Effects of Dam Removal on River Form and Process

JIM PIZZUTO

Dams have a profound influence on fluvial processes and morphology. Reservoirs formed by dams drown river channels and trap sediment. Downstream reaches respond to altered flow regimes and reduced sediment supply in varied ways (Williams and Wolman 1984, Collier et al. 1997) that are difficult to predict, although common responses include erosion and lowering of the channel bed (incision) and development of a coarse-grained surface layer (armor) in the riverbed downstream of a dam.

As dam removal continues to gain momentum as a restoration strategy, understanding how a river changes when a dam is removed is becoming increasingly important. Because few detailed geomorphic studies of dam removal have been conducted, however, there is little direct observational basis for predicting the geomorphic effects of dam removal. Furthermore, rivers are complex and fluvial processes often occur over decades or centuries, so predictions are inherently uncertain.

Fortunately for researchers, the processes associated with dam removal also occur naturally. For example, after dam removal the sediment fill in an impoundment is likely to become incised, and an equilibrium channel with a new floodplain is likely to form as sediment evacuated during incision increases the sediment supply to downstream reaches. Natural processes related to incision, floodplain formation, equilibrium channel development, and increased sediment supply have been widely studied by geomorphologists and engineers, providing useful conceptual models for evaluating the geomorphic effects of dam removal (Doyle et al. in press).

These models can rarely be quantified, however, and in many cases the appropriate model for a particular situation may not be apparent before dam removal. Thus future research will need to concentrate on discriminating among the myriad possible geomorphic responses to dam removal and improving the quantitative basis for predictions.

Geomorphic effects of different engineering strategies
The engineering design and implementation of dam removal plans can profoundly influence the subsequent geomorphic evolution of the impoundment, as well as the extent and nature of sediment impacts downstream of the dam. Important design considerations include strategies to stabilize or remove sediment fill above the dam, the timing and nature of the actual dam removal, and the extent to which the removal follows engineering design criteria.

A variety of strategies exist for minimizing erosion of the sediment fill above dams. Although it may be expensive, removing sediment fill behind the dam may be useful in some instances (Smith et al. 2000). Removing sediment is a particularly attractive alternative when dam fill sediments present an extreme hazard, or when other exceptional factors can justify the expense involved. Furthermore, the sediment that makes up the fill may consist of sand and gravel (Egan and Pizzuto 2000, Wilcox et al. 2000) that could be sold as aggregate for concrete or for construction fill (assuming that sediments are not contaminated). Regrading, revegetating, and riprapping (i.e., strengthening with a layer of stones) of the exposed dam fill have also been proposed as means of reducing the extent and rate of erosion (Harbor 1993, Kanehl et al. 1997).

Although many well-established concepts of fluvial geomorphology are relevant for evaluating the effects of dam removal, geomorphologists remain unable to forecast stream-channel changes caused by the removal of specific dams.

Jim Pizzuto (e-mail: pizzuto@udel.edu) received his PhD in geology from the University of Minnesota in 1982. He is a fluvial geomorphologist at the Department of Geology, University of Delaware, Newark, DE 19716. © 2002 American Institute of Biological Sciences.

August 2002 / Vol. 52 No. 8 • BioScience 683
The engineering design of the actual dam removal may have a significant influence on sediment-related impacts. In many cases, dams are breached only over short sections to allow the reservoir to drain before removing the remainder of the dam (Egan and Pizzuto 2000). Drawing down the reservoir before removal can achieve the same effect, in addition to allowing fine-grained reservoir sediments to consolidate and strengthen (Kanehl et al. 1997). To minimize the potential impacts of eroded reservoir sediments downstream of high dams on the Elwha River in Washington, Harbor (1993) advocated “controlled lowering” of the dams on the Elwha River in Washington, in which removal would occur in stages.

It is also important for engineering designs to be specific and for the removal process to be monitored by qualified inspectors. When the Manatawny Dam in Pottstown, Pennsylvania, was removed in August 2000, the contractor was simply directed to remove the dam: No detailed specifications for removal were given to the contractor, and the dam removal process was not monitored by surveyors. After the dam had been “removed,” surveys revealed that the contractor had removed only half of the 2-meter (m) height of this dam. The remaining 1 m of the dam consisted of large blocks that could not be transported by the stream. These blocks made erosion at the dam site impossible, in addition to controlling the elevation of the streambed above the dam. As a result, the channel upstream did not change initially. In November 2000, the remaining half of the dam was removed, and by June 2001 sand and gravel had accumulated in the streambed above the dam and finer-grained sediments had been swept downstream to expose gravel ripples (steep, rocky sections of the channel with shallow, fast-moving water) (Egan 2001).

Such problems may not necessarily be caused by a contractor’s negligence. Rather, the desired elevation of the dam site following dam removal may not be explicitly defined or discussed. Indeed, it is an easily neglected concept: What could be simpler than just “removing” the dam? At the Manatawny Dam, the problem was clearly illustrated only following a detailed survey of the longitudinal profile over the dam site. Ideally, the design should have included a target longitudinal profile for the postdam channel, which, when projected over the dam site, would have indicated the appropriate elevation to which the contractor should have excavated.

**Incision processes.** The sediment fill in the impoundment could be incised by a variety of processes that will probably depend on the height of the sediment fill and its grain size (figure 2). In cohesive silt and clay sediments, a vertical headcut (an eroding vertical face in the stream bed) is likely to migrate upstream through the fill (Doyle et al. forthcoming). Sandy fills could be subject to sapping as groundwater emerges at the base of a headcut. Other mass wasting processes related to liquefaction of sandy sediment could also occur, particularly when the reservoir fill is thick. Otherwise, a knickpoint (an abrupt increase in slope) could migrate upstream through a sandy fill. Fills composed of sand or cohesive silt and clay are likely to erode even during low flows, but fills composed of gravel may be incised only during high-flow events that are competent to move coarse sediment (Egan 2001, Doyle et al. forthcoming). For this reason, gravel fills are labeled as “event-driven” in figure 2.

Incision rates for removing dam fill sediments are poorly documented. Gerrits (1994) documented 300 m of knickpoint migration in the year following the removal of Musser Dam in Pennsylvania, a 10-m-high run-of-river dam (a small dam that does not significantly influence the water discharge into the stream). Doyle and colleagues (forthcoming) describe the migration of knickpoints following the removal of two low-head dams in Wisconsin, but they do not provide quantitative results.

**Development of a stable channel morphology.** As noted in considerable detail by Doyle and colleagues (forthcoming), field studies of the development of incised channels provide a useful conceptual model of how channels could respond to dam removal (Schumm et al. 1984, Harvey and Watson 1986, Simon 1989a, 1989b, Simon and Hupp 1992). Harvey and Watson (1986) developed a six-stage conceptual model for the evolution of Oaklimiter Creek in northern Mississippi (also summarized by the Task Committee on River Width Adjustment [TCRWA 1998b]) (figure 3). The six stages may be observed at any time along the longitudinal profile of an incising channel, but they also indicate the evolution of individual cross-sections through time. In stage I, the channel slope is steepened above its equilibrium value, but incision has not yet occurred and the banks are stable. During stage II, the channel incises. Stage III is characterized by extensive bank erosion. The additional supply of sediment from the banks causes aggradation of the bed (stage IV), which gradually becomes vegetated (stage V) and ultimately develops into a mature floodplain with an equilibrium channel (stage VI).

Monitoring studies of incised channels indicate that the complete sequence occurs over several decades. Because comparable observations of dam removals are lacking, the appropriate time scale for incision and recovery following dam removal is undocumented. However, when describing the geomorphic response of the removal of two small low-head dams in Wisconsin, Stanley et al. (2002) observed “relatively small and transient geomorphic changes in downstream...”
reaches, and apparently rapid channel development to an equilibrium form within the impoundment." In this case, dam sediments were composed of readily transportable sand, and extensive floodplain development was apparently not required to form an equilibrium channel.

![Figure 1. Schematic illustration of geomorphic processes above and below removed dams. The time scale is highly speculative and will vary considerably from site to site, depending on the size of the dam, the mass of sediment impounded, and other variables.](image)

Figure 1. Schematic illustration of geomorphic processes above and below removed dams. The time scale is highly speculative and will vary considerably from site to site, depending on the size of the dam, the mass of sediment impounded, and other variables.

If the sediment fill in the impoundment is thin, incision may not occur (figure 2). Draining a wide impoundment may create extensive flat areas upstream with a wide, shallow channel (Egan and Pizzuto 2000). To develop a narrower, deeper equilibrium channel, floodplains may have to form by vertical accretion as sediment is deposited from overbank flows. These processes are well documented in the geomorphic literature (Schumm and Lichty 1963, Allred and Schmidt 1999, Moody et al. 1999). For example, Moody and colleagues (1999) described floodplain development and channel narrowing following a large flood on the Powder River in southeastern Montana. The floodplain, which grew over approximately 20 years, was built by the deposition of decimeter-thick layers of sand and mud when annual or biannual floods overtopped the growing floodplain.

After the Manatowry Dam was removed, extensive gravel bars formed. These probably represent the initial stages of floodplain development required to narrow the channel by about 10 m (Egan 2001). The deposition required to accrete the gravel bars far exceeds the volume of erosion at Manatowry Dam, indicating that the primary response to dam removal in this case was deposition rather than erosion and incision. Thus sediment budgets for downstream reaches may need to be reconsidered depending on whether incision or floodplain development is expected to dominate at a particular site.

**Predicting morphology of the equilibrium channel.**

It is often desirable to be able to predict the size and shape of the equilibrium channel that will ultimately form upstream from the dam. Channel width and depth are needed, for example, to design river restoration projects. However, making such predictions is very difficult. Although the dimensions of undisturbed reaches upstream can provide a useful guide (Egan and Pizzuto 2000, Egan 2001), the banks of the channel within the former impoundment will likely have a different sediment type and different riparian vegetation from any reach upstream. Thus even empirical methods may not provide an accurate assessment of the equilibrium channel width and depth in the impoundment. Furthermore, empirical methods "cannot predict either the rate of change or intermediate widths attained during dynamic adjustment of channel morphology" (TCRWA 1998b). The American Society of Civil Engineers' Task Committee on River Width Adjustment provides a useful review of these issues (TCRWA 1998a, 1998b).

**Geomorphic processes downstream from the dam**

**Overview.** Downstream from the dam, the channel will respond to the increased sediment load from the eroding fill, as well as to the reestablishment of a natural flow regime.

![Figure 2. Speculative relationships between the height of a reservoir sediment fill, the dominant grain size of the fill, and different processes of incision. Erosion of gravel depends on high-flow events; therefore these incision processes are "event-driven." Incision of sand and of silt and clay do not depend on high-flow events, but rather on the mechanism of incision; therefore, removal of fills of sand and of silt and clay are "process-driven."](image)
Although many geomorphologists have suggested that sediment inputs translate as waves (Gilbert 1917, Madej and Ozaki 1996), recent experimental (Lisle et al. 1997, 2001), theoretical (Cui and Parker 1997), and field studies (Ball et al. forthcoming) suggest that dispersion should predominate. For example, Lisle et al. (1997) introduced a pulse of sediment into an experimental equilibrium gravel channel. The pulse essentially decayed in place, evolving almost entirely by dispersion (figure 5). Lisle et al. (1997) were able to explain their observations using a relatively simple mathematical model of hydraulics and sediment transport. More extensive flume experiments and modeling results partly reported by Lisle et al. (2001) also emphasize the importance of dispersion. The erosion of a landslide dam on the Navarro River in California also was almost entirely dispersive (Ball et al. forthcoming).

Determining the relative importance of dispersion and translation is significant because the two models have different implications for downstream sediment impacts following dam removal. If a bed material wave translates without decreasing in amplitude, then serious sediment impacts could propagate downstream. Dispersive bed material waves, on the other hand, create sediment impacts that decrease in severity both with time and distance downstream.

Ecological impacts could also vary in response to these two contrasting processes. For example, translation might have larger short-term impacts at a particular location, but then the sediment wave would pass that location and have no further effect. By contrast, a dispersive process might have a smaller effect per unit time at a particular location, but impacts at that site could last much longer.

The results described above that emphasize the importance of dispersion apply primarily to gravel-bed rivers and do not take into account factors such as floodplain processes and width adjustment. Nonetheless, they suggest that impacts from bed material following dam removal will not influence the channel far downstream. Doyle et al. (forthcoming) and Stanley et al. (2002) disagree, however, and suggest that downstream translation of sediment waves can be significant under certain circumstances following dam removal.

Reach-scale changes in bed texture and morphology. An increase in sediment supply downstream caused by dam removal could have significant impacts at the reach scale, where a reach is defined as a length of stream that contains several pool and riffle sequences or meanders, or that is 10 to 30 channel widths in length (Leopold et al. 1964). These impacts include destruction of pools and ripples, burial of coarse-grained ripples by finer-grained sediment, and modification of bedforms and armor.
Flume studies are particularly effective for investigating bed processes in gravel-bed rivers. Analyses of scaling laws and the relevant fluid mechanical principles indicate that small-scale flumes are excellent physical analogues for real gravel-bed rivers (Shvidchenko 1998).

Observations from flume studies suggest that changes in bed texture and morphology resulting from an increase in sediment supply may occur in a predictable sequence (figure 6). The experiments described by Lisle et al. (2001) involved (a) creating an equilibrium channel with an armored gravel bed and well-developed alternate bars (the uppermost map in figure 6), (b) introducing a pulse of sediment that could represent a dam fill (figure 6), and (c) observing the response of the channel downstream as the pulse was eroded. In these experiments, the pulse was approximately 15 channel widths long and 3.5 centimeters (cm) high—about the same height as the equilibrium depth of flow. The transient evolution of the“dam fill” and the reach downstream was observed for 8.5 hours. After 0.6 hours, the sediment from the dam fill had migrated at least 25 m downstream, destroying both the pools and riffles created by alternate bars and the armored bed. A bed with scattered sandy patches replaced the preexisting armored bed. After 5.2 hours, the armored bed was reestablished, but the alternate bars had not reappeared. Finally, after 8.5 hours, the same pattern of alternate bars and pools and riffles that characterized the initial equilibrium channel had reappeared.

These observations suggest that the sediment supplied by dam removal could rapidly destroy the structure of the bed at the reach scale. This conclusion is supported by many field studies demonstrating a decrease in surface grain size in gravel-bed rivers that is caused by an increased supply of finer grained sediment (Montgomery et al. 1999). During the ensuing recovery, as the extra sediment

Figure 5. Evolution of a sediment wave in an experimental channel. The horizontal axis represents the longitudinal distance down the flume. The vertical axis is the thickness of sediment above the sloping base of the flume. At 0 hours (hrs), an equilibrium channel is illustrated. After 0.75 hrs, a pulse of sediment 3 cm high and 20 meters long was introduced into the channel. This pulse essentially decayed in place. The “observed” data have been smoothed, and the solid line represents predictions from a mathematical model (after Lisle et al. 1997).
is removed, the armored bed is reestablished first, followed by alternate bars and pools and riffles. Although these changes were observed in a matter of hours in a laboratory flume, the time scale for equivalent changes in a field situation is difficult to specify precisely, but it is likely to be at least several years (Madej 2001).

Observations at the reach scale by Egan (2001) following the removal of Manatawny Dam provided some information on the nature of the evolution of alternate bars and pools and riffles. Downstream from the dam, cobble riffles were buried by a mixture of sand, pebbles, and granules eroded from the dam fill upstream. (Buried riffles following dam removal were also noted by Kanelh et al. 1997 and Stanley et al. forthcoming, documenting aggradation downstream of removed dams.) After 11 months of monitoring, these riffles remained buried. In the impoundment itself, incipient pools and riffles and a midchannel bar formed during a 2.5-year flood (a flood that, on average, will be equaled or exceeded only once every 2.5 years) that occurred 5 months after the dam was removed. After 11 months, however, the spacing of the pools was relatively incoherent compared with a control reach upstream, in which pools and riffles exhibited fairly regular spacing of five channel widths. Pools were also deeper in the control reach than in the impoundment area. These observations suggest that complete development of pools and riffles in a gravel-bed channel following dam removal could take at least several years, depending on the frequency of discharges competent to move the bed sediment.

Other, more complex responses at the reach scale are also possible. Gerrits (1994), for example, documented sediment storage in backwater areas and on the floodplain following the removal of Musser Dam. Stanley and colleagues (2002) observed similar deposits following the removal of small dams in Wisconsin. Sediment could also be stored in areas of low current velocity close to stream banks (Stanley et al. 2002).

**Numerical models of geomorphic response**

Numerical models are commonly used to evaluate sediment transport and hydraulic processes associated with dam removal. These models predict the average velocity and water surface elevation for a reach, and use these hydraulic data to estimate reach-averaged rates of sediment transport and changes in bed elevation.

At a symposium on “Rehabilitation and Decommissioning of Aging Dams” at the 2000 fall meeting of the American Geophysical Union, five of ten presentations emphasized predictions based on numerical models (the abstracts are published in the 2000 fall meeting supplement of EOS and are also available at www.agu.org). How robust are these predictions?

The impacts of most dam removal projects are likely to extend far enough downstream to require the use of one-dimensional models, rather than more complex two- or three-dimensional models, because of limitations in computer information storage capacity and computational power. For
example, Wilcox et al. (2000) modeled approximately 45 kilometers of the Sandy River in Oregon to predict the potential impacts of the proposed removal of Marmot Dam. Although it would clearly be impractical to represent meter-scale spatial and temporal variations in hydraulics, morphology, and sediment transport over such distances, this is precisely the resolution required by two- or three-dimensional models.

One-dimensional models can predict only changes in grain size and bed elevation in the downstream direction, and all results are averaged across the width of the channel. Furthermore, predictions in the downstream direction are typically associated with a computational grid that is widely spaced relative to channel width. As a result, one-dimensional models predict single, reach-averaged values of grain size and bed elevation. Predictions of smaller scale or multi-dimensional features such as alternate bars or grain-size patches cannot be obtained from one-dimensional models.

One-dimensional sedimentation models are, however, relatively well-established tools in river engineering. Useful reviews of older models were presented by Dawdy and Vanoni (1983) and the National Academy of Sciences (1983). More up-to-date reviews will be available with the publication of the American Society of Civil Engineers Manual 54, Sedimentation Engineering, which will contain chapters on “Sediment Transport Mechanics,” “Transport of Gravel and Sediment Mixtures,” and “1-D Computational Modeling of Sedimentation Processes.” One-dimensional models have been used in thousands of field studies (Ball et al. forthcoming provide an excellent example) and laboratory studies (Cui et al. 1996), often with useful results.

Nonetheless, many of the processes represented by current one-dimensional sediment transport models are not well understood. For example, methods for computing transport rates of sand and gravel mixtures are in their infancy (Wilcock 1997). Methods for computing transport processes of silt and clay are also rudimentary (Packman 2001). Mixtures of sand and gravel are very common in nature, and most of the sediment load of rivers is represented by the transport of silt and clay. Furthermore, these processes are only selected examples. Nearly all existing models neglect many other important processes, including upstream propagation of knickpoints and headcuts; changes in width due to bank erosion or deposition (TCRWA 1998a, 1998b, Doyle et al. forthcoming); processes associated with floodplains, including overbank flows and associated sediment transport; and the influence of vegetation on sediment transport processes.

An additional impediment to the development and use of improved numerical models is the poorly developed state of conceptual models that identify controlling geomorphic processes (Grant 2001). As a result, the processes that should be included in a quantitative model forecast at a particular site are not well constrained. Empirical observations are also needed to better define the processes that will probably occur during particular dam removal projects (Grant 2001). It is difficult to provide accurate, quantitative forecasts of the effects of dam removal using a numerical model if the processes represented by the model cannot be identified before a dam is removed.

**Toward improved forecasting of dam removal effects**

Improving our ability to forecast the effects of dam removal will require a concerted, well-designed effort. Table 1 outlines some components of a research program that could help achieve this goal.

Our greatest need is to improve the ability to develop and test conceptual models that will indicate the relevant processes controlling the evolution of the river following dam removal. This will require observations from dam removal projects under a wide variety of conditions, with varying dam heights, fill sediment types, impoundment sizes, and a host of other variables. Because it is impractical to study a large number of dam removal projects in detail, geomorphologists, engineers, ecologists, and others will need to develop rapid protocols for semi-quantitative documentation of dam removal processes through a multidisciplinary effort.

Researchers should also develop improved numerical models to quantify the relevant processes identified by improved conceptual models. Although current models do not include many relevant processes, the rapid development of computing power and the widespread availability of modeling expertise should allow development of useful predictive models. The current widespread use of numerical models indicates that models will always be needed to provide quantitative predictions to guide management decisions. If models are to be used, then both researchers and managers should have confidence in them.
Studies using flumes or other physical models could be extremely useful for improving our conceptual knowledge of dam removal processes and testing numerical models under rigorously controlled conditions. Physical models have provided extremely useful results in many areas of fluvial geomorphology, including landscape evolution (Hasbargen and Paola 2000), the development of drainage basins (Parker 1976), watershed-scale sediment routing (Parker 1976), the evolution of localized sediment inputs (Lisle et al. 1997, 2001), the development of armor in gravel bed rivers (Parker et al. 1982), and the evolution of bedrock channels (Wohl and Ikeda 1997).

Physical models could provide a cost-effective means of studying dam removal processes under controlled conditions that cannot be duplicated by field studies. Scaled physical models have significant limitations, however. Sedimentary processes involving clay, silt, or fine sand often cannot be effectively scaled because of the surface chemistry of the finest grain sizes. Varying discharges are difficult to create and scale in the laboratory, and scale models cannot represent important effects caused by vegetation in the field. Finally, the geometry of scale models does not always correspond to field conditions.

Developing improved conceptual and numerical models of hydrodynamic and geomorphic processes will not suffice. Ecologists also need predictions of changing river morphology and sediment transport processes to predict changes in ecological processes following dam removal. However, the nature and scale of geomorphic predictions that are most useful to ecologists are not necessarily those that geomorphologists are most likely to produce. For example, a one-dimensional model used by an engineer or geomorphologist might predict the mean grain size of the bed material or even the extent of bed armor. Ecological processes might be linked more strongly to the percentage of silt and clay in the bed—a quantity that has received little attention from geomorphologists and engineers. To maximize the utility of geomorphic predictions for ecologists, a coordinated multidisciplinary effort is needed to develop integrated geomorphic and ecological models. This will require a conscious, planned collaboration between ecologists and geomorphologists throughout entire projects, from initial study design to final model development and testing.

To gain confidence in the reliability and precision of improved predictive models, comprehensive, quantitative, multidisciplinary monitoring studies are needed. A coordinated study of the removal of a dam on Manatawny Creek in Pottstown, Pennsylvania, provides a useful example (Johnson 2001). These studies will be expensive and difficult, and therefore only a small number of such efforts can be funded. However, they represent the only means of thoroughly evaluating our forecasting ability and of understanding the effects of dam removal on fluvial and biological processes.

Conclusions

Previous research on fluvial processes provides many useful models for evaluating the geomorphic effects of dam removal. Studies of the evolution of incised channels, knickpoint and headcut migration, floodplain formation and channel narrowing, bank erosion and channel widening, the movement of sediment waves, the formation of alternate bars, the origin of patches of differing grain sizes in gravel bed rivers, and the development of armored beds all provide insights into potential trajectories of channel evolution following dam removal.

Upstream from the dam, geomorphic processes should be dominated by evolution of the channel as it incises into the sediments trapped in the impoundment. Case studies of the evolution of incised channels suggest several stages that will ultimately lead to development of a new equilibrium channel. The initial stages involve downcutting, followed by bank erosion and aggradation of the bed and floodplain development. If the impoundment contains relatively little sediment and is significantly wider than equilibrium channels upstream and downstream of the dam, then the primary processes above the dam are likely to be deposition and floodplain construction (Egan 2001) rather than erosion and incision.

Downstream from the dam, geomorphic processes should be dominated by fluvial responses to temporally varying sediment supply. Observations in the field and in laboratory flumes suggest that the dam fill will not migrate downstream as a coherent "sediment wave," but is more likely to disperse in place, leading to sediment impacts that decrease with the time since removal and the distance from the dam. Increased sediment supply at the reach scale could destroy alternate bars, pools and riffles, and armored beds. Enhanced sediment storage on floodplains, in backwater areas, and along the banks is also likely. The time scale for recovery from downstream transient sediment impacts is currently difficult to predict, but the available evidence suggests that years or decades may be required.

Although a variety of useful models exist for predicting the geomorphic effects of dam removal, site-specific forecasts are unlikely to be reliable. Coordinated research is needed to define the geomorphic processes that are most likely to dominate under different conditions, develop improved conceptual and numerical models, couple geomorphic and ecological models, and monitor selected dam removal projects in sufficient detail to evaluate both qualitative and quantitative forecasts.

The geomorphic effects of dam removal can be significantly influenced by different strategies of design, management, and construction. The removal process can potentially be scheduled and manipulated to minimize undesirable impacts. A variety of methods are available to control erosion of the sediment fill and therefore to minimize the effects of increased sediment supply downstream. Well-conceived restoration strategies could potentially increase the rate of recovery both above and below the dam. Future research programs
should be designed to provide the scientific knowledge to
guide management decisions so that informed choices can be
made as to whether dams should be removed, and if so, how,
when, and where.

Acknowledgments
This paper would not have been written without Dave Hart’s
encouragement and enthusiasm. Helpful reviews were pro-
vided by Dave Hart and Thomas Johnson of the Patrick Cen-
ter of the Academy of Natural Sciences and three anonym-
umous reviewers. I would particularly like to thank The Pew
Charitable Trusts for providing support that helped me com-
plete this paper.

References cited
Alfred TM, Schmidt JC. 1999. Channel narrowing by vertical accretion
along the Green River near Green River, Utah. Geological Society of
Ball MH, Sutherland DG, Hilton SJ, Liske TE. Evolution of a landslide-induced
sediment wave in the Navarro River, California. Geological Society of
Cui Y, Parker G. 1997. Linear analysis of coupled equations for sediment trans-
port. Pages 1256–1261 in 27th International Congress. San Francisco: In-
ternational Association of Hydraulic Research.
Cui Y, Parker G, Paola C. 1996. Numerical simulation of aggradation and
downstream fining. Journal of Hydraulic Research 34: 185–204.
Dawdy D, Vanoni V. 1983. Modeling alluvial channels, Water Resources Re-
Doyle MW, Stanley EH, Harbor JM. Geomorphic analysis for assessing prob-
able channel response to dam removal. Journal of the American Water
Resources Association. Forthcoming.
Egan J. 2001. Geomorphic effects of dam removal on the Manatowick Creek,
Pottstown, PA. Master’s thesis, Department of Geography, University of
Delaware, Newark.
Dam, Pottstown, PA, EOS, Transactions, American Geophysical Union
81 (fall meeting supplement).
Gerrits M. 1994. Physical effects on Middle Creek due to the construction of
Musser Dam. Geology senior thesis, Bucknell University, Lewisburg,
PA.
Gilbert GK. 1917. Hydraulic Mining Debris in the Sierra Nevada. Washing-
Grant G. 2001. Dam removal: Panacea or Pandora for rivers? Hydrological
Processes 15: 1531–1532.
Harbor JM, ed. 1993. Proposed Measures to Alleviate the Environmental Impacts
of Hydroelectric Dams on the Elwha River, Washington, U.S.A.
Harvey MD, Watson CC. 1986. Fluvial processes and morphological thresh-
Hasbargen LE, Paola C. 2000. Landscape instability in an experimental
Johnson TE, Pizzuto J, Egan J, Bushaw-Newton K, Hart D, Lawrence J,
Lynch E. 2001. The Manatowick Creek dam removal project: Overview and
geoorphic characteristics. Bulletin of the North American Benthological
Kanehl PD, Lyons J, Nelson JE. 1997. Changes in the habitat and fish com-
unity of the Milwaukee River, Wisconsin, following removal of the
17: 387–400.
Liske TE, Cui Y, Parker G, Pizzuto JE, Dodd AM. 2001. The dominance of dis-
persion in the evolution of bed material waves in gravel-bed rivers.
ment wave in an experimental channel. Water Resources Research 33:
Mao J, Ozaki V. 1996. Channel response to sediment wave propagation
and movement, Redwood Creek, California. Earth Surface Processes and
Montgomery DR, Panfil MS, Hayes SK. 1999. Channel-bed mobili-
ty response to extreme sediment loading at Mount Pinatubo, Geology 27:
271–274.
National Academy of Sciences, Committee on Hydrodynamic: Computer
Models for Flood Insurance Studies, Advisory Board on the Built Envi-
Packman AL. 2001. Re-examination of the wash load concept: Role of physi-
chemical processes. World Water and Environmental Resources Con-
gress. Orlando (FL): American Society of Civil Engineers.
Parker G, Dhanotharan S, Stefan H. 1982. Model experiments on mobile,
Parker RS. 1976. Experimental Study of Drainage Basin Evolution and its Hy-
drologic Implications. Fort Collins: Colorado State University.
Schumm SA, Harvey MD, Watson CC. 1984. Incised Channels: Morphology,
Shvidchenko AB, Kopalini A. 1998. Hydraulic modeling of bed load transport
in gravel-bed Laba River. Journal of Hydraulic Engineering 124:
778–785.
along modified stream channels of West Tennessee. Washington (DC):
US Geological Survey.
Smith IW, Dittmer E, Prevost M, Burt DR. 2000. Breaching of a small irriga-
tion dam in Oregon: A case history. North American Journal of Fish-
in channel form and macroinvertebrate communities following low-
head dam removal. Journal of the North American Benthological
[TCRWA] Task Committee on River Width Adjustment, American Society
of Civil Engineers. 1998a. River width adjustment, II: Modeling. Jour-
———. 1998b. River width adjustment, I: Processes and mechanisms. Jour-
rivers. Baltimore: Johns Hopkins University.
Wilcox AC, Cui Y, Vick JC. 2000. Geomorphic assessment and numerical mod-
eling of sediment transport associated with dam removal: Case study of
Marmot Dam, Sandy River, OR. EOS, Transactions, American Ge-
ophysical Union 81 (fall meeting supplement).
Wohl E, Ikeda H. 1999. Experimental simulation of channel incision into a