What is Geomorphology’s Dam Role??

Investigations into Current Research in Dam Removal Planning and Processes in Fluvial Geomorphology

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Abstract

In the last half-century, and in particular the last two decades, dam removal has emerged as an economically viable and socially desirable watershed and stream management option. The role geomorphology plays in dam removal research, planning, designing, execution, and monitoring has also expanded considerably. Multidisciplinary challenges between disciplines still present barriers to encompassing studies involving all aspects of fluvial and ecosystem response and recovery. The tools and skills of geomorphology can help to solve such challenges with time, data, and an increased leadership role for the discipline. This paper summarizes recent geomorphic work in dam removal studies, emphasizing aspects well known and well-suited to geomorphology such as stream channel morphology and response, sediment management, and biological and ecological responses to dam removal disturbance events. The paper examines recent case studies as examples of directions geomorphology can take in order to achieve a greater role in decision making and enhancing public education and awareness. Finally the paper looks at remaining challenges to encompassing, multidisciplinary, and properly scaled research in dam removal, and presents avenues and suggestions to address such challenges.
As dam removal evolves as an economically feasible and effective watershed and river management option in the United States, the role geomorphology plays in dam removal research and planning should also grow exponentially with time. Geomorphologists’ thorough knowledge of fluvial systems and processes, and the interrelationships with ecosystems, anthropogenic modifications and landforms represent a discipline located at a key interface between science, nature, and society. Thus, geomorphologists should be called upon to engage in multidisciplinary, mutually cooperative research paradigms with experts from diverse fields such as geology, ecology, engineering, and the social sciences. Geomorphology also must take a greater role in public education and awareness in future dam removal projects by working closely and sharing research with politicians, decision makers and community planners. This study examines the various roles geomorphology plays in dam removal research. It attempts a review of the recent literature of geomorphic study in dam removal planning, execution, and subsequent restoration monitoring.

In recent years several major academic journals dedicated special issues to dam removal and river restoration research. *BioScience* (2002), *Water Resources Research* (2003), *Journal of the American Water Resources Association* (2002), and *Geomorphology* (forthcoming) are only a few of these publications. Journals predominantly authored by researchers in other fields such as engineering and geology also have recently dedicated issues to dam removal research, such as *Sediment Engineering* and *Transactions of the American Geophysical Union*.

It must be acknowledged here that a complete literature review of dam removal as a general topic is well beyond the scope of this paper. I intend rather to narrow the literature scope of this paper’s review to cover only certain aspects of recent dam removal research in which geomorphology plays a greater role than others. Such aspects addressed in this paper include geomorphology’s role in ecological effects of dam removal and subsequent restoration; conceptual modeling of channel morphology; and sediment management strategies relating to dam removal. The paper also highlights key
recent studies by geomorphologists on the current paradigms, research trends, and future needs and challenges for the discipline.

**Introduction**

There are between 75,000 and 80,000 dams currently in U.S. stream systems (Graf 2003). This fact leaves only 42 high-quality undammed rivers longer than 200 km remaining in the continental U.S. (American Rivers 2005). Reasons for dam construction are varied, but include flood protection, water storage, hydroelectric power generation, irrigation, industrial and commercial water uses, and navigation (Pohl 2002; Collier, Webb, & Schmidt 1996). The overwhelming majority of these dams are between 80 and 120 years old, and many have long outlived their original purpose or usefulness. In most cases the costs of repairing or retrofitting a dam far outweighs the cost of removing the structure (Pohl 2002). Social movements in the 1980s and 1990s helped advance popular support for environmental and ecological restoration projects at all scales and in a variety of industries.

For these reasons and others, dam removal and stream restoration have gained popularity as management options. The reasons for removing a dam are also varied, but generally are grouped into general rationales including safety, failure, economics, environmental/ecological restoration, recreation, and other legal rationales such as discovery of unauthorized dams by state management agencies, including beaver dams. In the last 30 years, Wisconsin has led the U.S. in the total number of dams removed, the total number of dam removals for safety and economic reasons, and dam removal research in general (Pohl 2002).

While dam removal has evolved recently as a viable and even desired watershed management alternative, opposing societal, political and economic factors remain the major barriers to greater dam removal and fluvial and ecological restoration projects. This is largely due to the lack of public education and awareness and persistence of dam removal myths. Societal and political resistance to dam removal is especially acute in the American West, where water issues are more contentious. In arid Western regions, dams are generally larger and more depended upon, and debates about water resource rights are notoriously and endlessly fought, as powerful stakeholders have interests in water.
resources for different reasons due to the lack of water in arid regions when compared to humid regions.

How geomorphologists attempt to predict fluvial and ecological responses to dam removal disturbance is an important factor in determining the relative success of predictive modeling. One way to predict morphologic and ecologic responses is by conceptual modeling. Such modeling represents one of the immediate and analogous approaches to take in dam removal projects, mainly because of the lag time between the disturbance to the system and its resultant recovery. It has been suggested that response times to dam removal can take anywhere from months to centuries, depending on the component in question (Wildman & MacBroom 2005). Generally speaking, responses of certain components of the ecosystem and fluvial systems can be expected to begin to recover in weeks and completely recover in one to five years (Doyle & Stanley 2005; Graf 2003; Pizzuto 2002). Of course, this may not be the case; in many instances some ecosystem or fluvial components’ recovery may take decades, centuries, or perhaps only partially recover or possibly never recover at all (Doyle & Stanley 2005).

**Ecological Effects of Dam Removal**

While describing encompassing reviews of the totality of ecological effects of dam removal on stream systems is well beyond the scope of this paper, ecological restoration and recovery is perhaps the most important and highly visible aspect of any dam removal process, and it is often ecological or environmental rationales that lead to dam removal projects. California has emerged as a leader in dam removal for environmental and ecological restoration rationales (Pohl 2002).

Geomorphic research on the ecological effects of dam removal considers post-removal effects for a variety of biotic components, including fish, channel and bank flora such as grasses and riparian trees, benthic macroinvertebrates, and nutrient retention. While ecological response research involving fish, especially anadromous and salmonid species has always attracted the popular spotlight, recently more geomorphic ecology studies have focused on the effects of benthic macroinvertebrates and nutrient retention (Doyle & Stanley 2005; Stanley & Doyle 2002; Graf 1999). Both ecological components serve as vital members of stream system communities and biological food webs, and they
both also provide relatively easy to study and observe indicators of relative stream system health. This is especially true regarding long-term observations of stream systems following dam removal.

Doyle and Stanley (2005) have submitted a workable conceptual model of expected recovery time scales for different components of an ecosystem following dam removal for full or partial ecosystem restoration modeling (Figure 1). With more time, research, observed responses and other data, the effectiveness of perceptual models will emerge, but in the meantime they provide managers, decision makers, stakeholders, and the general public with a simple conceptual analog on what could be expected in a dam removal event.

Such recent studies reveal the continuing trend towards biogeomorphology in dam removal research, as many of the major names in geomorphology have moved in this direction. Leading the way in this academic transition are prominent figures in the field including Martin Doyle, Emily Stanley, Jon Harbor, David Hart, Jim Pizzuto, Leroy Poff, Jennifer Egan, and Michael Collier. Often these authors attempt to predict or model the expected ecological responses following dam removal by articulating conceptual models or expected post-dam effects (Doyle & Stanley 2005; Pizzuto 2002; Hart 2002; Graf 2002). While the relative accuracy and success of such perceptual models still remains in question, the models can provide a general modicum of reasonably accurate expectation and can serve as valuable public education and awareness tools.

Interestingly, geomorphic study in dam removal ecology research has been critiqued as being bio-and flora-centric, meaning geomorphologists at present are unable or unwilling to view stream ecosystems from perspectives other than those heavily weighted towards certain species of fish (charismatic megafauna) or riparian trees (Doyle & Stanley 2005). This criticism represents a problematic aspect of dam removal research for geomorphology, as it calls into question the credibility of methods and techniques, undermines the credibility of such methods, and impedes the advancement in leadership roles for geomorphologists in the process. This further illustrates the need for multidisciplinary study and cooperation between disciplines in order to elicit encompassing ecological and environmental responses, predictive modeling and assessments in dam removal. As a result, over the last decade or so, biogeomorphology
Figure 1. Conceptual framework for ecosystem recovery following removal of a small dam. Full ecosystem recovery assumes that all components of the stream ecosystem return to pre-dam conditions, but at variable rates of recovery. Partial ecosystem recovery assumes that some components recover to pre-dam conditions, but that others only partially recover while still others are actually damaged by dam removal and not able to recover at all. Taken from Doyle & Stanley (2005, in press).
has emerged as a research paradigm for geomorphology to help bridge the intellectual
gaps between biology, geology, engineering, and geomorphology. Biogeomorphology
examines the relationships between biota and geomorphic forms and processes with a
focus on multidisciplinary research paradigms (Doyle & Stanley 2005; Graf 2002, 1999).

**Channel Evolution Modeling**

One aspect of dam removal monitoring and restoration design that has always
found its natural place in geomorphology is the dynamics of stream channel evolution
and response. For centuries now geomorphology researchers report on the changing
morphology of stream systems and their relation to a host of anthropogenic and natural
disturbances, and resulting changes to their hydraulic regimes. Therefore, conceptual
modeling of stream channel evolution is a practice well suited to the discipline. What has
changed in regards to geomorphology’s role in dam removal prediction and assessment is
the importance of qualitative pre-dam removal research and data in order to evaluate and
accurately predict changes to the stream system and hydraulic regime before the dam
removal occurs. This is important for many reasons but one important aspect from a
planning perspective is that such pre-dam removal data and modeling can be incorporated
into the dam removal design plan, and this information should be included in construction
applications and permits in order to adapt to changing conditions as they are discovered
(Wildman & MacBroom 2005; Doyle, Stanley, and Harbor 2003). Stream channel
evaluations over time also provide an opportunity to view and describe dam removal
projects at stream-wide or even watershed-wide scales. Authors unanimously agree that
dam removal and restoration processes must be viewed from larger scales than are
currently employed.

In order to accurately predict or model stream channel evolution, geomorphic
assessment must be conducted on the stream channel characteristics both upstream and
downstream of the dam. Wildman & MacBroom (2005) describe the geomorphic factors
that must be included in stream channel evolution predictive models. Ideally, these
factors would include extensive data on the stream channel’s sediment gradation, quality,
thickness, and distribution and relation to channel slope; the ratio of pool width to
channel width; bank stability analyses; channel Width-Depth Ratios; and the ratio between applied tractive stress (or stream power) to the threshold critical stress.

**Sediment Management**

Managing what happens to impounded sediment behind a dam is perhaps the single most vital aspect of dam removal planning and restoration efforts. Sediment management is the most costly aspect of the dam removal process (Randle 2003). Depending on the type, condition, composition, dimensions, and relative level of contamination of toxic substances to biota or humans, several management options are available to deal effectively with impounded sediment while allowing for more effective fluvial and ecosystem restoration to occur.

Depending on various factors that determine the composition of an impoundment, sediments may contain toxic chemicals and nutrients that present major problems downstream when released after dam removal. Agricultural and industrial inputs, such as phosphorous and nitrogen are commonly found in impoundments, and these nutrients tend to damage the health of stream systems, especially biological components such as benthic macroinvertebrates, mussels, and fish (Doyle & Stanley 2005). Other toxic inputs come from industrial wastewater inputs and illegal dumping by a host of actors both upstream and in the impoundment itself (Wildman & MacBroom 2005). Frequently, heavy metals, polychlorinated biphenyls (PCBs), and coal tars are discovered through pre-removal sediment core borings, and these chemicals present serious threats to biological and human health (Francisco 2004). The most famous example of contaminated sediment resulting in environmental disaster was the 1973 removal of Fort Edwards dam on the Hudson River near Albany, New York. Tons of PCB-contaminated sediment released from the impoundment caused pervasive toxic impacts on all biological components downstream. As a result, the State of New York closed the Hudson to fishing activities (Francisco 2004).

As management options depend on the quality of impounded sediments, manual or mechanical sediment impoundment borings are now routinely taken as part of the dam removal planning process. Depending on the composition and size of the impoundment, as well as the downstream factors, any one or a combination of four types of Sediment
Management Plans can be adopted (Wildman & MacBroom 2005). The four types are: No Action (meaning leaving the dam and impoundment in place), River Erosion (the stream removes the sediment through natural evolution; essentially no anthropogenic management), Mechanical Removal (all or part of the impoundment is dredged or extracted and deposited elsewhere than downstream), and Stabilization (the impoundment is deliberately kept in place by reinforcing with riprap, boulder weirs, or vegetation). In most recorded cases, combinations of the four types of management plans are commonly adopted and implemented.

**Sediment Pulse Literature**

The ways in which sediment moves from an impoundment downstream is often referred to as a wave or pulse-type movement (Pizzuto 2002; Gilbert 1917). Sediment pulses can move downstream in waves via *dispersion*, where sediment essentially decays in place, or *translation*, where sediment material moves downstream “without a decrease in amplitude”, essentially moving as one cohesive mass (Pizzuto 2002, 686). Often sediment pulses behave in a manner where both movement types are observed. Numerous analogous studies document the different types and behaviors of sediment pulses (Wildman & MacBroom 2005; Randle 2003; Doyle, Stanley, & Harbor 2002; Pizzuto 2002; Egan and Pizzuto 2000; Lisle, et al, 1997). However, the predictive behavior of sediment pulses eludes simple classification, and all of the studies acknowledge the need to treat each impoundment differently and to consider each downstream pulse as a unique case, encompassing a variety of ever-changing fluvial and ecological variables.

To that end, other researchers, primarily engineers and geologists, attempt multidimensional modeling of sediment movement in stream systems. Mapping sediment grain-size distribution with shear stress and sediment transport capacity is one example of such a model that has gained some effective predictive capabilities (Rathburn & Wohl 2003). The U.S. Army Corps of Engineers’ HEC modeling program has been utilized for decades with growing effectiveness (Doyle, Stanley & Harbor 2002). Additionally, within the last five years, *Journal of American Water Resources Association*, *Journal of Hydraulic Research*, and *Sediment Engineering* produced dam removal special issues with articles dedicated to sediment transport modeling. A detailed literature review of
these publications is, however, beyond the scope and limitations of this paper. Following instead is a review one recent case study found in *Geomorphology* that adequately provides an effective overview of some of the difficulties and complexities associated with sediment management plans and predictive modeling relating to dam removal.

**Naugatuck River Case Study**

Wildman and MacBroom (2005) examined sediment discharges following two dam removals on the Naugatuck River in Connecticut. The authors document the changing morphology of two impoundments upstream from dams over a four-year period. Their case study represents one of the best examples to date of the geomorphic and ecological complexities encountered when attempting a total sediment management study of dam removal event. The Anaconda Dam and Union City Dam were removed in 1999. In both cases initial predictive sediment pulse modeling was conducted along with impoundment sediment borings to determine management options. The initial borings showed traces of PAHs (polycyclic aromatic hydrocarbons) in the impoundment, a potentially damaging element in the impoundment for downstream biota. Before construction commenced on Anaconda Dam, the timber crib run-of-the-river structure was partially breached during a storm by natural forces. This event released a sediment pulse downstream mainly composed of fine sediments. Because of the safety liability of the remaining timber crib, the rest of the dam was removed four days later.

Neither the fluvial nor sedimentary responses to the dam’s removal followed the initially predicted results in any accurate way, save for a close correlation between the average predicted with-to-depth ratio of the upstream headcutting channel. Rather than returning the predicted results presumed to follow Doyle & Stanley’s (2003) conceptual channel evolution model, factors unknown to the planners created different responses in the impoundment and upstream response process. In the Anaconda dam removal case, after the remaining dam parts were removed, the upstream channelized after the initial sediment pulse, but the headcut stopped degrading (downcutting) when it reached the armored cobbles of the former riverbed, and began widening instead to compensate. This was an unexpected development not predicted in the initial assessment. Because of the arrested degradation into the impoundment, much of the stored sediment was then
retained on eastern shore, where eventual islands formed and helped to stabilize the sediment and establish vegetation on the impoundment (Wildman & MacBroom 2005).

The authors found that unexpected results also occurred upon removal of the Union City Dam. This dam was also a timber crib, run-of-river dam, reinforced by rock weirs, and frequently used by picnickers, making the dam particularly dangerous. Initial borings showed some contaminants (PAH’s) in impoundment. As a result pre-removal dredging occurred along the east side prior to dam removal. Immediately after dam removal however, released sediment filled in the dredged area within one day, leaving the engineer to inquire how often the impoundment was to be dredged! Dam removal also created a riffle upstream, instead of a headcut, as was expected in the initial predictive models. Because of this unexpected riffle, negligible further sediment deposition occurred downstream during this period. The riffle upstream of the impoundment was caused by the later discovery of a previously unnoticed abandoned sewer pipe with riprap protection. Essentially this pipe and its weir stopped all headward migration of channel, and caused the river to downcut into the armored former channel bed. Once the sewage pipe was removed, downcutting continued as headward migration moved upstream. Because of this impediment, the stream channel focused incision toward west side. Impounded sediment is now stabilized with vegetation strengthening (Wildman & MacBroom 2005).

Considering Pizzuto’s (2002) sediment wave analysis, the evidence in the Naugatuck River cases are clear examples of sediment movement working both as translation and dispersion, and a combination of types. Wildman & Macbroom’s (2005) case study clearly illustrates another example of the challenging complexity of processes and planning associated with dam removal. It also shows the need to incorporate design flexibility in construction and application permits into the planning process well before the dam removal event in order to effectively and immediately deal with unforeseen problems and challenges after the removal occurs.

**Synthesis: Needs and Challenges for Future Research**

Geomorphology’s role in dam removal research encompasses a burgeoning paradigm. The overall, large-scale aspects of dam removal processes are intricate,
complex, and constantly encounter cross-disciplinary difficulties. Despite this challenge, the tools and methods of geomorphology are well designed to and take a leadership position in raising public awareness, and play a much larger role in management plans for dam removal. There are, however, several challenges and needs to geomorphology’s expanded role in dam removal processes. First, there must be an increase in reliable quantitative data to go along with existing qualitative data. The continuing need for real-time and long-term data on fluvial and ecosystem responses to dam removal is an endeavor necessary in order to construct complete and centralized national databases to inventory dam removal research. American Rivers and the National Inventory of Dams (NID) are currently collecting dam removal data in a collaborative effort, but cooperation and data sharing problems still present major challenges to this end. Eventually, however, such encompassing databases as those proposed by American Rivers and NID will significantly contribute to greater understanding of how fluvial and ecological processes act to respond to such disturbances.

As mentioned above, there is also a pressing need to change the locus of scale for studying dam removal effects to encompass a much larger setting. Watershed-wide scalar analysis would accomplish this objective, although the logistics and costs of such an expanded methodology may render such an objective unrealistic without a demonstrably beneficial outcome for some social or ecological component afterwards. Such watershed-wide encompassing analyses are feasible only with the continued and expanded role of Geographic Information Systems and Remote Sensing software applications. These applications could also help in addressing and mitigating sediment modeling and fluvial response biases away from flora- and biocentric approaches by geomorphologists and toward entire ecosystem-wide components. This direction would also yield results in terms of raising geomorphology’s status in dam removal research.

Other challenges include temporal difficulties. Once a management plan is in place the actual construction is usually not far behind, leaving little time for pre-removal data gathering. Of course, after the dam is removed, there is accompanied lag time, generally at least one to five years and often much longer, between disturbance and recovery of fluvial and ecological responses. This problem can only be solved with time, as more and more studies take place as more dams are removed with time. Similarly, the
dearth of interdisciplinary cooperation and collaboration present difficult obstacles to overcome in attempting is encompassing multidisciplinary dam removal research. The lack of accurate, reliable and timely predictive data and modeling presents further difficulties for researchers. As with temporal challenges, the predictive accuracy of geomorphic responses is expected to improve with time, space and data.

The need for flexible design plans and construction and application permits are also necessary to be able to address unforeseen or unexpected consequences to dam removal, not only in the immediate upstream and downstream reaches, but also on the entire stream system or watershed if necessary. Again, advancement of mixed-methods research agendas and the expanded capacities and roles of GIS and Remote Sensing in physical and social science research will no doubt continue to address the challenges and enhance dam removal research paradigms.

Finally, dam removal research requires funding, and dam removal projects can be very expensive and socially and politically unpopular for a variety of reasons. Often, obtaining funding for a dam removal project can be a great challenge, unless there is a demonstrable and relatively immediate positively perceived or predicted ecological or economic response, such as restored fish habitat or whitewater rafting enterprises.

Advances in research in dam removal effects on geomorphic and ecological systems further illustrate the key role geomorphology can play in this bourgeoning field. The knowledge, tools, and methods long familiar to geographers are tailor-made for taking leadership positions in dam removal projects, and geomorphologists’ continued cooperation with other fields of knowledge can only help strengthen the quality and quantity of fluvial and ecosystem morphology and response related to dam removal projects.
References


