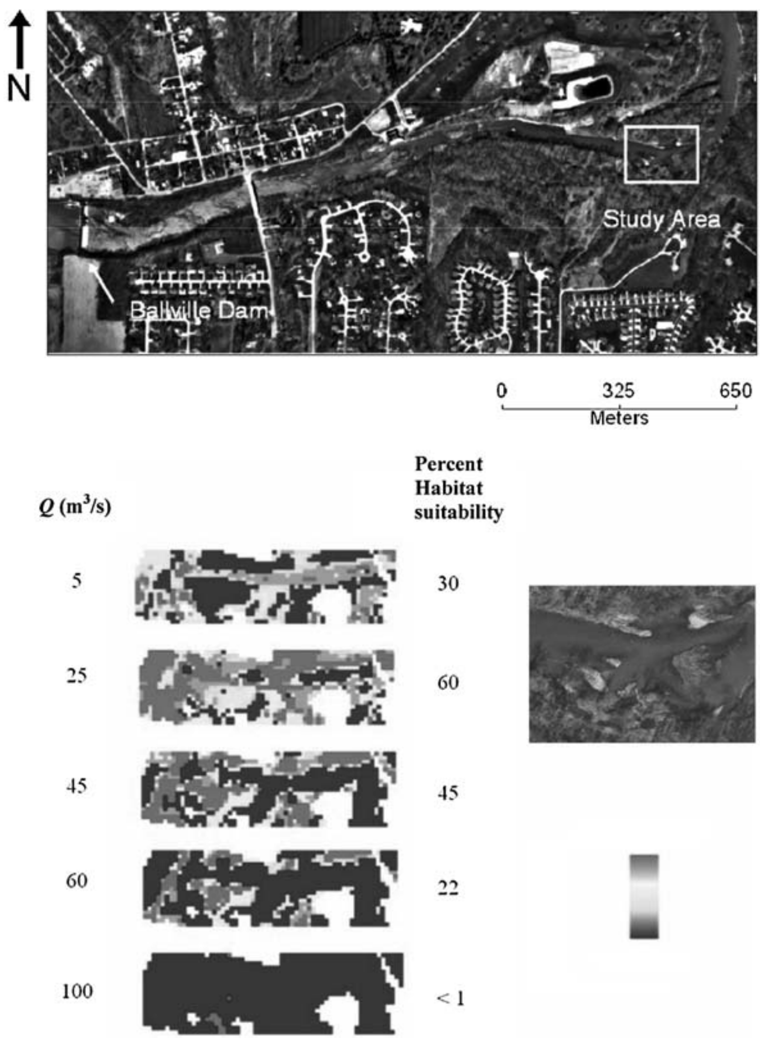


Figure 8-8. A 2-D habitat model downstream of Ballville Dam to assess walleye spawning grounds. The dam is located at the far left in the top image. Q, water discharge. Source: Modified from Gillenwater et al. (2006).

removal and river restoration to ecological issues, which often drives restoration in rivers. The use of ecohydraulic models to predict habitat and species shifts could be valuable to evaluate future restoration projects, just as hydraulic and dam break models are for assessing flooding.

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CHAPTER 9

MOVEMENT OF SEDIMENT ACCUMULATIONS

Blair Greimann

9.1 INTRODUCTION

Estimating the deposition downstream of dams following dam removal is important to the design of dam removal strategies and mitigation measures. For example, deposition downstream of dam removal may increase flood elevations, which in turn requires that levees be constructed or bridge openings redesigned. A variety of methods are used to analyze sediment impacts after dam removal. Most often, the prediction of the movement of these accumulations is accomplished by using a one-dimensional (1-D) hydraulic model coupled with a sediment transport model (Bountry and Randle 2001; Greimann 2003; Mobile Boundary Hydraulics 2001; Stillwater Sciences 2002). However, such models can be complex and require large amounts of input data.

A simple method would be beneficial in providing initial estimates and for cases where complex models are not necessary. One such method was developed by Soni et al. (1980) to model aggradation due to overloading. This model used the steady-flow equations, a flow resistance relation, sediment continuity, and a sediment transport function to develop a diffusive wave model. These researchers then developed an analytical solution for the diffusive wave model for the case of a sudden and permanent increase in sediment concentration in a previously stable reach. Jain (1981) improved the analytical solution by using more appropriate boundary conditions. The models of Soni et al. (1980) and Jain (1981) were applicable to the case of a constant overloading of single-sized sediment. Begin et al. (1980) applied a diffusive wave model to the upstream migration of a knickpoint.

These models were applicable to single-sized sediment, but in the case of sediment accumulations, the accumulated sediment may be much finer than the original bed material. Greimann et al. (2006) built upon the previous work and developed a diffusive wave model applicable to the movement of finite-amplitude sediment accumulations. This chapter further explores the applicability of this diffusive wave model.

9.2 MODEL DESCRIPTION

The model idealizes the movement of sediment accumulations, as shown in Fig. 9-1. The sediment accumulation lies over a bed of uniform slope. The sediment accumulation is composed of a single size class, as is the original bed material. Due to the increase in slope on the front face of the sediment accumulation, the sediment accumulation will travel downslope.

An advection-diffusion equation was derived in Greimann et al. (2006) to explain the motion of such accumulations, as shown in Fig. 9-1:

$$\frac{\partial z_b}{\partial t} + u_d \frac{\partial z_b}{\partial x} = K_d \frac{\partial^2 z_b}{\partial x^2} \tag{9-1}$$

where u_d is the velocity of accumulation translation, defined as:

$$u_d = \frac{(G_d^* - G_0^*)}{h_d (1-\lambda)} \tag{9-2}$$

The other parameter, K_d, is the diffusion coefficient of the sediment accumulation, defined as:

$$K_d = \frac{(b_d G_d^* + b_0 G_0^*)}{6 S_0 (1-\lambda)} \tag{9-3}$$

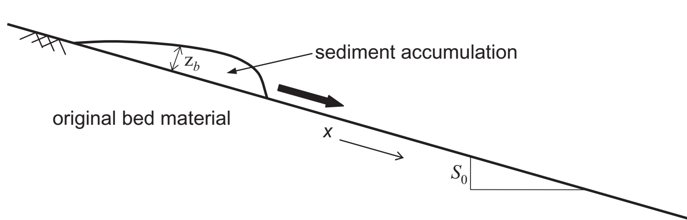

Figure 9-1. Schematic of idealized movement of sediment accumulations.

and where
t = time
x = stream-wise distance
b = exponent of velocity in sediment transport relation
S_0 = original bed slope
z_b = depth of sediment above the original river bed
h_d = maximum depth of sediment accumulation
λ = porosity
G_d^* = sediment transport rate per unit width of the sediment accumulation
G_0^* = sediment transport rate per unit width of the original bed material.

These equations were derived starting from the water and sediment continuity equations. For the water flow, normal depth was assumed along with a Chezy resistance relation. The sediment transport was assumed to be related to the water velocity through a simple power function. The constant value of "6" appearing in the dominator of K_d is the result of the substitution of slope and sediment transport rate for the velocity. Details are found in Greimann et al. (2006).

The solution to Eq. 9-1 with the initial depth of the sediment accumulation given by z_1 is:

$$z_b(x,\tau) = \int_0^\infty \frac{z_{1i}}{\sqrt{4\pi K_d t}} \left[\exp\left(\frac{-(x-u_d t-\xi)^2}{2\sqrt{K_d t}} \right) + \exp\left(\frac{-(x+u_d t+\xi)^2}{2\sqrt{K_d t}} \right) \right] d\xi \quad (9\text{-}4)$$

where z_{1i} = initial height of sediment accumulation.

The second term in the integral of Eq. 9-4 is due to the reflection of the boundary at $x = 0$, where it is assumed that the sediment deposit begins at $x = 0$. The integral in Eq. 9-4 can be numerically approximated by dividing the stream into N segments and assuming a constant depth of the sediment accumulation over each segment.

The derivation of Eq. 9-1 and its solution (Eq. 9-4) required several assumptions. A partial list of the most important assumptions is:

- Accumulation depth is not large compared to flow depth
- A rectangular cross section
- Constant bed slope
- The flow rate, sediment transport rate, and roughness are constant in space and time
- Is not applicable upstream of the sediment accumulation
- Accumulation can be represented by a single size class
- Accumulation travels as bed load; ignores sediment sizes that travel as pure suspended load.

9.3 RESULTS

In Greimann et al. (2006), the diffusive wave model as described above was tested against the data from laboratory experiments performed at the St. Anthony Falls Laboratory in Minnesota (Cui et al. 2003). In these experiments, a sediment accumulation was placed by hand and had an approximate thickness of 4 cm. The flow had a depth of approximately 3 to 4 cm. The diffusive wave model was able to reproduce the general movement of the accumulation as it dispersed in the downstream direction. An example of the comparison for Run 4b is shown in Fig. 9-2. It was necessary to assume values for sediment transport rate per unit width of the sediment accumulation (G_d^*). The analytical model predicts the approximate wave velocity and dispersion. It does not predict the variation of the bed elevation, but does seem to capture the general trends.

Laboratory experiments made to simulate dam removal were conducted by J. Wooster for his 2003 master's thesis "A Flume Study Investigating the Erosional Processes Following Dam Removal" (University of California–Davis). In these experiments, a gravel bed with a slope of approximately 1% was placed in a flume. A metal sheet 0.13 m high was placed in the middle of a flume to act as a dam and a flow of 2.34 L/s

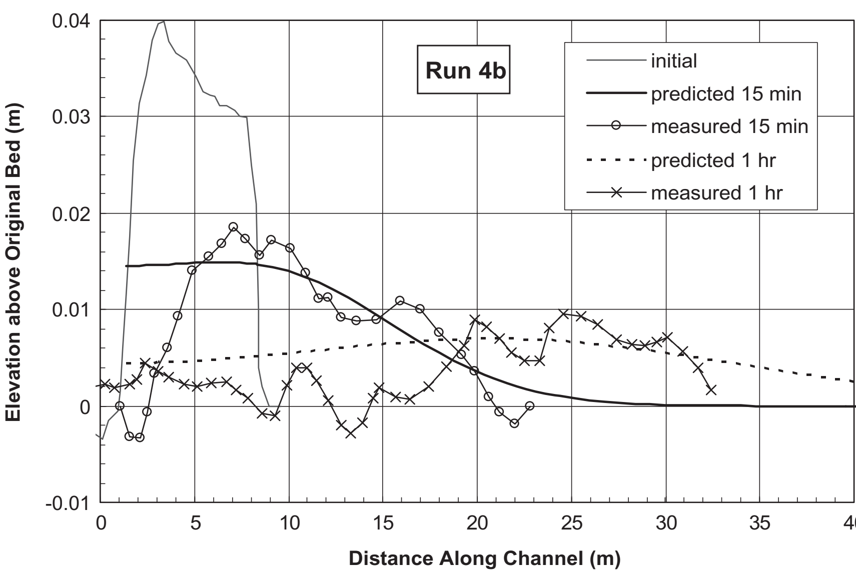

Figure 9-2. Comparison between diffusive wave model and Run 4b performed at St. Anthony Falls, Minnesota. Source: From Greimann et al. (2006).

was begun along with a sediment feed of 20 to 25 g/s. The flow rate and sediment feed were held constant until the sediment delta reached the metal sheet. The entire dam was then removed in one stage. The flow and sediment feed were started again and detailed measurements of the evolution of the sediment accumulation were taken. A comparison between Run 89 of this study is shown in Fig. 9-3. The erosion upstream of the dam and deposition downstream of the dam are accurately predicted. Again, it was necessary to assume values for the sediment transport rate of the sediment accumulation.

GSTAR-1D (Generalized Sediment Transport for Alluvial Rivers—One Dimension) is a 1-D hydraulic and sediment transport model for use in natural rivers and manmade canals. It is a mobile boundary model with the ability to simulate steady or unsteady flows, internal boundary conditions, looped river networks, cohesive and noncohesive sediment transport, and lateral inflows. The U.S. Environmental Protection Agency (EPA) and the U.S. Department of the Interior, Bureau of Reclamation (Reclamation) are funding partners in the development of the GSTAR-1D model.

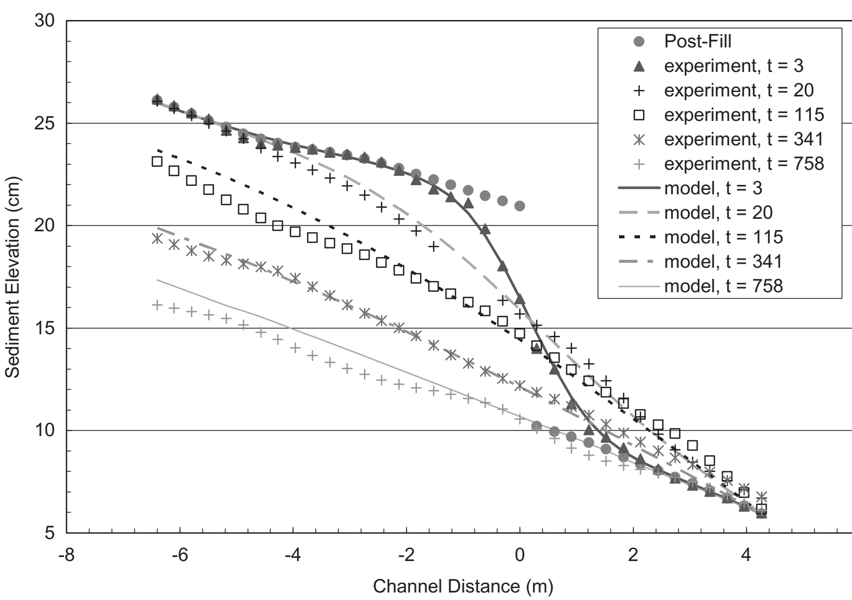

Figure 9-3. Comparison between diffusive wave model and Run 89 performed at St. Anthony Falls, Minnesota by Wooster in 2003. Time is in minutes. Source: J. Wooster M.Sc. thesis, "A Flume Study Investigating the Erosional Processes Following Dam Removal," 2003, University of California–Davis, Davis, California.

GSTAR-1D was used to predict the impacts associated with the removal of Matilija Dam, which is located in the Ventura River basin in California. It is approximately 120 ft high with 4.5 million m^3 of sediment trapped behind it. Approximately 2.1 million m^3 of that sediment is silt and clay, 1.6 million m^3 is sand, and 0.8 million m^3 is gravel and cobble. The Ventura River downstream of Matilija Dam has a stream slope of approximately 1% and a D_{50} of around 100 mm. Details of the application of GSTAR-1D to the removal of Matilija Dam are given in Greimann (2003).

The diffusive wave model was also applied to the Matilija Dam removal. It was assumed that the dam is removed in one stage. Two different simulations were performed: in one the silt and clay move through the system as wash load, and in the other all the silt and clay and 75% of the sand move through the system as wash load. Therefore, two different estimates of the deposition downstream were obtained. One of the most important parameters in the sediment impacts analysis was the maximum deposition expected at any given time. Therefore, the maximum deposition predicted by GSTAR-1D and the diffusive was model were compared (Fig. 9-4). The dam is located at River Mile (RM) 16.5.

As shown in Fig. 9-4, the upper and lower bounds of the diffusive wave estimates generally bracket the results from GSTAR-1D. Notable exceptions include the most upstream reach from RM 16 to 15.5. In this reach, the river passes through a bedrock canyon and the GSTAR-1D model predicts little to no deposition. Because the diffusive wave model does not model hydraulic controls and assumes a uniform downstream slope, it cannot model steep canyon reaches. Another exception to the agreement between the diffusive wave model and GSTAR-1D occurs upstream of RM 14 and RM 9. At RM 14 there is a small diversion dam which traps sediment, and at RM 9 there is a severe constriction caused by a bridge. Again, GSTAR-1D can model the deposition induced by such structures, but the diffusive wave model cannot.

9.4 CONCLUSIONS

The movement of sediment accumulations downstream is shown to be primarily a diffusive process with a small advective component resulting from the difference in transport rates between the sediment in the accumulation and the sediment in the original bed material. An analytical diffusive wave model was derived in Greimann et al. (2006) assuming normal depth, steady sediment transport, and a linear relationship between accumulation depth and the fraction of accumulation sediment present in the bed.

This analytical diffusive wave model was tested against two laboratory experiments. If the proper constant sediment transport rate is prescribed,

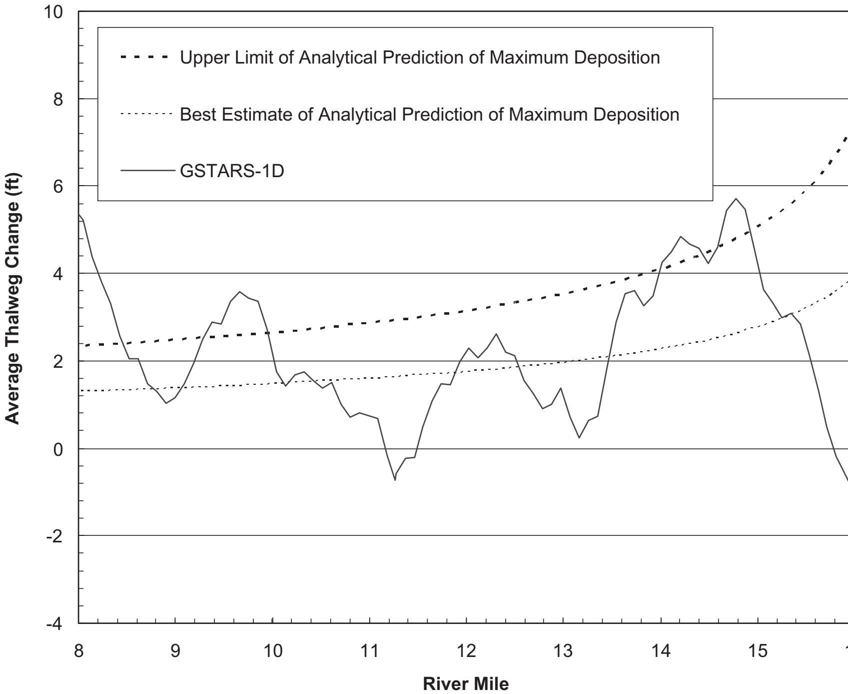

Figure 9-4. Comparison between diffusive wave model ("Analytical Prediction") and GSTAR-1D applied to Matilija Dam removal. The dam is located at River Mile 16.5. Source: From Greimann (2003).

the model accurately predicts the downstream diffusion of sediment in these cases. Further work should be done to develop predictive relationships for the sediment transport rates of the accumulation. Presently, it is assumed that relationships derived for uniform bed conditions apply.

The analytical diffusive wave model was also compared to the results of GSTAR-1D, a 1-D hydraulic and sediment transport model. The analytical diffusive wave model generally agrees with the results of GSTAR-1D except for where bedrock or hydraulic controls are present. The diffusive wave model requires that the sediment transport rates are specified. In addition, the sediment in the accumulation that is expected to travel as suspended or wash load should not be included in the volume estimates used as initial conditions in the model. The diffusive wave model can be used in cases where detailed deposition information is not required, or it can be used as an initial assessment tool.

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CHAPTER 10

GUIDELINES FOR NUMERICAL MODELING OF DAM REMOVALS

Timothy J. Randle and Jennifer A. Bountry

10.1 INTRODUCTION

Dam removal projects are becoming increasingly common, yet the accuracy of quantitative sediment predictions remains uncertain. This situation results from a general lack of scientific monitoring during dam removals, and the fact that the majority of dams that have been removed were small in size. Resource managers dealing with dam removal projects rely heavily on results from predictive numerical modeling to assess environmental impacts on the human environment and ecosystems. If the models are not properly applied, predicted impacts can be erroneous. This chapter provides some guidance for the application of numerical sediment transport models to improve their accuracy and utility for dam removal investigations.

10.2 CONCEPTUAL MODELS

The successful application of a numerical sediment model must begin with a good conceptual model that describes what will happen to the reservoir sediment and upstream sediment load as a result of a dam removal project. Conceptual models are developed based on existing knowledge of hydraulic and sediment processes. Processes described in the conceptual model should provide a qualitative understanding of the complex physical interactions between various stages in dam removal that cannot always be captured in a numerical model. The conceptual model should first address the sediment erosion and redistribution process in the reservoir, and then evaluate the impact on the downstream river channel. This integrated framework is used as a guideline for establishing the numerical model approach and as a check on the results.

The key questions that must be addressed to formulate the conceptual model for the reservoir sediment are:

- What are the volume and particle size distribution of the reservoir sedimentation?
- What portion of the reservoir sediments has cohesive properties?
- What is the chemical composition of the reservoir sediment relative to background levels?
- How much of the dam must be removed in order to achieve the project?
- What portion of the reservoir sediments would be expected to erode from the reservoir area as a result of dam removal?
- Does the reservoir sediment include a delta? If so, has the delta already reached the dam (Fig. 10-1)?

A good example of a conceptual model for reservoir sediment erosion during dam removal was published by Doyle et al. (2003) and is presented

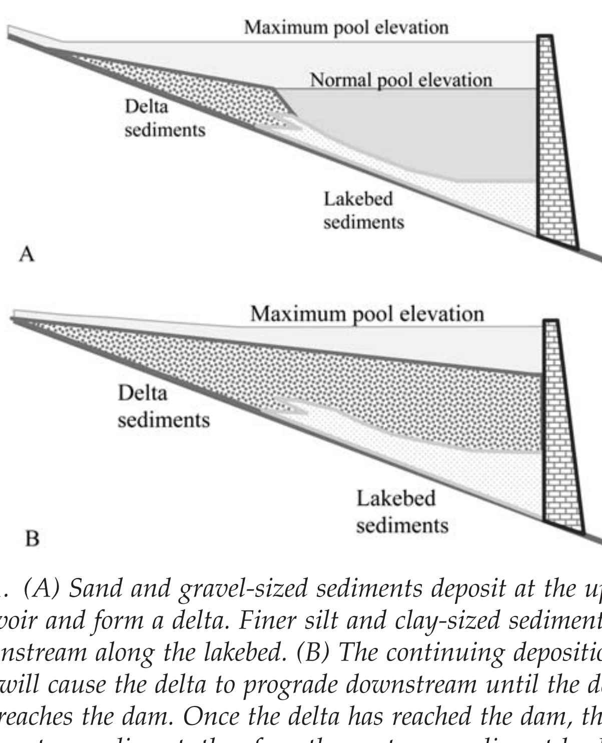

Figure 10-1. (A) Sand and gravel-sized sediments deposit at the upstream end of the reservoir and form a delta. Finer silt and clay-sized sediments deposit farther downstream along the lakebed. (B) The continuing deposition of sand and gravel will cause the delta to prograde downstream until the delta eventually reaches the dam. Once the delta has reached the dam, the reservoir will no longer trap sediment; therefore, the upstream sediment load will reach the downstream river channel.

again here in Fig. 10-2. For this conceptual model, the reservoir delta has already progressed to the dam.

The stages of this conceptual model are summarized below:

Stage A. In the initial conditions before dam removal, the reservoir delta has already prograded to the dam.

Stage B. The remaining reservoir is drawn down and the dam has been removed.

Stage C. As soon as the reservoir is drawn down, the stream flows across the exposed sediment, initiating a process of rapid, primarily vertical erosion that begins at the downstream end of the delta and progresses upstream. The eroding channels may develop along the margins of the reservoir rather than down the middle of the delta, as shown in the figure. If the erosion channel forms along the margin of a wide reservoir, a substantial amount of the reservoir sediment could be left behind. Large amounts of sediments are released at this stage and the downstream concentrations will be the highest of any stage. Depending upon the grain sizes present in the reservoir and the depth of the initial reservoir drawdown, this erosion may proceed as a headcut or may be primarily fluvial. The erosion is not expected to cut below the original bed elevation. The initial width of the channel formed by this erosion will be governed by the stream flow and the stability of the sediment in the reservoir.

Stage D. If the incision of Stage C produces banks that are too steep to be stable, channel widening will occur by means of mass wasting of banks.

Stage E. Sediment from the upstream reach starts to be supplied to the previously inundated reach. Some of this sediment is deposited in the reach as the degradation and widening processes have reduced the energy slope within the reach. Some additional widening may occur during this stage, but at a reduced rate as compared to Stage D.

Stage F. A state of dynamic equilibrium is reached in which net sediment deposition or erosion in the former reservoir area is near zero.

For dam removal investigations where the reservoir delta has not yet reached the dam, the processes of erosion and redeposition of delta sediments within the reservoir also need to be considered. Some reservoirs are many times wider than the active river channel, and have delta deposits at the upstream end of the reservoir that are much thicker than the mean depth of the river channel. In this case, it may be desirable to induce lateral erosion of the delta sediments and redeposition across the receding

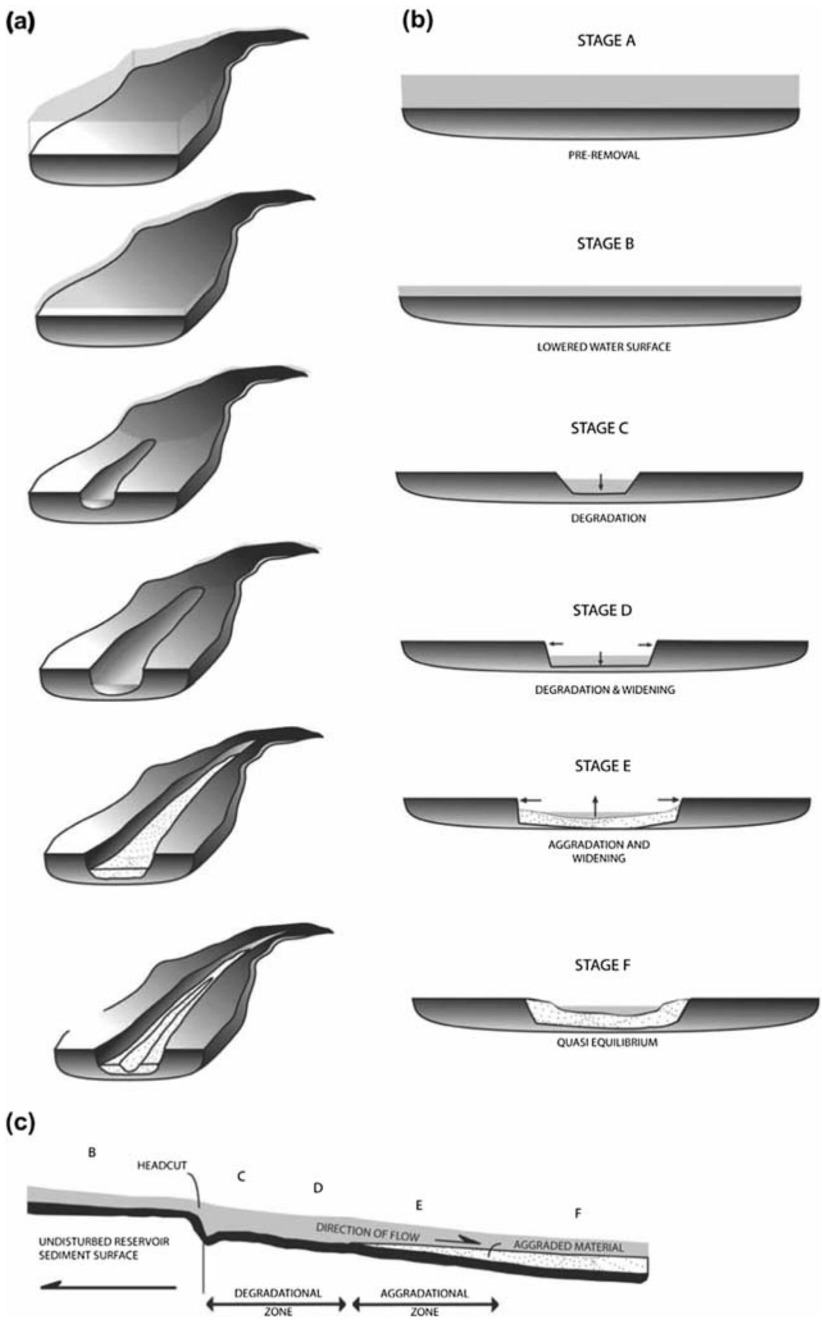

Figure 10-2. Schematic description of reservoir erosion process through delta deposits. (A) Oblique view; (B) cross-section view; (C) profile view. Source: From Doyle et al. (2003).

reservoir. This would result in leaving the remaining delta sediment as a series of low terraces rather than one high terrace with eroding banks.

During a reservoir drawdown increment, the river would incise a relatively narrow channel through the exposed delta (much like Stage C in Fig. 10-2). As long as a reservoir pool continues to remain between the delta and the dam, the eroded delta sediments would redeposit as a new delta across the width of the receded reservoir. As the new delta is deposited across the receded lake, the erosion channel is forced to move laterally to meet deeper areas of the reservoir. Thus, the width of the erosion channel, on the exposed delta surface, is narrow at the upstream end, but increases to the reservoir width where the channel enters the receded lake (Fig. 10-3).

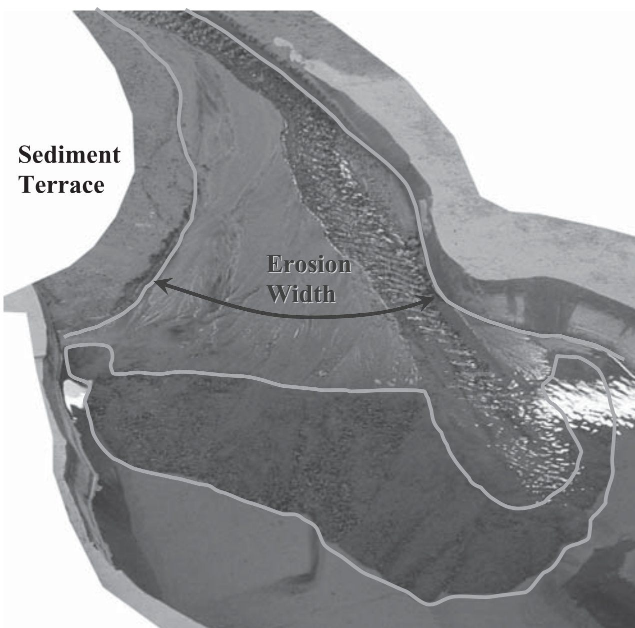

Figure 10-3. Reservoir drawdown causes delta erosion and redeposition within the reservoir. For each drawdown increment, the delta advances downstream toward the dam and sediment terraces are left along the margins of the reservoir. The delta erosion width increases in the downstream direction and can equal the reservoir width where the delta intersects the reservoir surface. This photograph is of a physical model experiment conducted by Chris Bromley at the St. Anthony Falls (Minnesota) Hydraulic Laboratory on September 24, 2003. Source: Bromley and Thorne (2005).

Reservoir delta erosion and redistribution can be induced by holding the reservoir level at a constant elevation between drawdown increments. The duration of constant reservoir elevation between drawdown increments (a few days to a few weeks) corresponds to the length of time necessary for the river channel to redeposit the eroding reservoir delta sediments across the width of the receded reservoir (Randle et al. 1996; Randle 2003).

The conceptual model for the downstream river channel builds upon the conceptual model for the reservoir sediment erosion. If the reservoir is still trapping sediment, then upon removal of the dam the downstream river channel will have to adjust to the sediment loads of the upstream river channel in addition to the reservoir sediment erosion.

The key questions that must be addressed to formulate the conceptual model for the downstream river channel are:

- Has the dam altered the flow regime in the downstream river channel?
- Is the reservoir still trapping bed-material load? If so, has the downstream channel responded to the reduced sediment supply (e.g., degraded, armored, become more meandering)?
- What portion of the eroding reservoir sediments is likely to be transported as wash load and what portion is likely to be transported as bed-material load?
- How does the annual sediment transport capacity of the downstream river channel, for delta-sized sediment, compare with the reservoir delta volume?
- How quickly might the dam be removed?
- What is the existing river channel planform and how might that planform change with sediment loads from the reservoir and upstream river channel?
- Are there pools and riffles or rapids?
- If significant channel aggradation could occur, to which floodplain areas would the channel likely migrate? Would a migrating river channel likely erode the terrace banks at the floodplain boundaries?
- What are the likely deposition environments for the sediment eroded from the reservoir (e.g., downstream channel pools, eddies, and backwaters; downstream lake, reservoir, or estuary)?

10.3 NUMERICAL MODELS

Numerical models provide quantitative predictions of the volume, rate, and duration of reservoir sediment erosion, and predictions of the downstream sediment transport rate and depositional thicknesses during and after the dam removal process. Numerical hydraulic and sediment transport models can be grouped into three general categories: one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D). 1-D models have been most commonly applied to dam removal investigations. Examples of 1-D sediment transport models include the U.S. Department of the Interior, Bureau of Reclamation's GSTAR-1D (Yang et al. 2005) and HEC-6 (USACE 1993). 1-D models can simulate the longest river distance and time duration. 2- and 3-D models, such as SRH-W (Lai 2006) and U2RANS (Lai et al. 2003a; 2003b), are best applied to smaller spatial and time scales.

All models are forced to make simplifying assumptions and thus have limitations. The choice of model is often governed by such factors as time and budget constraints, access to and knowledge of existing models, and the ability to develop models. The important points are to understand the formulation of the selected model, recognize its limitations, and apply it in a manner that takes advantage of the model's strengths. If the selected model does not simulate important processes, these processes must be added to the model through boundary conditions known to exist from the conceptual model. Sometimes this may require that the model simulation be periodically stopped, the model geometry or boundary conditions be adjusted by the user, and the simulation resumed.

10.3.1 Reservoir Sediment Erosion

Sediment modeling for dam removal investigations begins with the simulation of the reservoir sediment erosion, which will affect the prediction of sediment impacts to the downstream river channel. The key aspects of modeling the reservoir sediment erosion include the alignment and width of the erosion channel, the headcut erosion process, bank erosion and channel migration, and the erosion of sediment layers. The following discussion provides guidance for incorporation of these processes in a numerical model.

10.3.2 Erosion Channel Alignment and Width

The alignment of the erosion channel may not need to be specified for a 2- or 3-D model, but it does need to be clearly defined in the initial cross-section geometry of a 1-D model. Otherwise, the model will incorrectly simulate the gradual incision of a wide shallow channel. If there is no distinct channel in the surface topography of the reservoir sediment, a pilot channel must be specified in the initial cross-section geometry. Even if the actual delta surface has multiple channels, one or two erosion channels will likely capture the flow from the other channels during reservoir drawdown. This condition may have to be initially specified in a 1-D model. The upstream ends of deltas tend to be highest in elevation along the middle of the reservoir because the sudden expansion in hydraulic width makes this region the most vulnerable to sediment deposition from the upstream river channel. Therefore, erosion channels across the delta surface are often observed along the margins of the reservoir.

For some 1-D models, the width of the erosion channel can be specified as a power function of the stream flow (Eq. 10-1). This will allow the erosion channel to become wider as the stream flow increases, even though the bank may not be overtopped. The empirical coefficient and exponent of the power curve can be calibrated to the dimensions of the upstream river channel.

$$W = aQ^b \tag{10-1}$$

where
W = the channel width
Q = the stream flow
a = an empirical coefficient
b = an empirical exponent, typically equal to 0.5.

Two- and 3-D models will also need some sort of algorithm to cause channel widening when there are high velocities along the banks of the erosion channel, even if the top of bank is not inundated. If a model does not have this capability, the user may have to periodically stop the model simulation, adjust the model grid to create a wider channel, add sediment eroded from the banks to the channel bottom, and then restart the model.

Channel incision can also cause bank erosion when the banks become too steep. Therefore, a 1-, 2-, or 3-D model also needs to compute bank erosion based on some slope stability criteria (Langendoen 2007; Pollen et al. 2006). Because bank failure is likely to occur in an incising channel, it may be sufficient to predict that bank erosion will occur when the bank angle exceeds a specified angle of repose for the given bank material.

The angle of repose may have to be adjusted in the model, depending on the amount of incision and horizontal spacing of points within the model cross section or grid. For example, consider the case where a channel incises 2 m into a sand delta with an angle of repose equal to 40 degrees. If the lateral spacing between model points was 6 m, then the computed angle would be only 18 degrees. If the lateral spacing between points was reduced to 3 m, then the computed bank angle would increase to 34 degrees. In either case, 2 m of channel incision might very well exceed the actual angle of repose, but not the angle of repose computed by the model. Therefore, the specified angle of repose must be adjusted to account for the lateral spacing of points in the model (Eq. 10-2).

$$\Phi_{adj} = \tan^{-1}\left(\frac{\Delta y_{\max}}{\Delta x}\right) \tag{10-2}$$

where

Φ_{adj} = the adjusted angle of repose

Δy_{max} = the maximum vertical change where the angle of repose is thought to be exceeded

Δx = the lateral spacing between model cross section or grid points.

10.3.3 Headcut Erosion Process

Channel incision of the reservoir sediments will likely occur during reservoir drawdown and dam removal through the process of headcut erosion. The headcut process was found to easily erode through armor layers in the reservoir delta during the 1994 drawdown experiment at Lake Mills on the Elwha River in northwestern Washington (Childers et al. 2000). The longitudinal spacing between grid points or cross sections must be close in order to simulate this process. Otherwise, the model may incorrectly predict that the vertical incision is very slow or stops due to armoring. The longitudinal spacing of grid points or model cross section could be based on Eq. 10-3:

$$\Delta x = \frac{\Delta y}{S_{erosion}} \tag{10-3}$$

where

Δx = the longitudinal spacing between model grid points or cross sections

Δy = the amount of incision that is expected to cause headcut erosion

$S_{erosion}$ = the longitudinal slope that will cause the model to compute rapid erosion for a given grain size (e.g., 5%).

10.3.4 Bank Erosion and Channel Migration

Bank erosion and channel migration within the former reservoir area can be induced by the redeposition of eroding delta material, evolution of the incising river channel to a braided planform, or evolution of the incised channel to a meandering planform. A braided channel planform can result from a large sediment supply to the eroding river channel, which can be caused by the rapid erosion of reservoir sediment. The sediment load will diminish after the river channel has eroded down to the pre-dam elevation of the reservoir bottom. The reduced sediment load can lead to bank erosion as the channel becomes more meandering.

Channel migration is difficult to predict with numerical sediment models. Two- and 3-D models have the best chance of predicting channel migration, but only if they have an algorithm to erode the banks. Only 3-D models can predict secondary currents that produce bank erosion along the outside of a meander curve and point-bar deposition along the inside of the curve. Some 2-D models, such as SRH-W, can infer the secondary currents based on channel curvature. A 1-D model might have an algorithm to predict channel widening, but the proportion of erosion along the left and right banks must be specified by some other boundary condition.

For the Elwha River Restoration Project, channel migration, bank erosion, and widening were predicted for the reservoir by a field drawdown experiment (Childers et al. 2000), a new mass balance numerical model (Randle et al. 1996), and a physical model (Bromley and Thorne 2005).

10.3.5 Erosion of Sediment Layers

Layers of clay, silt, sand, and gravel can be deposited in reservoirs because of the varying particle sizes and concentrations of the upstream sediment load and because of the sorting that takes place within the reservoir (Fig. 10-1). Some sediment layers can be relatively thin and may appear somewhat random in order. However, the sediment layers caused by the reservoir sorting tend to be more distinct and should be considered in model simulations.

In the early stages of reservoir drawdown and dam removal, suspended sediment concentrations tend to be lowest. This is because there are relatively few fine sediments to be eroded from the upper elevations of the reservoir pool, and those fine particles that do erode can be mixed with a nearly full reservoir. As more of the reservoir is lowered, suspended sediment concentrations increase because more fine sediment particles are accessed and eroded and they are mixed with an ever-smaller reservoir. The coarse sediment from an eroding delta would likely deposit on top of finer lakebed sediments, although some mixing may occur. These finer lakebed sediments would be eroded following the erosion of the coarser overlying sediments, and the suspended sediment concentrations would substantially increase at this stage because the reservoir pool would be mostly drained.

The significant layers of reservoir sediment need to be identified and specified in the initial model conditions. If the model is not capable of accounting for multiple sediment layers, the model simulation may have to be stopped after the erosion of each layer; then the bed-material sizes could be changed to represent the underlying layer, and the model simulation resumed until the next layer is eroded.

10.4 SEDIMENT TRANSPORT AND DEPOSITION ALONG THE DOWNSTREAM RIVER CHANNEL

10.4.1 Wash Load and Bed-Material Load

Fine sediments that are eroded from the reservoir may be transported in suspension through the downstream river as wash load. Although the wash load may not be expected to deposit along the downstream river channel, the effects of sediment concentration and turbidity on water quality may be of great interest. The sediment concentration could be computed just below the dam, and at points downstream from significant tributaries, without detailed sediment transport modeling of the downstream river channel. In contrast, the transport and deposition of coarse sediments (bed-material load) must be modeled through the downstream river channel.

The initial sediment grain-size distribution must be specified at all model cross sections or grid points. If the bed-material size of the downstream channel (before dam removal) is significantly coarser than the reservoir delta material, then in the model it may be necessary to specify that the bed of the river channel is composed of a thin layer of delta material with an underlying layer that cannot erode. This will prevent the model from eroding the riverbed beyond the initially thin layer of delta sediment, but, more importantly, it will prevent the model from mixing reservoir sediment with the initially coarse material from the river bed. If the model were allowed to mix the finer reservoir sediment with the coarse river bed material, then the resulting mixture may be too coarse for transport and the model will overestimate the process of channel aggradation.

10.4.2 River Pools and Eddies

Dams are often removed during low-flow periods, which can mean that reservoir sediment erosion is induced during a period when the sediment transport capacity of the downstream river channel is low. River pools are often scoured during floods, but would likely become depositional areas for reservoir delta sediment during low-flow periods. Eddies along the river channel are likely depositional areas during all flows, except when the eddies are already full of sediment. However, the size of the eddies tends to expand as river flows increase.

One-D models cannot simulate eddy depositional processes and they usually compute relatively slow river velocities in river pools, even during floods. In a river pool below a riffle or rapid, the high-flow velocity tends to enter the pool along the bottom, which can be much greater than the average channel velocity computed by a 1-D model or the depth-averaged velocity computed by a 2-D model. Therefore, 1- and 2-D models tend to overpredict deposition in river pools. This can be partially overcome by running the model through a warm-up period, ahead of dam removal, where the river pools and other slow-velocity cross sections or grid points can fill with sediment to an equilibrium condition. Then the amount of sediment deposition predicted by the model, as a result of dam removal, can be compared to the equilibrium condition predicted during the warm-up period.

The warm-up period can be simulated with a steady flow and corresponding sediment supply rate representing equilibrium river conditions long after the dam has been removed. The steady flow and sediment load corresponding to the effective discharge would typically be used. If river pool deposition during the low-flow period of dam removal is of interest, then a low steady flow, and corresponding sediment supply rate, could be used during the warm-up period to estimate the potential sediment storage volume in river pools. This potential storage volume can then be compared to the reservoir delta volume to determine whether sediment aggradation would increase flood stage. Sediment deposition in river pools may not have much effect on river stage, but deposition on riffles would increase flood stage and could lead to channel migration and a braided planform.

10.4.3 Channel Migration

A sudden and large sediment load from an upstream reservoir could cause aggradation of the river bed and could also cause a meandering river channel to straighten, become wider, and even become braided. An increase in channel width through bank erosion would add even more sediment to the downstream river channel. The model would predict aggradation of the river bed if the sediment transport capacity of the downstream river channel is insufficient to transport the upstream sediment load from the reservoir. However, the river channel can also respond by becoming straighter, so the model user may want to include a straighter channel alignment as the initial condition before simulating the reservoir sediment release from dam removal.

If a straighter channel alignment is still not sufficient to prevent significant aggradation of the river bed, then the channel is expected to migrate and become braided. In this case, the user may have to anticipate and specify when and to where the channel will migrate. In addition, the user may have to specify how channel and floodplain roughness will change during channel migration as vegetation is eroded. Results from the conceptual model can be particularly useful for determining boundary conditions in the model runs.

10.5 MODEL UNCERTAINTY AND ADAPTIVE MANAGEMENT

The results from a physical model and field experiments can be used to verify and improve the predictions of numerical models and, thus, reduce the uncertainty of predictions. However, numerical model predictions will always include some uncertainty because the physical processes being modeled are not completely understood and there is uncertainty in the data describing the initial and future boundary conditions.

The uncertainty of model predictions can be better managed through an adaptive management program that includes two key elements:

1. Real-time monitoring of sediment processes in the reservoir and the downstream river channel in order to verify the model predictions. The model predictions can be treated as hypotheses and the monitoring program can be designed to test these hypotheses. This is much more effective than simply monitoring a list of parameters to test for possible trends.
2. Corrective action if the field conditions are significantly different from the model predictions. The adaptive management responses could include (1) additional levels of monitoring, including an increase in the frequency or extent of monitoring; (2) locally implementing contingency actions to mitigate for impacts; and (3) modifying the scheduled rate of dam removal.

Although hundreds of dams have been removed, there have been very few, if any, cases where sediment model predictions were made and the predictions were later checked with monitoring data from the actual field conditions. Additional monitoring and research are also needed to more fully document and explain the actual conditions that result from a dam removal. Although the results from more detailed monitoring and research may not be available in time to take corrective action on a given project, the results will improve our understanding of physical processes and will benefit subsequent model development and future projects.

10.6 CONCLUSIONS

Development of a good conceptual model should precede any numerical modeling to help capture the timing and integration of important physical processes that occur as a result of dam removal. The conceptual model can then provide a basis for choosing a numerical model and guide its proper application. The choice of numerical model is often governed by such factors as time and budget constraints, access to and knowledge of existing models, and the ability to develop or modify an existing model. The important points are to understand the formulation of the selected model, recognize its limitations, and apply it in a manner that takes advantage of the model's strengths.

Adaptive management monitoring during dam removal will help verify predictions and help determine whether there is a need to adjust the dam removal plans. Monitoring will also provide a feedback loop for researchers that will benefit subsequent model development and future projects.

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CHAPTER 11

SEDIMENTATION STUDIES FOR DAM REMOVAL USING HEC-6T

William A. Thomas

11.1 INTRODUCTION

The computer program *Sedimentation in Stream Networks* (HEC-6T) is a proprietary program developed by the author. It is an extension of the U.S. Army Corps of Engineers (USACE) program *Scour in Rivers and Reservoirs* (HEC-6), which the author also developed. This paper develops two points about HEC-6T: (1) It is a general-purpose computational sedimentation program, which makes it appropriate for dam removal studies; and (2) it contains features that facilitate the computation of sedimentation processes following the removal of a dam. The following three examples illustrate these points. The lack of a standard set of specifications for what constitutes a "computational model" makes it necessary to state the questions to be answered when evaluating a computer program.

11.2 REMOVAL OF WASHINGTON WATER POWER DAM

The Washington Water Power Dam was located at River Mile 4.72 on the Clearwater River, near Lewiston, Idaho. It was a gated, low-head, hydroelectric dam built in the 1920s. The gate sill stood about 20 ft above the channel invert, and sand and gravel had deposited to the top of the sill. The entire structure was removed in 1973 because Lower Granite Dam, being constructed downstream on the Snake River, would impound water to Elevation 738. Figure 11-1 shows computed water surface and bed surface profiles for a water discharge of 100,000 cfs with the Washington Water Power Dam in place.

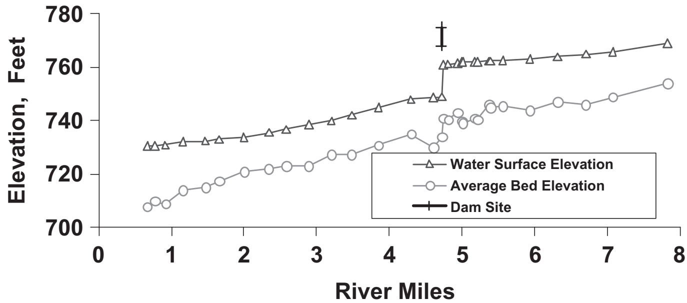

Figure 11-1. Water surface and bed surface profiles for a water discharge of 100,000 cfs with Washington Water Power Dam in place. Source: D. T. Williams, M.Sc. thesis, "The Effects of Dam Removal: An Analytical Approach to Sedimentation," 1977, University of California–Davis, Davis, California.

D. T. Williams, in his 1977 M.Sc. thesis, "The Effects of Dam Removal: An Analytical Approach to Sedimentation" (University of California–Davis), simulated the changes in cross sections and computed the resulting water surface profiles when the dam was removed. He used an early version of HEC-6 designated as *Scour and Deposition in Rivers and Reservoirs*, USACE Hydrologic Engineering Center Computer Program No. 723-62-L2470. Figure 11-2 shows the measured and computed bed erosion at the dam axis, and Fig. 11-3 shows the measured and computed changes in bed elevation at cross section 3.48, which is located about 6,500 ft downstream of the dam. The calculation was performed as a continuous simulation for 10 years, and field measurements were available for the first 3.5 years. Lower Granite Pool was impounded by 1976.

Williams reported,

> The comparison of measured and computed final bed elevations, with the dam removed, was very satisfactory. Overall long range trends for each operating condition [were] as expected. The calculated rate of scour was accurate at the WWPD Site but lagged by approximately ten months at other upstream sections. This difference can be attributed to localized scour and "layering" of the bed particle distribution. Neither can be modeled by HEC-6. (D. T. Williams, M.Sc. thesis, "The Effects of Dam Removal: An Analytical Approach to Sedimentation," 1977, University of California–Davis, Davis, California)

This application was highly successful because the model answered the three questions being asked of it:

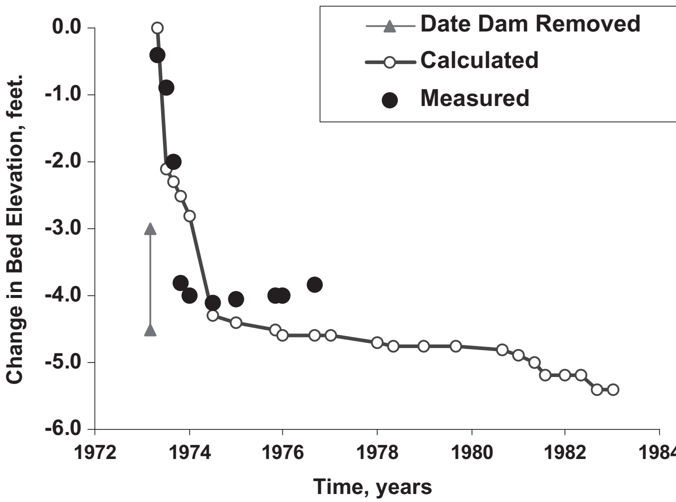

Figure 11-2. Measured and computed erosion of cross section at Washington Water Power Dam axis. Source: D. T. Williams, M.Sc. thesis, "The Effects of Dam Removal: An Analytical Approach to Sedimentation," 1977, University of California–Davis, Davis, California.

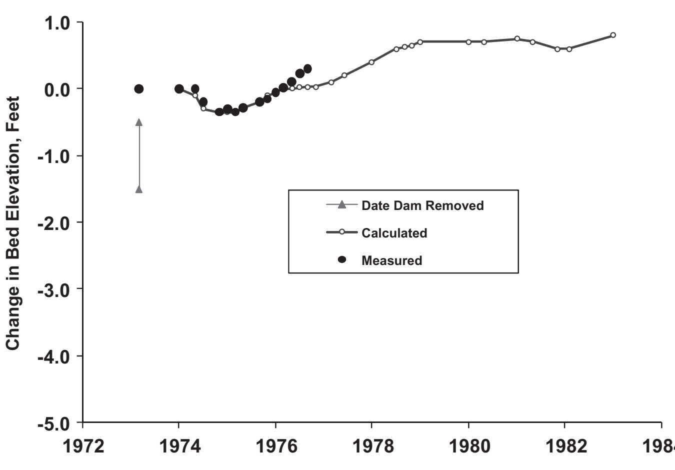

Figure 11-3. Measured and computed changes in bed elevation at cross section (River Mile) 3.48, caused by deposition 6,500 ft downstream of Washington Water Power Dam. Source: D. T. Williams, M.Sc. thesis, "The Effects of Dam Removal: An Analytical Approach to Sedimentation," 1977, University of California–Davis, Davis, California.

1. How much of the sediment deposited behind Washington Water Power Dam would be removed?
2. How much of the sediment being eroded would deposit in the Clearwater River channel downstream of the dam site?
3. How much time would pass before the river returned to a state of equilibrium?

Because of the relatively small size of the dam, all of these questions were about sedimentation processes, not channel or floodplain evolution.

According to ASCE Manuals and Reports of Practice No. 54, *Sedimentation Engineering* (ASCE 1975), there are five basic sedimentation processes: *erosion, entrainment, transportation, deposition,* and *compaction of deposits.* HEC-6T calculates all five; four were active in the removal of Washington Water Power Dam.

Thus, in reference to question 1 above, there is no general standard by which a computer program can be certified as a computational model. Consequently, to advocate that no sedimentation computations are available for studying the removal of a dam is not accurate without stipulating what questions are being asked of the computer program.

11.2.1 Effects of Mount St. Helens Eruption: Breach of the N1 Structure

The eruption of Mount St. Helens (southwest Washington State) on May 18, 1980 reconfigured the topography, land use, and stream channels in 155 mi^2 of watersheds surrounding the mountain. The debris flow that ensued delivered more than 100 million yd^3 of sediment to the Cowlitz and Columbia Rivers in a few hours, and much of that sediment was sand. The watershed most affected was the North Fork of the Toutle River. More than 3 billion yd^3 of sediment was moved from the mountain into the valley of that watershed by the blast, the avalanche, and the debris flow that followed.

USACE responded immediately with a number of countermeasures. One was the construction of a small sediment detention basin near the mouth of Hoffstadt Creek. The dam, referred to as the N1 Structure in anticipation of additional structures to follow, was an earth-fill embankment about 20 ft high and a mile long. A spillway was provided near each end of the embankment. The N1 basin filled with sediment shortly after the rainy season started in the fall, and about 10 million yd^3 were excavated. The particle specific gravity of that sediment was 2.73, and particle sizes in the mixture ranged from sands to cobbles. Forty percent of the excavated sediment was gravel.

Figure 11-4. Breach of the N1 structure, Hoffstadt Creek near Mount St. Helens. Source: © MBH Software, Inc. Used with permission.

As the winter rains continued, the N1 basin quickly refilled, and before the sediment could be removed again, the embankment overtopped and breached. The right side of Fig. 11-4 shows the breach between the spillway and valley wall. Even though the basin was completely full of sediment, the width of the breach and the width of deposits that eroded from the basin were about equal to that of the channel upstream and downstream of the basin. This sequence of events was not modeled, but the observations were used in sediment studies for the large Sediment Retention Structure that was built on the North Fork of the Toutle River in 1986.

By applying this observation to erosion following the removal of a dam, the volume of erosion can be predicted from two processes: (1) incision into the deposit the width of the active channel, and (2) erosion off the surface of the deposit. HEC-6T will calculate the channel incision process, and the sediment load from land surface erosion can be added as a lateral-inflow, boundary condition.

11.3 EFFECTS OF MOUNT ST. HELENS ERUPTION: PUMPING SPIRIT LAKE

The third example is also from the Mount St. Helens experience. The eruption blocked the outflow channel from Spirit Lake, which is about

Figure 11-5. Channel from pumping Spirit Lake, 60 miles from Mount St. Helens. Source: © MBH Software, Inc. Used with permission.

60 mi north of the volcano. While a permanent outflow structure was being designed and constructed, the lake level was maintained by pumping. The discharge rate was 182 cfs and the pump discharge drained directly onto the surface of the debris avalanche. After a year of pumping, the discharge had eroded a channel more than 100 ft deep into the debris; Fig. 11-5 shows a typical site. A few measurements indicated that the average top width was 38 ft and the channel was less than 2 ft deep. Although 182 cfs was not the only flow in this channel, it was the dominant flow at this location.

If the dominant discharge is known, the top width of a regime channel can be computed from the simple regression equation:

$$W = C\sqrt{Q} \tag{11-1}$$

where Q = water discharge. Using a C coefficient of 2.7, which is the value suggested for sandy alluvial banks in USACE's *Engineering and Design Manual EM 1110-2-1418* (USACE 1994), the top width of a 182-cfs channel should be 36 ft.

The observations of channel erosion following the breach of N1 and the observations of channel width from pumping Spirit Lake were used in the application of HEC-6 to design the large Sediment Retention Structure that was built to manage sediment yield in this watershed. USACE has monitored the volume of sediment accumulated behind that structure to date, and the rate of filling agrees remarkably well with the predicted rate of filling (USACE 2002).

At the time these design studies were performed, there was no known computer program for computing the evolution of the highly disturbed channels in the Toutle River watershed. Certainly HEC-6 was not, nor is it today, an "expert system." However, by coupling the computational capability in that program with principles of river morphology, sedimentation predictions were made for the design of the Sediment Retention Structure in the N1 case. Likewise, by applying HEC-6T to study sedimentation processes following the removal of any dam, one will discover much about the channel that will be produced in the reservoir deposit and about the transportation of sediment through the channel downstream of the dam. The challenges are to formulate what questions to ask of the model and to design experiments that will answer those questions.

11.4 CONCEPTUAL MODEL OF CHANNEL AND FLOODPLAIN EVOLUTION

An effective analytical approach to sedimentation problems combines a channel evolution model [usually the one proposed by Schumm et al. (1984), hereafter called the Channel Evolution Model], general principles of geomorphology, and the computational capability of HEC-6T. The Channel Evolution Model was based on studying channel development in highly disturbed watersheds of northern Mississippi. The streams were made unstable in the mid-1900s by replacing the natural sinuous channel with a straight trapezoidal ditch. This increased energy gradient caused erosion of the main channel, which lowered the base energy level at the tributaries. The Channel Evolution Model explains this morphology by substituting space for time, that is, the form and dimensions of the stable channel that will develop in the future can be predicted from observations made at different locations along the disturbed channel at the present time.

The Channel Evolution Model recognizes five typical stages in the progression from a highly erodible condition to a stable channel (Fig. 11-6). The following interpretation illustrates how to apply the model to a dam removal study.

1. The channel profile shows a knickpoint in the bed profile. The Stage I cross section is located upstream from the knickpoint. Bank height, "h," is less than the critical bank height for the existing bank angle. Therefore, the Stage I channel cross section is stable.
2. The Stage II cross section is located immediately downstream of the knickpoint. Note the absence of bed material on the invert. One would conclude that the dominant sedimentation process is bed

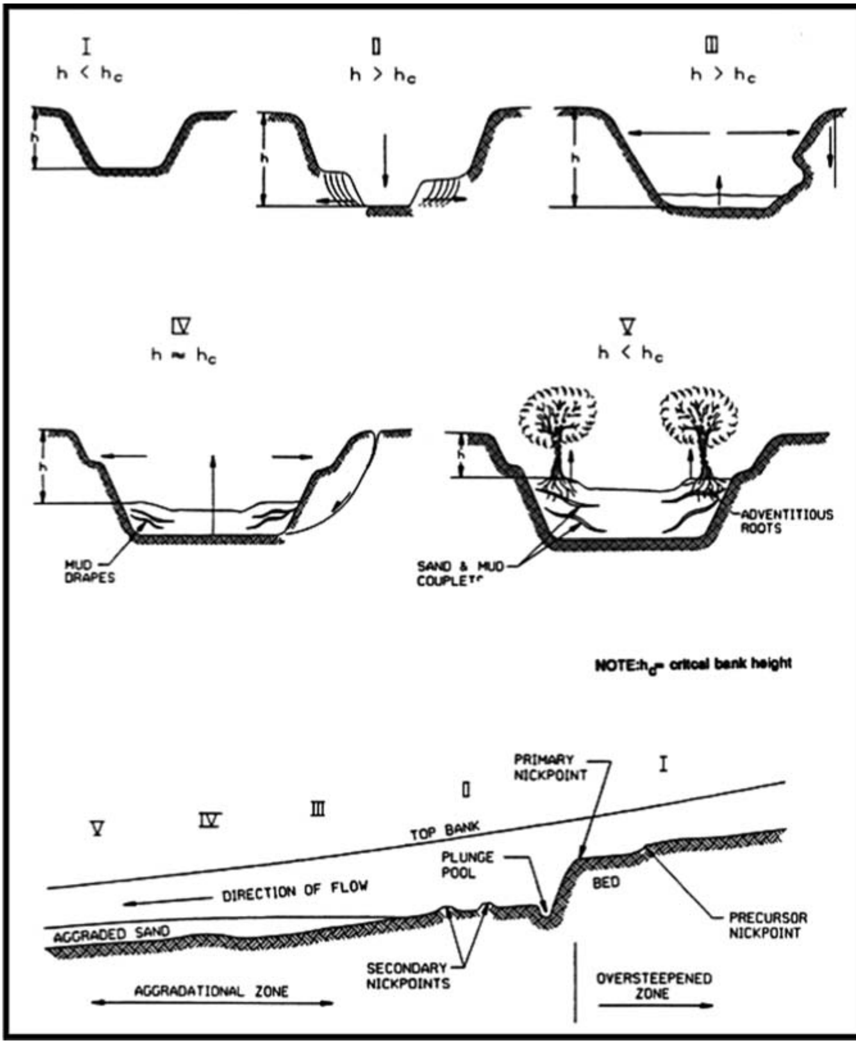

Figure 11-6. The five-stage Channel Evolution Model developed by Schumm, Harvey, and Watson in 1984. Source: Water Engineering and Technology (1987).

erosion in this stage. Moreover, the bed erosion is a vertical incision which does not touch the banks. Therefore, the banks remain stable during Stage II.

3. Stage III is a cross section that differs from Stage II in two respects: (1) a sediment deposit is forming on the bed, and (2) the energy

dissipation is no longer concentrated in the center of the channel. Consequently, toe erosion will be initiated, and this will increase the bank angle until the bank fails. Stage III is an intermediate step in the evolution of the new channel. It is not necessary to model the details of this step because, as time passes, the channel shape will evolve into the final cross-section dimensions shown in Stage V.

4. Stage IV shows a new alluvial channel forming within the new bed deposit. The new channel has a lower potential energy than the original channel. The new flood plain has not yet started to develop. The dimension shown as "h" in Stage IV is no longer the channel bank height; it is the height of the new high terrace. The arrows indicate that channel widening is a dominant process. The new bottom width would be expected to approach the stable dimension more quickly than does the bank height.
5. Stage V is the final stage of development. Vegetation is now established on the channel banks, which encourages overbank deposition adjacent to the new channel as shown by the arrows. A new flood plain has begun to develop inside of the high banks. The high terrace is now protected from direct impingement by the flow during normal runoff events. Future channel erosion and overbank deposition are the processes that will eventually build the banks of the new channel. The channel depth in Stage V is not the depth shown by "h"; the channel depth is the depth from the channel invert to the surface of the new overbank. If the historical water and sediment discharges from the watershed continue, then the dimensions of the new channel will approach those of the historical channel shown in Stage I.

Stages II and III in this conceptual model of channel evolution are different from the morphology that would result from minimization principles. The dominant sedimentation processes in these stages are erosion and entrainment, and the primary erosion pattern is a vertical cut in the existing channel invert. During Stages IV and V, minimization principles might begin to provide useful information, but the processes causing channel evolution are physics—not mathematics. That is, the minimum rate of energy expenditure might predict the energy slope that will evolve as the erosion, entrainment, and deposition processes approach zero in Stage V. If so, it will be the slope that is required to sustain the transportation process. However, the Stage V slope and channel depth can be computed with HEC-6T.

When a dam is lowered or removed, a hydraulic condition similar to the knickpoint is created. This initiates the erosion process. Whether the erosion moves upstream as a knickpoint, or simply as bed degradation, depends on the amount of cohesive sediment in the reservoir deposit. In either case, the interpretation of the Channel Evolution Model that is presented above will describe the channel development.

11.5 PRINCIPLES OF RIVER MORPHOLOGY

Rosgen (1996) includes stream channel dimensions, stream channel pattern, and stream channel profile in his analysis of a river. He states,

> Underlying a presumably complex set of channel and watershed variables which follow the laws of physics, is a predictable adjustment process of rivers toward their most probable stable form. Natural rivers, which are self-constructed and self-maintained, constantly seek their own stability. (Rosgen 1996)

The challenge is to express this concept in terms of variables which can be quantified, such as:

- Channel width
- Channel depth
- Channel slope
- Hydraulic roughness
- Bank line migration
- Channel pattern

These "hydraulic design variables" are commonly used in the hydraulic design of channels. However, they also describe six degrees of freedom of a natural channel.

Leopold et al. (1964) developed empirical equations for channel width, channel depth, and water velocity for regime channels. They named them "hydraulic geometry relationships." The parameter that was found to be effective for correlating regime dimensions was the water discharge at bank-full stage. Regarding bank-full stage, this report states, "In general a value of 1.5 years seems a good average. This means the discharge in a river will equal or exceed bank-full two out of three years" (Leopold et al. 1964, p. 319).

The Spirit Lake pumping experience shows that the hydraulic geometry equation for channel top width can be used even in highly disturbed channels. To use that equation in forming an HEC-6T model, it needs to be converted from a top-width equation to a bottom-width equation. The values of C and Q would not change for the bottom-width computation, but the Q would then be used to estimate the water depth. The channel bed width would be computed by subtracting the width of side slopes from the top width. That computation would be made for crossings in the channel pattern because they are trapezoidal in shape. Angle of repose values could be used to predict side slopes.

The existence of a channel-forming water discharge is a concept, not an equation. It is mentioned in USACE's *Engineering and Design Manual 1110-2-1418* (USACE 1994) but it is not defined. The actual value to use is defined differently from one investigator to another. For example, Leopold et al. (1964) proposed the 1.5-year annual peak frequency flood, and Rosgen (1996) uses that value in his method; they call it the bank-full discharge. The technical report by Copeland et al. (2001) presents three methods for determining a channel-forming discharge. These references also give values for the *C* coefficient.

11.6 FEATURES IN HEC-6T

To use HEC-6T for dam removal studies, calculation of the sedimentation processes must be related to the six degrees of freedom of a river channel. The channel depth, channel slope, and hydraulic roughness variables are computed directly by HEC-6T. Relationships for channel width, bank line migration, and channel pattern must be evaluated externally, converted into parameters, and modeled using HEC-6T features. The following sections describe this approach.

11.6.1 Channel Width and HEC-6T

There are no channel width equations in HEC-6T. If a dam is relatively low and occupies the entire channel, as was the case for the Washington Water Power Dam, the width of the post-removal channel will be the same as the measured width of the pre-removal channel.

If the reservoir pool submerged the channel and floodplains such that sediment is deposited across the entire valley, the dimensions of the post-removal channel may not be the same as the channel in reservoir surveys. The final bottom width of the post-removal channel (Stage V in the Channel Evolution Model) must be determined separately from HEC-6T. That width can be coded as the lateral limits of "bed erosion" by using a feature that allows the erosion limits to be smaller than the total width of deposition. When bed erosion increases the bank angle beyond the specified factor of safety, the program will fail the banks. It will add the bank material to the bed sediment reservoir and the mixture will be transported out of the reach as transport capacity becomes sufficient (Thomas 2002).

One method for predicting the bottom width of the post-removal channel is to compute it from observations upstream and downstream of the reservoir. Based on the Mount St. Helens experience, the hydraulic geometry relationship for width can be used to transfer those observations to inflow points along the length of the reservoir. A range of bed widths can be modeled to test the sensitivity.

11.6.2 Channel Depth and Slope Calculations in HEC-6T

Channel depth and slope are the natural end-products from the sedimentation calculations. The program calculates the volume of erosion or deposition in a reach. This volume is converted into a depth of bed erosion or bed deposition, and the value is added to the cross-section elevations. These new invert elevations provide the new channel slope.

The feature that allows the width of erosion to be coded separately from the total width of sediment deposition allows the program to erode the bed of the channel while continuing to deposit sediment on the floodplains. This simulates the growth of channel banks.

11.6.3 Bed and Bank Roughness in HEC-6T

The hydraulic roughness of an alluvial channel can be separated into bed roughness and bank roughness. The bed roughness is composed of grain roughness and bed form roughness. The Brownlie method (Brownlie 1983) is used to compute the bed roughness in sand bed streams where bed forms grow and decay, and the Limerinos equation (Limerinos 1970) is used to compute roughness in gravel bed streams.

A feature is provided in HEC-6T to separate bed roughness from bank roughness. This creates a five-strip model. Because there are no equations for bank roughness, it is prescribed by *n*-values. A composite value is computed for the three channel strips (i.e., the left bank, bed, and right bank) before the water surface profile computations are made. Since the part of bank roughness caused by vegetation will change over time, there is a feature to change *n*-values within the simulation hydrograph.

11.6.4 Channel Pattern and HEC-6T

"Channel pattern" refers to the alignment and appearance of a channel when studied in Plan View. The Channel Evolution Model does not address the evolution of channel patterns. As a general principle, it seems important to consider more than one approach for predicting channel patterns.

Fifteen different channel patterns are presented in USACE's *Engineering and Design Manual EM 1110-2-1418* (USACE 1994). Historically, those were grouped into three general categories: straight, meandering, and braided. That manual states, "Relationships between planform and other aspects of geometry and processes are difficult to systematize [...]" (pp. 2–6). Copeland et al. (2001) provide hydraulic geometry equations for meanders. On p. 81 of "Hydraulic Design of Stream Restoration Projects," they conclude, "The most reliable hydraulic geometry relationship is wavelength vs. width." Although there is uncertainty associated with applying hydraulic geometry equations to compute channel pattern, they should not be ignored. Invert slope, on the other hand, is sometimes used as the independent variable in a channel pattern equation, but those equations should be avoided in highly disturbed areas.

Another approach is to base the predicted alignment for the post-removal channel on historical maps. This technique must recognize changes that will result from new soil and vegetation types in the reservoir deposit.

A third approach is to infer the channel pattern from the sedimentation process calculated by HEC-6T. The program does not compute channel pattern directly, but it provides a feature called Sediment Delivery. From that output, the modeler can predict the channel pattern using the Channel Evolution Model. Meandering, or perhaps braiding, will develop in deposition zones as in Stages IV and V described above. Minimization principles can provide the lower limit of the invert slope in these zones, and that can be converted into channel length. Vertical erosion, with the associated bank failure like Stages II and III in the Channel Evolution Model, will develop in erosion zones.

Dam removal studies can involve a network of tributaries; each tributary will develop a channel pattern. The procedural steps are:

1. Predict the alignments.
2. Locate cross sections.
3. Assign reach lengths according to the predicted channel patterns.
4. Estimate the bottom width of each tributary channel.
5. Assign *n*-values appropriate for the vegetation that is anticipated after the dam is removed. (These n-values can be changed within the simulation hydrograph as needed to model changes in the prototype.)

Each tributary data set can be developed separately, and they can be linked together into a network. The program will simulate the development of the entire network.

11.7 SUMMARY AND CONCLUSIONS

When a dam is removed, a hydraulic condition similar to the knickpoint in the Channel Evolution Model is created. Whether the erosion moves upstream as a knickpoint or simply as bed degradation depends on the amount of cohesive sediment in the reservoir deposit. In either case, the conceptual Channel Evolution Model of Schumm et al. (1984) can be applied to study the channel evolution problem.

HEC-6T is a general-purpose computer program. It has been applied to a wide variety of sedimentation studies since 1967. In addition to providing new water surface and bed surface profiles, other pertinent questions that HEC-6T can answer are:

- How deep will the bed erode?
- How deep will the sediment deposit?
- Will the banks fail due to degradation?
- What will the average boundary shear stress be?
- What will the gradation of the surface layer become?
- How will the concentration of sediment in the water column vary over time?
- How many tons of sediment will be delivered downstream?
- How much sediment will be transported out of the reservoir?
- Is dredging required to restore the river?

HEC-6T has many features that facilitate dam removal studies:

- Erosion limits can be set separately from deposition limits in the cross section.
- Special input concepts allow the width of the channel bed and the channel pattern to be coded into the input data file.
- The program will fail the channel banks if bed erosion produces excessive bank heights.
- Bed roughness can be separated from bank roughness and computed using bed roughness equations.
- Roughness can be modeled as a function of depth of water or depth of sediment deposits.
- The dam can be placed at an internal cross section in the model, and the computations will simulate processes both upstream and downstream in a continuous simulation.
- The entire dam can be removed instantly, or it can be removed in stages by notching.
- Wash-off from the land surface can be coded as lateral inflows.
- The model can contain a network of tributaries. It will compute the flow distribution around islands, and the network can have two outlets.

HEC-6T is not an expert system. It is a generalized computer program that allows competent engineers and scientists to study a host of sediment problems. These studies can be for dam removal as well as for many other issues dealing with river systems.

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