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Managing reservoir sediment release in dam removal projects: An approach informed by physical and numerical modelling of non-cohesive sediment

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ABSTRACT

Sediment management is frequently the most challenging concern in dam removal but there is as yet little guidance available to resource managers. For those rivers with beds composed primarily of non-cohesive sediments, we document recent numerical and physical modelling of two processes critical to evaluating the effects of dam removal: the morphologic response to a sediment pulse, and the infiltration of fine sediment into coarser bed material. We demonstrate that (1) one-dimensional numerical modelling of sediment pulses can simulate reach-averaged transport and deposition over tens of kilometres, with sufficient certainty for managers to make informed decisions; (2) physical modelling of a coarse sediment pulse moving through an armoured pool-bar complex shows deposition in pool tails and along bar margins while maintaining channel complexity and pool depth similar to pre-pulse conditions; (3) physical modelling and theoretical analysis show that fine sediment will infiltrate into an immobile coarse channel bed to only a few median bed material particle diameters. We develop a generic approach to sediment management during dam removal using our experimental understanding to guide baseline data requirements, likely environmental constraints, and alternative removal strategies. In uncontaminated, non-cohesive reservoir sediments we conclude that the management impacts of rapid sediment release may be of limited magnitude in many situations, and so the choice of dam removal strategy merits site-specific evaluation of the environmental impacts associated with a full range of alternatives.

Keywords: Dam removal sediment management; sediment pulse; numerical modelling; physical modelling; environmental impacts.

Introduction

Dams and reservoirs provide important functions such as electricity generation, flood control, and water supply, but they have also played a significant role in declining ecosystem health through alterations to hydrologic regimes, sediment supply, and blockage of pathways for migratory fish such as salmonids. Downstream ecosystem changes associated with dams frequently are caused by reductions in natural flood events, altered seasonality of flows, channel incision, loss of morphological complexity, coarsening of surface bed materials, increased interstitial fine-sediment (sand and finer) content in surface and subsurface sediments, encroachment of riparian vegetation, and physical disconnection of habitats above and below the dam (e.g., Petts, 1984; Williams and Wolman, 1984; Ligon *et al*., 1995; Collier *et al*., 1996; Graf, 2001). In California, for instance, operations associated with flow management of the state's more than 1,400 dams and reservoirs are argued to be largely responsible for a loss of 80% of the salmon and steelhead population since the 1950s, 90% of delta smelt, 96% of Pacific Flyway wetlands, 89% of riparian woodlands and 95% of spawning habitat for spring-run salmon (American Rivers *et al*., 1999). While dams and reservoirs are not the only cause of declining ecosystem health, the timing of these losses coincides with the 'golden age' of dam-building in the United States from 1950 to 1970, and the water resource demands associated with the more than tripling of California's population since 1950.

In river restoration, it has long been understood (although far less well-practiced) that restoration strategies based on natural process regimes of flow and sediment transport are preferable to strategies based primarily on reconstructing channel morphology (NRC, 1992; Sear, 1994; Petts, 1996; Graf, 2001). Clear ecosystem benefits are therefore related to restoring natural pulses of flow and sediment to downstream reaches and floodplains, such as occur in river systems that retain their longitudinal connections (Poff *et al*., 1997; Bushaw-Newton *et al*., 2002). Reversing river ecosystem fragmentation (Graf, 2001) is therefore a primary goal of dam removal as a restoration strategy (e.g., The Aspen Institute, 2002; The Heinz Center, 2002; Bushaw-Newton *et al*., 2002). In many fluvial systems, dam removal will restore the 'flood pulse' process that controls ecosystem function both within the channel and across its adjacent floodplain (Junk *et al*., 1989; Bayley, 1991). Other benefits of dam removal can include restoring complex alluvial channel morphology and enhancing sediment storage in bedrock-confined settings; restoring longitudinal habitat connectivity, including access to ancestral spawning

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and rearing grounds for anadromous fish species; and increasing downstream colonization potential by drifting invertebrate populations and by fluvially dispersing tree seeds.

Dam removal is now considered a viable river management alternative, but only in part because of this shifting ethos towards environmental stewardship that creates the 'feel-good' factor in dam removal (Grant, 2001). Dam removal has actually occurred most frequently for two other reasons. First, the prohibitive cost of rehabilitating privately owned dams now deemed unsafe and a potential hazard to downstream floodplain settlements (Shuman, 1995) has led to dam removal for public-safety and to reduce the owner's liability from a potential dam break. In the United States, for instance, the Federal Emergency Management Agency classifies 9,200 dams as high hazard (Evans *et al*., 2002). Second, in cases where the dam's original function is now obsolete, there can be economic benefit to water resource providers of removing the dam rather than continuing to pay for its maintenance. This is frequently the case for older, smaller, and privately owned dams and, unsurprisingly, it is this cohort of dams that form the majority of dams removed in the U.S. (Doyle *et al*., 2000).

Future dam removals may also involve larger dams: over 85% of major dams in the USA (over 7.6 m high or impounding more than 61,650 m^3 of water) will be at the end of their operational design lives by 2020 (Evans *et al*., 2000), and removal may be the most cost-effective solution for some of these structures. Furthermore, for some dams regulated by the Federal Energy Regulatory Commission that require re-licensing in a process that stipulates a critical examination of future environmental impacts, dam removal may be more cost-effective than performing the necessary environmental mitigation. Therefore, dam removal can provide long-term advantages to each of the three core concerns in river management (Downs and Gregory, 2004): water resource use, hazard avoidance, and species and habitat conservation and restoration.

Sediment management issues related to dam removal

While there are usually complicated social, economical, ecological, environmental, and engineering issues integral to dam removal (e.g., ASCE, 1997; Bednarek, 2001; The Aspen Institute, 2002; The Heinz Center, 2002), the management of the reservoir sediment deposit is frequently the most challenging and critical concern, even in the removal of small dams (Graber *et al*., 2001). For instance, release of sediment stored behind dams can temporarily bury ecologically sensitive downstream habitats such as spawning riffles, cause increased flood risks, and/or release contaminants. These factors may encourage resource managers to require the disposal of reservoir sediment prior to dam removal, but this is a very costly and environmentally disruptive option due to air quality, traffic noise, and disposal site impacts. Disposal also prevents downstream reaches from receiving the potential long-term benefits of the released sediment. Reinforcing this dilemma, many river conservation policies and regulations, such the as U.S. Clean Water Act, were drafted to protect existing river habitats from anticipated further degradation, rather than to accommodate an activity like dam removal (or, indeed, river restoration) that requires weighing the competing benefits and drawbacks of short-term and long-term effects to determine the overall value of the activity. As such, short-term concerns become a real and tangible part of the dam-removal decision process, especially for single-purpose river management agencies that cannot take a broader view and for private dam owners who may not be able to afford the inherently higher costs associated with a protracted period of permitting the removal.

Therefore, the fundamental management challenge in dam removal is commonly how to accommodate or offset the potential short-term impacts associated with the release of a significant volume of stored sediment, while waiting for anticipated long-term benefits to accrue. This concern affects each of the three core areas of river channel management identified earlier as potentially benefiting from dam removal in the long-term: some examples are provided below.

For water resources:

1. water-quality impacts arising from high total suspended sediment (TSS) concentrations during the first significant flow events after dam removal;
2. fine sediment deposition on the channel bed surface and infiltrating into the subsurface, reducing the conductivity of infiltration galleries for water abstraction; and
3. coarse sediment (mostly gravel and coarser) deposition, changing the river morphology near culverts or canals.

With regards to hazard avoidance:

4. increased exposure to flood risk caused by coarse sediment deposition raising river-bed elevations near downstream settlements (in addition to the loss of reservoir attenuation caused directly by dam removal);
5. increased downstream bank erosion related to the restoration of the natural flow regime in a formerly regulated river; and
6. pollution impacts resulting from the mobilization of potentially bioavailable nutrients and contaminants held in stasis in the reservoir sediment deposit and commonly bound to fine sediments.

In terms of species and habitat conservation and restoration:

7. impacts to spawning habitat of salmonid (*Onchorynchus spp*.) and/or other fish species caused by burial of existing spawning riffles by deposited coarse and fine sediments;
8. impacts on juvenile salmonid emergence related to 'entombment' of spawning nests, or redds, by deposited fine sediment;
9. reduced invertebrate production caused by fine sediment deposition in the interstices of coarser sediments;
10. impacts to fish holding and rearing habitat caused by sediment deposition that reduces pool depths;
11. impediments to fish migration caused by loss of channel complexity resulting from the mass transport of the released sediments; and

12. threats to native fish species resulting from removing the dam that acted as a migration barrier to exotic aquatic species.

The majority of these concerns relate to potential impacts associated with the erosion, transport, and deposition of the large volume of fine and/or coarse sediment released from the freed reservoir deposit. While the volume of sediment released following the removal of many dams may be equivalent only to the sediment volume released during an high-magnitude flood event, issues frequently arise because the sediment (especially the coarser fraction) will not initially travel far downstream of the dam – unless a commensurately large flood event occurs at the same time as dam removal. And, although principles arising from various strands of geomorphic research provide a broad understanding of the likely morphological changes following dam removal (see Pizzuto, 2002), there are sufficient concerns over perceived uncertainties related to the downstream movement of reservoir sediments to be a major impediment in planning for dam removal. Such uncertainties have been compounded by the lack of monitoring in the majority of smaller dam removals (Bednarek, 2001).

The implications of these uncertainties are considerable and have led, on occasion, to a requirement for the complete mechanical removal of the sediment deposit ahead of dam removal, or highly complex sediment management procedures. For example, studies prior to the proposed removal of the 60-m-high Matilija Dam on the Ventura River in California have recommended a 'preferred alternative' for managing the 4.5 million m^3 of sediment deposited behind the dam that includes dredging of fine sediment and transportation off-site using a slurry pipe, excavation of an initial channel through the deposit, temporary stabilization of coarse sediments, installation of a high-flow sediment bypass at a downstream diversion structure, installation of a fine-sediment catchment basin along a diversion canal, enlargement of several flood control levees, retrofitting of several bridges to accommodate anticipated increases in flood flow elevations, and acquisition of several floodplain properties (reported in Capelli, 2007). The estimated cost for this preferred alternative in 2007 was US$130M.

An improved understanding and management of downstream sediment pulses following dam removal is thus critical to determine both the true cost-effectiveness of removal and the real environmental impacts of the released sediment. Improved predictions of the transport dynamics of very large pulses of sediment typically released during dam removal can allow resources managers to make better-informed management responses to potential short-term impacts (and avoid unnecessary expenditures to mitigate for implausible ones), and better specify necessary pre-removal studies. Two critical aspects of sediment pulse dynamics that are frequently important to dam removal projects involve the downstream transport characteristics of released coarse sediment (sand, gravel and coarser), both in reach-averaged and reach-differentiated terms (central to issues 3, 4, 7, 10, and 11 above), and the interaction of the finer fraction of released sediments (sand and finer) with the coarser material on the channel bed (issues 2, 8, 9, and 10). Below, we summarize the results of recent case studies and numerical and physical modelling experiments investigating these concerns, and subsequently integrate the findings into approach for sediment management during dam removal.

Advances in understanding the transport dynamics of large sediment pulses

A significant contribution to the understanding of erosion, transport, and deposition of non-cohesive sediment following dam removal has been provided by studies on the behaviour of large sediment pulses (or waves) introduced into upland rivers following hillslope failures. Observations from physical modelling and theoretical explorations by Lisle *et al.* (1997) indicate that when the Froude number is close to unity, which is expected in many mountain rivers during floods, introduced coarse sediment pulses are dispersed in place, progressively reducing the maximum thickness of pulse at the point of input while lengthening the deposit downstream. Upstream, the pulse causes backwater flow that results in the deposition of incoming sediment as a delta that grows in amplitude and migrates downstream until it eventually joins the introduced sediment pulse (Fig. 1). Further laboratory flume studies, field observations, and numerical simulations indicate that while coarse sediment pulses in rivers evolve both by dispersion and translation, dispersion dominates the mode of transport (Lisle *et al.*, 2001; Sutherland *et al.*, 2002; Cui *et al.*, 2003a, b; Cui and Parker, 2005; Cui *et al.*, 2005a). Overall, dam removal should result in the downstream dispersal of the bed material component of the reservoir sediment deposit (Fig. 2) when the reservoir sediment deposit and downstream bed material have similar grain-size distributions. The maximum thickness of the sediment deposit downstream of the dam will progressively thin in the downstream direction. Erosion of the reservoir deposit will greatly reduce (if not completely eliminate) any backwater effect and thus remove the mechanism for upstream sediment accumulation (*cf.* Figs. 1 and 2).

While the prospect that dam removal will result in a downstream dispersing sediment pulse has been confirmed in several flume experiments (Wooster, 2002; Cantelli *et al.*, 2004) and theoretical studies (Greimann *et al.*, 2006), the idealized, uniform conditions illustrated in Fig. 2 rarely exist in natural rivers. Commonly, there is instead a downstream decrease in reach-averaged channel gradient, and some layers of a stratified reservoir deposit will be finer than the downstream bed material. Flume experiments (Lisle *et al.*, 2001; Cui *et al.*, 2003a; Sklar *et al.*, 2009) and numerical investigations (Cui *et al.*, 2003b; Cui and Parker, 2005) both suggest that a sediment pulse finer than the downstream bed material will exhibit more translation than a sediment pulse with a grain size similar to downstream bed material (Fig. 3). Consequently, for dam removal projects where the sediment deposit is relatively finer than downstream, the deposit should exhibit a greater overall degree of translational behaviour, although dispersion is still likely to dominate (Lisle *et al.*, 2001, and see Fig. 3(b)).

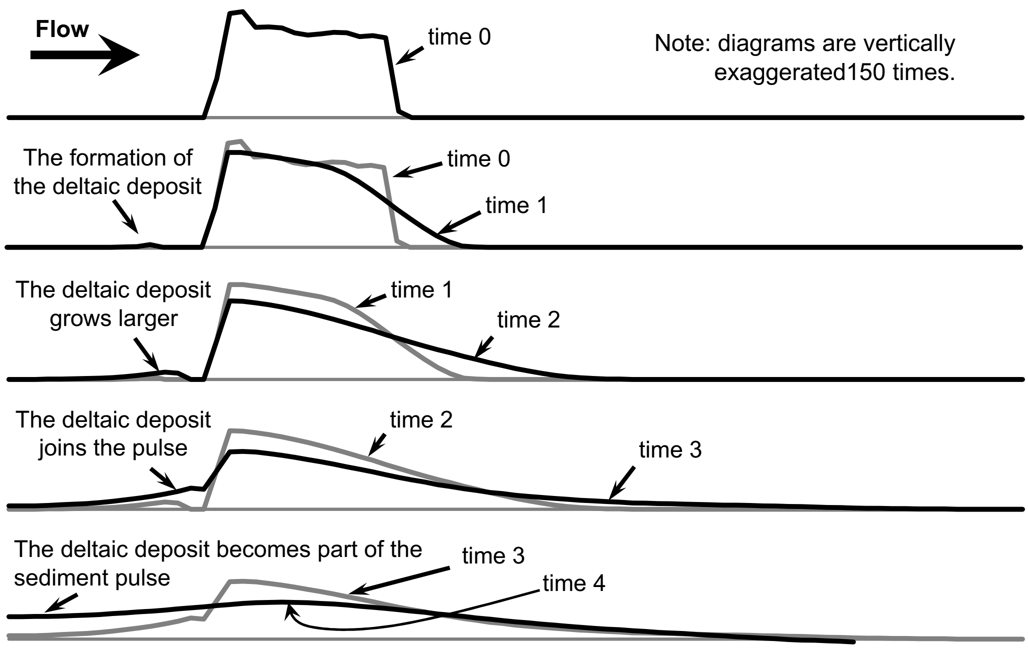


Figure 1 Numerical simulation of the evolution of a bed material sediment pulse introduced into the river as a mass deposit (e.g., as might result from a landslide). The initial stream bed is represented horizontally. Note the progressive pulse dispersion downstream and the development of the deltaic deposit upstream of the pulse. A similar pattern was observed in related flume experiments: both the flume experiments and numerical simulations are detailed in Cui *et al*. (2003a, b). Figure adapted from Fig. 9 in Cui *et al*. (2003b).

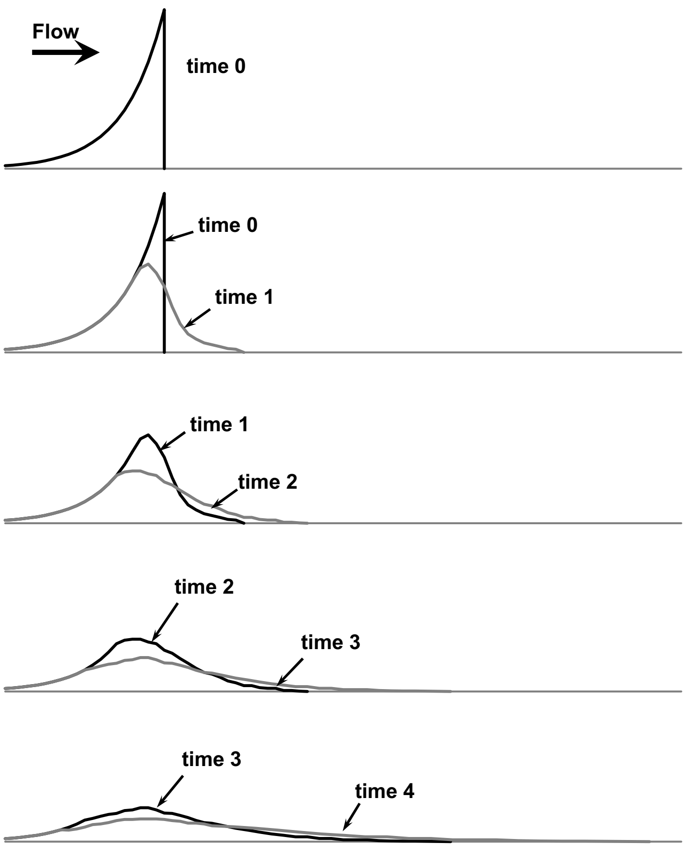


Figure 2 Idealized evolution of a reservoir sediment deposit following dam removal under conditions of constant slope and channel width, and where the deposit has a similar grain size to the downstream channel bed. In comparison to Fig. 1, the deltaic deposit has already formed due to a long period of dam closure. In other regards the evolutionary characteristics of the pulse following dam removal are very similar.

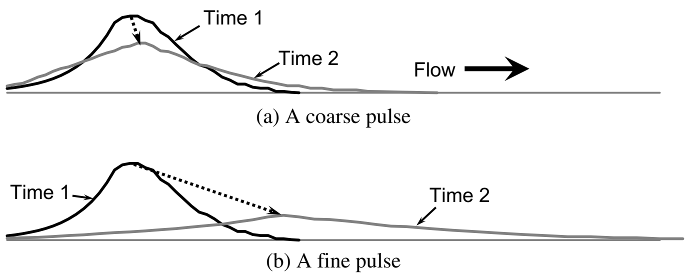


Figure 3 Conceptual difference between pulses of different grain-size distributions; the dashed lines indicate changes in pulse apex location: (a) dispersion of a sediment pulse with sediment grain sizes similar to that of downstream bed material; and (b) translation of a pulse with sediment grain sizes finer than the downstream bed material.

This understanding of sediment-pulse behaviour formed the basis for several numerical and physical modelling efforts evaluating the potential short-term impacts of sediment release following dam removal, described in the sections below. Where possible, the results are compared to field monitoring. Here, "short-term" is defined as a few days to a few years and will depend on specifics of the river, the deposit in the reservoir, method used for dam removal, and the specific management concern. Related to the recurring management issues outlined above, the following overarching issues were addressed:

1. the reach-scale transport and deposition characteristics of non-cohesive sediment pulses, related to the likely extent and short-term severity of downstream sediment deposition following dam removal;

2. bed material sediment pulse movement through a bar-pool complex, as an indication of likely short-term morphological impacts on channel habitats; and
3. the infiltration potential of sand and finer sediment pulses into coarser bed sediments, related to the likely short-term implications on water resources and channel bed habitats.

Reach-scale transport and deposition characteristics of non-cohesive sediment pulses

One-dimensional numerical simulation that predicts reach-averaged channel responses is the most practical tool currently available for understanding the evolution of non-cohesive reservoir sediment deposits following dam removal, over spatial and temporal scales that are meaningful for planning. Consequently, one-dimensional numerical simulation is being used with increasing frequency for planning dam removal, including for two dams on the Elwha River, Washington (U. S. Bureau of Reclamation, 1996a, b); Soda Springs Dam on the North Umpqua River, Oregon (Stillwater Sciences, 1999); Marmot Dam on the Sandy River, Oregon (Stillwater Sciences, 2000a, 2000b; Cui and Wilcox, 2008); Saeltzer Dam on Clear Creek, California (Stillwater Sciences, 2001); dams on the Klamath River, Oregon and California (Stillwater Sciences, 2004, Cui *et al*., 2005b, Stillwater Sciences, 2008); San Clemente Dam on the Carmel River, California (Mussetter and Trabant, 2005); Savage Rapids Dam on Rogue River, Oregon (Bountry and Randle, 2001); and Matilija Dam on the Ventura River, California (Chang, 2005).

Data inputs for one-dimensional models typically include the volume and grain-size distribution of the reservoir sediment deposit, downstream longitudinal profile and channel cross sections, downstream surface grain-size distribution and grade control locations, and estimates of the post-dam flow regime and sediment supply. Modelling gravel pulse evolution over long reaches also requires an estimate of particle attrition rates. Attrition of gravel particles caused by particles colliding with each other and with the channel bed is one of the factors responsible for downstream bed slope decline (e.g., Yatsu, 1955; Parker and Cui, 1998; Cui and Parker, 1998) and is likely to have particular relevance in dam removal simulation because of the large volumes of coarse sediment available for transport and the long reach of the potential impact (Parker, 1991a, b; Cui and Parker, 1998, 2005; Parker and Cui, 1998). Incorporating particle attrition into numerical models of sediment transport is important for modelling long river reaches because attrition both reduces the grain size of bedload particles and converts part of the bedload to suspended load, thus reducing the overall volume of bed material to be transported (Cui *et al*., 2006a, b).

An example application for the Marmot Dam on the Sandy River in Oregon is provided below, utilizing a one-dimensional sediment transport model that was later improved to become DREAM-2, one of the two Dam Removal Express Assessment Models that simulate non-cohesive sediment transport following dam removal. DREAM-1 simulates fine (i.e., sand and finer) sediment transport, while DREAM-2 simulates both coarse (i.e., gravel and coarser) and fine sediments (Cui *et al*., 2006a, b).

Marmot Dam was a 14-m-tall concrete dam on the Sandy River, a tributary of the Columbia River. Sediment had deposited to the elevation of the dam crest many years before 1999 when the owner decided to decommission the dam. Based on coring of deep reservoir sediments upstream of the dam, and mechanically dug pits in the shallower deposits, it was estimated that there was approximately 750,000 m^3 of uncontaminated sediment deposited upstream of the dam, stratified over the pre-dam coarse sediment deposit of cobbles and boulders to form a finer lower layer composed primarily of sand, and an upper layer composed primarily of cobble, gravel, and sand (Squier Associates, 2000). The sediment pulse model of Cui and Parker (2005), modified to include the transport of both coarse sediment (i.e., gravel and coarser) and sand, was used to simulate sediment transport following dam removal under several removal alternatives and hydrologic conditions (Stillwater Sciences, 2000a; Cui and Wilcox, 2008). Modelling predicted the thicknesses of gravel and sand deposition and the suspended sediment concentration along the 48-km river reach between the dam and the Columbia River confluence for the 10 years following dam removal (Fig. 4). This information was used by geomorphologists, fisheries biologists, and ecologists to interpret the potential ecological impact of dam removal (Stillwater Sciences, 2000b).

For ‘single season’ dam removal (i.e., where the dam is removed during one summer period when heavy equipment is permitted to access the river), with minimal dredging, the reservoir sediment was predicted to evolve as a dispersive wave that would largely bypass the high transport capacity reaches (e.g., most of Reach 2 in Fig. 4, and the downstream component of Reach 3), and instead deposit in the relatively wide reaches farther downstream. The predicted daily average suspended-sediment concentration was typically an increase of less than 200 ppm with short spikes of less then 500 ppm near the dam, decreasing with time and distance downstream. The predicted maximum increase of 500 ppm was believed to be within the range of suspended sediment concentrations in the Sandy River during high flow events prior to dam removal (indeed, later monitoring observed approximately 7,000 ppm background suspended sediment concentration). Simulations of alternative dam removal strategies indicated that dredging between 13% and 30% of the sediment deposit (the most possible in any one year) would not significantly alter deposition patterns compared to a single-season removal with minimal dredging, and removing the dam over two seasons provided no net environmental benefit compared to the single season alternative.

The results provided by the analyses helped the owner, the regulating agencies, and other stakeholders agree on a removal alternative to allow almost all the reservoir sediment deposit to be released downstream. Dam removal commenced in July 2007 and transport of sediment from the reservoir deposit began on 19 October following cofferdam breaching during the first high flow event in the winter of 2007-8. Information obtained a year after dam removal indicates that the model predictions were broadly accurate in the following regards: (a) suspended sediment concentration was generally low (i.e., similar to background values) except for a few hours following cofferdam breaching (Major

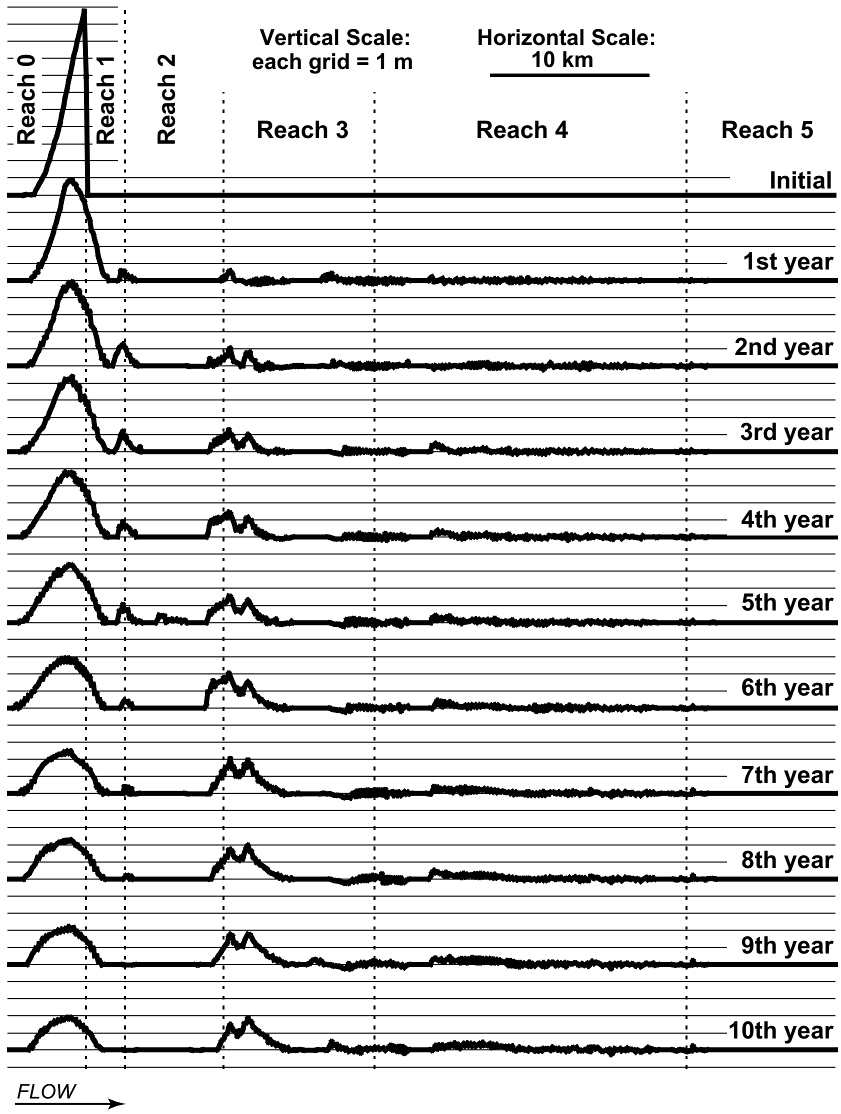


Figure 4 Simulated changes in bed elevation on a yearly time step predicted to follow removal of the Marmot Dam, on the Sandy River, Oregon. Simulation was conducted with an average year discharge series as input for the first year. Figure is repeated from Fig. 23–15 in Cui and Wilcox (2008). (Reproduced with the permission from the ASCE).

et al., 2008); (b) very fast initial erosion of the reservoir deposit caused bed slope in the vicinity of the former dam to decrease rapidly, to the extent that upstream migrating adult salmon were observed to pass the dam site within 3 days of dam removal (the prediction was that bed slope would decrease from the angle of repose to less than 2% within 5 days); and (c) observed erosion within the former impoundment and deposition downstream of the former dam site generally fell within the predicted range as indicated in Fig. 5.

Bed material pulse movement through a bar-pool complex

While reach-averaged one-dimensional sediment transport models can help plan for the regional impact of dam removal over multiple years, such models cannot predict the short-term impacts on channel habitat distribution. One practical alternative is to test individual concerns related to a specific project by building a scaled physical model, such as in Bromley and Thorne's (2005) investigation of the sediment impacts associated with removing the Glines Canyon Dam. Another alternative is to use flume experiments to test generic hypotheses highly relevant to dam removal, such as the lateral characteristics of re-deposited sediments and the evolution of bedforms. Below, we outline recent understanding gained in two of these topics, namely, the movement of bed material pulses through a pool-riffle complex, and the infiltration of fine sediment into coarser bed material. The results stem from experiments conducted in the 28-m-long, 0.86-m-wide and 0.9-m-deep flume at the Richmond Field Station (RFS) of the University of California, Berkeley (see Cui *et al.*, 2008a for experimental details).

Physical modelling

Flume experiments were conducted to examine sediment pulse movement and morphologic response in an armoured, degraded gravel-bedded channel with a repeated bar-pool morphology (Cui *et al.*, 2008a, Wooster, *et al.*, 2006). The experimental bed was constructed with alternate bar topography, forced by the placement of sand bags and cobble-sized stones spaced five

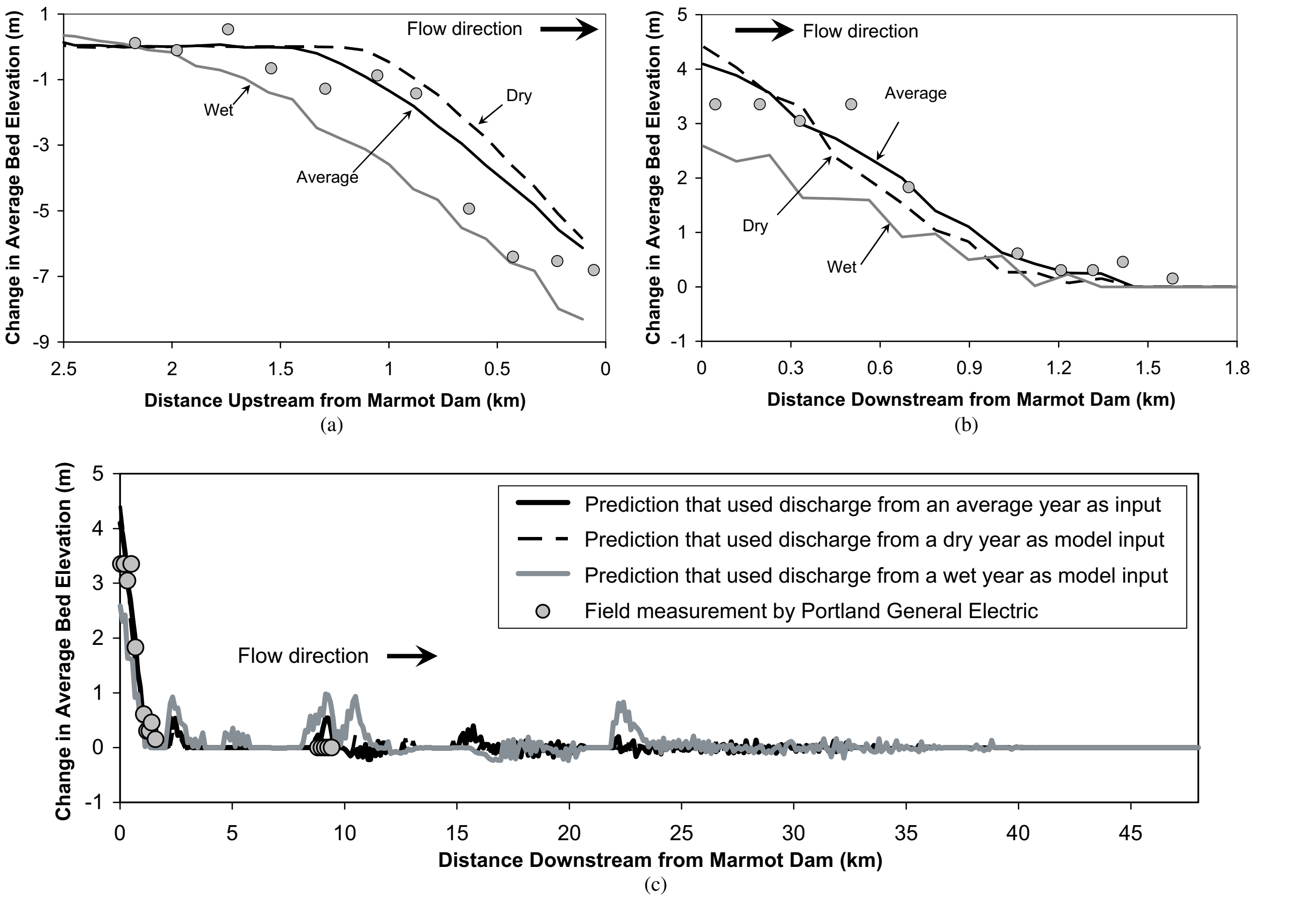


Figure 5 Comparison of observed change in average bed elevation in the Sandy River one year following Marmot Dam removal to pre-removal predictions: (a) former reservoir area; (b) the depositional wedge immediately downstream of Marmot Dam; and (c) the entire downstream reach between Marmot Dam (0 km) and the Columbia River confluence (48 km). Observations are based on pre-removal (2006 and 2007) and post-removal (2008) topographic survey data by Portland General Electric. Predictions were made in 1999 with a sediment transport model based on three hydrologic scenarios (Stillwater Sciences 2000a; Cui and Wilcox 2008): an average year with peak flow and annual run-off at approximately 50% exceedance probability; a wet year with peak flow and annual run-off at approximately 10% exceedance probability; and a dry year with peak flow and annual run-off at approximately 90% exceedance probability. The year following dam removal had an annual run-off exceedance probability of approximately 29%.

channel-widths apart on alternate sides of the flume. During the initial experimental set-up, a quasi-equilibrium degraded channel was created by eliminating sediment supply while continuing to run flow through the flume, similar to the process of sediment-starvation that happens downstream of sediment-trapping dams. Gravel with a geometric mean grain size (D_{50}) of 4.5 mm and sand (D_{50} of 1.4 mm) pulses were then fed into the flume at different feed rates and durations to observe sediment-pulse evolution and morphologic-unit response under a constant discharge, analogous to large pulses of sediment being released following dam removal.

Six runs were conducted: two with gravel and four with sand pulses of different volumes. Sand pulses moved rapidly through the system through a combination of translation and dispersion. Sand pulses also caused mobilization of the previously armoured gravel bed, resulting in a net loss of stored sediment along the channel once the pulse exited the system. Gravel pulses evolved more slowly through the system, primarily by dispersion which induced a sustained increase in channel slope and sediment storage along the flume. Gravel pulse material also deposited in lobes at pool-tails and bars, which forced localized scour adjacent to the deposits. By experiment completion, sand pulses left minimal topographic imprint on the bed other than slight channel degradation, whereas gravel pulses left remnant deposits along bar margins that rebuilt some of the bar topography that was lost during the sediment-starvation phases of the initial set-up. This resulted in an increase in average bed elevation (Fig. 6).

Of the individual morphological units (bars, pools, riffles), pools initially had the highest magnitude and variance in bed elevation change (Fig. 7). Pools did not ubiquitously fill with sediment but instead maintained water depths similar to their initial depths in areas of higher shear stress while contracting in aerial extent as sediment accumulated in areas of lower shear stress. Following the initial response, pools, bars, and riffles exhibited similar magnitudes of sediment accumulation. As the pulse exited a given reach, pools exhibited the fastest evacuation of sediment and, for gravel pulses, bars retained sediment the longest (Fig. 6). Figure 7 depicts responses in the first morphologic unit downstream of the sediment pulse introduction,

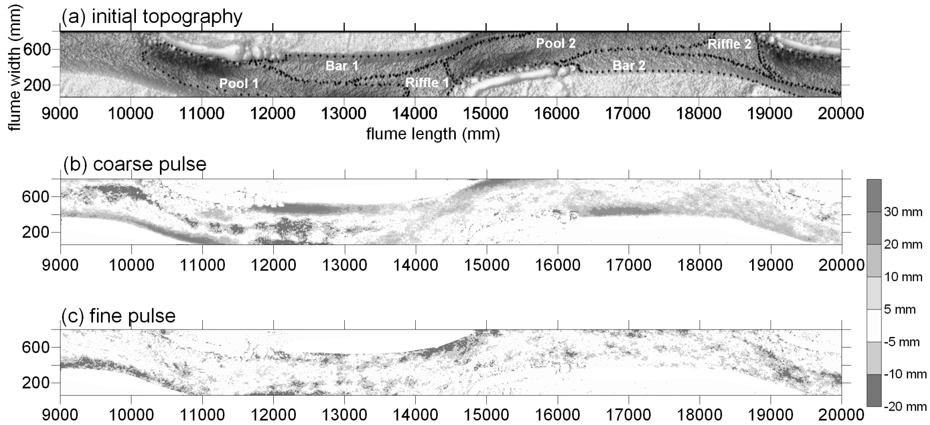


Figure 6 High resolution bed surface topography scans illustrating: (a) digital elevation model (DEM) and units of initial bed topography prior to coarse pulse introduction; and DEMs of difference between initial topography and topography at experiment completion for (b) large volume coarse pulse and (c) large volume fine pulse (see online for color version).

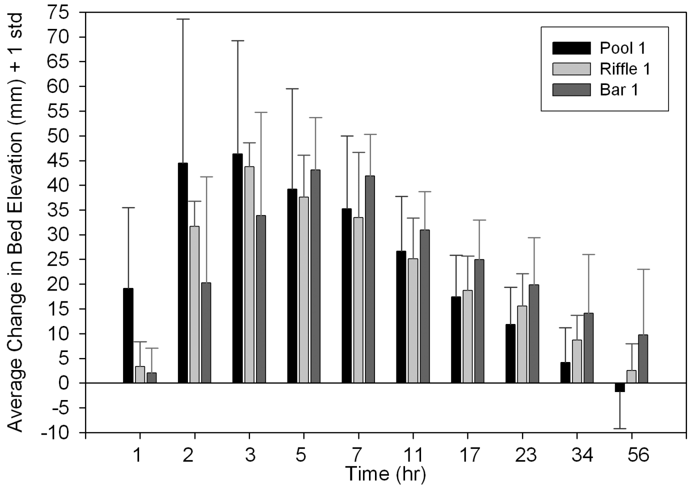
where the magnitude of bed elevation change was highest and a reached maximum of about 50% of the flow depth. Although the magnitude of bed elevation change decreases with downstream distance, the patterns and timing of morphologic unit response are all similar to those depicted in Fig. 7. Based on variogram analyses of high-resolution bed topography scans, the high-volume sand pulse initially decreased bed topographic complexity as the pool-riffle topography became less pronounced due to burial under the sediment pulse. Bed topographic complexity returned to pre-pulse levels once the pulse passed through a reach. Conversely, a large volume gravel pulse increased the streamwise topographic heterogeneity and some of this added topographic complexity was maintained after the bulk of the pulse passed through the reach (primarily due to remnant deposits along bars and localized scour induced by sediment lobes deposited at pool-tails and along bars).

Simulating the physical modelling with numerical models

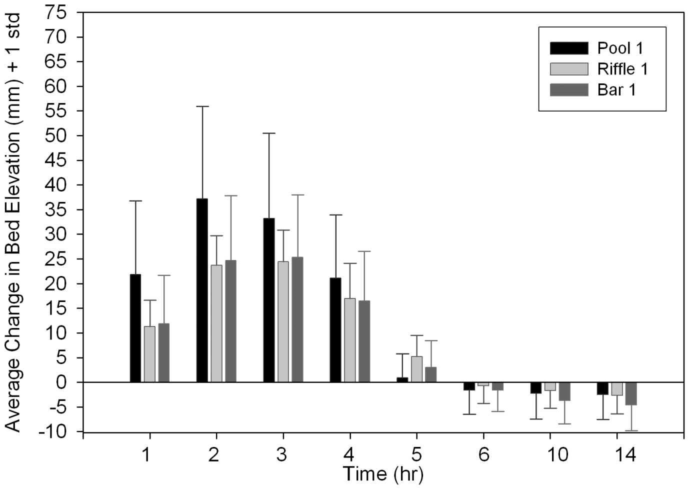
DREAM-1 and DREAM-2 numerical models were used to replicate the flume experiments above (Cui *et al*., 2008a). DREAM-1 was applied without calibration, while a minor calibration of DREAM-2 was performed to adjust the reference Shields stress based on the observed equilibrium slope prior to the sediment starvation run. The simulated cumulative sediment transport flux at the flume exit in the DREAM-1 (sand pulses) simulations was within 10% of the measured values, and was within a factor of two of the measured values in DREAM-2 (gravel pulses) simulations. Comparison of simulated and measured reach-averaged aggradation and degradation (i.e., bed elevation averaged over a longitudinal distance of one pool-riffle sequence) indicated that 84% of the DREAM-1 simulation results have errors less than 3.3 mm, which is approximately 0.8 times the bed material D_{50} (3.7% of the mean flow depth), while 84% of DREAM-2 simulation results have errors less than 7.0 mm, which is approximately 1.7 times the bed material D_{50} (11% of the mean flow depth). Thus, both DREAM-1 and -2 adequately reproduced both the measured sediment fluxes and the observed evolutionary process of the sediment pulses on a reach-averaged basis; however, they were not capable of simulating the detailed channel responses at the morphological unit scale (Cui *et al*., 2008a), reinforcing earlier arguments that one-dimensional sediment transport models are best utilized over large spatial and temporal scales (e.g., Cui *et al*., 2006b; Cui and Wilcox, 2008).

Infiltration of sand and finer sediment into coarser bed sediment

A fundamental concern for dam removal projects in gravel-bedded rivers is the habitat impact of rapidly releasing the large volume of accumulated fine sediments (i.e., sand and finer), even if the deposit in a reservoir is predominantly gravel and coarser. In studies on the Elwha River, Washington, for example, the anticipated high suspended sediment concentration and turbidity following dam removal led water supply agencies to review alternative sources of water supply, and similar issues have been raised in considering options for dam removal on Matilija Creek, California. Ecologically, there is considerable concern that fine sediment infiltration following dam removal may result in short- and long-term degradation of salmonid spawning habitat. Previous field and flume studies have made several important observations pertaining to sand and finer sediment infiltrating a gravel bed: (1) the absolute grain size of the underlying framework of subsurface materials and the ratio of the subsurface material size to the grain size of the infiltrating sediment are both important in determining the amount of fine sediment infiltration (Beschta and Jackson, 1979, Frostick *et al*., 1984; and Diplas and Parker, 1985); (2) well sorted gravel deposits tend to contain relatively more sand than poorly sorted gravels because they have relatively greater interstitial space (i.e., the fine sediment fraction in gravel bed material is negatively correlated to the standard deviation of the mean grain size of the gravel deposit) (Cui and Parker, 1998); and (3) fine sediment particles do not infiltrate below a certain depth in a gravel-bedded river (Beschta and Jackson, 1979; Carling, 1984; Schälchli, 1992). However, impacts of varying the rates and durations of fine sediment release were relatively unknown, and so experiments were conducted to quantitatively



(a) coarse pulse



(b) fine pulse

Figure 7 Average change in bed elevation (plus one standard deviation), by morphological unit, as a sediment pulse passes through a forced pool-riffle morphology (a) a large volume, gravel pulse; (b) a large volume, sand pulse. Note that average flow depth is approximately 110 to 120 mm, and the coarse pulse D_{50} is 4.5 mm and the fine pulse D_{50} is 1.4 mm.

predict fine sediment infiltration into gravel deposits according to grain size distributions of infiltrating and framework material.

Wooster *et al.* (2008) conducted flume experiments at the RFS flume to examine the effects of sediment supply and grain-size distribution on fine sediment infiltration into immobile gravel deposits initially devoid of fine sediments. Based on three runs of experimental data, relationships were derived to predict the expected depth and fraction of fine sediment infiltration as a function of the grain size distributions of the bed material and the infiltrating fine sediment (Wooster *et al.*, 2008). Relations derived from the flume data indicated that fine sediment infiltration is strongly related to the relative difference in grain size distributions of the bed material and the infiltrating fine sediment (e.g., Beschta and Jackson, 1979; Frostick *et al.*, 1984). The relationships described an exponential decrease in fine sediment infiltration with depth into a channel bed initially devoid of fine sediment, which was confirmed through theoretical analysis (Cui *et al.*, 2008b). Further, the amount of fine sediment infiltration decreased once the rate of fine sediment supply increased above a certain level, suggesting that rapid fine-sediment deposition on the channel bed acts to limit the interaction between potential infiltrating fine sediment and the subsurface deposit (Wooster *et al.*, 2008). Comparing the predicted fine sediment fraction from their semi-empirical relationships and weighted-average experimental data provided a root mean square error of 7.3%, indicating a good agreement between modelled and observed data (Fig. 8(a)).

An illustration of the relationships derived by Wooster *et al.* (2008) is provided in Fig. 8(b). Using a scenario of gravel bed material with a D_{50} of 25 mm and a geometric standard deviation (σ_g) of 3, infiltration by fine sediment (D_{50} of 0.5 mm and σ_g of 2) is predicted to achieve a maximum fraction of fine sediment of approximately 20% at the surface-subsurface interface. The fraction of infiltrated sediment decreases rapidly to approximately 3% at 15 cm and is negligible by 30 cm. A review of field samples of subsurface material from rivers that have not experienced a recent, large scale influx of fine sediment illustrates that gravel-bedded rivers often contain a substantial fraction of fine sediment as a background condition (Fig. 8(c)). This indicates the pore space available for additional infiltration is likely at least in part already occupied, making the potential infiltration due to releasing a fine sediment pulse even less significant than demonstrated in Figs. 8(a) and 8(b).

The experimental implications are that a predominately sand-sized sediment pulse will only infiltrate immobile gravel deposits to a few gravel diameters in depth (Figs. 8(a)–8(d)). Further, rapidly releasing and transporting a fine sediment pulse over a gravel deposit, rather than transporting the same volume of sediment at a slower rate over an extended time period, will not result in increased infiltration and may even limit infiltration. This effect was observed in Wooster *et al.* (2008) and is attributed to a smaller fraction of the total fine sediment deposit coming into contact with the coarse bed material as it transports over an area already covered in fine sediment. Additionally, a rapid release should exhaust a finite fine sediment source more quickly, allowing the subsequent high flows to erode the fine sediment deposited on channel surface and infiltrated into the shallow deposit. Note that these results are limited to fine sediment infiltration into immobile, coarser bed material.

Discussion: Implications for sediment management during dam removal in predominately non-cohesive fluvial systems

Together with earlier studies on fine sediment infiltration (e.g., Beschta and Jackson, 1979, Frostick *et al.*, 1984; and Diplas and Parker, 1985) and sediment pulse behaviour (e.g., Bountry and Randle 2001; Lisle *et al.*, 2001; Sutherland *et al.*, 2002; Cui *et al.*, 2003a, b, 2005a; Cui and Parker, 2005), the experiments described above assist in de-mystifying the management options when considering dam removal. In Fig. 9, we outline an adaptive management approach to sediment management during dam removal that builds on previous recommendations (ASCE,

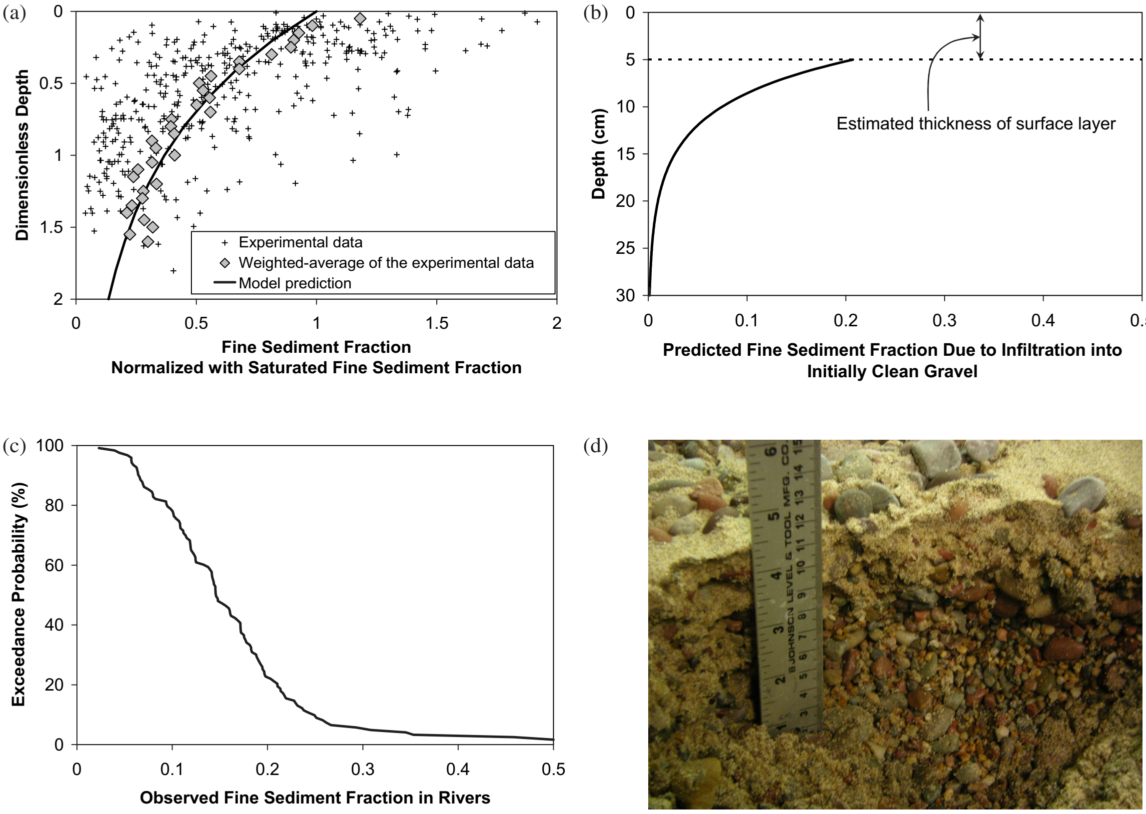


Figure 8 Illustrations of the limits to fine sediment infiltration: (a) comparison of experimental data with equations predicting fine sediment infiltration into an initially clean gravel deposit (Wooster *et al.*, 2008; Cui *et al.*, 2008b), showing good agreement between predictions and the weighted-averaged experimental data; (b) application of the equations in (a) to a hypothetical dimensional scenario; (c) cumulative distribution of the fine sediment fraction in gravel-bed rivers, based on 122 field observations in California (see Wooster *et al.*, 2008 for data details); and (d) a post-experiment photograph illustrating limited fine sediment infiltration into an initially clean gravel bed (Wooster *et al.*, 2008).

1997; Randle, 2003) and integrates process-based understanding informed by these experiments. The approach is intended as a generic, non-prescriptive guide for decision-makers, although it emphasizes the particular sediment issues allied to the release of non-cohesive sediment (normally under transport-limited conditions), which is a common situation in parts of the western United States and similar environments.

At the outset we assume that a rational process of river basin planning has occurred, including a historically informed analysis of geomorphological conditions in the catchment (see Downs and Gregory, 2004; Brierley and Fryirs, 2005). This planning process has identified dam removal as a potentially desirable management objective, but the feasibility of sediment release remains unproven. Proof can be informed by results of numerical and physical modelling in three ways: defining critical baseline data collection requirements, evaluating potential physical and biological constraints on dam removal, and informing appropriate dam removal alternatives (Fig. 9). These aspects are discussed below.

Baseline data requirements

Because risks associated with dam removal are largely determined by the transport characteristics of the released sediment pulse, the fundamental first step in sediment management during dam removal is to characterize the grain-size distribution of the reservoir sediment deposit and the downstream reach morphology (e.g., Wooster, 2002; Doyle *et al.*, 2003; Cui *et al.*, 2006a; Cui and Wilcox, 2008). This involves several parameters essential for dam removal planning (Fig. 9), including the volume, texture, and contaminant content of the reservoir deposit; details of the downstream channel morphology and bed texture; and the rate of sediment supply from the upstream catchment. Conversely, evidence from field (Doyle *et al.*, 2003; Cui and Wilcox, 2008) and flume studies (Wooster, 2002; Cantelli *et al.*, 2004) have indicated that the dimensions of the channel that forms in the former reservoir area following dam removal is similar to the downstream river reach, and so predicting its exact dimensions is not a particularly sensitive part of determining downstream sediment deposition, as long as it is assumed in a reasonable range (Cui *et al.*, 2006a).

Characterizing the reservoir sediment includes assessing grain-size characteristics, which can be achieved using a series of cores of up to 100 mm diameter (or more) for gravel sediment, and the use of ground-penetrating radar in fine sediment (e.g., Squier Associates, 2000; Snyder *et al.*, 2004). For shallow sediment deposits, grab samples may yield enough information in deep water, while mechanically dug pits should provide the required sediment samples in dry sediment bars or shallow water areas. An approximate estimate of the volume of the sediment

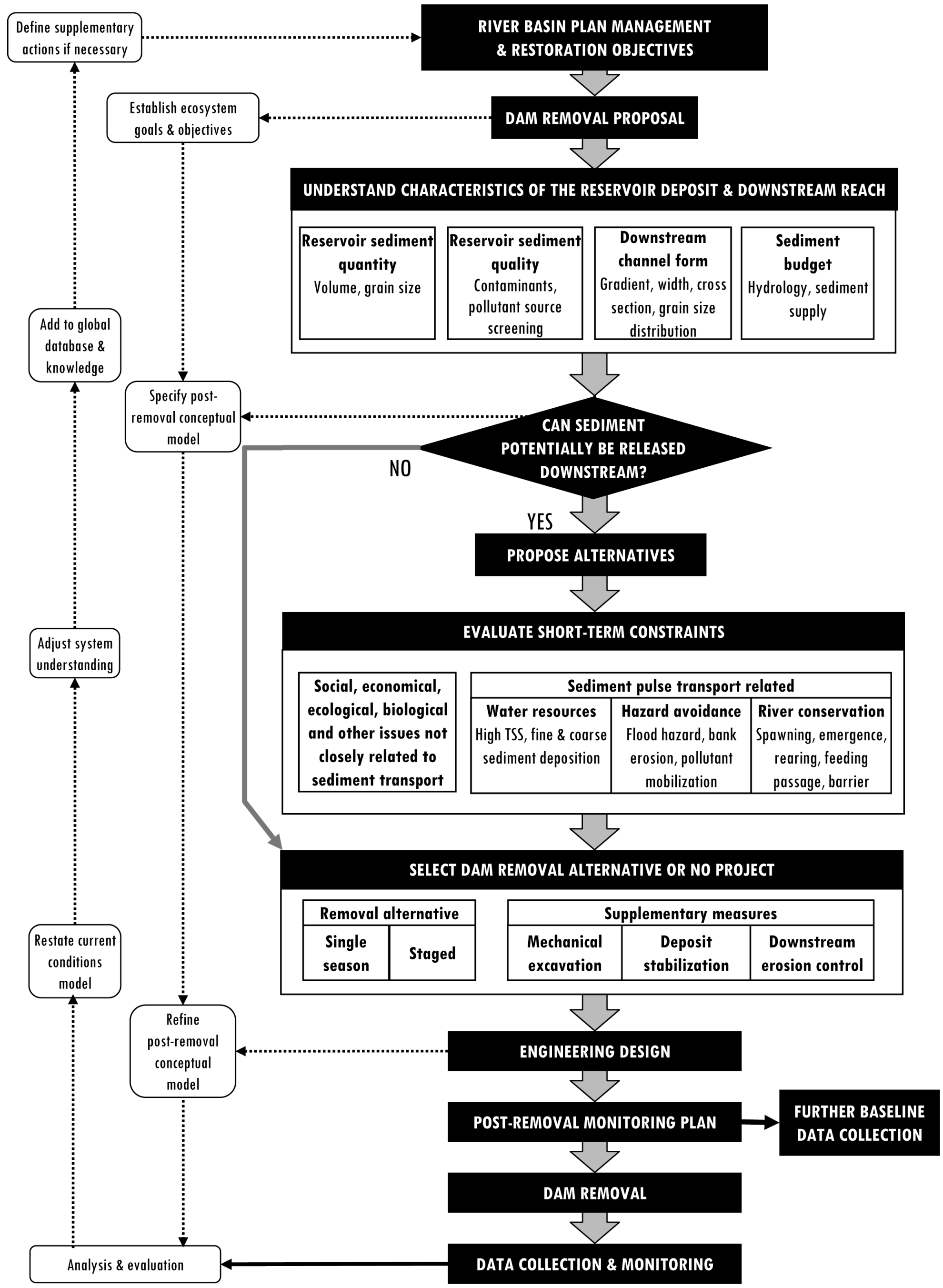


Figure 9 An approach to dam removal sediment management set in an adaptive management framework (left hand side of figure).

deposit can be achieved by assuming geometric properties to the sediment "wedge" (Childs *et al*., 2003) or, alternatively, by scanning the bathymetry of the reservoir deposit (Dudley, 1999) and, in GIS, subtracting the pre-dam topography recorded in earlier maps (e.g., Evans *et al*., 2002).

The release of contaminated sediment following dam removal can be a significant issue (e.g., Fort Edward Dam, Hudson River, New York: ASCE, 1997). The potential for reservoir sediment contamination can be examined using a combination of contaminant source screening and reservoir sediment sampling. Contaminant source screening can be conducted by identifying potential pollution sources upstream of the dam within the contributing watershed, for instance by using GIS-based analysis (Rathbun *et al*., 2005), while contaminant analysis is usually focused on fine sediment and so can be integrated into grain-size analysis. A rigorous sampling procedure is required because there can be large variations in grain-size distributions longitudinally, laterally, and vertically.

Channel morphology data are required to analyze risks related to potential flood hazard, the downstream transport and evolution of the sediment pulse, and potential adjustments in the downstream channel. Channel gradient and channel cross sections are important controls on the capacity of sediment transport under a given discharge and sediment grain-size distribution, and they can be obtained using photogrammetry, LiDAR data, high-resolution aerial photographs and field-based cross-section surveys. The detail required may depend on whether the downstream channel is confined by high terraces with limited floodplains, in which case simple cross-section data or measurements/estimates of bankfull channel width will suffice; or meanders across an extensive low-lying floodplain, where more detailed surveys are likely to be required. Changes in downstream flood risk occur as a function of progressive changes in channel-bed elevation by coarse sediment dispersion following dam removal, in addition to changes due to the loss in the reservoir's flood attenuation effect.

An estimate of the upstream sediment supply has numerous uses. In reservoirs that are full of sediment and are passing bedload, the upstream sediment supply can be used to calibrate a numerical model under current channel conditions as the basis for further analysis (see Stillwater Sciences, 2000a; Cui and Wilcox, 2008). For large dams in alluvial river systems with mostly sand and gravel bed material, and where reservoirs are still trapping bedload, the downstream reach has probably incised during the dam's operation; an estimate of sediment supply can be used in conjunction with one-dimensional numerical simulation to estimate the rate of bed elevation recovery following dam removal. Also, information on sediment supply during a moderate flood, if available, can be compared to the total volume of the sediment in the reservoir in order to judge whether the deposit is "significant" in physical terms and worthy of further detailed study, with the caveat that even a relatively small sediment deposit might be significant from other perspectives (such as potential for contamination or downstream biological effects).

Evaluating environmental constraints

As indicated earlier, the expected long-term benefits of dam removal are often in conflict with perceived short-term impacts associated with the release of a significant volume of stored sediment. These short-term impacts potentially affect numerous aspects of river management and will likely constrain dam removal options. Therefore, a rational evaluation of constraints is vital to reduce uncertainties in sediment management (Fig. 9); this provided the basis for the numerical and physical modelling investigations described previously: some implications are discussed below.

Water resources

Potential impacts on water quality and on the conductivity of infiltration galleries are closely linked to the dynamics of fine (sand and finer) sediment release, relative to the coarser material of the channel bed. Because fine sediment infiltration is limited to shallow depths into the channel bed, and will be shallower still in those (majority of) cases where the interstices of coarse bed sediment are already filled with sand, the primary impact of dam removal is likely to involve surface deposition. This implies a trade-off between managing for rapid or progressive release of fine sediments.

Rapid sediment release following a single-season dam removal potentially causes high concentrations of suspended sediment and significant fine sediment deposition across the channel bed, but it will be short-lived – potentially for only a few weeks (or less) depending on the reservoir deposit volume, channel gradient, and flows following dam removal (Stillwater Sciences 1999; Cui *et al.*, 2006a). Clearly, higher suspended sediment concentrations and turbidity will result from dam removals where fine sediment deposits predominate; for example, the Lake Mills drawdown experiment on the Elwha River (Childers *et al.*, 2000) indicated peak suspended sediment concentrations of between 5,000 and 6,000 ppm under relatively moderate discharges, leading to expectations that suspended sediment concentrations would be far greater at higher flows (and see Table 1). Conversely, metering out sediment during staged dam removal may reduce the initial depth of fine sediment deposition, but it will prolong the period of excess fine sediment on the bed. In either approach, there may be opportunities for reducing fine sediment impacts using prescribed flushing flow releases from regulating dams farther upstream, where they exist.

Hazard avoidance

Removing a dam that retains significant active water storage will change the magnitude and frequency of peak flood events, requiring the calculation of a new flood frequency curve based on the hydrologic record upstream of the removed reservoir. Increased flooding risks associated with temporary and permanent channel aggradation downstream of the dam can be assessed with appropriate numerical models of flow hydraulics, using the adjusted flood frequency curve and cross-sections that are altered to account for the predicted depth resulting from aggradation (temporary or permanent) following dam removal. However, where channel aggradation is predicted to last for only a short period of time following dam removal, using the aggraded cross-sections to predict a large recurrence-interval flood event (for instance the 100-year recurrence interval flow commonly used for flood insurance purposes in the USA) will overestimate the potential long-term flooding risks. In general, increases in flood stage are usually less than the full vertical extent of aggradation for several reasons, including: (a) channel cross sections become wider with aggradation in reaches with alluvial banks, (b) channel gradient generally increases in reaches of significant aggradation, and (c) channel aggradation with reservoir sediment normally reduces channel bed roughness.

Overall, the potential flood risk associated with dam removal is likely to be greatest when finer-grained reservoir deposits are released; allowing pronounced downstream translation of the sediment pulse, and/or where inhabited floodplains occur close to the dam site. However, in many gravel- and cobble-bedded rivers, the increase in flood hazard risk caused by dam removal may be far less significant (e.g., Stillwater Sciences, 1999, 2000a, 2001, 2008). This occurs because the dispersion of coarse reservoir deposits causes channel aggradation to be maximised near to the dam site which, for structural reasons, is typically situated in a bedrock-confined valley rather than in a floodplain setting with land uses vulnerable to flooding. The specific environmental parameters of each dam removal are thus required to determine the potential magnitude of the flood hazard.

Table 1 Examples of measured and predicted suspended sediment concentrations during reservoir drawdown experiments and following dam removal.

Project	Data Source	Reservoir Sediment	Suspended Sediment
Condit Dam, White Salmon River, WA	Dam removal assessment with numerical model (Beck, Inc. 1998)	Large amount of sand- and silt-sized sediment deposit in the deposit	Maximum TSS concentration reaches 50,000 to 500,000 ppm during the first day following dam removal that decreases in time. TSS concentration reaches background condition within one year following dam removal
Lake Mills, Elwha River, WA	Reservoir drawdown experiment (Childers *et al.*, 2000)	Sediment erosion occurred mostly at the delta area, which is composed primarily of sand and gravel	Maximum TSS concentration reached 5,000–6,000 ppm during the drawdown
Marmot Dam, Sandy River, OR	Dam removal assessment with numerical model (Stillwater Sciences 2000a; Cui and Wilcox 2008)	Stratified sediment deposit with the upper layer composed of primarily gravel and coarser, and lower layer composed mostly of sand	Instantaneous TSS concentration shortly following cofferdam breaching was slightly less than 37,000 ppm. Daily average TSS concentration within the first 24 hours following cofferdam breaching is approximately 3,000 ppm (roughly 4 times of the background TSS level). TSS concentration is low after the first day of cofferdam breaching
Saeltzer Dam, Clear Creek, CA	Dam removal (Stillwater Sciences, 2001)	Gravel and coarser, with some sand within the deposit	No significant increase in suspended sediment concentration was observed within the first year following dam removal. No observation was conducted in the following years
Soda Springs Dam, North Umpqua River, OR	Dam removal assessment with numerical model (Stillwater Sciences, 1999)	Mostly sand-sized sediment within the deposit	Predicted maximum TSS concentration reaches approximately 20,000 ppm that lasts for about two weeks under the hydrologic conditions simulated

River conservation

The long-term benefits of dam removal for aquatic habitats, especially fisheries, are assumed to follow from barrier removal and the unimpeded transport of sediment, and they are generally supported by pre-removal habitat modelling (Cheng *et al.*, 2006; Kocovsky *et al.*, 2009) and a limited number of case studies (Kanehl *et al.*, 1997; Burdick and Hightower, 2006; Catalano *et al.*, 2007). In contrast, the short-term effects are more difficult to model and observe, and so are less well understood. This leads to a conundrum in environments such as those in rivers draining the west coast of North America, where the potential short-term impacts of dam removal on anadromous salmon fisheries become of paramount concern, despite the fact that eliminating a fish-migration barrier is commonly a long-term rationale for dam removal.

Although the potential direct impacts of altered channel geomorphology and bed sediment on fish populations are well-recognized, possible indirect effects from altered nutrient and food-web dynamics are also potentially significant but much less well understood. Following the removal of several small dams in Wisconsin, Doyle *et al.* (2005) both measured and speculated on a suite of short-term ecological effects that emphasized potential alternative trajectories and timescales for recovery of different species including riparian vegetation, fish, macroinvertebrates, mussels, and periphyton. Extending these results, Stanley *et al.* (2007) and Orr *et al.* (2008) documented variable short-term impacts on benthic macroinvertebrates and fish populations following removal of two small dams on Boulder Creek, Wisconsin. However, these results from fine-grained fluvial systems may not apply universally: for instance, following removal of Marmot Dam on the Sandy River, Oregon, high suspended sediment concentrations were observed to last only for a few hours, suggesting only minimal ecological impact from fine sediment release (Major *et al.*, 2008). Below, we hypothesize several potential ecological aspects implied by our numerical and physical modelling experiments of non-cohesive sediment pulse release, acknowledging the narrow scope of our studies to date and the need for additional research on the topic. More generally, we note that any given dam-removal alternative uninformed by a knowledge of ecological conditions downstream will surely result in unintended and potentially deleterious consequences.

First, because bed material pulses are dominated by dispersion, annual channel adjustments will be gradual (e.g., Cui and Wilcox, 2008), thus limiting the severity of yearly changes in ecological conditions downstream, even in the immediate vicinity of the dam. Annual adjustment rates will most likely decline over time, further limiting potential ecological impacts, but with the consequence that the total time for the channel bed elevation to equilibrate following the passage of a coarse sediment pulse can be a decade or longer when the ratio of the reservoir deposit volume to flow transport capacity is high. In cases where species are dependent on particular configuration(s) of channel features and bed-sediment texture, the ecological impact will likely be as long as these adjustments are still in progress (e.g., Doyle *et al*., 2003, 2005), while in other cases the ecological impacts can be much shorter than the time needed for channel adjustments. For example, while the period of channel bed recovery near Marmot Dam is predicted to be a decade or longer, significant concerns for fish passage impediment became minimal only three days after the cofferdam was breached (following observations of fish passing through the former impoundment area). One year following dam removal, data indicated that topographic complexity of the channel bed was similar to pre-removal conditions (although the channel bed elevation near the dam is now many metres higher), suggesting that future fish migration impediment in these reaches will also not be a concern (Stillwater Sciences, 2009).

A related speculation, that of the burial of high-quality salmonid spawning gravels immediately below a dam, may be warranted only after the first bed-mobilizing flows that follow dam removal; in following years, annual morphological change will be far more limited and dispersion of coarse sediment by high flows will cause the zone of maximum impact to shrink annually. Therefore, assuming that fish utilize the newly deposited gravels, the primary risk to salmon redds after the first sediment-mobilizing flow is that the annual erosion of the sediment pulse may exceed the depth to which eggs are laid.

Because abundant fine sediment results in negative impacts on salmonid egg and alevin survival and to benthic macroinvertebrate production (McNeil, 1964; Cooper, 1965; Phillips *et al*., 1975; Platts, 1979; Suttle *et al*., 2004; Greig *et al*., 2007), dam-removal alternatives are commonly evaluated by the degree to which released fine sediment will infiltrate spawning gravel. Our experiments indicate that the maximum impact occurs when a large volume of fine sediment is released slowly into a relatively homogenous, clean, coarse gravel bed. Because natural gravel-bed rivers are generally poorly sorted and interstices are already partly filled with fine sediment from background conditions, this risk may be most significant in reaches that have been artificially augmented with clean, well-sorted gravel. We expect that the period of impact near the former dam site should be relatively short, as the increased mobility of coarse sediments in conjunction with resumed coarse sediment supply and a rapid exhaustion of fine sediments allows natural sediment-sorting processes to return. Farther downstream, the potentially significant short-term impacts of fine sediment deposition will eventually give way to the expected long-term benefit of reduced embeddedness, as previously static coarse sediment is remobilized following deregulation of river flows. The temporal extent of the potential concern will vary according to the balance between the volume and calibre of sediment in transport and the flood magnitudes of the de- or less-regulated flows following dam removal, and it cannot easily be generalised.

Our fourth observation is that in flume experiments with forced pool-bar morphologies typical of confined reaches where high dams are normally constructed, fine sediments passed rapidly across all morphological features, leaving little topographic imprint once the pulse passed through a given reach. This could suggest only limited short-term fine sediment impact to aquatic holding and rearing habitat. Conversely, coarse sediments were observed to pass more slowly through the forced pool-bar complex, depositing initially in pool tails and side bars. This deposition caused pool-bed elevations to rise more rapidly than the surrounding bed initially, but experiments indicated that the increases in pool-bed elevation are soon matched by elevation increases elsewhere on the channel bed, possibly within the passage of the first significant flow event, resulting in little net change in relief (Wooster *et al*., 2006). Some corroboration of these results is obtained in post-removal monitoring of the former Marmot Dam site where topographic complexity of the channel bed was similar to pre-removal conditions one year following dam removal, as described above (Stillwater Sciences, 2009).

Selecting a dam-removal strategy

Where constraints on dam removal do not suggest fatal flaws, resource managers need to determine a preferred strategy for dam removal (Fig. 9) based on numerous factors intimately related to the dynamics of downstream sediment transport. The basic options include a single-season complete removal, with a rapid initial release of sediment, or a staged removal process that progressively lowers the dam crest over several years to meter out the stored sediment (frequently in conjunction with various subsidiary options – see below). Single-season dam removal (colloquially, 'blow-and-go') is generally more cost-effective than a staged approach, especially when the sediment will be eroded rapidly (e.g., Gathard, 2005) but is often feared by resource managers and stakeholders because it will release the greatest amount of sediment downstream at the greatest intensity. Thus staged dam removal is the most widely recommended method, particularly for large dam-removal projects. Staged dam removal, for example, is proposed for two dams on the Elwha River, Washington (U.S. Bureau of Reclamation, 1996a, b) and the Matilija Dam on Matilija Creek, a tributary of the Ventura River, California, because of concerns that sediment deposition would cause unacceptable flooding risks downstream (Capelli, 2007).

Subsidiary and/or supplemental options include mechanical excavation of sediment prior to dam removal and stabilizing the sediment deposit prior to partially removing the dam. Mechanical excavation may be favoured where there are fears for downstream flood risk (e.g., ASCE, 1997) or where sediments are contaminated, but the approach involves greatly increased project cost due to sediment transportation, selecting appropriate disposal sites, and managing traffic flow and noise, and it reduces potential long-term benefits to downstream ecosystems of sediment release. Further, in some rivers with high sediment supply, rates of wet-season sediment supply may exceed potential rates of dry-season mechanical sediment excavation, thus making this approach infeasible (e.g., Stillwater Sciences, 2002). Stabilizing the reservoir deposit generally involves letting it dry to encourage vegetation growth to prevent downstream transport. The channel may then be rerouted through a notch created by partially removing the dam structure if geological and topographic conditions allow and other social, economic, and ecological issues can be avoided. Stabilization can be an effective option in removing low dams (see Graber *et al*., 2001) but may be less effective for larger dams in the long term if the channel progressively incises around the former reservoir sediment to achieve its preferred gradient. In highly populated settings, erosion fears may prompt a suite of bank protection and grade control measures to control channel response (e.g., Fullerton *et al*., 2005),

Overall, single-season dam removal without supplemental measures is likely to be cheapest alternative. Measures such as mechanical removal of the sediment or sediment stabilization not only add expense but also may require additional long-term commitment to maintenance and will probably reduce the long-term environmental benefit of dam removal. Selecting a strategy is therefore likely to depend on whether the reservoir sediment is highly contaminated, and whether the impact of rapid sediment release creates sufficient risk to other river management objectives, such as flood control, channel erosion, and aquatic ecology, that it cannot be allowed.

In this regard, application of numerical and physical modelling of non-cohesive reservoir deposits has contributed several perspectives on the extent of risk and benefit in selecting a dam removal strategy. First, numerical modelling has indicated that staged dam removal does not always provide the expected benefits of reduced sediment deposition over the single-season alternative in non-cohesive sediment environments (Stillwater Sciences, 2000a; Cui *et al*., 2006a; Cui and Wilcox, 2008). This occurs primarily because the dynamics of downstream coarse sediment release is self-regulating: eroding reservoir sediment deposits form a distal fan-delta that causes coarse sediment to be eroded downstream only gradually, irrespective of whether the dam is partially or fully removed. In the removal of the Marmot Dam on the Sandy River, for example, coarse sediment eroded from the reservoir area was deposited primarily in a short reach of a few kilometres in length one year following the removal of the dam (Fig. 5). Second, our physical modelling experiments (Cui *et al*., 2008a; Wooster *et al*., 2006) along with post-removal field monitoring on the Sandy River (Stillwater Sciences 2009) has demonstrated that the topographic relief and complexity of the channel bed is fairly robust to the passage of coarse and fine sediments suggesting that concerns for blanket deposition are unlikely to be fully realised for sediment pulses travelling through a forced pool-bar complex. Third, physical modelling (Wooster *et al*., 2008) and theoretical analysis (Cui *et al*., 2008b) indicate that fine sediments can infiltrate only a shallow depth into coarser bed material and a more rapid release of fine sediments may reduce the amount of infiltration, as well as reduce the overall period of fine sediment surface deposition. This leads us to conclude that the short-term impacts of non-cohesive (uncontaminated) reservoir sediment releases on water resources, flood control and aquatic habitats may be far less than those commonly feared, and that the costs and benefits of single-season dam removal relative to staged dam removal, particularly in terms of the magnitude and duration of impacts, merit case-specific scientific evaluation instead of a presumptive determination based on unproven assumptions.

Conclusion

Dam removal is a relatively recent addition to the suite of strategies for river management, and there is considerable uncertainty surrounding its potential short-term impacts on water resources, hazard avoidance, and river conservation. Concern over the release of a sediment pulse after dam removal is frequently the single largest environmental constraint, and its avoidance is potentially the greatest single cost element as well. Numerical and physical modelling can provide cost-effective methods to assess possible morphologic response and bed texture change due to a dam-released sediment pulse. One-dimensional numerical modelling of sediment-pulse behaviour provides a simple means of determining the reach-averaged downstream morphological impact of a migrating sediment pulse. Flume experiments and scaled physical models can address two- and three-dimensional aspects of the sediment pulse to answer questions relevant to engineering, biology, and ecology that can otherwise be addressed only through professional judgment. Flume experiments also assist in calibrating and verifying numerical models to improve confidence in their output. The primary cost in applying physical models lies in preparing the flume infrastructure; once available, subsequent experiments can be undertaken relatively efficiently by experienced researchers.

The approach outlined here for assessing sediment management challenges inherent to dam removal (Fig. 9) is intended as a starting point rather than as a prescription: each project will have specific conditions demanding attention to factors that cannot be covered as generalities. However, our numerical and physical modelling of non-cohesive sediment pulse behaviour to date implies that (1) there are a suite of baseline data requirements that should be common to all dam removal projects, not least of which is an assessment of reservoir grain-size distribution; (2) some of the preconceived concerns about short-term impacts on the management of water resources, flood control, and habitats for aquatic fauna may not be warranted in all cases; and (3) there is a distinct trade-off between the commonly perceived advantages of staged dam removal versus a single-season removal in non-cohesive fluvial systems, even for large dams.

Beyond numerical and physical modelling, there remains an urgent need for structured pre-project and long-term post-project monitoring and evaluation (e.g., Downs and Kondolf, 2002) to document the benefits achieved and lessons learned from dam removal. From our studies, we would highlight the particular need for research linking mechanisms of morphological changes, such as described here, to ecological responses at timescales that help determine the long-term significance of observed changes. More immediately, we conclude that numerical and physical modelling can contribute effectively to reduce the uncertainties associated with planning dam removal sediment management, especially with regard to comparing alternative proposed management actions.

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