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FINAL REPORT

Physical Modeling Experiments to Guide River Restoration Projects:

Restoration Manuals

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1 INTRODUCTION

Federal and California state agencies with jurisdiction over the San Francisco Bay – Delta region have identified a number of strategies for restoring Bay-Delta tributaries. Three such strategies include: (1) gravel augmentation to compensate for the loss of coarse sediment trapped behind dams and mined from the channel; (2) removing diversion dams to restore access to upstream habitats and restore fluvial geomorphic continuity; and (3) reconstructing river channels and floodplains to be more in balance with a regulated flow regime as a means of restoring fluvial geomorphic processes. Funding has been provided for several projects that employ these restoration strategies on the Tuolumne, Merced, and Stanislaus rivers, and Clear Creek. Experience with these projects highlights several significant gaps in the scientific understanding of fluvial geomorphic processes, particularly concerning how river bed texture and mobility are influenced by episodic sediment delivery, and how floodplain and channel geometry are influenced by changes in the discharge and sediment supply regimes. The lack of a strong scientific basis for design decisions has often forced project managers to rely on their professional judgment, which is typically based on qualitative conceptual models and site-specific past experience.

To further the quantitative understanding behind restoring rivers, Stillwater Sciences, in conjunction with the University of California, Berkeley and San Francisco State University, was awarded a project entitled "*Physical Modeling to Guide River Projects*" (CALFED Ecosystem Restoration Program Contract No. ERP-02D-P55). The purpose of the project was to build two state-of-the-art flumes and conduct a series of physical modeling experiments to address some of the fundamental and unresolved scientific questions underlying the river restoration strategies of gravel augmentation, dam removal, and channel-floodplain redesign. The experiments were conducted at the University of California Richmond Field Station and focused on achieving two broad goals. First, the experiments focused on developing a mechanistic understanding of river channel response to episodic delivery of bedload-sized sediments, as occurs in both gravel augmentation and dam removal projects. Second, the experiments focused on establishing quantitative relationships between channel morphologic dynamics and evolution, flow discharge, and sediment supply. As these overarching research goals deal with areas of inquiry in which limited progress has been made in previous field, experimental, and theoretical studies, the results from this physical and numerical modeling represent significant contributions towards furthering the state-of-the-science for designing, implementing, and monitoring river restoration projects for California watersheds and beyond.

This document details a comprehensive science-based understanding of gravel augmentation, dam removal, and channel-floodplain redesign as restoration tools within the framework of restoration 'manuals.' These three manuals (one for each of the three restoration practices) integrate results from laboratory experiments from this study with theoretical analysis, numerical modeling, and field case studies to produce scientifically-based guidelines for assessing, implementing, and predicting the in-channel response of these common restoration strategies. The manuals are intended for use by restoration practitioners and managers. The manuals have been peer-reviewed by the California Department of Fish and Game and members of the project's Scientific Advisory Panel. Abbreviated revisions of these manuals will be submitted for publication in a peer-reviewed scientific journal.

2 GRAVEL AUGMENTATION: LESSONS FROM THE LABORATORY

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ABSTRACT

Design of gravel augmentation projects, like other river restoration techniques, is currently as much an art as a science due to large gaps in our ability to predict how sediment pulses propagate downstream and interact with pre-existing bed material. Here we summarize the lessons learned from a series of laboratory experiments in which we subjected armored gravel beds of various morphologies to pulses of sediment of various amounts and grain-size distributions. Our results suggest that gravel augmentation can be used to achieve a number of river restoration objectives, provided that the size distribution, volume, and frequency of sediment addition are tailored to existing channel conditions. The potential benefits to be gained in terms of bed texture and channel morphology depend on the extent of translation and dispersion of the sediment pulses. Our experiments show that pulse translation prevails over dispersion only when sediment inputs are small and finer-grained, and in channels with a low roughness coefficient. Additions of gravel finer than the target bed-size distribution can mobilize armored beds, due to the destabilizing effect that occurs when smaller grains infiltrate the spaces between larger grains. Given a fixed volume of sediment, smaller, more frequent additions are most efficient at mobilizing armored beds. Bed mobilization and mixing of resident and added sediments can lead to net bed material fining after the pulses have passed through a given reach. Adding finer gravel to mobilize a coarse surface layer can also be used to flush finer sediments from the gravel matrix, reducing the need to use high flows to improve subsurface hydraulic conductivity. Our experiments suggest, however, that improvements in bar-pool morphology due to gravel augmentation may be short-lived, due to an observed sensitivity of bar topography to sediment supply. Further experiments, both in the laboratory and the field, along with improvements in numerical models of mixed grain size, gravel transport under unsteady flow conditions, are needed to help translate these insights into practical tools for stream restoration.

2.1 INTRODUCTION

Aquatic ecosystems downstream of dams have been widely degraded by physical changes to channels caused by reductions in both the frequency and magnitude of high flows and the supply of coarse sediment (*e.g.*, Ligon *et al.* 1995). Gravel augmentation, the artificial addition of bedload-sized sediments to channels, is a common river restoration strategy intended to partially compensate for the trapping of gravel behind dams (*e.g.*, Bunte 2004). The goals of gravel augmentation include reducing (or “fining”) the size of bed material to improve salmonid spawning habitat, increasing bed mobility to facilitate flushing of fine sediment (sand and silt) from the surface and subsurface layers, and rebuilding bar-pool topography to increase habitat diversity (*e.g.*, Pasternak *et al.* 2004, CALFED Bay-Delta Program 2005).

Effective design of gravel augmentation projects requires accurate prediction of the potential benefits to be gained for a given set of design parameters. Project designers must determine the volume of gravel to be added, its grain-size distribution, frequency and timing of augmentation, and method of delivery, such as placement in the channel bed or "injection" from the channel margins (Bunte 2004). Project designs also need to take into account existing channel conditions, such as channel geometry and slope, bed grain size and degree of armoring, and factors such as the availability of flows capable of mobilizing bed sediments and supply of both coarse and fine sediments from upstream sources. At present, project designers do not have sufficient analytical tools for determining how best to spend gravel augmentation budgets and meet restoration goals (*e.g.*, CALFED Bay-Delta Program 2005). As a result, most gravel augmentation projects are designed on the basis of qualitative conceptual models of channel dynamics and past experience with ad hoc project designs. Post-implementation monitoring often reveals that projects have performed poorly, with limited habitat restoration benefits (*e.g.*, Lutrick 2001, Kondolf *et al.* 1996, Wohl *et al.* 2005).

Sediment supply is naturally episodic across a wide range of temporal and spatial scales. Channels receive pulses of sediment from many sources, including bank failures, landslides, and debris and flood flows from tributaries. Gravel augmentation is a method of artificially enhancing sediment supply at a local scale, with the resulting sediment expected to evolve much the same way natural sediment pulses do. Natural sediment pulses, sometimes referred to as sediment waves, have received considerable attention in recent years, including field studies (*e.g.*, Sutherland *et al.* 2002, Madej 2001, Hoffman and Gabet 2007), flume experiments (Cui *et al.* 2002a, Lisle *et al.* 1997), and numerical analyses (*e.g.*, Cui *et al.* 2002b, Lisle *et al.* 2001). This work has largely focused on observing and modeling changes in bed elevation through time to determine if large-scale sediment pulses are dispersive or translational in nature, as described by Gilbert (1917) in his seminal treatise on the issue. In a dispersive pulse, the wave of added sediment gradually reduces in amplitude while dispersing downstream; in a translational pulse, the sediment wave moves downstream while generally maintaining its shape and features (Lisle *et al.* 2001). Results suggest that bed material pulses are, in fact, largely dispersive, as opposed to translational (Lisle *et al.* 2001) and that there is a Froude number ($Fr = \overline{U}/(gd)^{0.5}$, $\overline{U}$ is the mean flow velocity, g is gravitational acceleration, d is flow depth) effect that controls this phenomenon (Lisle *et al.* 1997). Providing that there is an upstream sediment source, a bed material wave will (1) propagate upstream if flow is super-critical (Fr > 1; Fr is defined at bankfull discharge), (2) disperse in place when the Froude number is trans-critical (Fr ≈ 1), and (3) translate downstream under sub-critical flows. The dominance of dispersion is supported by the argument that flow is near a trans-critical condition when sufficient to mobilize added sediment. In spite of these advances, research has not generally addressed how episodic sediment pulses affect bed mobility of river beds. Furthermore, dispersion appears to prevail over translation when sediment volumes are large relative to the channel receiving the input. Large volumes of added sediment, as occur in landslides (*e.g.*, Sutherland *et al.* 2002) and debris flows (*e.g.*, Hoffman and Gabet 2007), tend to form temporary channel-spanning dams, ponding water upstream and steepening the water surface downstream. This perturbation to the water surface profile favors deposition of sediment upstream of the pulse and increased sediment transport capacity downstream, which together cause the topographic wave-form on the bed to remain fixed in place while being reduced in magnitude (*e.g.*, Cui *et al.* 2002a).

Gravel augmentation pulses do not necessarily behave as described above. For example, the volume of sediment added is typically small relative to the channel and may not cause significant change in the water surface topography. Gravels added to armored beds downstream of dams are composed of sediments finer than the pre-existing bed, and are likely to have a relatively narrow size distribution (CALFED Bay-Delta Program 2005). Moreover, channels downstream of dams can differ in important ways from natural stream channels where sediment pulses have been studied. For example, directly below dams, sediment supply from upstream is negligible, and channels may lack the well-developed bar-pool topography that promotes pulse dispersion (*e.g.*, Lisle *et al.* 2001). In addition, because flood frequency is reduced below dams, added sediments may be more commonly mobilized under relatively low Froude number conditions.

Previous work has not addressed how sediment pulses affect the mobility of resident bed material in channels with low sediment supply (*e.g.*, downstream of dams). Yet, there is ample evidence in the literature that interactions between finer sediments with coarser bed material may significantly affect bed mobility, sediment transport rates, and scour (cf. Jackson and Beschta 1984, Iseya and Ikeda 1987, Wilcock and McArdell 1993, Wilcock and McArdell 1997, Wilcock 1998, Wilcock *et al.* 2001, Curran and Wilcock 2005). While changes in mobility have been studied when sand is added to gravel, it is less clear how additions of finer gravel affect the mobility of coarser bed material. However, it is reasonable to expect some interaction because adding finer gravel to a coarse bed reduces entrainment thresholds for the bed material, and under certain conditions, smooths the bed surface (Ikeda 1984, Iseya and Ikeda 1987, Dietrich *et al.* 1989, Whiting and Deitrich 1990). It is also relatively unknown whether gravel augmentation can be used to flush sand-sized sediments, which may reduce salmonid reproductive success, from bed material. Similarly, it is not known whether gravel augmentation can be used to build bed topography, enhancing topographic diversity, which is perceived as beneficial for many riverine species. In spite of this lack of knowledge, these remain oft-stated goals of gravel augmentation projects. A general lack of post-project monitoring promotes and maintains unacceptable degree of uncertainty.

There is some guidance available to river managers. Bunte (2004) presents a detailed review of gravel augmentation that includes information on ideal candidate channels, methods for preparation, design considerations, and monitoring suggestions. In spite of this guidance, a number of key uncertainties have been identified (CALFED Bay-Delta Program 2005), including:

1. What happens to the added sediment? Do the pulses disperse or translate? How does grain size affect this morphodynamic?
2. How do sediment pulses interact with resident bed material? Is it necessary to bury the bed material to achieve greater mobility? Can fine gravel be added to increase bed mobility without having to bury the bed?
3. Can gravel augmentation be used to fine the bed surface of channels without an upstream sediment supply?
4. Can gravel augmentation be used to flush fine sediment from bed material?
5. Can gravel augmentation be used to rebuild channel bed topography?

In order to address these key uncertainties, the authors and their collaborators conducted a series of laboratory experiments in 2005 and 2006 in two large flume channels. There are a series of publications detailing the results of these experiments including:

1. Simulating sediment transport in a flume with forced pool-riffle morphology: examinations of two one-dimensional numerical models (Cui *et al.*, *in press*);
2. Variable flow influences on sediment pulse dynamics in a forced-bar morphology experimental channel (Humphries *et al.*, *in prep.*);
3. Response of bed surface patchiness to reductions in sediment supply (Nelson *et al.*, *in prep.*);
4. Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams (Sklar *et al.*, *in prep.*);
5. Mobilization of coarse surface layers in gravel-bedded rivers by finer gravel bedload (Venditti *et al.*, *in prep.* A);
6. Sediment pulses in gravel bedded rivers: Pulse sediment size effects on bed mobility (Venditti *et al.*, *in prep.* B);
7. Response of alternate bar topography to variation in sediment supply in gravel-bedded rivers (Venditti *et al.*, *in prep. C*);
8. Gravel augmentation pulse routing through 2D fixed bars (Venditti *et al.*, *in prep. D*); and

9. Channel response to fine and coarse sediment pulses at varying spatial scales in a flume with forced pool-riffle morphology (Wooster *et al.*, *in prep.*).

In this report, we summarize and discuss the results of these publications for river managers interested in gravel augmentation. We begin with a brief review and discussion of options for reversing the effects of dams on downstream bed mobility and texture. We then describe the prototype channel that we used in our experimental design and the experiments we conducted. This is followed by a summary and discussion of our experimental results. We conclude by providing some suggestions for river managers about how to extrapolate our results to stream channels and how to optimize pulse size and frequency in order to achieve restoration goals.

2.2 Options for Reversing the Effects of Dams on Bed Mobility and Texture

Under natural conditions, bed material transported by a river is finer-grained than that on the bed surface and a small component remains immobile under the annual flood regime (Figure 2-1a). Dams block the supply of coarse sediment to downstream reaches and usually reduce the frequency and magnitude of high flows, thus reducing the stream's capacity to mobilize sediment downstream of the dam. Under these altered conditions, the bed surface will coarsen, the transported load will fine, and a much larger component of the bed will become immobile (Figure 2-1b).

A primary goal of gravel augmentation is to reverse this process, which can be accomplished using one of at least four methods:

1. *Release large volumes of water to mobilize beds.* This reduces the need for adding large amounts of gravel, but eventually the bed will scour to a base level, often resulting in a bedrock channel. A simple way to avoid this is to add gravel downstream of the dam to compensate for bed material lost at high flows. Unfortunately, the discharges required to mobilize beds downstream of dams are often too large to be accommodated due to competing water resource needs.

2. *Regrade the channel so the bed can be mobilized at a lower discharge.* This essentially requires redesigning the channel to match the hydrograph imposed by the dam operators. This poses a rather significant challenge—designing a stable channel is as much an art as a science. Furthermore, a large increase in channel slope is required where water available for downstream release is limited. The sediment needed to regrade an equilibrium channel is enormous and the cost often prohibitively expensive, making this an impractical solution for many areas. For example, a channel modification project on the Mokelumne River, California has increased slope from 0.002 to 0.008 (Pasternack *et al.* 2004, Elkins *et al.* 2007), but if the entire affected reach (from the Camanche Dam to the San Joaquin River confluence) was regraded to the new, higher slope, the upstream end of the sediment wedge would be higher than the dam. While this remains a useful way to improve habitat locally, it has little potential for restoring habitat beyond the reach scale.

3. *Periodically add enough gravel to bury the existing bed.* This essentially forces the channel from the condition depicted in Figure 2-1b back to that depicted in Figure 2-1a. The grain size of the added gravel needs to be sufficiently small so that the channel can mobilize the gravel during typical water releases, but within the range suitable for salmonid spawning. The pulses must also not be so large as to greatly increase slope (see #2 above). Such pulses are designed to be transient in nature, providing a temporary veneer of spawning gravel that extends downstream from an injection site that is periodically replenished.

> 4. *Add smaller amounts of fine gravel to mobilize and fine the bed.* This technique relies on the observation that finer sediment can mobilize a coarser bed surface, exposing the subsurface and thereby fining the bed (Figure 2-1c). This should increase near-bed velocities, which drive particle entrainment. The added sediment should be within the range used by salmon for spawning. Here, large water releases and channel slope redesign are not required, but ultimately, continuous mobilization of the bed surface will degrade the channel.

Our general assessment of gravel augmentation methods suggested that Option 1 is probably the best for restoring the integrity of the channel and instream habitat, but that most dam operators cannot provide the necessary water releases under current operating agreements. Option 2 remains in an experimental phase, with various channel redesign programs in progress. Many previous channel modification projects have performed poorly, resulting in limited habitat restoration benefits (*e.g.*, Lutrick 2001, Kondolf *et al.* 1996, Wohl *et al.* 2005); even when this technique is perfected, its utility will likely be limited to local (reach-scale) improvements. In designing our experimental gravel augmentation program, we were interested in procedures with the potential to result in large-scale, multi-reach improvements to river channels, with minimal interference to existing channel functions. As such, we chose to focus on examining passive gravel augmentation techniques where the sediment is supplied at an injection site (*i.e.*, from the bank as opposed to directly added to the channel bed) and carried as a pulse downstream by the river rather than active augmentation techniques that would require redesigning the channel (Bunte 2004). Therefore, our experiments focused on Options 3 and 4, as well as the latter component of Option 1, where gravel needs to be added to prevent large-scale degradation after high flows.

2.3 EXPERIMENTS

2.3.1 Prototype

The first step in setting up the experiment was to establish a channel prototype suitable for modeling the range of conditions we were interested in. We designed a generic prototype channel representative of those in the Central Valley of California, where gravel augmentation is now commonly used to increase salmonid spawning habitat. We assumed that these channels have the following characteristics: (1) the median bed surface grain size (D_{50surf}) is between 64 mm and 128 mm, with an overall grain-size distribution ranging as high as 256 mm; (2) channels are heavily armored (the subsurface materials are finer than the surface); (3) channel slopes range between approximately 0.006 and 0.004; (4) flows are subcritical and hydraulically rough, 5) there is little or no sediment supply in the reach immediately downstream of the dam; (6) flows are typically insufficient to mobilize the bed surface. We further assumed that a moderate increase in flow would be capable of mobilizing the bed. The above conditions generally describe the types of channels where gravel augmentation could be reasonably expected to improve salmonid spawning habitat (cf. Bunte 2004, CALFED Bay-Delta Program *2*005). Channels with sediment transport capacity well below that required to mobilize the bed would require redesign (c.f. Bunte 2004, CALFED Bay-Delta Program 2005) before augmentation would be a viable management technique. While there are many channels in the Central Valley that do not conform to this prototype, it does match the characteristics of channels downstream of many Central Valley dams in most respects.

The experiments can roughly be divided into one-dimensional (1D) and two-dimensional (2D) experiments. The 1D experiments treat the flume as a horizontal cross-section of a river downstream of a dam. We applied a high width-to-depth ratio to suppress the development of point bars. These experiments were Froude-scaled directly from the prototype (Yalin 1971). Froude-scaling is a technique by which all the relevant physical, hydraulic, and sediment-transport scales are reduced to that of the laboratory flume setting and can be "up-scaled" to natural channels by applying the scaling ratio. Later in the report we will discuss how to up-scale our results.

The 2D experiments treat the flume bed as slightly sinuous channel with a deformable boundary, much like a natural river channel. These experiments included adding gravel to a channel with fixed bars and constant (unchanging) flows, as well as examining the conditions necessary to create point bars using gravel augmentation (subsequently referred to as "free-bar" experiments). The fixed-bar experiments were designed as generic models of sediment pulse movement in a channel with pool-riffle morphology and were not scaled based on any specific river. Relaxation of the Froude model conditions was necessary to generate a bed with active sediment transport. Two sets of free-bar experiments were conducted. The first were conducted at the same scale as the fixed-bar experiments. A second set was conducted in a much larger flume; these were initially designed as a Froude-scale model, but we found these conditions insufficient to produce bar topography and we subsequently distorted the Froude number similarity to the prototype. While none of the 2D experiments are perfect Froude models of the prototype channel, they serve as generic analogues of processes active in gravel-bedded channels downstream of dams.

2.3.2 1D Experiments

The 1D experiments were conducted in a 28-m long, 0.86-m wide, and 0.86-m deep sediment-feed flume at the Richmond Field Station (RFS), University of California, Berkeley (Figure 2-2). Detailed information about the experiments and analyses can be found in Sklar *et al.* (*in prep.*), Venditti *et al.* (*in prep.* A), and Venditti *et al.* (*in prep.* B). The bed material was composed of gravel with a median grain size (D_{50}) of 8 mm, a distribution ranging between 2 and 32 mm, and no sand (Figure 2-3). Our first experiment was modeling a dam closure scenario at a constant flow of 0.2 m^3/s. An equilibrium channel bed was established where channel slope was constant, the sediment feed rate was approximately equal to the exit rate, and the median grain size of the bed surface (D_{50surf}) was 8–9 mm. Sediment supply to the channel was then discontinued for 24 hours, armoring the bed until the D_{50surf} ranged 10–12 mm. This produced the effect shown in Figure 2-1a and b. Cutting off the sediment supply eventually coarsened the bed by eliminating finer sediment (Figure 2-4), reduced channel slope by about 10%, and dramatically reduced the sediment transport rate (Nelson *et al.*, *in prep.*; Venditti *et al.*, *in prep.* B).

We then simulated gravel augmentation by supplying sediment 25 m upstream of the flume exit at approximately four times the bedload transport rate observed prior to terminating the sediment supply (Q_{eq} = 40 kg/s). Three types of augmentation pulses were used in the experiments: (1) single-addition pulses designed to cover the bed one median bed material grain diameter (D_{50bm}) deep over one-quarter of the flume's length ("quarter-unit pulses"); (2) single-addition pulses designed to cover the bed one D_{50bm} deep over the entire length of the flume ("full-unit pulses"); and (3) four quarter-unit pulses separated by short periods of time. Two narrowly graded grain-size distributions were used in the experiments. Coarse pulses were composed of sediment with a D_{50} of 8 mm and fine pulses were composed of the fine tail of the bed material grain-size distribution, with a D_{50} of 3 mm (Figure 2-3).

During each run, we monitored the movement of the sediment pulse through the flume and its effect on bed- and water-surface topography, as well as bedload transport, bedload grain size, and bed surface grain size. Bedload was monitored using a continuous weighing mechanism that recorded the weight of material leaving the flume at 60-second intervals. At each stage of the experiment, the material in the collection mechanism was removed and sieved. Where comparisons were made between samples obtained by different methods, the conversion techniques of Kellerhals and Bray (1971) were applied.

During the final, multiple-pulse experiment, we conducted a trial in which the upstream-most 10 m of channel bed was infiltrated with 0.35-mm sand using a low discharge (0.05 m^3/s), as in Beschta and Jackson (1979). The flow during this infiltration period was not competent to transport the bed material, but was sufficient to transport the sand as bedload, which allowed it to infiltrate the pre-existing bed. We then ran our design flow (0.2 m^3/s) until the bed surface was devoid of sand. This procedure provided a flushing flow for the sand infiltrated into the bed. Subsequent pulses of fine sediment were added to test how deeply the sand could be flushed from the bed using augmentation. Detailed information about these experiments and analyses of the results can be found in Wydzga *et al.* (2006). At no time during these experiments was the bed exposed to the augmentation design flow (0.2 m^3/s) when sand was exposed at the bed's surface, because this would have affected bed mobility.

2.3.3 2D Fixed Bar Experiments

The 2D experiments were also conducted in the 28-m long flume at RFS. Detailed information about the experiments and resulting analyses can be found in Humphries *et al.* (*in prep.*); Wooster *et al.* (*in prep.*); and Venditti *et al.* (*in prep.* C). The primary purpose of the 2D experiments was to examine the controls on sediment pulse movement resulting from gravel augmentation and dam removal in a channel with pool-riffle morphology. Sand-filled stockings and cobble-sized rocks were placed in the flume channel to mimic the structures in natural stream channels that create multidimensional flows and the alternating bar sequences that form through sediment scour and deposition (Figure 2-5). The sand bags were placed five flume-widths apart longitudinally, alternating between the left and right sides of the flume. With the sand bags and cobbles in place, a constant water discharge of 0.02 m^3/s and a constant sediment feed rate of 40 kg/hr were applied until the flume reached an equilibrium state where the cumulative aggradation and degradation within the flume became minimal. The bed material and sediment supply feed had a median size of 4.2 mm and a range from 0.7 to 8 mm (Figure 2-3). The equilibrium topography associated with this flow and sediment feed was characterized by alternating pool and riffle sequences and large variations in bed forms, as indicated by deep pools along the thalweg (Figure 2-5).

To simulate conditions downstream of a dam, we shut off the sediment feed for 66 hours, during which time the channel degraded and the reach-averaged channel slope decreased from 0.0095 to 0.0073. The channel degradation was restricted to the mobile portion of the bed, which caused pre-existing alternate bars to emerge from the water surface, forming terrace-like features along the downstream edges of bars (Figure 2-4). Our ability to monitor bed surface grain-size change in the fixed 2D experiment was more limited than in the 1D experiments due to the smaller grain-size used, and it was therefore difficult to determine if the bed coarsened as the channel degraded. Nevertheless, the sediment covering the cross-over riffles between alternate bars was clearly somewhat coarser than that in the pools (Figure 2-3).

We then simulated gravel augmentation pulses by feeding sediment to the apex of the upstream-most bar (*i.e.*, approximately 3 m downstream of the channel entrance). Two types of single-addition pulses were used: a full-unit pulse, in which sediment was fed at $4Q_{eq}$, and double-unit pulses, in which sediment was fed at $8Q_{eq}$. Two grain-size distributions were used for each pulse type. Coarse pulses were identical to the sediment feed used to create the initial equilibrium profile (D_{50} = 4.2 mm) and fine pulses were composed of the well-sorted sand that comprised the fine tail of the bed grain-size distribution (D_{50} = 1.3 mm) (Figure 2-3). As in the 1D experiments, we continuously monitored water- and bed-surface topography as well as the bedload transport rate and grain size of sediment exiting the flume.

In addition to the above experiments, we used the forced bar topography to examine the effects of variable discharge on the dynamics of sediment pulse transport. To facilitate comparison with the steady flow experiments we created two hydrographs, each of which passed the same net volume of water through the flume over a 15-hour period as the 0.02 m^3/s steady design flow. The two hydrographs were based on log-normal distributions and had peak discharges of 0.024 and 0.036 m^3/s, which we refer to as the large and medium hydrographs, respectively. Prior to using these hydrographs we ran a constant design discharge and sediment feed of 40 kg/hr of the 2D bed material distribution (Figure 2-3) until reaching an equilibrium between the supply and the sediment exiting from the flume. We then simulated dam closure by running a medium and then large hydrograph without any sediment supply and documented the resulting bed degradation and reduction in mean bed slope. We then supplied a full-unit gravel augmentation pulse and subjected the flume to a sequence of three medium hydrographs and documented the pattern of pulse migration through the bar-pool topography. This sequence was repeated with the same unit pulse and a set of three big hydrographs.

2.3.4 Free-bar experiments

Two sets of free-bar experiments were conducted. The first set was conducted in the 28-m long RFS flume using the same bed material as in the fixed-bed experiments. The goal of the experiments was to develop a set of freely formed alternate bars to simulate the dam-closure scenario as in the 1D experiments, and then to add augmentation pulses to observe changes in bar morphology. In order to accomplish this goal, sediment was fed into the flume at 80 kg/hr for the first 22 hours of the experiment, after which the feed was eliminated. Bar formation began minutes after the flow was started. Initially, the bars migrated downstream quite rapidly, but eventually fixed in place after about 20 hours. Following the feed elimination, the upstream-most bar underwent head- and side-slope erosion. This supplied sediment to bars in the lower part of the channel, and the bars began to migrate downstream again. However, there no new upstream bars developed, which resulted in bars being washed out of the channel, except in the last 5 m of the flume where some topography was retained (Figure 2-6). Ultimately, we chose not to continue the augmentation component of the experiment.

Following what we considered a failed experiment in the flume, we designed an experiment conducted in a flume 2.78-m wide and 55-m long (active bed) using sediment with a median diameter of 11 mm and a range between 2 and 32 mm (Figure 2-3). Alternate bars were formed in the channel by constricting the flow at the flume entrance and allowing bars downstream to form freely. The sediment size distribution used in this experiment was designed to match that in the 1D experiment as nearly as possible and was as close to a field-scale channel that can be currently realized in a laboratory. In order to develop stable alternate bars we chose a slope that could be easily accommodated in the flume. We then optimized stream discharge to get the maximum width-to-depth ratio and the non-dimensional shear stress (Shields number, $\theta = \tau / \left[gD(\rho_s - \rho) \right]$ where ρ_s is sediment density) that was well within the full mobility range. The need for a full mobility condition was motivated by the work of Lanzoni (2000) and our general inability to develop significant lateral topography at lower Shields numbers. We chose a Shields stress value of about two times the critical value based on the suggestion by Wilcock and McArdell (1993) that this provides full mobility for similarly sized particles.

As in the 2D free-bar experiments, bar development began shortly after the flow began and stabilized after 19.4 hrs (Figure 2-7). Sediment was recirculated at a rate of 3120 kg/hr until topographic change ceased, after which the sediment supply was eliminated and we monitored topographic adjustment, bed grain-size heterogeneity, and sediment transport. Immediately following the feed elimination, the bar topography began to damp (Figure 2-7) through erosion of the bar head and side as in the RFS flume experiments, which generally coincided with a dramatic reduction in the surface sediment heterogeneity (Figure 2-8) and a reduction in the channel slope from 0.013 to 0.007. This fundamentally altered the patterns of sediment transport in the channel and caused a reduction in total flux from 3123 to 114 kg/hr over an 8-hour period.

We then proceeded with two augmentations to the field-scale channel. The first was a single-addition pulse of 4.2-mm gravel scaled as a full-unit pulse (to cover the 55-m working section of the flume one D_{50bm} deep). We fed the augmentation pulse at a rate that visually recreated the bed coverage observed in the 1D experiments, which turned out to be ~$0.25Q_{eq}$ (853 kg/hr) during the first hour of the pulse input and $0.5Q_{eq}$ (1,706 kg/hr) for the second hour. The second augmentation was a coarse augmentation pulse of , bed material at ~1000 kg/hr over a 16-hour period.

2.4 SUMMARY AND DISCUSSION[1]

Given number of experiments, variety of types of experiments, and the overall purpose of this paper, we present the results and accompanying discussions as they address the key uncertainties in designing gravel augmentation projects.

2.4.1 What happens to the injected sediment?

Sediment waves in the field can be difficult to identify, much less quantify (*e.g.*, Lisle *et al.* 2001), in part because pre-pulse conditions are rarely well known and because small topographic and grain-size disturbances are difficult to measure reliably. Laboratory experiments allow control over initial and boundary conditions, facilitate more detailed and frequent measurements, and are more readily compared to numerical simulations (Lisle *et al.* 1997, Cui *et al.* 2002a). Lisle *et al.* (1997) provided graphic illustrations of translation, dispersion, and a mix of both, in sediment waves with an upstream supply, and showed that a downstream progression of bed elevation rise and fall was not diagnostic of pulse translation or dispersion. With field data, they quantify pulse evolution using the ratio of the height to length of the topographic deviation from pre-existing conditions, and show that in nearly all cases the wave aspect ratio declines over time.

Sklar *et al.* (*in prep.*) developed a method to quantify the extent of gravel augmentation pulse translation and dispersion by comparing the relative time-rates of change of the location of the centroid of the pulse volume and the longitudinal spread of the topographic wave form. Figure 2-9 shows theoretical pulses that evolve by pure translation (panels a and b), pure dispersion (panels c and d), and combinations of translation and dispersion (panels e and f) for the case of no upstream sediment supply. Sklar *et al.* (*in prep.*) compared the observed changes in bed elevation to the theoretical curves and found that all pulses showed elements of translation and dispersion, but that the pulses composed of coarse material were more likely to be dominated by dispersion, while pulses composed of the fine tail of the bed , grain-size distribution had a larger component of translation. Translation was particularly evident for the small volume (quarter-unit) pulses (Figure 2-10). The full-unit pulses showed a greater mixture of translation and dispersion behavior.

The 2D constant flow experiments showed increased pulse dispersion compared to the 1D experiments, presumably because form drag associated with the bar-pool topography reduced the shear stress available to transport bedload and because the more diverse topography provided more sites for temporary sediment storage. As in the 1D experiments, coarser pulse material and larger pulse volumes increased the dispersive component of pulse evolution. The hydrograph runs revealed an important source of complexity in predicting gravel augmentation pulse evolution. In the case of the medium hydrograph, in which the peak discharge (24 l/s) was moderately larger than the equivalent volume constant flow (20 l/s), sediment transport rates were significantly lower, averaged over the hydrograph, than for the same size pulse under constant flow. As a result, the time for the pulse to pass through the flume was nearly double that observed in the constant flow case, and the pulse evolution showed very little translation (Figure 2-11). In contrast, the big hydrograph, with a peak discharge of 34 l/s, had an average sediment transport rate equivalent to the constant flow, but the pulse evolution was primarily translational.

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[1] At the time of writing, the 1D experimental data has been analyzed and written up into manuscripts that are currently under revision by the authors, but the 2D analysis is currently underway. As such, some of the results from the 2D experiments are presented in a rather qualitative form. As results from the 2D experiments are completed, it is the intention of the author group to update this document to reflect a more quantitative analysis.

2.4.2 How do sediment pulses interact with resident bed material?

There are distinct interactions between gravel augmentation pulses and resident bed material that can be taken advantage of in gravel augmentation project design. *Venditti et al.* (*in prep.* B) demonstrated that sediment pulses in the 1D experiments caused well-defined increases in sediment flux exiting the channel characterized by a peak in transport that lasted for the duration (Figure 2-10). This period of high flux is followed by an extended period where mobility is affected by the presence of pulse particles on the bed surface. The peak in transport during the fine augmentation pulses were more substantial than during the coarse pulses, a phenomenon that is directly tied to their translational nature. More of the coarse augmentation pulse moved into temporary storage on the bed as it dispersed from the injection site, so the peak transport was not as large.

In the 1D experiments, with the exception of the quarter-unit coarse pulse, introducing the sediment pulses caused the bed material (bedload excluding pulse material particles) to mobilize. This caused bed material to be transported in a full-mobility regime where sediment particles are being transported in the same proportion as they occur in the bed (Figure 2-12). The quarter-unit coarse pulse dispersed into the bed without affecting sediment transport rates at the end of the channel, so we could not determine its effect on the bed material transport regime. Venditti *et al. (in prep.* A) demonstrated that bed mobilization occurs because the sediment pulse fills the spaces between larger particles on the bed. This reduces the mean flow energy converted to turbulence in the near-bed region and, as a result, near-bed flow is accelerated over the pulse. The lift and drag forces that are ultimately responsible for sediment grain entrainment are scaled to the near-bed flow velocity. Thus, larger particles can be entrained from the bed armor. One might reasonably expect the fine pulses to have a greater smoothing effect on the bed, a larger near-bed fluid acceleration, and a larger mobilization effect. Indeed, fractional bed material transport rates increased during both pulses, but the finer pulse caused a greater increase (Figure 2-12).

The full mobility regime for the bed material during the period of declining sediment flux differed for the fine and coarse pulses. Following passage of the fine pulses, a shift to a partial mobility regime occurred where transport favored finer particles. This regime persisted through the length of our experiments and would have probably continued until the fine particles had been winnowed from the surface. This does not result from the availability of pulse-related fine gravel because the pulse has been excluded from the grain-size distributions in Figure 2-12. Instead, the addition of the fines has fundamentally altered the sediment transport regime, and released finer gravel that had been stored in the subsurface. This implies that the armor has been altered by the fine pulse. In contrast, the coarse pulses suppressed transport of bed material after the peak in transport, hence the negative fractional transport rates displayed in Figure 2-12. Although the coarse particles interacted with the bed, increasing transport rates, the armor was not mobilized.

We can calculate how effective each pulse was at mobilizing material by dividing the volume of mobilized material V_{mob} by the volume of sediment mobilization required to entrain the entire bed by one-D_{50} deep (V_{surf}). We can also calculate a pulse efficiency by finding out how much of the bed material was mobilized relative to the pulse volume (V_{mob}/V_{in}). Table 2-1 displays the results, which indicate that the large fine pulse mobilized ~35% of the bed material surface and was therefore most effective at mobilizing the surface. However, the small fine pulse mobilized 50% of its input weight as it passed through the channel making it the most efficient at mobilizing bed material. In contrast, coarse pulses were not very effective or efficient at mobilizing the surface (Table 2-1). We also attempted to take advantage of the greater efficiency of the small fine pulse by adding the same volume as the full-unit fine pulse in four separate quarter-unit pulses added with a short intervening time interval. Overall, the integrated effects of the four pulses indicate a 10% increase in the effectiveness and efficiency of the pulse, but it is not clear that this difference is larger than the natural variability that would have occurred if we had run many replicates. Venditti *et al.* (*in prep.* B) demonstrated that this occurred because, after the second quarter-unit pulse, the third and fourth pulses became less efficient.

Table 2-1. Pulse effectiveness at mobilizing the surface V_{mob}/V_{surf} and pulse efficiency V_{mob}/V_{in} during the 1D experiments.

Run	V_{mob}/V_{surf} (%)	V_{mob}/V_{in} (%)
Small coarse	0.0	0.0
Large coarse	9.0	9.0
Small fine	12.6	50.0
Large fine	34.6	34.6
4 small fine	37.6	37.6

At the time of writing, grain-size analysis and fractional transport calculations for the 2D fixed-bar augmentations had not been completed. However, our qualitative observations during the 2D experiments suggest that the processes observed in the 1D experiments also occurred with the fixed-bar topography in the channel. Indeed, there are systematic scour and fill patterns in the pools that indicate bed material interactions during the pulse (Wooster *et al.*, *in prep.*).

2.4.3 Can gravel augmentations be used to fine gravel bed surfaces?

The observed changes in the grain size of sediment exiting the channel during the 1D experiments suggest fundamental changes in the surface armor during fine and coarse pulses. All the pulses cause a shift in bed material transport to a full-mobility sediment transport regime regardless of whether the channel was in a partial or full mobility regime prior to the pulses. When in the full mobility regime, surface particles are being dispersed laterally and downstream, which can cause a temporary coarsening of the bed material load as the armor is mobilized. For the fine pulses, the shift to full-mobility alters the armor such that a persistent partial mobility regime is established. In essence, the load fines after a fine pulse has passed through the channel and stays fine. This can only happen by a fining of the surface and exposure of subsurface material, because the pulse material is excluded in our calculation of the bed material load. The coarse pulses do not cause this shift to a partial mobility regime, suggesting the effects on surface armor are more moderate and that subsurface material is not exposed for long periods of time after pulse passage. This is a fundamental difference in the way the pulses interact with the bed material, but the process by which the mobilization occurs appears to be similar.

The issue of whether adding sediment pulses can reverse armoring can only be fully understood by examining changes in bed-surface grain size. Sklar *et al.* (*in prep.*) provides a detailed analysis of bed-surface grain-size evolution for the single-pulse experiments. The D_{50surf} was about 12 mm prior to the pulses in all experiments. As the pulse passes through the channel, D_{50surf} drops to the pulse grain size (8 mm for the coarse pulse or 3 mm for the fine pulse) and D_{50surf} coarsens back to the pre-pulse state over the course of the experiments (Figure 2-13). This suggests the pulses have a temporary effect on the bed material surface armor, which is consistent with the observations during coarse pulses, but not during the fine pulses where the transport regime shifts to a stable partial-mobility regime. The discrepancy occurs because patterns in D_{50surf} are masking some of the changes that occur in the armor.

Figure 2-13 summarizes changes in the bed surface that occurred in response to coarse and fine pulses 15 m downstream of the pulse input site. During the feed portion of the initial condition run for the coarse pulse D_{50surf} = 10.4 mm, and eliminating the feed results in a moderate coarsening. Addition of the full-unit coarse pulse fines the bed surface to ~8.5 mm and by the end of the experiment, the bed surface is very similar in appearance and, statistically, to the bed without a sediment feed. During the feed portion of the initial condition run for the small fine pulse, D_{50surf} = 9.7 mm and eliminating the feed significantly coarsened the bed to where D_{50surf} = 14.2 mm. Introduction of the quarter-unit fine pulse fines the surface so that D_{50surf} = 3 mm. At the end of the run, D_{50surf} coarsens to 10.3 mm. However, the surface grain-size distribution is bi-modal. This is partly because of pulse grains stored on the surface, but there is more fine bed material exposed here, which leads to the partial-mobility regime for the bed material transport.

Ultimately, the answer as to whether sediment pulses can reverse armoring is yes. The fining is temporary, which is particularly true for coarse pulses. Fine pulses also temporarily fine the bed in terms of the median grain size, but there is a fundamental shift to a bi-modal surface grain-size distribution and an associated partial-mobility regime that persists for longer periods of time. Whether this is beneficial from a stream restoration standpoint is yet to be determined.

2.4.4 Can gravel augmentations be used to flush fine sediment from bed material?

A goal of flushing flows is to mobilize the river bed's coarse surface layer and thus create the potential to release fine sediment trapped beneath the surface. Given the value of water, releasing flows large enough to generate shear stresses adequate to mobilize the coarse surface can be difficult. One of the oft-stated goals of gravel augmentation is increasing bed mobility to facilitate flushing of fine sediment from the surface and subsurface (*e.g.*, Pasternak *et al.* 2004, CALFED Bay-Delta Program 2005). Our observations that additions of fine gravel were capable of mobilizing significant portions of the bed surface motivated an experiment in which we infiltrated the bed with 0.35-mm fine sediment at low flow to saturate the gravel bed. Wydzga *et al.* (2006) demonstrated that when the bed was well armored and immobile, with no coarse sediment feed, fine sediments were selectively removed or flushed to a mean depth of 0.8 D_{90}. However, under mobile bed conditions, induced by fine gravel injections, the fine sediments were flushed to a mean depth of 1.6 D_{90}. The actual depth of flushing achieved is a function of how long the coarse surface layer is mobile and ultimately reaches its maximum flushing depth of ~2D_{90} (Frostick *et al.* 1984, Kondolf and Wilcock 1996, Wilcock *et al.* 1996) after prolonged periods of fine-augmentation-induced mobility.

Overall, the results suggest that sediment flushing of the bed surface and subsurface (up to 2D_{90}) can be accomplished by mobilizing the particles that compose the coarse surface layer. Our observations suggest that fine pulses are the most effective at this, and because flushing depth is a function of the duration of coarse surface layer mobility, multiple fine gravel pulses, as opposed to single gravel pulses, will be more effective in cleaning the bed.

2.4.5 Can augmentations rebuild channel topography?

Gravel augmentation projects are often designed with the explicit intent of forming or reactivating channel bars as a means to restoring geomorphic processes (CALFED Bay-Delta Program *2*005), yet our understanding of how channel bars respond to variations in sediment supply is incomplete. Our feed reduction experiments in the RFS and St. Anthony Falls Laboratory (SAFL) fumes were designed to help us better understand the response of channel topography to dam closure. The bar washout that occurred in response to the elimination of sediment supply is meaningful. Our observations seem to contradict those from previous experiments (Lisle *et al.* 1993) that suggested that alternate bars respond to sediment supply reductions by deepening in the pools and emergence of the bar tops. However, the prior work was designed to examine steep stream conditions where the maximum grain diameter (D_{max}) was equivalent to the flow depth (d). In our experiments, relative roughness (D_{max}/d) was <<1 in both experiments. In most other respects, our work was similar to previous observations on bar growth. The alternate bars that developed had an amplitude similar to the flow depth and, after some initial downstream migration, became stationary. As in previous work, bar-top surfaces were heavily armored, while adjacent pools and bar crossovers were considerably finer. Our experiments suggest that, during high flows in channels where $D_{max}/d \ll 1$ and full mobility conditions dominate, bars may be unstable without a sediment supply.

The specific mechanism for the observed topographic damping is not obvious. We hypothesize that the bars in our experiments washed out as a consequence of their effect on the boundary shear-stress field and coarsening of the bed surface. The alternate bar topography developed during the feed phase of the experiment produced a flow field that converged in the pools and diverged over the bars. When sediment supply was eliminated, the bed coarsened, reducing sediment transport. Because erosion rate is proportional to stress divergence, without sediment replenishment the relict topography promoted erosion of the sides and fronts of the bars. Without an upstream source of sediment to re-supply the bars, they eventually washed out. Erosion patterns clearly indicate that bar washout occurs by lateral erosion of the bar side slope and head. We are currently examining the stress fields that occur as the bar topography washes out to further test our hypothesis.

The goal of our fine sediment augmentation was to restore the full-mobility conditions that produced the alternate bars. After introduction, the fine augmentation pulse essentially moved down the center of the channel and clearly mobilized significant portions of the bed material along the centerline. In an attempt to get the pulse to spread laterally, we doubled the feed rate in the second hour of pulse addition. At the time of writing, grain-size analysis and fractional transport calculations for the 2D free-bar augmentations had not been completed. As such, we cannot comment on whether bed material transport was in the full-mobility regime. Regardless, the fine augmentation did not reactivate enough of the channel bed to restore the widespread full-mobility transport conditions necessary to form the bars.

Our coarse sediment augmentation was designed to determine how much sediment needed to be added to the channel before the bars would re-form. The coarse sediment pulse resulted in widespread transport on the bed after a few hours. The coarse pulse formed a clear wave that progressed downstream and reached the end of the flume after several hours (Figure 2-14). However, little lateral topographic development occurred until nearly all the sediment removed from the channel (16,000 kg) had been fed back in, increasing the channel slope and returning transport to a full-mobility condition.

Topographic damping has not previously been observed under experimental conditions, but it is consistent with observations of river channels downstream of many dams. Our results suggest that without a sediment supply, the flows that form bars will also degrade them once available sediment sources have been exhausted. Stream restoration strategies designed to form or reinvigorate channel bars require coupling hydrograph design with sediment supply to maintain the features. Ultimately, channel-scale restoration of geomorphic processes may require restoring the pre-impact grade and sediment supply (Patsernack *et al.* 2004, Elkins *et al.* 2007). The issue of how bars respond to changes in sediment supply linked with water flow needs to be addressed to resolve discrepancies between this and previous work.

2.5 OPTIMIZING PULSE SIZE AND FREQUENCY FOR STREAM RESTORATION

Translation of a gravel augmentation pulse can be beneficial for restoration. A translating sediment pulse may move downstream in a concentration sufficient to have a meaningful impact on the grain-size distribution of a river bed downstream. Our experimental results suggest that gravel augmentation projects designed to influence longer reaches may be more likely to succeed than previously thought (CALFED Bay-Delta Program 2005). This is particularly true for rivers where there are few good access points for sediment delivery, and for small-budget projects where few funds are available for the time-intensive process of placing and grading gravel within the river bed. When translation of a gravel augmentation pulse is desired, our results suggest that frequent small pulses will be more effective than fewer larger pulses. Supplying gravel to the channel by dumping it off the edge of a high bank or terrace to form a talus cone (also referred to as “gravel injection”) (Bunte 2004, CALFED Bay-Delta Program 2005) is particularly appropriate for generating pulses with a significant translational component. This is because gravel is mobilized from the talus slope toe by high flows only in quantities that can be immediately transported downstream, thus avoiding the changes in the water-surface slope that favor pulse dispersion (*e.g.*, Lisle *et al.* 2001).

Pulse dispersion is a preferred outcome where project goals call for long-lasting bed texture changes over a relatively short length of channel. In our experiments, we observed dispersion occurring primarily as pulses translated downstream and material was left behind. This suggests that gravel augmentation pulses can be designed to achieve local as well as downstream benefits through a mix of translational and dispersion behavior. The beneficial grain-size changes lasted longest in the downstream portion of the flume, due to the difference in celerity between the leading and trailing edges. Hence, it may be that the optimal location for sediment input in gravel augmentation projects is somewhat upstream of the target reach when a mix of translational and dispersive pulse evolution is expected. Where project goals call for maximizing pulse dispersion, large volumes of sediment should be used, although major changes to local water-surface slope, such as in the case of landslide inputs (*e.g.*, Sutherland *et al.* 2002), may degrade habitat by reducing flow velocity and trapping fine sediments.

Our results suggest that fine sediment pulses are capable of fundamentally altering the bed surface grain size and transport regime. The volume of sediment added ultimately dictates how long the shift to a full-mobility regime will last and how much of the bed material surface will be entrained. The longer-lasting partial-mobility regime that occurs after pulse passage may be influenced by pulse size, but only if significant bed mobilization occurs. In order for the desired effect of bed mobilization to occur, the size of a fine sediment pulse must not greatly exceed the volume required to cover the bed 1- or 2-D_{50} thick in the reach to be restored because complete bed coverage prohibits the mobilization of bed material. Smaller fine augmentations are more efficient at mobilizing bed material than larger pulses and multiple small fine pulses may be capable of mobilizing somewhat more bed material than a single large pulse of the same volume. Regardless of whether multiple pulses can mobilize more than a single pulse, shorter reaches of channel can be effectively mobilized by multiple small pulses where larger pulses would translate significantly.

Ultimately, a fine sediment pulse is only useful where there is suitable subsurface material. In cases where the subsurface material is not within the desired range, an augmentation of the desired subsurface median grain size is more appropriate. We simplified our experiments by using a single median grain-size (8-mm) pulse, but using a wider range would not greatly affect the results. For these coarser augmentations, changes in the bed surface and bed mobility occur as a result of burying the former bed surface. There is some moderate interaction between the bed and pulse material, with some bed mobilization, but the pulse material transport replaces the transport of bed material. Augmentations composed of the desired grain size have a temporary fining effect and are an effective solution to improving mobility providing that augmentation pulses are added frequently enough to continually bury the bed surface.

To maximize the temporal and spatial extent of beneficial bed texture changes, it is not clear whether the fine-grained or coarse-grained pulses are preferable. The high celerity of the fine-grained pulses means that more frequent augmentations would be required to achieve the same duration of bed fining as a slower-moving, coarser-grained pulse. Fine-grained pulses, however, produced a larger magnitude change in median grain size (from 14 mm to 3 mm), and were more effective at mobilizing the existing armored bed (Venditti *et al.*, *in prep.* A). As Figure 2-11 illustrates, it is possible to overshoot the target grain-size range by augmenting with finer-grained gravel (*e.g.*, Kondolf *et al.* 1993, Phillips *et al.* 1975). Moreover, the coarse-grained pulses produced a net fining, comparing the pre- and post-pulse median grain size, while the fine-grained pulses resulted in no net fining and even net coarsening, as has been observed in the field following large fine-sediment pulses (Meade 1985, Roberts and Church 1986, Miller and Benda 2000). Ultimately, it may be most beneficial to alternate between fine- and coarse-grained gravel additions, or use a distribution intermediate between the two end members we explored in these experiments.

2.6 SCALING-UP FROM THE LABORATORY TO THE FIELD

2.6.1 Scaling-up the 1D laboratory experiments to the field

In order to achieve the bed mobility results observed in our 1D experiments in natural channels, the results need to be scaled up. The 1D experiments were scaled down from the prototype using a 1:4 ratio, but the results need not be scaled up using that same ratio. In fact, providing that flow conditions and bed parameters are not altered, the mobility conditions described herein can be achieved in any gravel-bedded channel. Flow conditions in a Froude model are scaled using three dimensionless numbers: (1) the Froude number, (2) the mean flow Reynolds number ($Re = d\overline{U}/\nu$, ν is the kinematic viscosity), and (3) the grain-size Reynolds number ($Re_g = D_{50surf}u_*/\nu$, $u_* = (\tau / \rho)^{0.5}$ is the shear velocity, $\tau = \rho gSd$ is the boundary shear stress, ρ is water density, S is channel slope). These conditions need not be matched exactly, but the flow conditions should be lower regime (Fr <1), fully turbulent (Re >>2000), and hydraulically rough (Re_g >>70). It is not clear whether the Fr <1 condition needs to be met because there is no documented change in sediment transport across the critical threshold. However, it is a convenient way to scale the flow depth and velocity in a channel and other channel conditions (high relative roughness, shallow depths, steep channel slope) that cause changes in sediment dynamics are characteristic of upper regime flow.

The two most important parameters to properly scale up is the bed-state parameter (Shields number) and the grain size of the pulse relative to D_{50surf} . For a fine-sediment augmentation, a hydrograph needs to be designed to provide the channel with a transport condition just below the threshold of motion for the bed (θ_c = 0.047; Wilcock 1993). In our 1D experiments, θ/θ_c = 0.8. Table 2-2 shows field channels that have been scaled up from the 1D experiments using 1:4 and 1:8 scaling ratios where D_{50surf} = 64 mm and 128 mm, respectively, and the flow conditions match the criteria given above. In our 1D experiments, the 3-mm gravel pulses were composed of the material that makes up the fine tail of the bed material grain-size distribution. When the grain size of all the gravel augmentation is scaled up in the field, 3-mm gravel additions are equivalent to adding 12-mm particles to a bed with a D_{50surf} = 64 mm, or 24-mm particles to a bed with a D_{50surf} = 128 mm. Ideal salmon spawning gravels range from 10 to 50 mm in diameter (Kondolf and Wolman 1993). So, additions of the fine gravel to a coarser bed surface to achieve mobilization does utilize gravel that falls within the ideal range for maintaining suitable gravel for spawning.

Table 2-2. Scale-up of model parameters to field prototype scale.[2]

Parameter	Model	Prototype (1:4)	Prototype (1:8)
S	~0.0045	~0.0045	~0.0045
d, m	0.22	0.88	1.76
$D_{50\ surf}$, mm	16 [12]†	64 [48]†	128 [96]†
θ	0.038	0.038	0.038
$Re \times 10^6$	0.24	1.9	5.5
$Re_g \times 10^5$	0.12	0.95	2.7
Fr	0.75	0.75	0.75

† Area-by-weight sample of the surface material with Wolman count equivalents in brackets.

To achieve the mobility conditions we observed for a coarse pulse, a similar procedure needs to be implemented. However, it seems unlikely that the goal of a coarse augmentation would be to reproduce our observed interactions between the pulse and bed material. A more reasonable goal for a coarse augmentation is to provide a veneer of material similar to the subsurface that can be used by salmon for spawning. In our experiments we achieved this goal by using a flow where the Shields number ratio θ/θ_c for the 8-mm augmentation sediment was 1.4 to 1.45. Hydrographs designed to meet this mobility condition for a period of time should provide the veneer observed in our experiments in a rather simple, straight channel.

2.6.2 Using 2D experiments as process analogues for the field

The flow- and bed-state conditions used in the 2D experiments can also be directly scaled to field conditions in the same way as the 1D conditions. The flow conditions in the fixed- and free-bar experiments were lower regime, fully turbulent, and hydraulically rough. The bed-state parameter was set so that $\theta/\theta_c >> 1$ and a full mobility condition would prevail. Yet, some caution needs to be exercised in scaling up results from the 2D experiments. Natural channels generally do not have rigid boundaries and natural channel sinuosity is expressed as a feature of the channel, not just the thalweg as in our experiments. This results in added flow resistance and different arrangements of pools and riffles that may buffer the downstream movement of sediment pulses. The most reasonable way to apply the results of our 2D experiments are to treat the observations as analogues of pulse behavior to formulate hypotheses about how sediment pulses will move in a specific natural channel.

2.6.3 Spatial scaling considerations

Two key considerations for gravel augmentation are determining how long the beneficial effects of the augmentation will last and how far downstream beneficial results should be expected. Length scales in rivers can typically be scaled using the dimensional arguments from Froude scaling. For example, the flume length in our experiments would scale up to 120 or 240 m using 1:4 and 1:8 scaling ratios, respectively, and the SAFL flume scales up to 220 or 440 m using 1:4 and 1:8 scaling ratios, respectively. These length scales are not very large for field-scale channels. Indeed, a major limitation of our experiments is the short length of the flume relative to pulse sizes and celerity. For example, the full-unit pulses spanned the length of flume, such that the leading edge exited the flume before the sediment feed

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[2] The grain-sizes given in the table are based on weight-by-area samples where all exposed particles have been collected from the bed surface, sieved and weighed to obtain the grain-size distribution. Since this is the sediment that the flow interacts with, this distribution is most relevant for hydraulics calculations. Equivalent values for a Wolman count, which is similar to a weight-by-area sample where a set volume of material has been sieved and weighed to obtain the grain-size distribution (Kellerhals and Bray 1971, Church *et al.* 1987), are given in Table 2-2.

was complete. Similarly, the gravel augmentation pulses grew in size while moving downstream despite a tendency for dispersion. Had our flume been infinitely long and had the sediment collection mechanism not interrupted pulse movement, we would have been able to examine how the effect of the pulses diminished as they moved downstream. Had our flume been large enough for these types of observations, we could have calculated length scales using Froude scaling, yet we cannot.

Probably the most reasonable way to examine length scales is to use a numerical model that matches the dynamics observed in the experimental data over the length of the flume, but with a much greater numerical domain. Our 1D data are particularly well-suited to such an exercise because the full-unit sediment pulses must decrease in size as they move downstream until at some point they are one quarter-unit in size. In effect, the large pulses reflect the near-field behavior of an augmentation and small pulses reflect the far field. This provides two observations to match at two separate locations in a numerical modeling domain. Although we do not know the appropriate length scales for our pulses, the observations do form a conceptual framework for river managers to form hypotheses about augmentation pulse dynamics in the near- and far-field domains.

2.6.4 Temporal scaling considerations

There are formal methods for scaling time from models of sedimentary processes to prototype scales. Yalin (1971) argues that, provided the model and prototype are both lower regime, fully turbulent, and hydraulically rough, scaling up time can be accomplished by raising the scaling factor (4 or 8 in Table 2-2) to a power. The numerical value of the power varies depending on the process that is being scaled up. For example, the scaling factor for mean velocity and sediment transport is 0.5 and for saltation -1. To scale up time from our experiments, it is probably most useful to think about augmentation pulses as either a general sediment transport phenomenon where the scaling ratio power is 1.5, or as an erosion/accretion phenomenon where the scaling ratio power is 2 (Yalin 1971). This means that for the 1:8 scaling up ratio given above, each time step for a general sediment transport phenomenon in the model is 23 time steps in the field. Similarly, for an erosion/accretion phenomenon, each time step in the model is equivalent to 64 time steps in the field.

It is difficult to provide discrete time periods over which we would expect changes in the condition of bed sediment in a natural channel scaled up from our models because we fundamentally don't know the length scale for improvements. The time scale for improving bed mobility over a reach long enough for both fine and coarse sediment pulses to dissipate would be much longer than the time taken in our experiments. However, for the 1D experiments, we know that the fine pulse remained in the channel for ~2.5 hours and the coarse pulse remained in the channel for ~4 hours. In a channel that is scaled up using a 1:8 ratio, and using the time-scaling ratios above for a general sediment transport phenomenon and an erosion/accretion phenomenon as upper and lower boundaries, the fine pulses would remain in a channel for 2.4 to 7 days at high flows and the coarse pulse would persist for 3.8 to 10 days. Assuming augmentation might be coupled with a hydrograph where pulse translation and dispersion occurs at high flows and low flows persist for long periods afterwards, the effects of a single pulse could be extended for a considerable period of time following injection. Nevertheless, these are ad hoc calculations and further work on establishing length scales for pulse interactions with bed materials and critical field testing is required to establish the best practices for calculating temporal and spatial improvements.

2.7 CONCLUSIONS

In summary, several key observations emerge from this experimental investigation into the morphodynamics of gravel augmentation:

1. Gravel augmentation pulses evolve through a combination of translation and dispersion, with translation becoming dominant for small augmentation volumes and fine grain sizes under approximately plane-bed conditions. Translational pulse propagation has the potential to provide bed texture and mobility benefits over a longer distance than dispersive pulses, but also results in shorter duration of local bed improvements. Gravel augmentation projects designed to take advantage of the potential for translational pulse evolution will likely require more frequent gravel additions and are thus more compatible with gravel injection from the channel margins than direct placement in the channel bed.

2. Pulse evolution in channels with forced bar-pool topography is more dispersive than in those with plane-bed topography for constant flow conditions and similar grain sizes and pulse volumes. Pools, pool tail-outs, and bars all served as temporary sediment storage reservoirs that slowed pulse movement in general and retarded the movement of the pulse tail in particular. Propagation of the fine gravel pulses in the forced bar-pool channel showed some translational behavior, but the coarse gravel pulses were nearly entirely dispersive. Dispersive pulse behavior was strongest for fine sediment pulses when subjected to the moderate flood hydrograph, however, the large flood hydrograph produced a strongly translational pulse propagation pattern. Interpretation of the effects of the flood hydrographs is complicated by net erosion of the bars due to incomplete channel adjustment to the variable flow regime. These results suggest that gravel augmentation project designs should consider the shape and magnitude of typical flood hydrographs and not rely solely on effective discharges (such as bankfull).

3. Gravel augmentation using relatively fine gravel is capable of mobilizing armored beds due to a hydrodynamic smoothing effect. Armor mobilization can expose previously buried sub-surface sediments, leading to enhanced bedload transport rates, mixing of pre-existing and augmented gravels to form a finer surface layer, and net degradation of the channel bed. Multiple small pulses of gravel four times smaller than the median diameter of the armor were most efficient at mobilizing the static surface layer. To prevent long-term re-armoring and maintain enhanced bed mobility, fine gravel augmentation pulses should be followed by additions of gravel in the target grain-size distribution suitable for salmonid spawning. This strategy has the potential to achieve desired benefits using much smaller quantities of gravel than the traditional approach of burying static armor, but requires more frequent gravel additions and increased quality control when acquiring gravel. Field experiments are needed to fully test this new gravel augmentation technique.

Bed texture response to gravel augmentation pulses depends on the grain size of the pre-existing bed, the grain size of the added gravel, the volume of added material, and the spatial and temporal pattern of pulse evolution. Large augmentation volumes created longer-lasting improvements in bed texture compared to smaller augmentation volumes. Augmentation with finer gravel led to greater decreases in median bed grain size but shorter durations of bed fining due to the higher celerity of fine-grained augmentation pulses. Use of gravel finer than the lower bound of the spawning size range for static armor mobilization can delay the development of a bed size distribution in the spawnable range by temporarily overshooting the intended magnitude of bed texture fining. However, due to mixing with the pre-pulse sub-surface sediments, fine gravel augmentation may lead to longer-lasting bed texture benefits than augmentation with coarser gravel.

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2.10 FIGURES

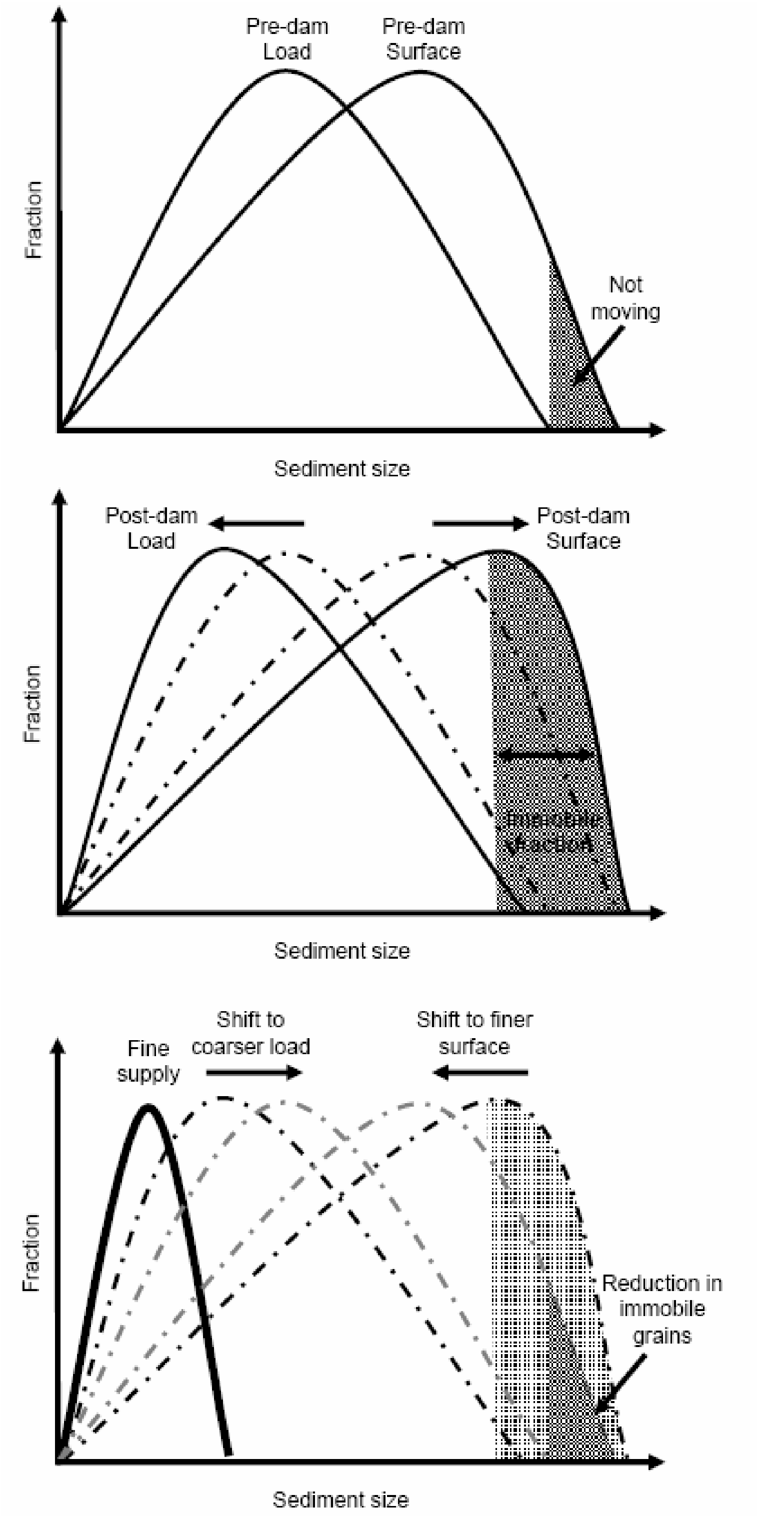

Figure 2-1. Shifting surface grain-sizes using gravel augmentation.

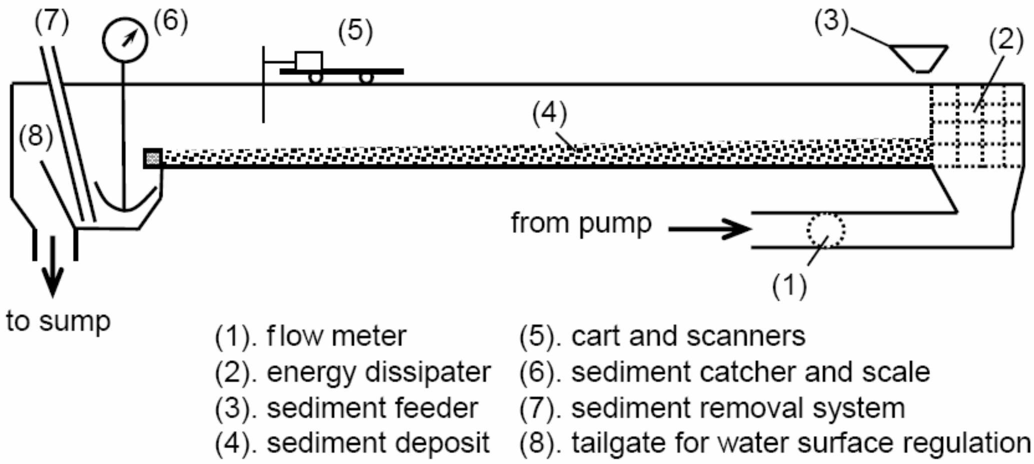

Figure 2-2. Schematic diagram of the RFS flume and its associated facilities (From Cui *et al.*, *in review* A).

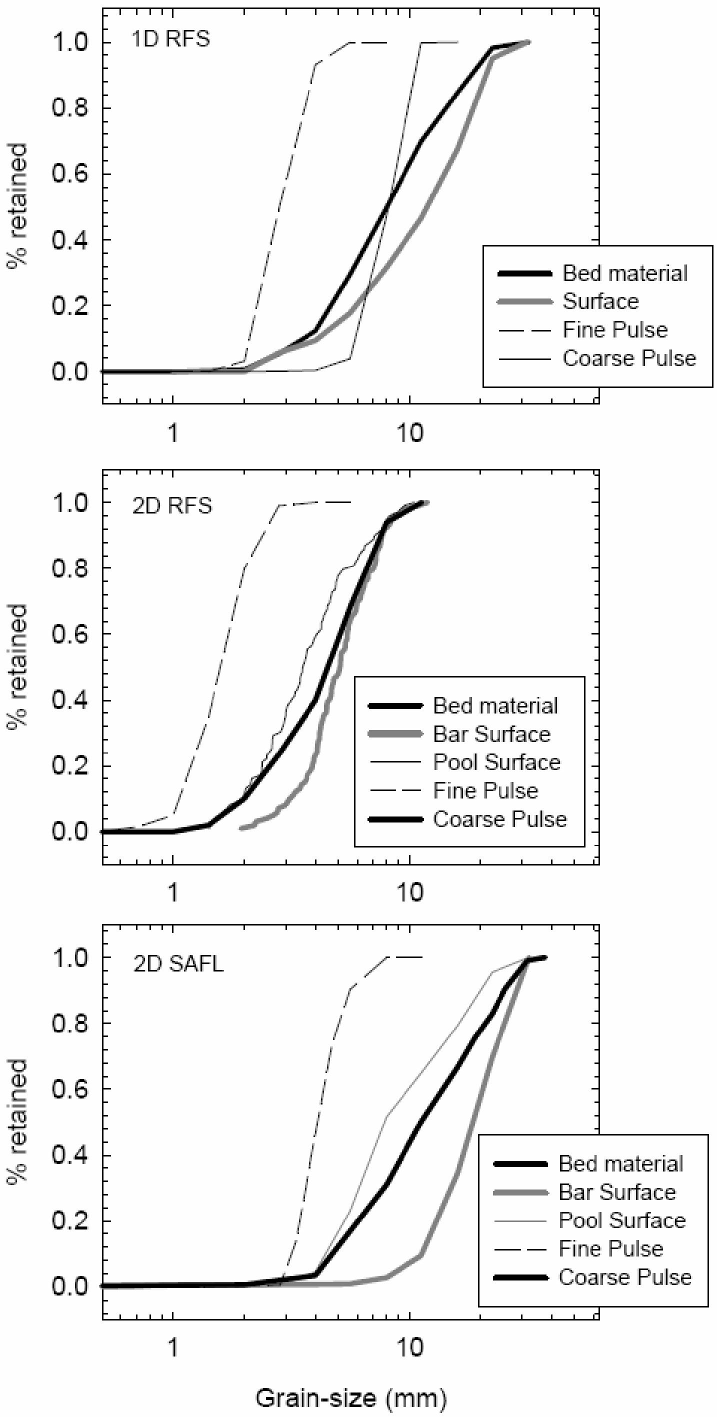

Figure 2-3. Sediment size distribution of the bed material, bed surface, and the sediment pulses during the 1D RFS, 2D RFS, and 2D SAFL experiments. Surface from the SAFL experiment is an area by weight.

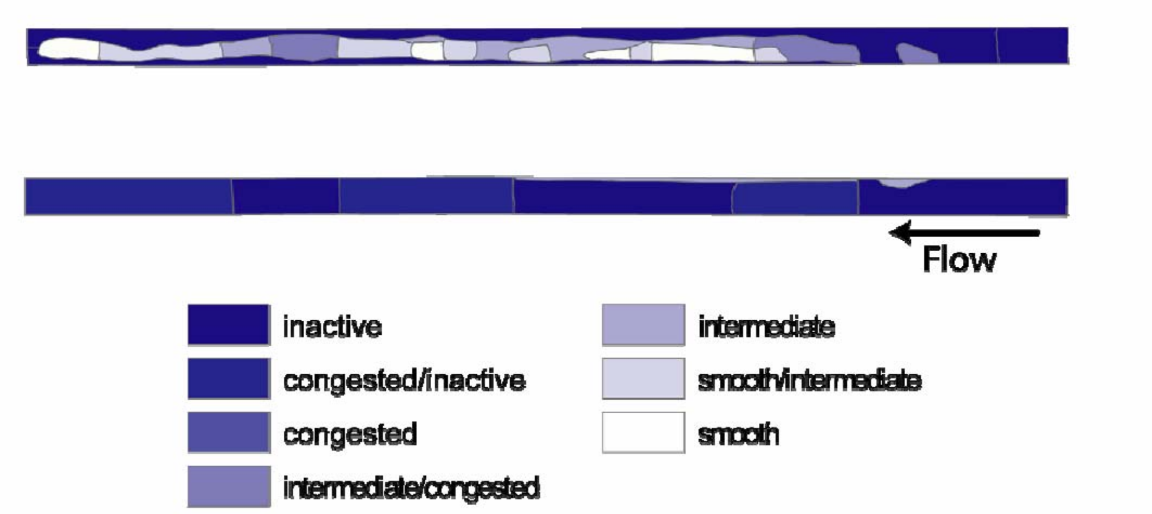

Figure 2-4. Facies map of the bed of the RFS experiments at the end of the 40 kg/hr run feed (top) and the end of the no feed experiment (bottom). Terms in the legend refer to the transport condition of the bed. Congested refers to a coarse patch and smooth refers to a patch of fine gravel. See Nelson *et al.* (*in prep.*) for further details.

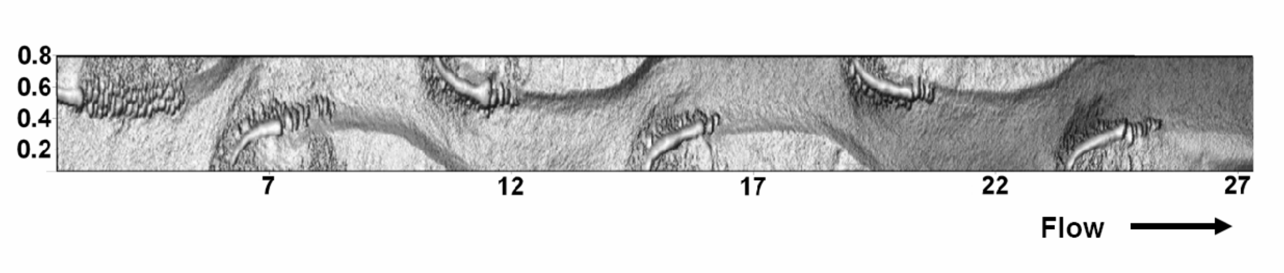

Figure 2-5. RFS 2D Fixed bar configuration during equilibrium conditions with a constant 0.02 m^3/s water discharge and 40 kg/hr sediment feed (From Cui *et al.*, *in review* B).

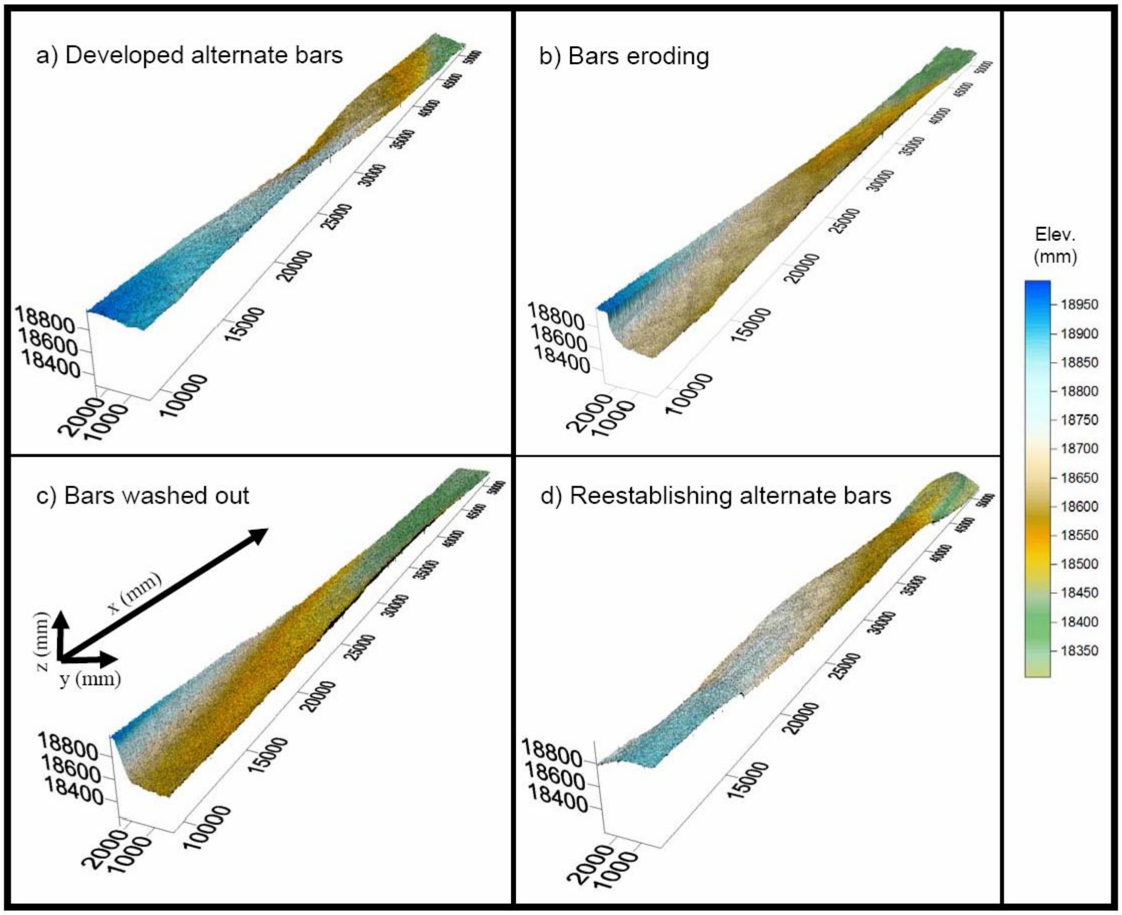

Figure 2-6. Topographic adjustment of the bed following elimination of the upstream sediment supply during the 2D SAFL experiments. (a) Fully developed alternate bars at 19.4 hrs into the experiment. (b) Damped topography at 27.4 hrs (8 hours without an upstream sediment supply) due to erosion of the bar head and side. (c) Washed out bars at 75.6hrs (41.1 hours without an upstream sediment supply). The flat surface on the left hand side of the flume was a former bar surface that had emerged and later eroded due to undercutting at its base. (d) Developing alternate bars after adding sediment to the flume for 14 hours ~1000kg/hr.

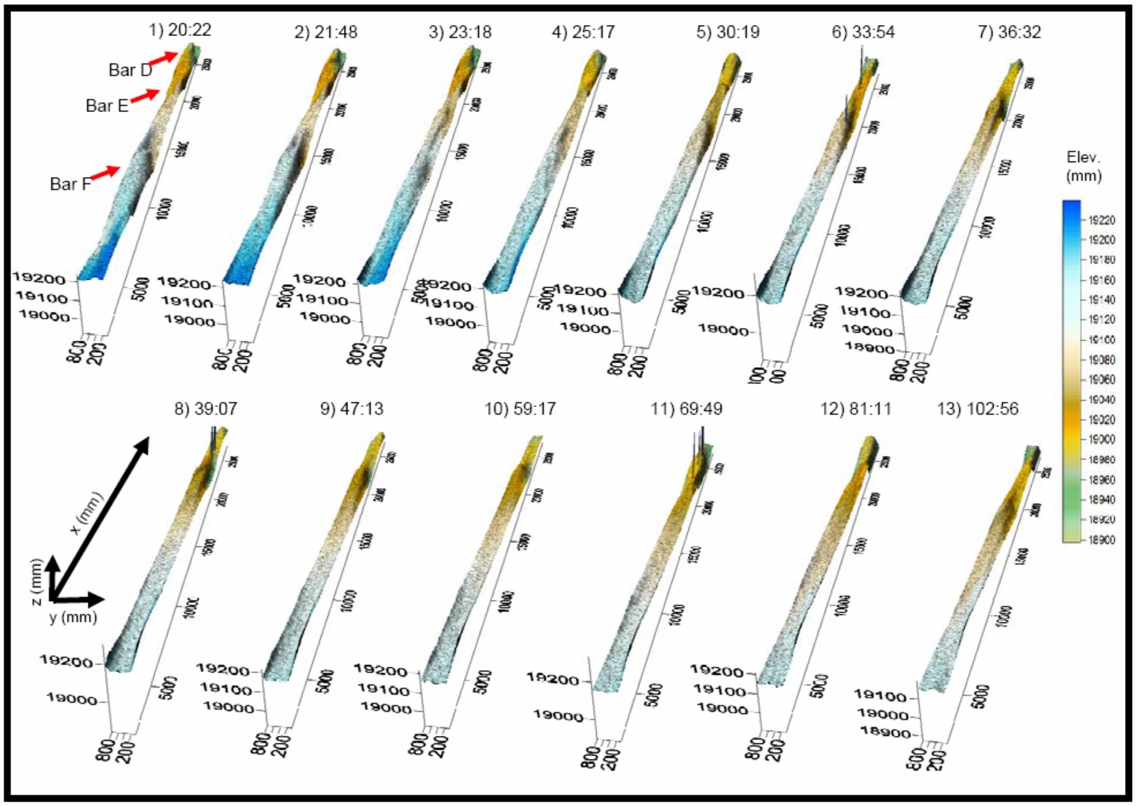

Figure 2-7. Topographic adjustment following the feed reduction during the 2D RFS free bar experiment. Feed was eliminated at 22.00. Bars D and E migrated out of the flume. Any remnant topography from these features was eventually overtaken by Bar F which did not leave the flume entirely. The bar between 10 and 15m at 102.56 was Bar G, which was formed from sediment excavated from near the side walls (see deposit at ~10m at 81.11).

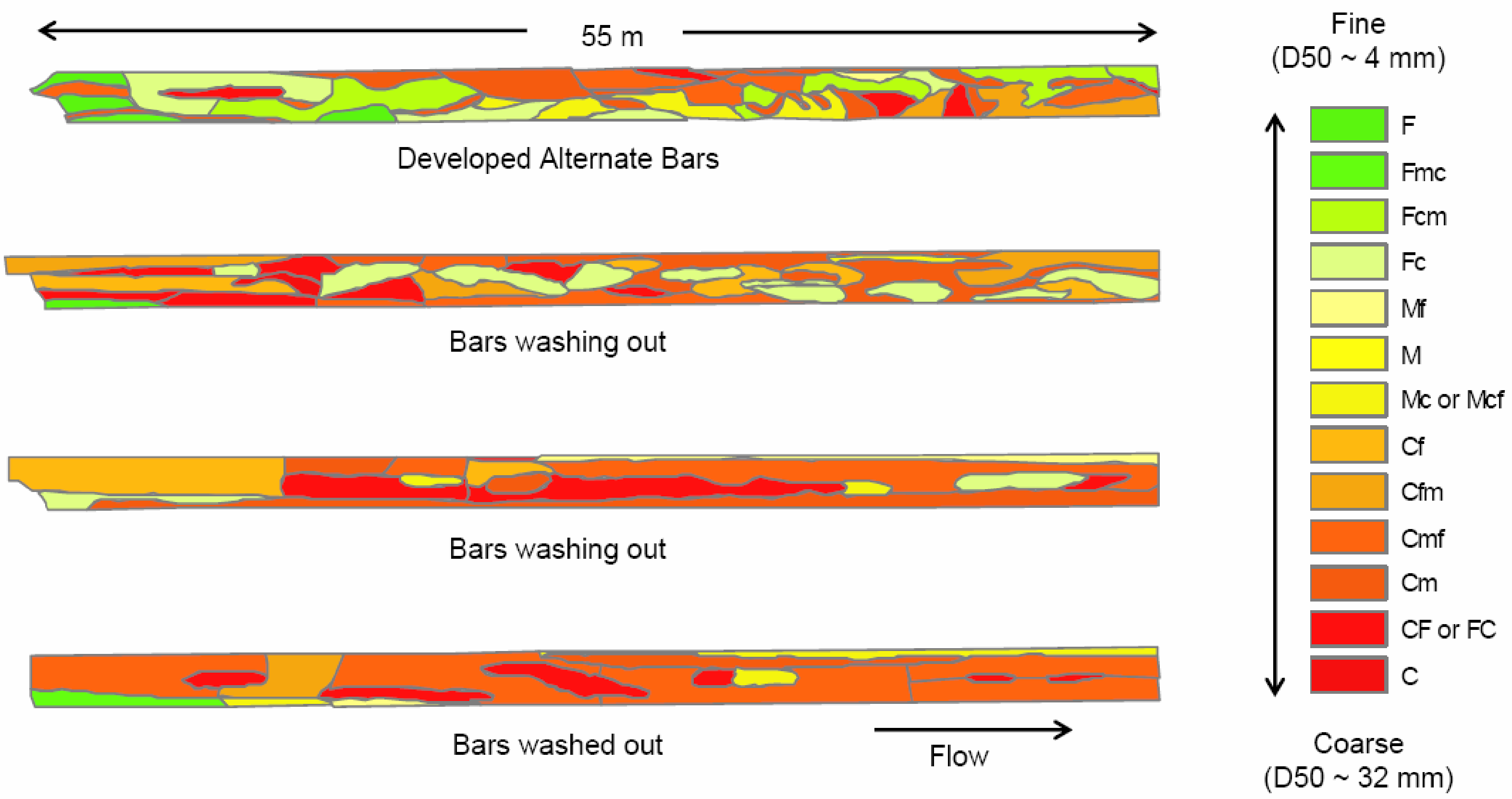

Figure 2-8. Facies maps of bed surface texture drawn at the end of the alternate bar run (top), during the armoring phase (two middle figures), and at the end of the armoring phase (bottom). Upon elimination of the upstream sediment supply, fine patches (green) contracted and coarse patches (orange/red) expanded. The overall bed surface heterogeneity was reduced until the bed was uniformly coarse (see Venditti *et al.*, *in prep* D).

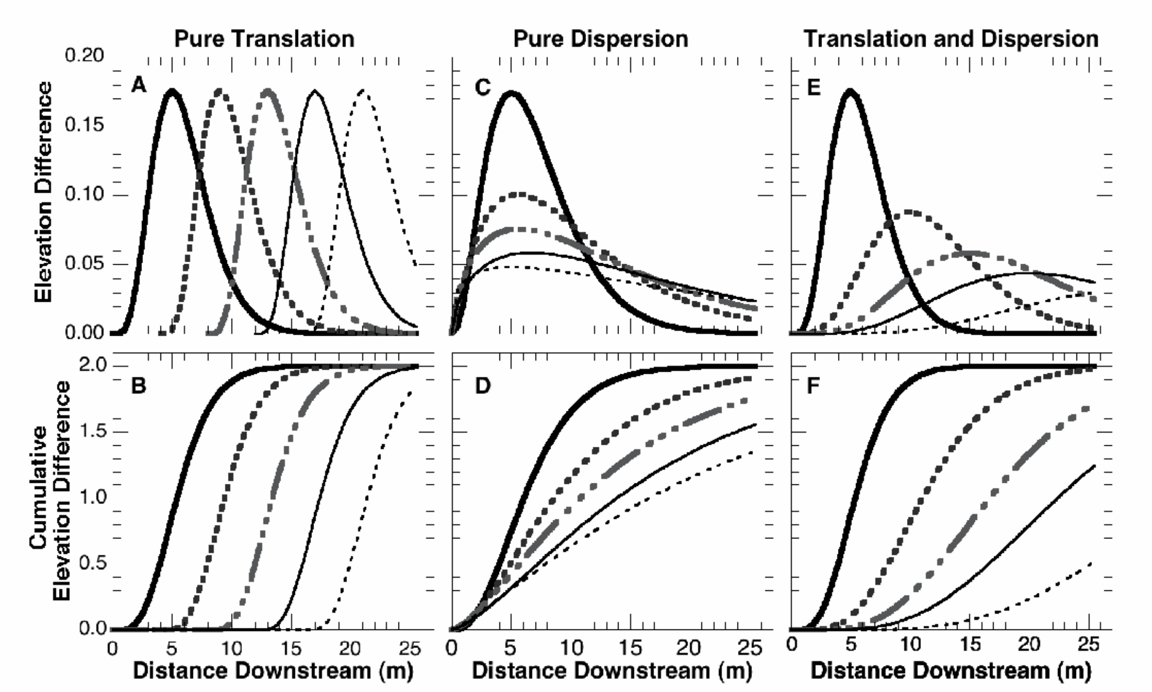

Figure 2-9. Theoretical examples of pulse evolution showing elevation difference between bed elevation and prepulse bed elevation and downstream-cumulative elevation difference for cases of pure translation (A and B), pure dispersion (C and D), and simultaneous translation and dispersion (E and F). From Sklar *et al.* (*in prep.*).

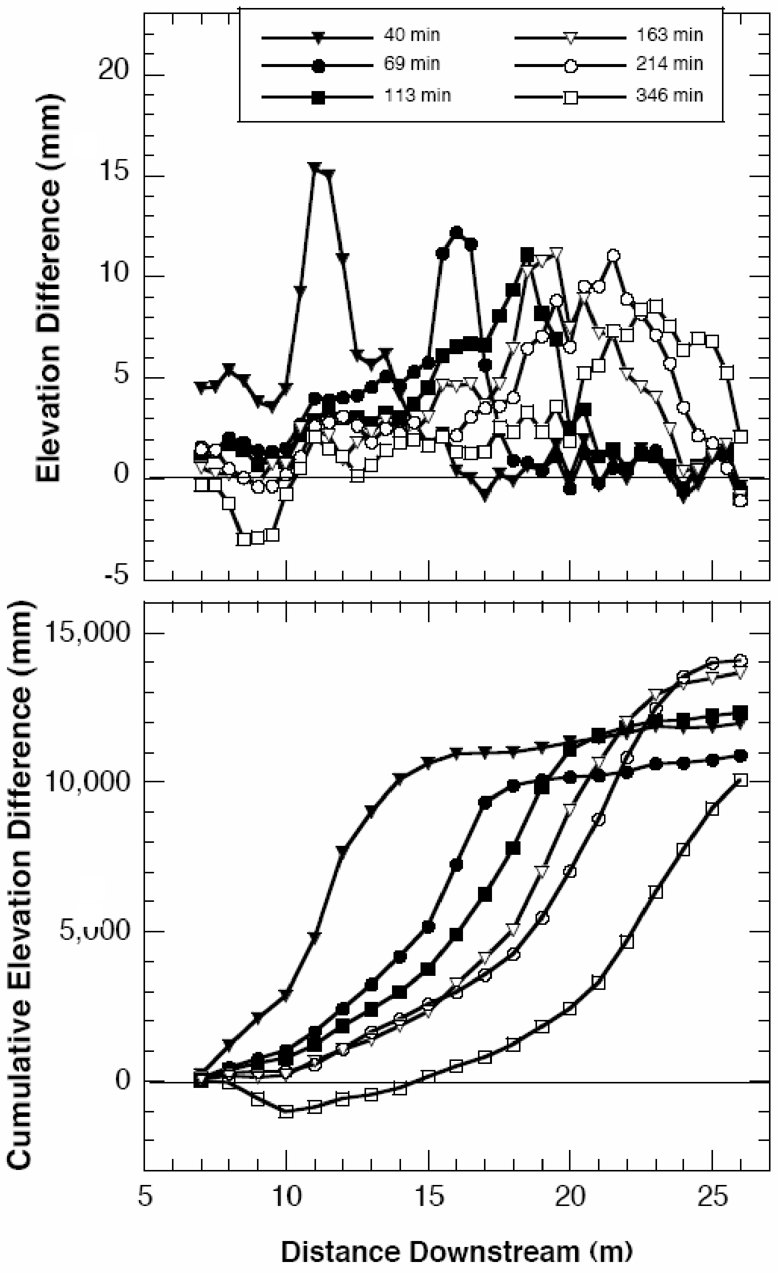

Figure 2-10. Topographic evolution of small volume (1/4 unit), coarse-grained pulse (Run 23). (A) Elevation difference from pre-pulse bed, and (B) downstream cumulative elevation difference. From Sklar *et al.* (*in prep.*).

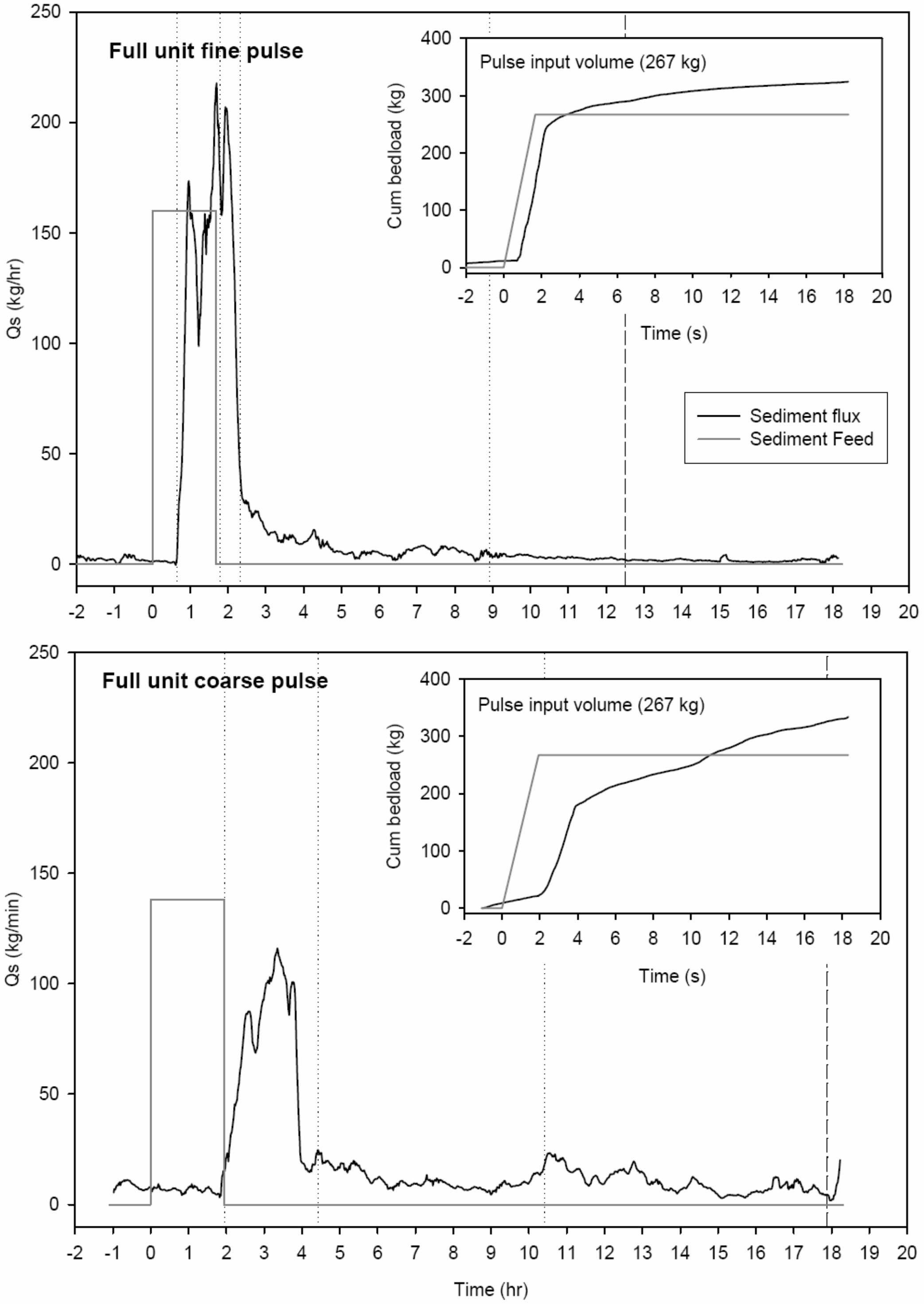

Figure 2-11. Measured bedload transport during the full unit single pulse experiments. Vertical dotted lines represent periods when the flume was stopped to obtain the bedload materials from the collection mechanism and for photos of the bed surface grains-size distributions. Grain-size distributions in Figure 2-12 (top) represent these sampling periods. The vertical dashed lines indicate when the effects of the pulse on transport rates has ended, which is designated as the time when the transport rate systematically declines to the pre-pulse rate.

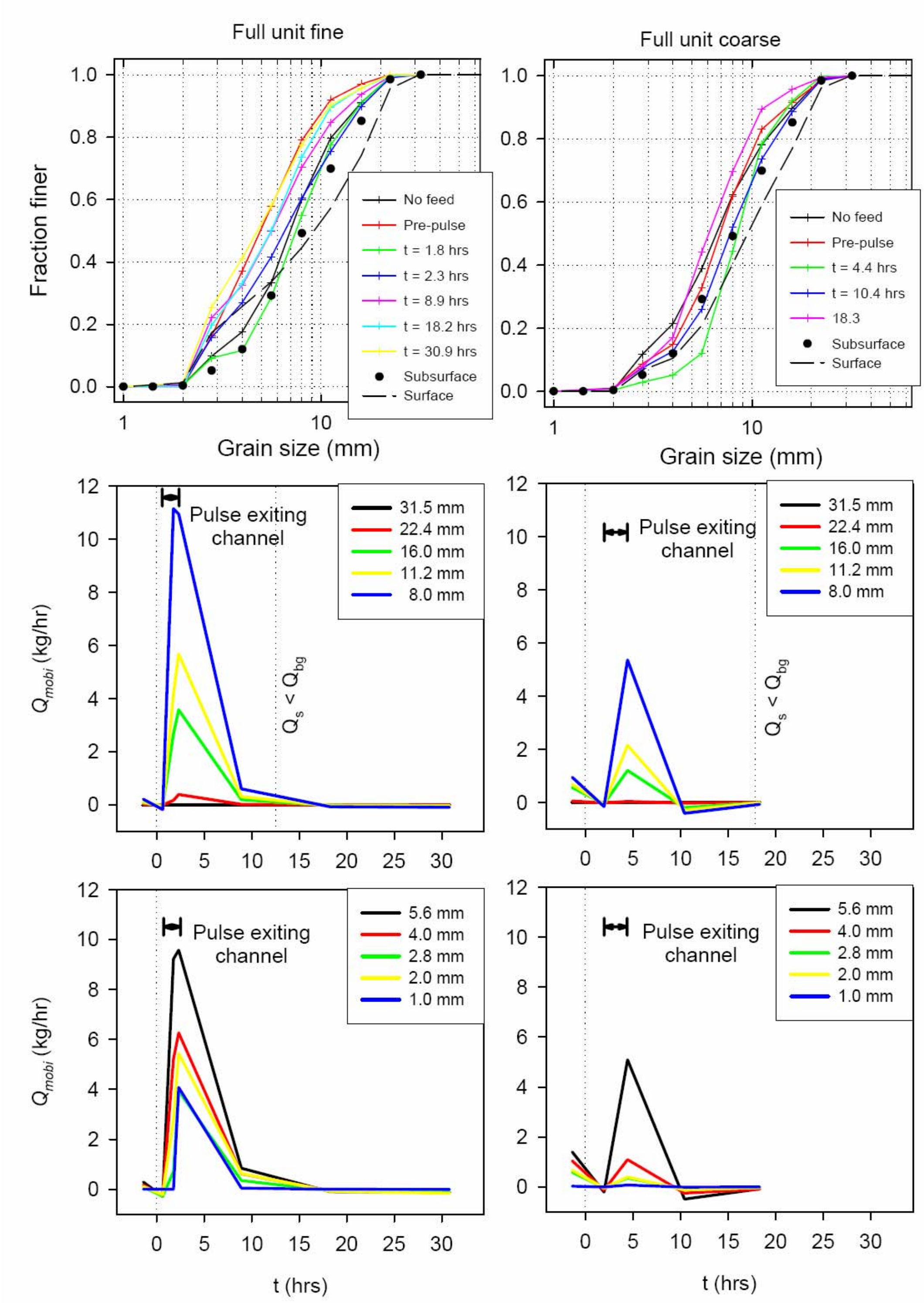

Figure 2-12. Bed material load grain-size distributions of all the non-pulse material exiting then channel from the single pulse experiments (top). Fractional transport rates of mobilized material for the full unit fine pulse and full unit coarse pulse (middle and bottom). Data plotted as negative run times are for the zero-feed condition.

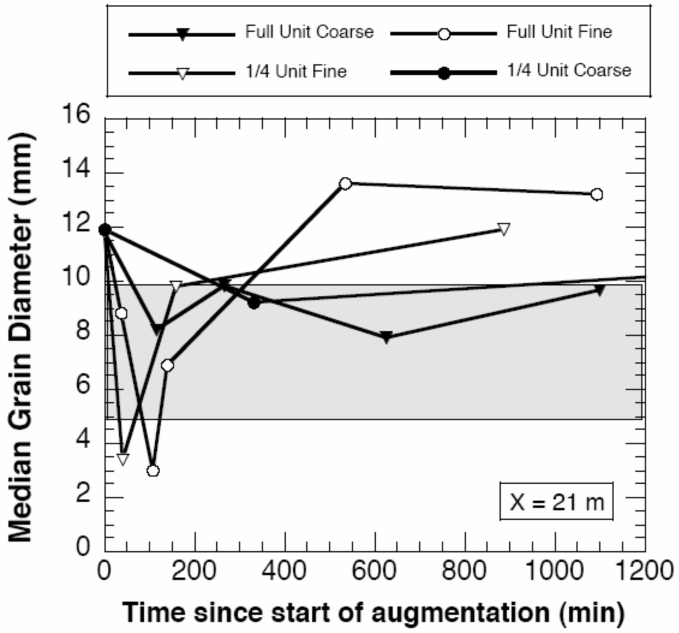

Figure 2-13. Change in bed median grain diameter with time for each run at position 21 m downstream of flume inlet. Shaded area represents hypothetical range of potentially spawning grain sizes.

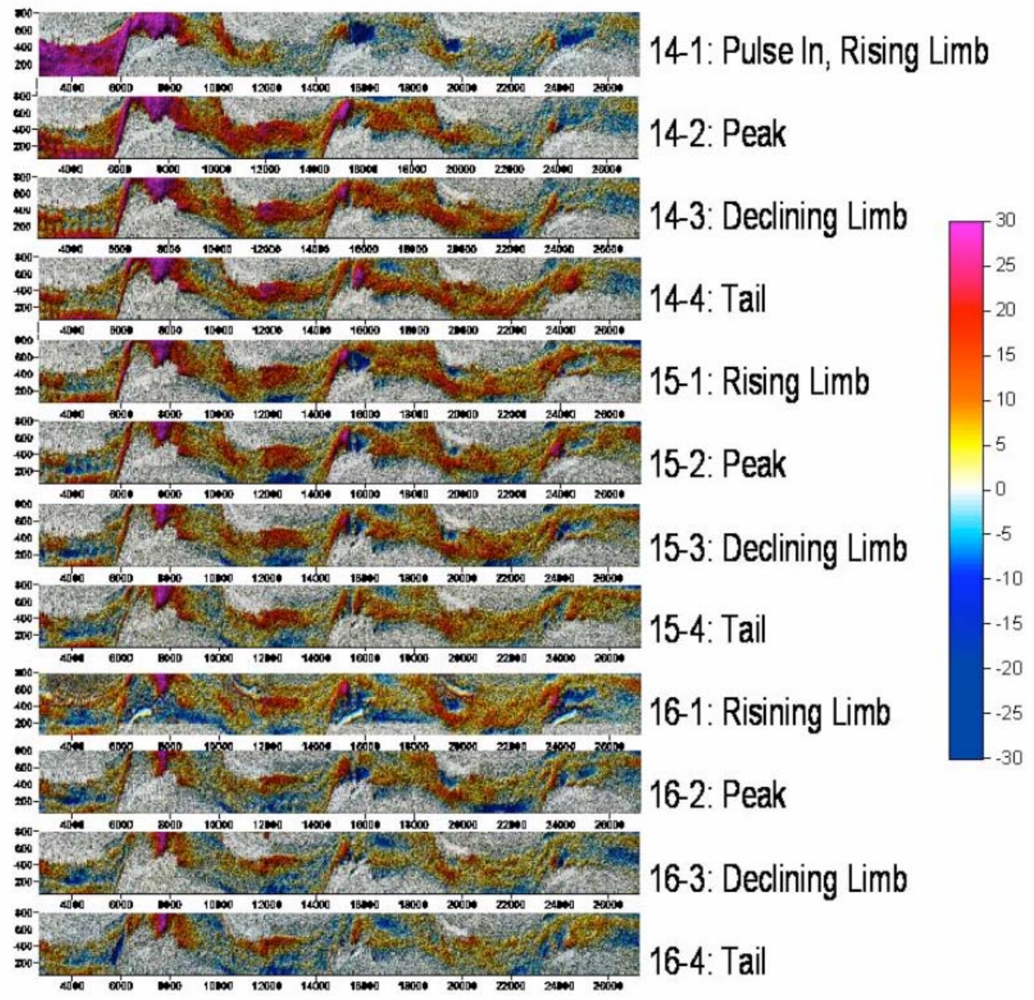

Figure 2-14. Shaded relief map of flume bed topography showing net topographic change from pre-pulse conditions for passage of pulse during three medium hydrographs. Bed elevation changes shown in mm. From Humphries *et al.* (*in prep.*).

3 MANAGING THE RELEASE OF SEDIMENT RESULTING FROM DAM REMOVAL: AN APPROACH INFORMED BY PHYSICAL AND NUMERICAL MODELING

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ABSTRACT

Dam removal is now considered a viable river management alternative that can address issues of water resources, hazard avoidance, and river conservation. Managing the pulse of sediment released as a result of dam removal is a challenging concern for river managers and subject to significant uncertainties because very few dam removal projects have been thoroughly monitored. We propose an approach to dam removal sediment management that integrates understanding gained from recent advances in physical and numerical modeling to address some of these uncertainties. We focus on two factors extremely pertinent to gravel-bedded rivers: namely, the dynamics of the sediment pulse, and the interaction of the released fine sediment with coarser bed material. Following an initial generation of dam removal alternatives and after a thorough investigation of reservoir sediment characteristics (*e.g.*, volume and grain size distribution), numerous sediment-related constraints need to be assessed, including the downstream transport and deposition dynamics of the released sediment pulse, details of sediment pulse movement through a pool-bar morphology, and fine sediment infiltration into coarse bed material. Recent developments in numerical modeling of sediment pulses provide tools to simulate the one-dimensional transport and deposition of silts, sand, and gravel. This is demonstrated in the simulation of the proposed Marmot Dam removal in Oregon, the results of which were the basis for deciding to remove Marmot Dam in a single season and with little ancillary sediment management. Physical modeling of sediment pulse movement through a forced pool-bar morphology with an armored bed indicated a slow dispersal of coarse sediment pulses with deposition in pool tails and along bar margins, while fine sediment pulses left less topographic signature on the channel bed. Pools contracted in area as the pulses moved though, then recovered, and the overall topographic diversity was maintained because pools, bars, and riffles exhibited similar magnitudes of sediment accumulation. Examining one-dimensional numerical sediment pulse models against these responses indicate that numerical simulation can adequately reproduce the deposition and erosional patterns on a reach-averaged basis. Theoretical analysis and physical modeling indicated that fine sediment can potentially infiltrate only a shallow depth of a few bed material median diameters, suggesting that a quick release of large volumes of sediment following dam removal will likely result in a reduced period of impact. These developments suggest that there is a distinct trade-off in the commonly perceived advantages of a staged dam removal over a single-season removal in terms of the intensity and duration of environmental impacts. Numerical and physical modeling can help reduce uncertainties related to dam removal, and flume experiments have particular utility in relation to ecological impacts. The proposed approach for dam removal sediment management can help rationalize the associated uncertainties, and assist in developing targeted research questions into unknown aspects of the downstream transport of sediment pulses.

3.1 INTRODUCTION

Dams and reservoirs in the western United States provide important resources such as electricity, flood control, and water supply to assist economic development in the region. Accompanying these economic contributions, dams and reservoirs have also played a significant role in declining ecosystem health through alterations to hydrologic regimes, sediment supply, and blockage of pathways for salmonids and other fish species. Ecosystem changes frequently include downstream reductions of natural flood events, altered seasonality of flows, channel incision, loss of morphological complexity, coarsening of surface bed materials, increased interstitial fine-sediment 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). The resulting impacts can be dramatic. 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, these losses coincide 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.

The ecosystem impacts of dams became apparent at approximately the same time as revisions to the practice of river management (see Downs and Gregory 2004). River management no longer focused only on water resource provision (*i.e.*, providing water of sufficient quantity and quality at times dictated by the human user rather than according to climatic drivers) and hazard avoidance (*i.e.*, attempts to isolate floodplain dwellers from the potential impact of flooding, erosion, deposition, and contaminant releases) but, additionally, had an increasing concern for conserving natural riverine ecosystems and the native species that inhabit them, and for restoring degraded habitats and repopulating them with native species. In restoration, it has long been understood (*e.g.*, NRC 1992, Sear 1994, Petts 1996, Graf 2001), although far less well-practiced, that restoration strategies based on natural process regimes of flow and sediment transport are preferable to morphology-based strategies. Clear ecosystem benefits are therefore related to restoring natural pulses of flow and sediment to downstream reaches and floodplains, such as occur in longitudinally-connected river systems (*e.g.*, Poff *et al.* 1997, Bushaw-Newton *et al.* 2002). Reversing fragmentation in river ecosystems (Graf 2001) is the essential basis for recognizing dam removal as a river restoration initiative (*e.g.*, The Aspen Institute 2002, The Heinz Center 2002, Bushaw-Newton *et al.* 2002). In some valley-bottom areas, dam removal can restore the 'flood pulse' advantage to the ecosystem (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 and rearing grounds for anadromous fish species; and downstream colonization potential by drifting invertebrate populations and by fluvially dispersing tree seeds.

Nationally and internationally, dam removal is now considered a viable river management alternative (Table 3-1; Figure 3-1), 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 as a public-safety issue intended 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 is 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 to date in the U.S. (Doyle *et al.* 2000).

Table 3-1. Proposed or completed dam removal projects in the western United States.

	Dam	**River**	**Year constructed**	**Height**	**Estimated sediment volume**	**Removal status**	**Removal alternatives**	**Source**
1	Elwha Dam	Elwha River (WA)	1913*	108 ft* (33 m)	5 million yd^3† (3.8 million m^3)	Planned 2008*	Staged removal*	* Popular Mechanics: Tearing Down The Elwha River Dam http://www.popularmechanics.com/science/earth/2294301.html † Elwha and Glines Canyon Dams, Elwha River near Port Angeles, Washington USBR http://www.usbr.gov/pmts/sediment/projects/ElwhaRiver/ElwhaGlinesCanyon.htm
2	Marmot Dam	Sandy River (OR)	1912*	47 ft† (14 m)	960,000 yd^3† (734,000 m^3)	Removed 2007†	One season staged demolition with sediment removal*	* The Oregonian - This is the way the dam crumbles http://www.oregonlive.com/news/oregonian/index.ssf?/base/news/1185166534198320.xml&coll=7&thispage=2 † Economic Benefits to Mendocino and Lake Counties from Removing the Dams on the Eel River http://www.ceedweb.org/PDFs/EelEconReport2.pdf
3	Iron Gate Dam	Klamath River (CA)	1962*	188 ft* (33 m)	4.8 million yd^3† (3.7 million m^3)	Proposed†	One-shot: diversion, notching or other technique†	* CA Dam Safety Alphabetical Dam List http://damsafety.water.ca.gov/docs/Juris_H-M_5-07.pdf † G&G Assoc. Klamath River Dam Removal Investigation http://klamathsalmonlibrary.org/documents/G&G2003pd.pdf
4	Copco 1,2 Dams	Klamath River (CA)	1: 1922* 2: 1925*	132 ft* (40 m) 37 ft* (11 m)	Combined 9.6 million yd^3† (7.3 million m^3)	Proposed†	One-shot: diversion, notching or other technique†	* CA Dam Safety Alphabetical Dam List http://damsafety.water.ca.gov/docs/Juris_H-M_5-07.pdf † G&G Assoc. Klamath River Dam Removal Investigation http://klamathsalmonlibrary.org/documents/G&G2003pd.pdf
5	McCormick-Saeltzer Dam	Clear Creek (CA)	Saeltzer: 1903* McCormick-Saeltzer: 1912†	15 ft* (4.6 m)	25,000 yd^3† (19,100 m^3)	Saeltzer Dam removed 2002†	One season removal with partial dredging	* Western Shasta Resource Conservation District Clear Creek Case Study http://www.watershednetwork.org/docs/2006/LowerClearCreek_CaseSudy.pdf † Distribution of bed sediment on Clear Creek after removal of Saeltzer Dam http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1044&context=wrca
6	South Fork Dam	Battle Creek (CA)	1910	16 ft (4.9 m)	30,000 yd^3 (22,900 m^3)	Planned 2006	River re-route One shot	Battle Creek Salmon and Steelhead Restoration Project EIS/EIR http://www.usbr.gov/mp/battlecreek/index.html
7	Sunol Dam	Alameda Creek (CA)	1900*	28 ft * (8.5 m)	37,000 yd^3* (28,300 m^3)	Removed 2006†	One shot *	* San Francisco Public Utilities Commission Sunol/Niles Dam Removal Project - Environmental Impact Report http://sfwater.org/detail.cfm/MC_ID/15/MSC_ID/186/PRJ_ID/225/C_ID/2701 † SF Chronicle Article: ALAMEDA CREEK 2 dams come down 9-22-06
8	San Clemente Dam	Carmel River (CA)	1921*	106 ft† (32 m)	2.5 million yd^3* (1.9 million m^3)	Proposed†	Stabilization River reroute Staged removal Sediment removal with slurry pipe*	* San Clemente Dam Draft EIR/EIS http://www.sjd.water.ca.gov/environmentalservices/sanclemente/index.cfm † Coastal Conservancy Memorandum http://www.scc.ca.gov/sccbb/0705bb/0705Board08_San_Clemente_Dam_Removal_Ex2.pdf

	Dam	River	Year constructed	Height	Estimated sediment volume	Removal status	Removal alternatives	Source
9	Cascade Dam	Merced River (CA)	1917*	10 ft* (3 m)	Completely full Sediments have been removed at previous times*	Removed 2003†	Diversion and one-shot Dry season removal †	* USGS - Assessment of hydraulic changes associated with removal of Cascade Dam, Merced river, Yosemite Valley, California http://onlinepubs.er.usgs.gov/djvu/OFR/1988/ofr_88_733.djvu † Modesto Bee - Cascades Dam Removal Lets River Flow Free in Yosemite Jan 12, 2004 http://www.yosemite.org/newsroom/clips2004/january/011204.htm
10	Rindge Dam	Malibu Creek (CA)	1925	100 ft (30 m)	0.8–1.6 million yd^3 (0.6–1.2 million m^3)	Proposed (feasibility study completed 2001)	Dam removal Sediment removal Fish ladders	Malibu Creek Environmental Restoration Project Management Plan http://www.spd.usace.army.mil/cwpm/public/plan/pdguide/policy_review/MalibuPSP_June01.pdf

Future dam removals may not only involve small 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 also 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.

Dam removal can therefore provide long-term advantages to each of the core concerns in river management: water resource use, hazard avoidance, and species and habitat conservation and restoration. Unfortunately, achieving the potential long-term benefits of dam removal is frequently far from straightforward, especially in the removal of large dams. 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) but, directly or indirectly, 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, 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 (in terms of air quality, traffic noise, disposal site impacts) that also prevents downstream reaches from receiving the benefits of sediment that has been denied for decades. Thus, an improved understanding and management of downstream sediment releases following dam removal is critical to determine both the true cost-effectiveness of removal and the true environmental impacts of the released sediment. These improvements should assist in costing dam-removal projects and streamlining the process of receiving the necessary environmental permits. Below, we investigate the sediment management issues related to dam removal before outlining and detailing an approach to management that combines empirical data with recent understanding gained from physical and numerical modeling. Based on this improved understanding, we discuss the apparent implications for considering dam removal as a river management option.

3.2 SEDIMENT MANAGEMENT ISSUES RELATED TO DAM REMOVAL

Overall, the ultimate dilemma 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. Part of this problem, in practice, is that most river conservation policies and regulations were drafted to protect existing river habitats at a time when there was a reasonable expectation that all management actions would result in degradation of river conditions. Many existing policies were not designed to accommodate an activity like dam removal (or, indeed, river restoration), where logic dictates that one should weigh the benefits and drawbacks of short-term and long-term effects in determining the overall value of the activity. This shortcoming can lead to apparently incongruous decisions by river management agencies to oppose dam removal on environmental grounds, even as the long-term outcome would seem entirely beneficial. For instance, agencies charged with management of native fish populations may be extremely concerned about uncertainties related to the short-term burial of existing spawning grounds, even if dam removal would open up many kilometers of superior habitat upstream. Short-term concerns become a real and tangible part of the dam-removal decision process, especially for single-purpose river management agencies, and have the potential to cause considerable delay or a halt to the dam-removal process. These concerns are in addition to those likely to be voiced by riparian landowners and stakeholders fearful of the impact on flood risk, recreational opportunity, and property values. Overall, short-term concerns are potentially a barrier not only for resource managers, whose goal is long-term environmental benefit, but also for private dam owners, who may not be able to afford the inherently higher costs associated with a protracted period of permitting the removal.

There are potential short-term impacts of dam removal associated with each of the three broad concerns of river management. Examples include:

Water resources:

- water-quality impacts from the high total suspended sediment (TSS) concentrations during the first significant flow events after dam removal;
- fine sediment deposited on the bed surface and infiltrating into the subsurface, potentially reducing the conductivity of infiltration galleries for water abstraction;
- deposited coarse sediment changing the river morphology near culverts or canals;

Hazard avoidance:

- flooding impacts, a consequence of the loss of reservoir attenuation and the deposition of coarse sediment, which can raise river-bed elevations near downstream settlements;
- increased downstream erosion, related to the restoration of the natural flow regime in a formerly regulated river;
- pollution impacts, following the re-mobilization of potentially bioavailable nutrients and contaminants currently held in stasis in the reservoir sediment deposit and commonly bound to fine sediments;

River conservation:

- spawning habitat impacts, related to burial of existing spawning riffles by deposited coarse and fine sediment;
- impacts on juvenile fish emergence, related to ‘entombment’ of redds by deposited fine sediment;
- reduced invertebrate production, caused by (particularly fine) sediment deposition;
- holding and rearing habitat impacts caused by sediment deposition that reduces pool depths;
- impediments to fish migration caused by loss of channel complexity;
- removal of a migration barrier to exotic aquatic species.

It is apparent from the above list that the majority of the potential impacts are related to the erosion, transport, and deposition of fine and coarse sediment released from the reservoir deposit following dam removal. In many instances, the volume of sediment released following the removal of a medium- to large-sized dam will produce a significant pulse of material at least equivalent to sediment released during an extremely high-magnitude flood event. Unless a commensurately large flood event occurs at the same time, however, the sediment first will be flushed by a much smaller flow event and so will not travel far downstream of the dam.

The uncertainty related to these processes is considerable and has 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 (Capelli 2007). The estimated cost for this preferred alternative is US$130M. While principles arising from various strands of geomorphic research provide a broad understanding of the likely morphological changes following dam removal (see Pizzuto 2002), concern over the downstream movement of reservoir sediments still remain a major impediment (real or perceived) in planning for dam removal.

3.3 AN APPROACH TO DAM REMOVAL SEDIMENT MANAGEMENT

Clearly, better understanding of the transport dynamics of the very large pulses of sediment typically released during dam removal would allow resources managers to make better-informed decisions ahead of dam removal. Such understanding would improve predictions of the impact of such sediment releases, the development of appropriate management responses for the potential short-term impacts (and the avoidance of unnecessary expenditures to mitigate for implausible ones), and the specification of necessary pre-removal studies. Two particular aspects of sediment dynamics that recur in the list above include the dynamics of the coarse sediment pulse (*i.e.*, sand and gravel) transported downstream following dam removal (central to numbered issues #3, 4, 7, 10, and 11 above) and the interaction of released fine sediments (silt and clay) with the coarser material on the channel bed (issues #2, 8, 9, and 10).

A significant contribution to the understanding of sediment erosion, transport, and deposition following dam removal has been provided by studies on the behavior of sediment pulses (or waves) introduced into upland rivers following hillslope failures. Based on observations from physical modeling and theoretical explorations, Lisle *et al.* (1997) argued that, when the Froude number is close to unity, which is expected in many mountain rivers during floods, introduced bed material pulses disperse in place by lowering their amplitude in time and expanding their spatial occupancy downstream and also “upstream,” because the pulse produces a backwater that allows sediment transported from upstream to form a deltaic deposit that grows in amplitude and migrates downstream until it eventually joins and becomes part of the sediment pulse (Figure 3-2). Further studies in laboratory flumes, field observations, and numerical explorations indicate that while, in general, the evolution of bed material sediment pulses in rivers exhibits both dispersive and translational characteristics, dispersion always dominates (Lisle *et al.* 2001; Sutherland *et al.* 2002; Cui *et al.* 2002a, b; Cui and Parker 2005; Cui *et al.* 2005a). Under idealized conditions of constant bed slope and channel width, and when the reservoir sediment deposit and downstream bed material have similar grain-size distributions, dam removal should result in the coarse reservoir sediment deposits dispersing downstream (Figure 3-3). The thickness of remaining reservoir sediment deposits should gradually decrease, and the maximum thickness of transported sediment will progressively thin downstream. 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. Figure 3-2 and Figure 3-3).

Overall, there is insufficient dam removal field data available to verify this pulse-based conceptual model and so develop sediment management recommendations based solely on these principles. Instead, we propose an approach in Figure 3-4 that builds on previous management recommendations (ASCE 1997, Randle 2003), field observations, and the insights gained from recent advances in physical and numerical modeling of sediment pulse dynamics outlined below. The approach is intended as a non-prescriptive guide for decision-makers, one that should also assist researchers in prioritizing further studies to advance understanding. The approach should be generally applicable to dam removal, although we emphasize sediment transport issues associated with the release of relatively large volumes of non-cohesive sediment (normally under transport-limited conditions), which is a common situation in parts of the western United States and similar environments.

3.4 UNDERSTANDING CHARACTERISTICS OF THE RESERVOIR DEPOSIT AND DOWNSTREAM REACH

The prospect that dam removal will result in a downstream dispersing sediment pulse has been confirmed in several flume experiments (*e.g.*, Wooster 2002, Cantelli *et al.* 2004) and theoretical studies (Greimann *et al.* 2006). However, the idealized conditions illustrated by Figure 3-3 rarely exist in natural rivers: commonly, the uniform conditions assumed under experimental conditions are replaced by an upward concave longitudinal profile (*i.e.*, reach-averaged channel slope decreases in the downstream direction), considerable spatial variation in local channel width and local channel slope, and a reservoir sediment deposit that is finer than the downstream bed material. Flume experiments (*e.g.*, Lisle *et al.* 2001, Cui *et al.* 2002a) and numerical exploration (*e.g.*, Cui *et al.* 2002b) 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 (Figure 3-5). Consequently, for dam removal projects where the sediment deposit is relatively finer than downstream, the deposit will exhibit a greater overall degree of translational behavior, although dispersion will still dominate (Figure 3-5b).

3.4.1 Grain-size distribution, volume and quality

As indicated by field, flume, and numerical explorations (*e.g.*, Wooster 2002, Doyle *et al.* 2003, Cui *et al.* 2006a), sediment transport following dam removal is particularly sensitive to the grain-size distribution of the reservoir sediment deposit; therefore, characterizing the reservoir sediment deposit is an essential first step in dam removal sediment management. In thick sediment deposits, coring of the sediment deposit to assess grain size characteristics requires a core of up to 100 mm or more in diameter for gravel sediments, the use of ground-penetrating radar in fine sediment, and/or geochronology techniques to date layers in the deposit. 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 deposit can be achieved simply by assuming simple geometric properties to the sediment “wedge” or, alternatively, by scanning the bathymetry of the reservoir deposit (Dudley 2000) and, in GIS, subtracting the pre-dam topography recorded in earlier maps (*e.g.*, Evans *et al.* 2002).

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. Rathbun *et al.* (2005), for example, provided a GIS-based screening approach for assessing potential sediment contamination in dam removal projects as the basis for determining whether sediment sampling and contaminant analysis is needed, and if so, at what intensity. In general, contaminant analysis involves the collection of sediment samples and, as contaminant is usually associated with fine sediment, sampling for potential contaminants should be designed to integrate both the grain-size distribution and contaminant content analyses. Because there can be large variations in grain-size distributions longitudinally, laterally, and vertically, a rigorous sampling procedure is required for grain-size distribution and contaminant content analyses.

Release of contaminated sediment following dam removal can be a serious issue, as demonstrated by the removal of the Fort Edward Dam on the Hudson River, New York (ASCE 1997). This 177-m-long low-head timber crib dam (average height 5.8 m) was removed in September 1973 after 75 years in service. Despite the mechanical removal of approximately 2,400 m^3 of sludge and loose material prior to dam breaching, high levels of PCB contaminants subsequently required the additional downstream excavation of 140,000 m^3 of material to reduce the risks of downstream PCB contamination. The discovery of contaminants in a reservoir deposit need not necessarily prohibit downstream sediment release, however, and the potential impacts can be predicted using numerical models of sediment transport that can simulate the transport and deposition of sediment by grain-size classes. Cui and Parker (1999), for example, simulated the transport of mine-derived sediment by grain-size classes, the result of which was given to environmental scientists to evaluate the potential consequences of copper contamination in the watershed. Examples of reservoir sediment sampling for analysis of grain-size distributions and contamination can be found in Dudley (2000), Squire Associates (2000), Evans *et al.* (2002) and Snyder *et al.* (2004).

3.4.2 Channel morphology downstream of the dam

Analyses of the risks related to flood hazard, downstream transport and evolution of the sediment pulse, and potential adjustments in the channel downstream of the dam require information about the channel morphology well downstream of the dam. Characteristics including channel gradient and channel cross sections are important controls on the capacity of sediment transport under a given discharge and sediment grain-size distribution. In the study for the removal of Marmot Dam on the Sandy River, Oregon, for example, channel gradient (river longitudinal profile) was acquired using photogrammetry (use of LIDAR data would be an alternative), and channel cross sections were simplified as rectangles, with the channel width read from high-resolution aerial photographs. Such resolution was appropriate in this case because (a) the Sandy River is primarily a canyon river, confined with high terraces and limited floodplains; and (b) reach-averaged sediment transport models require only an approximation of channel width instead of detailed channel cross sections (see below). Where extensive low-lying floodplains are prevalent, more detailed surveys that include the elevation and width of floodplains may be required in order to better quantify sediment transport processes following dam removal.

3.4.3 Reach sediment budget

Although the volume of sediment released immediately following dam removal is probably far greater than the volume of the upstream sediment supply during the same period, even a rough estimate of that upstream supply can be extremely useful. First, for reservoirs that are still trapping bedload, the downstream reach has in all likelihood incised during the dam's operation and bed elevation recovery to a condition close to the pre-dam period will occur following dam removal. Through one-dimensional numerical simulation, the estimated upstream sediment supply can be used to approximate the post-dam removal downstream geomorphic condition following export of the majority of the reservoir sediment deposit. Second, in cases where the reservoir is full of sediment and bedload has been passing through the dam to the downstream reach for many years, the estimated upstream sediment supply can be used to calibrate a numerical model so that it produces the current channel condition under the recorded hydrologic conditions and estimated sediment supply (see Stillwater Sciences 2000a). Third, the relative volume of the sediment deposit versus the volume of sediment expected to be transported in moderate flood events can be used to judge whether the reservoir deposit is "significant" in physical terms, and whether the downstream release of sediment is worthy of further detailed study. Because a sediment deposit may also be "significant" in terms including potential contamination or biological effect, a deposit that is insignificant in purely physical terms may still require sediment transport analysis to help determine these other concerns.

Evolution of a channel through the reservoir sediment follows a broadly predictable trend. The channel first propagates headward by narrow incision followed by channel widening (Doyle *et al.* 2003), similar to generalized channel responses to channelization (*e.g.*, Schumm *et al.* 1984, Simon 1989) but with specific responses conditioned by the size, cohesiveness, and consolidation of the sediment deposit. A similar response was observed in a flume experiment simulating the evolution of a coarse-grained sediment deposit in a confined river setting (Wooster 2002) and in other flume experiments (Cantelli *et al.* 2004). Channel widening follows rapid incision and will ultimately be controlled by the channel gradient when the reservoir deposit reaches a relatively stable value (Cui *et al.* 2006a, b). Eventually, channel width (and cross-section dimensions) should approach those of the channel downstream of the dam (see Cui and Wilcox 2008, with evidence from a dam failure in Town Creek, California and a dam removal in Clear Creek, California). Thus, the initial release of reservoir sediment following dam removal is probably restricted to a channel of similar dimensions to the river reach downstream of the dam, and tests have indicated that reservoir channel dimension is not a particularly sensitive parameter in determining downstream sediment deposition (Cui *et al.* 2006a).

3.5 ESTIMATING FLOOD RISK

There are several components to the downstream flood risk that relate to sediment management in the removal of large dams (Figure 3-4). In particular, where a reservoir is not full of sediment, the removal of significant reservoir water storage capacity will greatly reduce the reservoir's attenuation effect on incoming flood events and so standard hydrologic and/or hydraulic analyses will be required to document changes in flood frequency and elevation following dam removal. Second, both temporary and permanent changes in channel bed elevation following dam removal will determine flood risk, as the bulk of the coarse sediment disperses.

3.6 EVALUATING CONSTRAINTS 1: REACH-SCALE TRANSPORT AND DEPOSITION CHARACTERISTICS OF SEDIMENT PULSES

3.6.1 Numerical modeling

The most useful tool currently for understanding the evolution of reservoir sediment deposits following dam removal over spatial and temporal scales that are meaningful for assessment is a one-dimensional numerical simulation that predicts reach-averaged channel responses. Studies of sediment pulse dynamics have been adapted for simulating sediment transport following dam removal (summarized in Cui and Wilcox 2008), resulting in two models, Dam Removal Express Assessment Models (DREAM) 1 and 2, specifically designed to simulate sediment transport following dam removal with predominantly non-cohesive fine (*i.e.*, silt) and coarse (*i.e.*, sand and gravel) sediment, respectively (Cui *et al.* 2006a, b).

Of particular note, the role of particle attrition in reducing reservoir sediment particle grain size while transporting it downstream may be another important characteristic of sediment pulse behavior following dam removal and needs to be explicitly accounted for in numerical modeling efforts. Attrition caused by particles colliding with each other and with the channel bed (*e.g.*, Sternberg 1875) 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 because of the large volumes of coarse sediment available for transport and the long reach of potential impact (Parker 1991a, b; Parker and Cui 1998; Cui and Parker 1998, 2005). Incorporating particle attrition into numerical models of sediment transport is important for modeling long river reaches where attrition both reduces the grain size of bedload particles (allowing bedload transport at higher rates), and converts part of the bedload to suspended load, thus reducing the overall bed material to be transported (Cui *et al.* 2006a, b).

The input parameters for one-dimensional sediment transport models for dam removal include: (a) volume and grain-size distribution of the reservoir sediment deposit; (b) longitudinal profile and channel cross sections for the reach downstream of the dam; (c) surface grain-size distribution and grade control locations downstream of the dam; (d) an estimate of the typical flow regime that will follow dam removal; (d) a rough sediment budget for the watershed, and (e) preliminary engineering designs for the proposed removal. There is now a growing body of literature detailing the application of one-dimensional sediment transport numerical modeling as preparation for dam removal including four 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, 2002; Cui and Wilcox 2008); Saeltzer Dam on Clear Creek, California; dams on the Klamath River, California (Stillwater Sciences 2004, Cui *et al.* 2005b); and San Clemente Dam on the Carmel River, California (Mussetter and Trabant 2005). Several case studies using DREAM-1 and -2, and the early versions of sediment pulse models are provided below, illustrating the utility of the approach under conditions of different baseline data availability.

Marmot Dam is a 14-m-tall concrete dam on the Sandy River, Oregon approximately 48 km upstream of its confluence with the Columbia River. Sediment had deposited to the elevation of the dam crest many years before 1999, when Portland General Electric (PGE) decided to decommission the dam. Based on sediment coring 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 of primarily gravel, coarser sediment, and some sand (Squire Associates 2000). The sediment pulse model of Cui and Parker (2005) was modified to include the transport of both gravel and sand to simulate sediment transport following dam removal under several removal alternatives and hydrologic conditions (Stillwater Sciences 2000a, Cui and Wilcox 2008). Modeling predicted the thicknesses of gravel and sand deposition and the suspended sediment concentration along the river within the next 10 years following dam removal (Figure 3-5), which was used by geomorphologists, fisheries biologists, and ecologists to interpret the potential ecological impact (Stillwater Sciences 2000b).

Overall, the reservoir sediment deposit was predicted to evolve as a dispersive wave, bypassing some of the high transport capacity reaches (*e.g.*, most of Reach 2 in Figure 3-6, and downstream of Reach 3), and depositing in the relatively wide reaches farther downstream. The predicted suspended sediment concentration was only moderately high (typically an increase of less than 200 ppm with short spikes of less then 500 ppm) and decreased with time and distance downstream. Sensitivity tests indicated that a staged dam removal that included dredging between 13% and 30% of the sediment deposit would not significantly alter deposition patterns compared to a single-season removal with minimal dredging.

The results provided by the analyses helped PGE, the regulating agencies, and other stakeholders to agree on a removal alternative to allow almost all the reservoir sediment deposit to be transported downstream by flow alone. Dam removal commenced in July 2007 and transport of sediment from the reservoir deposit began on 19 October following coffer dam breaching during the first high flow event in the winter of 2007. Anecdotal accounts of the first few days of sediment transport following coffer dam breaching indicated fast initial incision of the reservoir sediment (G. Grant, *pers. comm.*, 22 October 2007), similar to early numerical model predictions (Stillwater Sciences 2000a, Cui and Wilcox 2008).

J.C. Boyle, Copco (1 and 2), and Iron Gate dams are the four downstream-most dams on the Klamath River in Oregon and California. Relying on available data and a one-day reconnaissance field trip, a preliminary DREAM-1 modeling exercise was conducted to evaluate whether significant channel aggradation would occur downstream of Iron Gate Dam, the downstream-most of the four dams, if the dams were removed (Stillwater Sciences 2004, Cui *et al.* 2005b). Through a series of worst-case-scenario assumptions to accommodate existing data gaps, the study predicted that minimal channel aggradation would occur within a short distance downstream of Iron Gate Dam, despite an estimated 12 million m^3 of sediment deposited behind the four dams. This outcome resulted from the fine texture of the sediment in the reservoirs, high channel gradients downstream of the dam, extensive channel confinement downstream of the dam, and relatively large discharges in the river throughout the year. Consequently, it appears that even limited information in combination with professional judgment can assist resource managers in making potential dam removal decisions.

3.6.2 Suspended sediment and turbidity

The release of reservoir sediment following dam removal will likely result in a temporary increase in suspended sediment and turbidity (Table 3-2). The occurrence, duration, and magnitude of elevated suspended sediment concentrations and turbidity following dam removal is largely a function of the grain-size distribution of the reservoir sediment deposit, hydrologic conditions following dam removal, and channel width and gradient downstream of the dam. For reservoir sediment deposits composed primarily of coarse sediment (gravel and coarser), one-dimensional numerical models (*e.g.*, Cui *et al.* 2006a, b; Cui and Wilcox 2008) indicated that high total suspended sediment concentrations (TSS) will be limited to a short period of time following dam removal, and then episodically thereafter during flow events of sufficient magnitude to mobilize the coarse sediments. Higher suspended sediment concentrations and turbidity will occur from fine sediment deposits (*i.e.*, sand and finer); 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 flow discharges, leading to expectations that suspended sediment concentrations would be far greater at higher flows. Because of the lack of corroborating field measurements, data presented in Table 3-2 are a first approximation and numerical modeling data and or drawdown experiments will remain necessary in dam removal projects until comparable field measurements are available.

Table 3-2. 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 (R.W. 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.	Predicted increase in TSS concentration is generally within 500 ppm, which occurs episodically and decreases over time.

Project	**Data Source**	**Reservoir Sediment**	**Suspended Sediment**
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.

3.7 EVALUATING CONSTRAINTS 2: SEDIMENT PULSE MOVEMENT THROUGH A POOL-BAR MORPHOLOGY

3.7.1 Physical modeling

Despite the utility of reach-averaged one-dimensional sediment transport models in simulating the effects of dam removal, such models cannot predict the lateral distribution of sediment deposits, details related to the filling and scouring of pools, and the evolution of topographic features such as alternate bars and pool-riffle complexes. A practical alternative is to use scaled physical models that attempt to answer a specific project question (*e.g.*, Bromley and Thorne 2005), and flume experiments to inform general principles. The majority of the results described in the following sections are drawn 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.

Flume experiments were conducted in 2005 and 2006 to examine sediment pulse movement and morphologic response in a degraded gravel-bedded channel with pool-riffle morphology. The experimental bed was constructed with a pool-bar topography, forced by the placement of sand bags and cobble-sized stones spaced five channel-widths apart on alternate sides of the flume. During the initial experimental set-up, a quasi-equilibrium channel that was degraded and armored was created, similar to those observed downstream of large dams, by eliminating the sediment supply to a flume channel at equilibrium (see Wooster *et al.*, *in prep*., and Cui *et al.*, *in press* B, for detailed experimental set-up). While flow remained constant, fine and coarse sediment pulses were fed into the flume at different feed rates and durations to observe sediment-pulse evolution and morphologic-unit response. A total of six runs were conducted: two coarse-sediment pulse runs, and four fine-sediment pulse runs. Three of those runs were designed as large-volume pulses intended to model sediment release after dam removal.

Both small and large fine sediment pulses moved rapidly through the system at similar speeds through a combination of translation and dispersion (Wooster *et al.*, *in prep*.). The previously armored gravel bed was also mobilized, resulting in a net loss of stored sediment along the channel once the fine pulse exited the system. Coarse sediment pulses evolved more slowly through the system, primarily by dispersion which induced a sustained increase in channel slope along the flume. Coarse material also deposited in lobes at pool tails and bars, which forced localized scour. By experiment completion, fine pulses left minimal topographic signature on the bed other than slight channel degradation, whereas coarse 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 (Figure 3-7). On the scale of a pool-bar-riffle sequence, pools initially had the highest magnitude and variance in bed elevation change (Figure 3-7). Pools did not ubiquitously fill with sediment, but 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 coarse experiments, bars retained sediment the longest. Based on variogram analyses of high-resolution bed images, the large fine-sediment pulse decreased topographic complexity from one pool tail to the next. Bed topography quickly returned to pre-pulse levels, however, once the pulse passed through a reach. Conversely, the large coarse-sediment pulse increased the streamwise topographic heterogeneity and this variance was maintained after the bulk of the pulse passed through a reach (primarily due to remnant deposits along bars and localized scour created by sediment lobes as the pulse moved downstream).

3.7.2 Representing complex pulse movement using numerical models

DREAM-1 and DREAM-2 numerical models were used to simulate these flume experiments (Cui *et al.*, *in press* B). Both DREAM-1 and -2 adequately reproduced the observed evolutionary process of the sediment pulses on a reach-averaged basis (*i.e.*, bed elevation averaged over a longitudinal distance of one pool-riffle sequence) and the measured sediment fluxes, without or with only minimal model calibration. The cumulative sediment transport at the flume exit in a DREAM-1 simulation is within 10% of the measured values, and cumulative sediment transport at flume exit in a DREAM-2 simulation is within a factor of two of the measured values. Comparison of simulated and measured reach-averaged aggradation and degradation indicates that 84% of the DREAM-1 simulation results have errors less than 3.3 mm, which is approximately 77% of the bed material geometric mean grain size while 84% of DREAM-2 simulation results have errors less than 7.0 mm, which is approximately 1.7 times the geometric mean grain size of the bed.

Although providing successful predictions of sediment pulse evolution on a reach-averaged basis, these one-dimensional numerical models were not capable of simulating the detailed channel responses at the morphological unit (Cui *et al.*, *in press* B). This shortcoming reinforces earlier acknowledgment that one-dimensional sediment transport models are best utilized at large spatial and temporal scales (Cui and Parker 1999, Sutherland *et al.* 2002, Cui and Wilcox 2008, Bountry and Randle 2001).

3.8 PREDICTING IMPACTS 3: FINE SEDIMENT INFILTRATION INTO COARSE BED SEDIMENT

The rapid release of a large volume of accumulated fine sediments is a primary concern in dam removal projects, even from coarse reservoir deposits in gravel-bedded rivers. 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.

Field and flume observations indicate that fine sediment particles do not infiltrate below a certain depth in a gravel-bedded river (Beschta and Jackson 1979, Frostick *et al.* 1984, Diplas and Parker 1985, Lisle 1989). However, the specific influence of bed-particle size distribution on the infiltration of fine sediment is poorly quantified. The rate and duration of the fine sediment release surely also affect the extent of fine sediment infiltration into bed sediments, but this has not been well-studied.

3.8.1 Theoretical analysis

Cui *et al.* (*in press* A) described fine sediment infiltration into coarse sediment deposits based on mass conservation and relevant physical processes. They reasoned that the fine sediment trapping coefficient, defined as the volumetric fraction of fine sediment trapped in the deposit per distance traveled, is either independent of fine sediment fraction (FSF) within the deposit or increases monotonically as FSF increases. Their solution indicates that the equilibrium FSF should decrease exponentially with depth into the deposit following fine sediment infiltration. If the trapping coefficient increases progressively as fines plug the interstices, then fine sediment penetrates even less deeply. Cui *et al.* (*in press* A) also found that the process of intra-gravel-driven fine sediment infiltration behaves similarly to gravity-driven fine sediment infiltration (unlike the assumptions of Sakthivadivel and Einstein 1970), resulting in fine sediment sealing the near-surface layer and preventing further infiltration into the depth of the deposit (Figure 3-8).

3.8.2 Flume experiments

Wooster *et al.* (*in press*) conducted three runs of 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 sediment. The amount of fine sediment infiltrated into the deposit decreased once the rate of fine sediment supply increased up to a certain level. They reasoned that rapid surface fine-sediment deposition limited the interaction between the fine sediment carried in the water column and the subsurface deposit. This suggests that a quick sediment release following a dam removal may reduce fine sediment infiltration.

Experimental data analyses also provided data on fine-sediment infiltration that could be compared directly to model results. Comparison between the exponential decay function and weighted-averaged experimental data provided a root mean square error of 7.3% of the predicted saturated FSF value, indicating a good agreement. Substantial fine sediment infiltration occurs only to a few gravel diameters deep into clean immobile gravel deposits. For silt infiltrating a gravel deposit already saturated with sand, substantial infiltration occurs to a depth of only a few sand diameters. The two relations suggest that significant fine sediment infiltration can potentially occur only to very shallow depths in the channel bed (Figure 3-9). It also suggests that a rapid release of fine sediment following dam removal has the potential advantage over a slow release for an extended period, because it allows the fine sediment source to transport away quickly, and subsequent flows to transport fine sediment previously deposited on the surface of (and at shallow depths into) the channel-bed sediment.

3.9 SELECTING THE DAM REMOVAL ALTERNATIVE

Resource managers require a preferred dam removal alternative (Figure 3-4) based on numerous factors intimately related to the dynamics of downstream sediment transport, including the implications for biology, ecology, near-channel infrastructure, flood risk, and other factors (Figure 3-4). Common options that allow the sediment deposit to be transported downstream include “one-shot” removal, whereby the dam is removed in a single season, or a staged dam removal process that progressively lowers the dam crest over several years to meter out the stored sediment. In cases where fear over the consequences of sediment release persist, active sediment management may be pursued, including mechanical excavation of the reservoir sediment deposit before dam removal, re-routing of the river channel around a stabilized reservoir sediment deposit with the dam either removed or left in place, and stabilizing the deposit prior dam removal using engineering means.

Frequently, one-shot dam removal is feared by resources 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. However, one-shot dam removal has the advantage of generally being the most cost-effective approach, especially when the sediment will be eroded rapidly (*e.g.*, Gathard 2005) and, in comparison to the staged approach, will minimize the period of impact from sediment release. For instance, in planning the removal of Marmot Dam on the Sandy River, Oregon, numerical sediment transport models indicated that more expensive, staged removal provided no benefit in terms of downstream sediment deposition over the one-shot case (Stillwater Sciences 2000a); ultimately, the one-shot approach was employed in July 2007. Further research on the relative ecological impacts and flood-risk advantages of each method would have enormous benefits for planning dam removal projects.

In other cases, sediment management procedures may be employed to reduce or prevent downstream transport of the reservoir sediment deposit (see discussion in ASCE 1997). Mechanical excavation is most likely to be favored in cases where contaminant pollution of the deposit may result in ecological consequences. However, the approach involves greatly increased project cost due to sediment transportation, selecting appropriate disposal sites, and managing traffic flow and noise. Mechanical excavation also reduces potential long-term benefits to downstream ecosystems of sediment release. Multi-year mechanical sediment removal probably cannot match the level of sediment supply during the high flow season in rivers with high sediment supply. In our Marmot Dam removal study, numerical simulation indicated that dredging 13% of the 750,000 m^3 of reservoir sediment deposit, which is the maximum possible dredge volume during one dry season, would only slightly reduce the amount of downstream sediment deposition and would not alter the downstream depositional pattern compared with a one-shot dam removal option (Stillwater Sciences 2002). Rerouting the river channel to bypass flows around the sediment deposit also addresses downstream sediment pulse concerns, but is only an alternative if geological and topographic conditions allow for such an option, and other social, economic, and ecological issues can be avoided.

A third prospect is on-site engineering stabilization of the reservoir deposit, letting it dry, and encouraging vegetation growth to prevent downstream transport. This can be an effective option for low-head dam removal projects (see Graber *et al.* 2001), but for relatively high dams any long-term stabilization may be compromised as the channel eventually incises through the deposit in order to achieve its preferred gradient. Therefore, stabilization may be more successful in projects when the dam is only partially removed, or the channel also re-routed. In some approaches, especially those in populated settings, concerns for channel adjustment after dam removal have prompted highly structural engineering approaches, such as at Goldsborough Creek Dam, Washington, where the dam was replaced by 36 structural weirs, boulders, large wood installation, revegetation of the channel banks, and bioengineered bank protection (Fullerton *et al.* 2005).

3.10 MONITORING AND EVALUATION

Dam removal is one of a suite of river management measures often intended, at least in part, to provide environmental benefit. Therefore, a series of pre- and post-project monitoring steps are required to document the benefits achieved and to learn from the project (Downs and Kondolf 2002). A sequence of monitoring-related activities derived from adaptive management best practice is provided in Figure 3-4. Three particular objectives for a post-dam removal monitoring program include (1) monitoring the evolution of the eroding reservoir sediments and downstream sediment deposition to see if there are significant deviations from the predicted impacts that require corrective actions; (2) determining when certain responsibilities of the dam owners can be terminated following the achievement of project goals; and (3) increasing understanding of dam removal sediment dynamics and the associated biological and ecological effects so that the knowledge gained from the project can be used elsewhere. Unfortunately, smaller dam removals and those at privately-owned dams have frequently gone unmonitored (Bednarek 2001), continuing to 'mystify' the impacts of dam removal.

3.11 LESSONS FOR DAM REMOVAL PROJECTS

This integration of recent literature, advances in numerical modeling, and physical modeling experiments illustrates recent improvements in the understanding of the downstream dynamics of sediment pulses and fine sediment infiltration into coarser bed material. Such understanding provides basis both for a generic approach to managing sediment releases downstream of dam removal projects (*e.g.*, Figure 3-4) and also for addressing some of the perceived short-term impacts of dam removal. These responses are outlined below in relation to the potential impacts on water resources, hazard avoidance, and river conservation (with a focus on aquatic habitats).

Water resources impacts. The potential impacts on water quality and on the conductivity of infiltration galleries are closely linked to the details of fine sediment release. 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 partially filled with sand, the primary concern is the extent of surface deposition during the primary fine sediment release. This implies a trade-off between managing for a rapid or progressive release of fine sediments. Rapid release following a single-season dam removal potentially causes high concentrations of suspended sediment and significant fine sediment deposition across the channel bed but will be short-lived, potentially for weeks or less depending on the amount of reservoir deposit, the channel gradient, and the flows following dam removal (Cui *et al.* 2006a). Conversely, metering out sediment during staged dam removal may reduce the initial depth of fine sediment deposition, but it will probably prolong the period of excess fine sediment in the bed. Because fine sediment is highly mobile, opportunities may exist for reducing fine sediment impacts by flushing fine sediment, using prescribed flow releases from regulating dams farther upstream, where they exist. The most beneficial strategy will depend on details of the remaining regulating structures and the hydroclimate of the river system. With regard to potential adverse impacts on river morphology near points of surface water flow abstraction, laboratory experiments with coarse sediment pulses (Wooster *et al.*, *in prep*.) indicate that the most likely site for conflict would be where deposition occurs in a pool tail that also serves as the abstraction point.

Hazard avoidance. Removing a dam that retains significant water storage will change the flood frequency curve, requiring a new 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. If channel aggradation is predicted to last for only one season following dam removal, however, providing a modified flood analysis with a 100-year recurrence interval flow will probably overestimate potential flooding risks. Furthermore, increases in flood stage are usually less than the full vertical extent of aggradation for several reasons: (a) channel cross sections become wider with aggradation, (b) channel gradient generally increases in reaches of significant aggradation, and (c) channel aggradation with reservoir sediment reduces the roughness of the channel bed.

River conservation. Concerns over the short-term impacts of dam removal frequently focus on the effects on aquatic habitat. Experimental data should be tied more closely to biological studies and monitoring to ascertain short-term biological responses. In this regard, flume experiments with a forced pool-bar morphology clearly provide a greater utility than reach-averaged sediment transport modeling and show promise to progressively replace "best professional judgment" with empirical results as the basis for predicting the ecological impact of dam removal. Generally, for coarse sediment, annual channel adjustment will be gradual, thus limiting the severity of annual changes in ecological conditions downstream even in the immediate vicinity of the dam. However, the total time for the channel morphology near the dam to recover from the passage of a coarse sediment pulse can be great (where the ratio of the reservoir deposit volume to flow transport capacity is high). Also, staged dam removal does not appear to provide the expected benefits of reduced sediment deposition over the single-season, "one-shot" alternative (Cui *et al.* 2006a), primarily because the dynamics of downstream coarse sediment release is self-regulated by the distal fan-delta that forms from the eroding reservoir sediment deposit. For fine sediment deposits, where the impact on aquatic habitats from surface sediment deposition and elevated suspended sediment levels can be large but potentially very short-lived, staged dam removal significantly reduces the magnitude of short-term sediment deposition but at the cost of a greatly-extended impact duration (Cui *et al.* 2006a).

Because coarse sediment aggradation is generally a progressive phenomenon and experimentally quite uniform across riffles, concern for the burial of high-quality salmonid spawning habitat immediately below a dam in the zone of maximum probable coarse sediment dispersion may be warranted only in the first season after dam removal. Following the first year, assuming that the fish use the new gravel, dispersion of coarse sediment by high flows will cause this zone of maximum impact to shrink annually. Therefore, the primary risk to salmon redds after the first year may occur where annual erosion of the sediment pulse exceeds the depth to which eggs are laid. Two factors reduce this risk. First, dam removal should provide access to spawning habitat upstream of the former dam, reducing over time the proportion of spawning that occurs downstream of the former dam site. Second, the increased gradient of the primary dispersion reach may modify flow velocities so they are no longer optimal for salmon spawning, displacing spawning activity to locations farther upstream and downstream. This phenomenon, although plausible, clearly requires field verification.

From physical and theoretical explorations, adverse impacts to salmonid eggs and alevins and reductions in macroinvertebrate production are most likely where 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, this risk may be most significant in reaches below the dam site that have previously been augmented by well-sorted spawning gravel. Potentially, the significant short-term impact of fine sediment deposition in some reaches below the dam may be offset in other reaches farther downstream, as previously static and embedded coarse sediment is remobilized following de-regulation of river flows. This process represents the beginning of the long-term benefit of dam removal in reducing the relative embeddedness in coarse-bedded rivers. Likewise, the rapid passage of fine sediment, especially if released as one pulse, in combination with increased mobility of the coarse sediment fraction should reduce the interval of concern for fine sediment impacts on eggs and alevins, and allow invertebrate populations to recover rapidly

Pulses of either coarse or fine sediment can produce impacts to aquatic holding and rearing habitats. Flume experiments with a forced pool-bar morphology suggest that fine sediments will pass rapidly across all morphological features in the confined reaches where high dams are normally constructed. The rapid passage of sediment leaves little topographic imprint and so raises little concern, even in the short term. In river systems with additional upstream regulation, however, this may not be the case and prescribed high flow releases may be necessary to reduce fine sediment impact. Coarse sediments pass more slowly through a reach with forced pool-bar morphology and will initially deposit in pool tails. This deposition causes pool-bed elevations to rise more rapidly than the surrounding bed in the reach previously degraded during dam operation. Physical modeling suggested that these increases in pool-bed elevation were soon matched by elevation increases in the surrounding morphological elements, resulting in little net change (Wooster *et al.*, *in press*). Whether initial deposition in the pool tail is important may depend on whether the existing pools were originally scoured deeper following dam closure, in which case a temporary decrease in pool depth may not adversely impact native fish species. The roughly equitable morphologic changes in the forced bar-pool experiment also suggest that no significant loss in aquatic habitat complexity will occur to compromise upstream movements of fish. An exception to this situation may exist, however, if base flows remain low and highly regulated through upstream flow controls.

3.12 CONCLUSIONS

Management of various aspects of the sediment pulse released following dam removal is the single largest environmental issue for dam removal projects. Numerous river management concerns are intrinsically linked to the short-term dynamics of the pulse, and there is enormous cost variability across the suite of available sediment management options. In general, a "one-shot" dam removal, in which the reservoir sediment is progressively transported downstream over the course of a single high-flow season, will be the cheapest option for large dams and probably of greatest long-term environmental benefit. Active sediment management options, either the mechanical removal of the sediment or sediment stabilization using structural engineering approaches, will be the most expensive and may require additional long-term maintenance. Developing sediment management strategies for dam removal is largely a question of whether the short-term behavior of the released sediment creates sufficient risk to other river management objectives that it cannot be allowed. Recent developments in our understanding of sediment pulses from physical and numerical modeling indicate that there are trade-offs in impacts implicit to a staged dam removal relative to single-season dam removal; *i.e.*, staged dam removal is not inherently the "preferred" alternative. Such preconceptions should be carefully analyzed, and we offer new results and a conceptual framework in which to do that.

Because the study of the effects of dam removal is still in its infancy, field monitoring is inadequate to reliably predict the specific level of risk associated with the downstream transport of a sediment pulse. Numerical and physical modeling is needed to reduce some of the uncertainties involved in these predictions. Recent advances in one-dimensional numerical modeling of sediment-pulse behavior provide a simple and apparently reliable means of determining the downstream impact of a migrating sediment pulse on a reach-averaged and average-annual basis. However, many of the risk assessment questions related to specific details of the sediment pulse can currently be addressed only through professional judgment, and so there remains a great need for both flume experiments and scaled physical models to answer questions of engineering, biology, and ecology related to the two- and three-dimensional aspects of water resource, hazard avoidance, and river conservation concerns. Furthermore, flume experiments assist in calibrating and verifying numerical models and so provide greater 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.

Integrating recent investigations with prior studies has allowed us to propose a framework for assessing the sediment management challenges inherent to dam removal projects. This framework is intended as a starting point rather than as a prescription: each project is likely to have specific nuances demanding attention to factors that cannot be covered as generalities. The framework as described focuses attention on the likely data needs and analytical options in assessing the impacts of a dam removal project. In addition to numerical and physical modeling, pre- and post-project monitoring and evaluation will improve the empirical database available to inform future practice and is a vital part of learning. Together, these analyses will provide a focus for decreasing the uncertainties associated with dam removal sediment management, and prompting future research questions into aspects of the downstream transport of sediment pulses that are not yet well-predicted.

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3.15 FIGURES

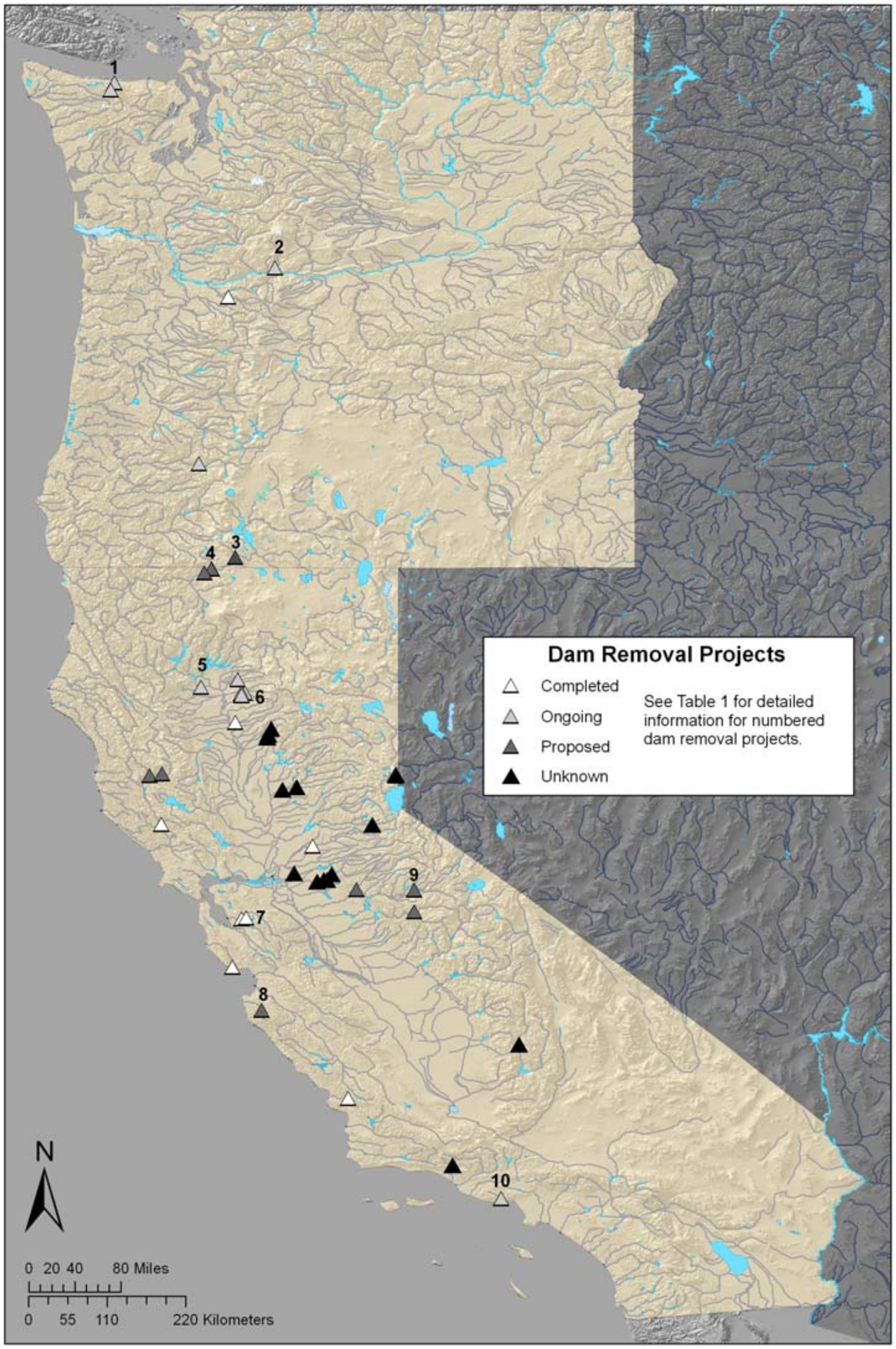

Figure 3-1. Locations of dam removal projects in Washington, Oregon, and California, USA.

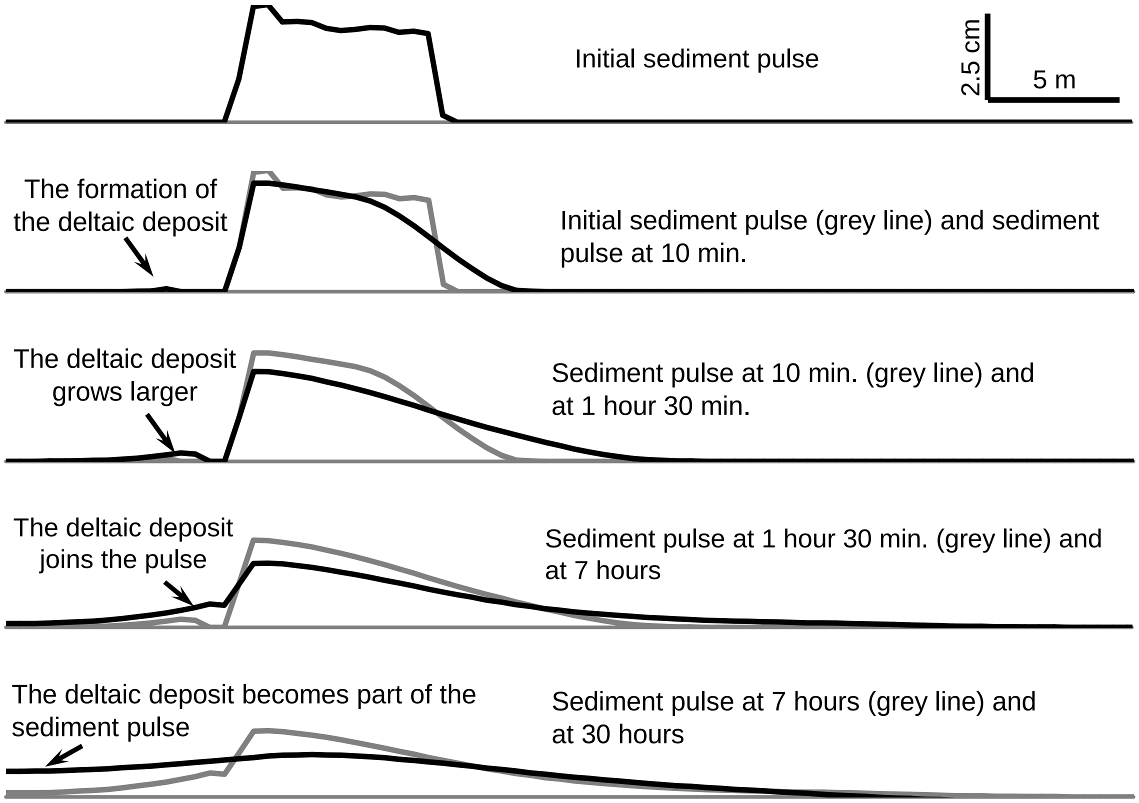

Figure 3-2. Simulated evolution of a sediment pulse in a laboratory flume, demonstrating the formation of a deltaic deposit upstream of the sediment pulse, which subsequently joins the sediment pulse and results in the upstream dispersion of the sediment pulse. Observed sediment pulse evolution in the flume was similar to the numerical simulation and is not provided here. Details of the flume experiments and numerical simulations can be found in Cui *et al.* (2003a,b). This diagram is adapted from Figure 9 in Cui *et al.* (2003b).

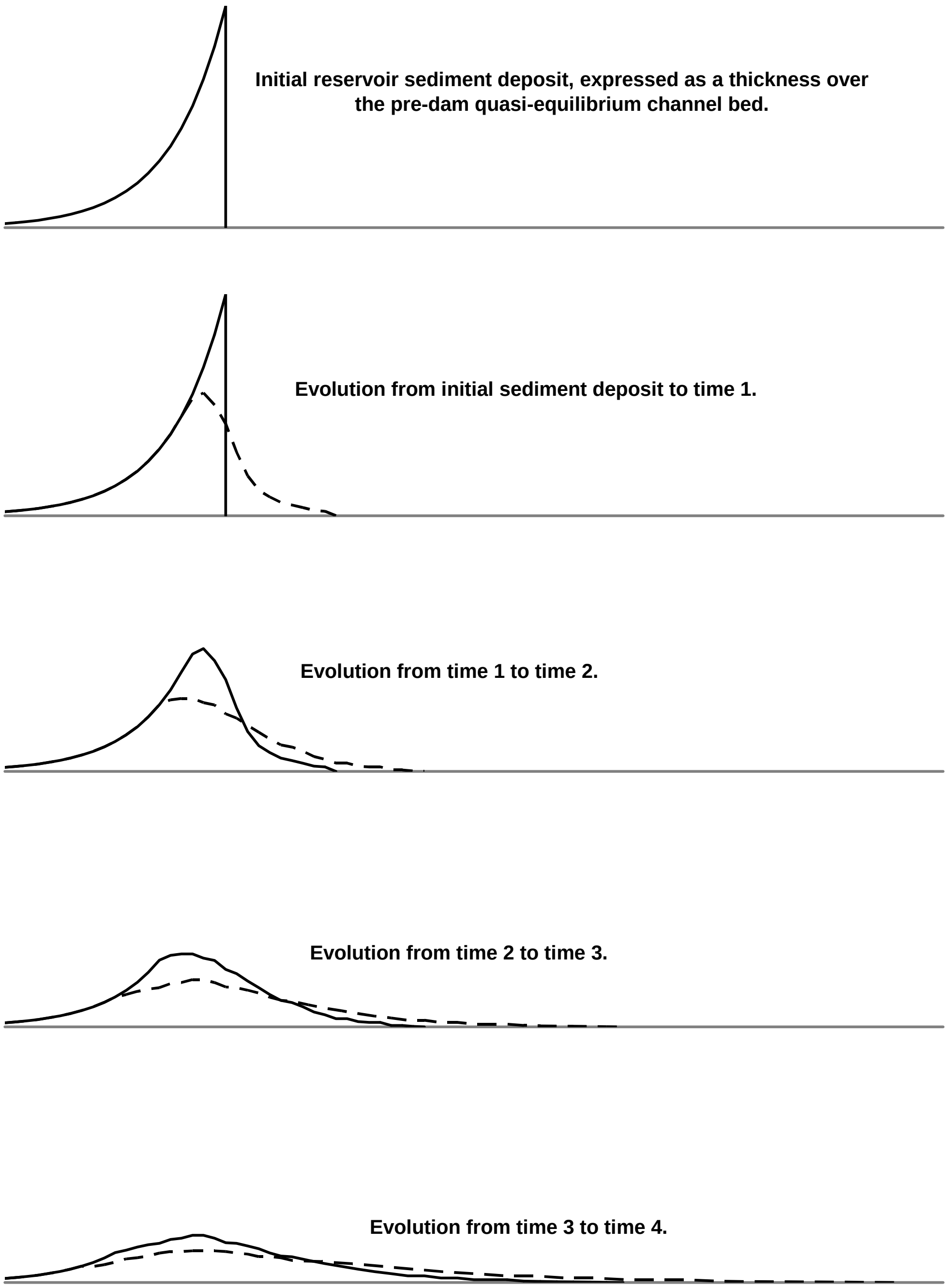

Figure 3-3. A sketch demonstrating the evolution of reservoir sediment deposit following dam removal under an idealized condition (*i.e.*, constant slope and constant channel width, reservoir sediment deposit is similar to downstream sediment in grain size). Because reservoir sediment deposit was formed over a long-period of time following dam construction, it can be expected that no upstream dispersion will be observed following the reduced backwater effect from the removal of the dam. Other than the absence of upstream dispersion, the evolution of the reservoir sediment deposit is identical to the evolution of a sediment pulse demonstrated in Figure 3-2.

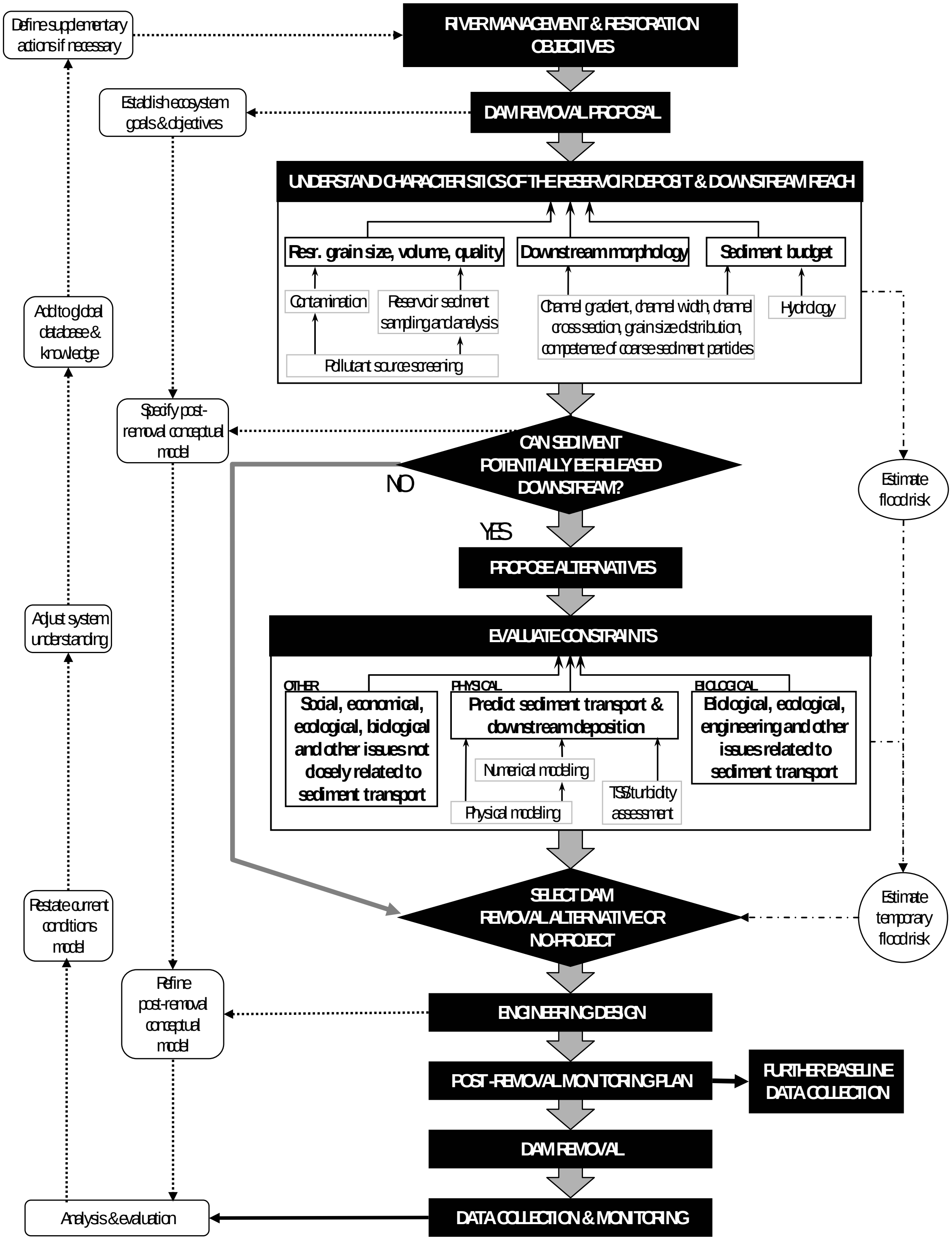

Figure 3-4. A framework for sediment management analysis in dam removal projects.

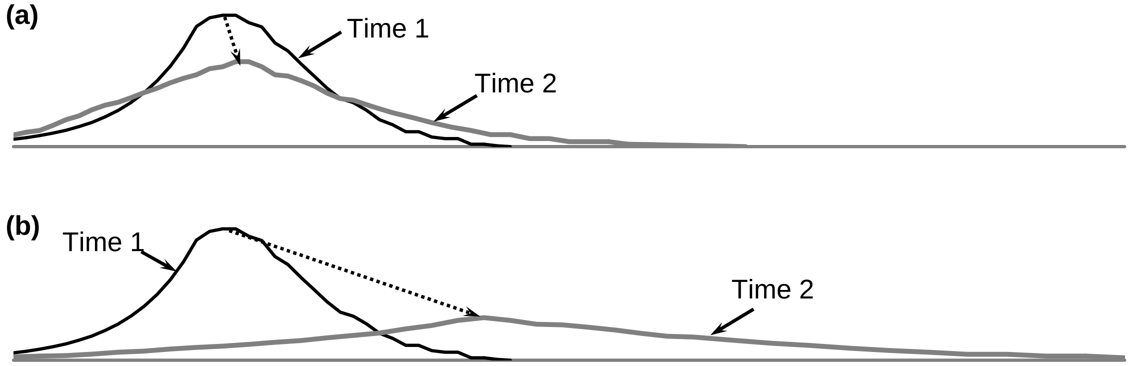

Figure 3-5. Sketches demonstrating the effect of pulse sediment grain size distribution on the evolution of sediment pulse; the dashed lines with arrows indicate the changes in pulse apex location: (a) the evolution of a sediment pulse with sediment grain size similar to that of downstream bed material; and (b) the evolution of a finer sediment pulse.

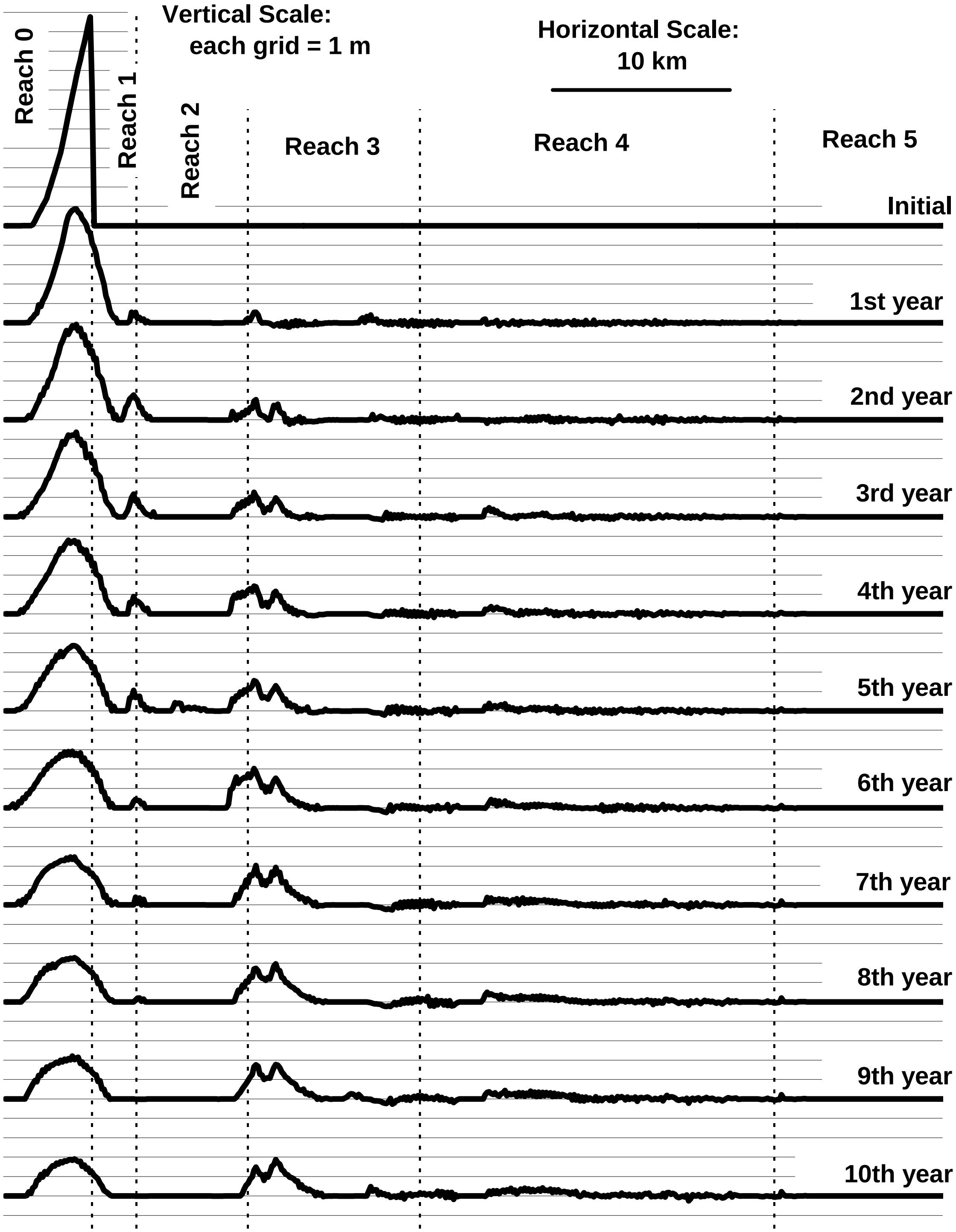

Figure 3-6. Simulated erosion of reservoir sediment and sediment deposition downstream of the dam in the Sandy River, Oregon following the removal of Marmot Dam. This diagram is a reproduction of Figure 23-15 in Cui and Wilcox (2008).

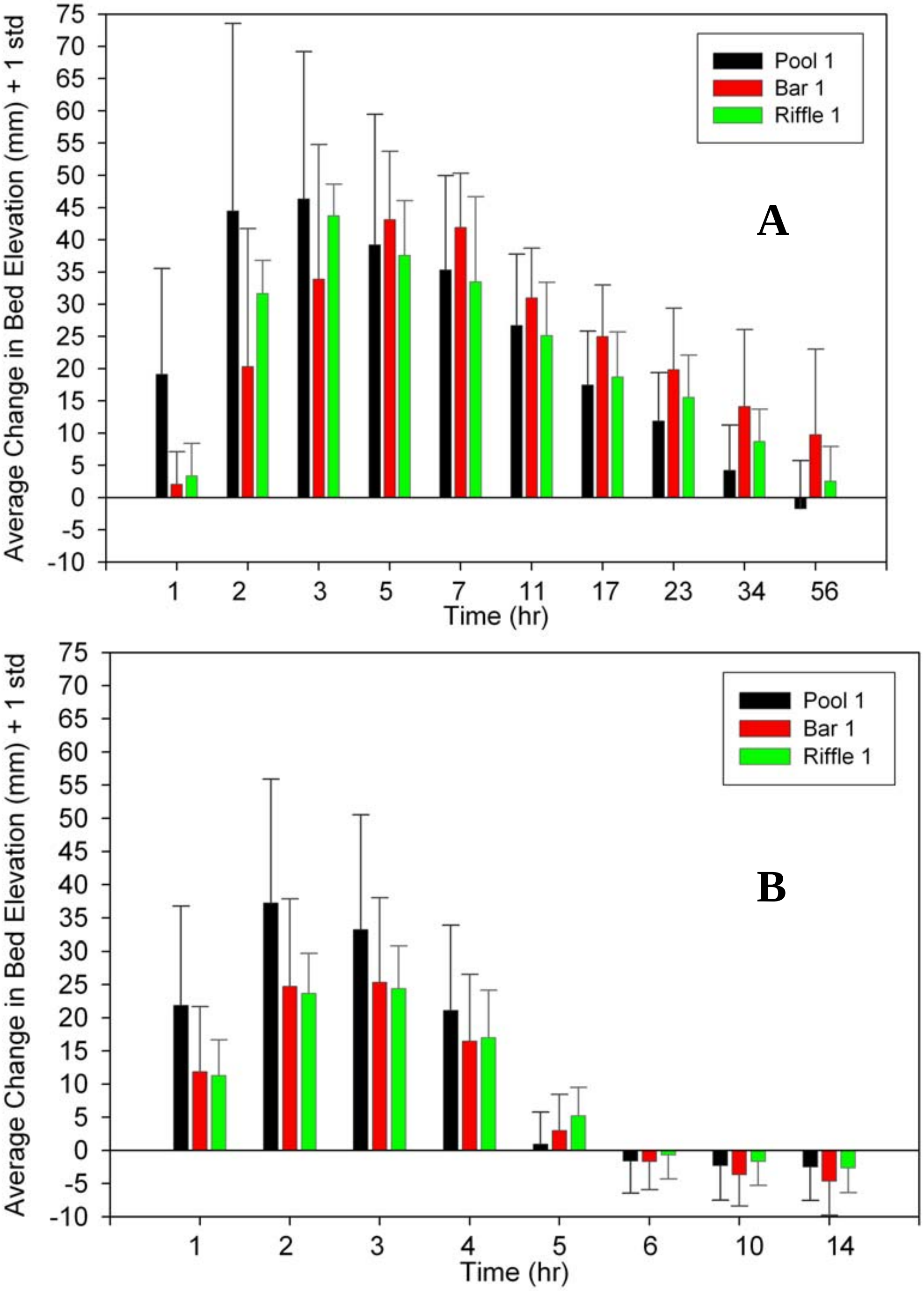

Figure 3-7. Average change in bed elevation + one standard deviation for large coarse (A) and large fine (B) pulses designed to investigate sediment pulse evolution in an experimental channel with pool-riffle morphology.

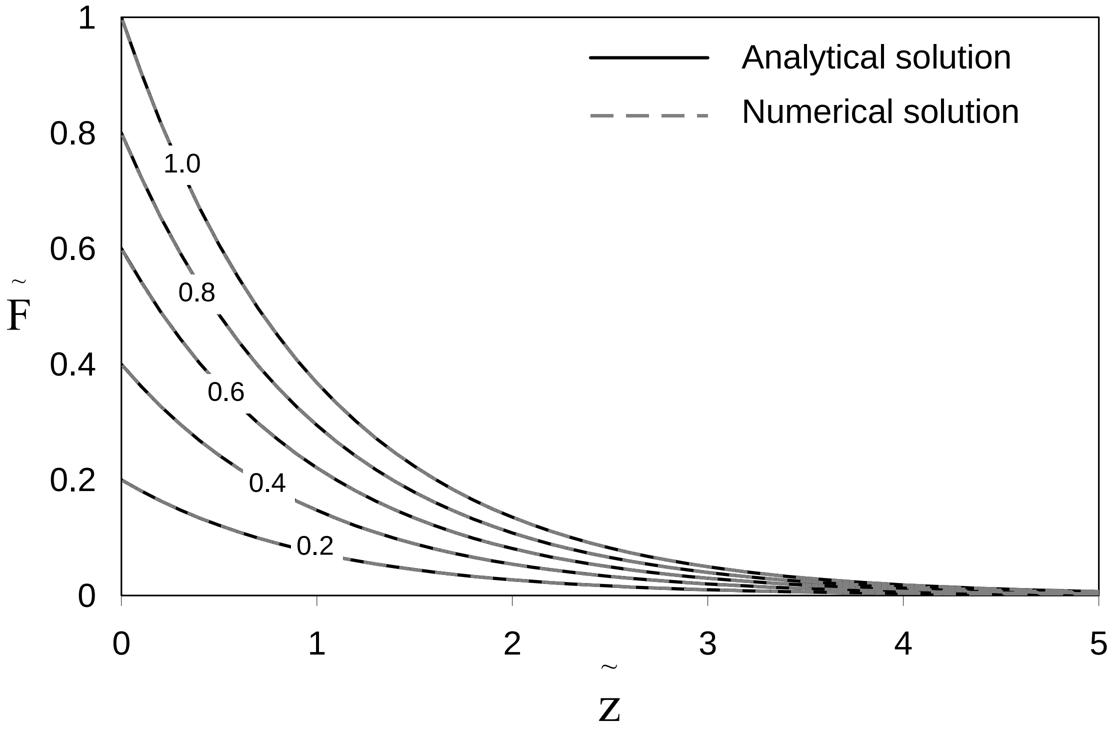

Figure 3-8. Fine sediment fraction in a gravel deposit as a result of fine sediment infiltration into the gravel deposit initially devoid of fine sediment. Fine sediment profiles are solutions to the theory of Cui *et al.* (2007a) under the assumption that fine sediment trapping efficiency is independent of fine sediment fraction. $\tilde{F}$ denotes fine sediment fraction normalized with saturated fine sediment fraction (*i.e.*, maximum possible fine sediment fraction as a result of fine sediment infiltration); $\tilde{z}$ denotes depth into the deposit normalized with β^{-1}, where β is fine sediment trapping efficiency; and the numerical labels are time normalized with a base-time so that the surface of the deposit becomes saturated with fine sediment at 1. This diagram is modified from Cui *et al.* (2007a).

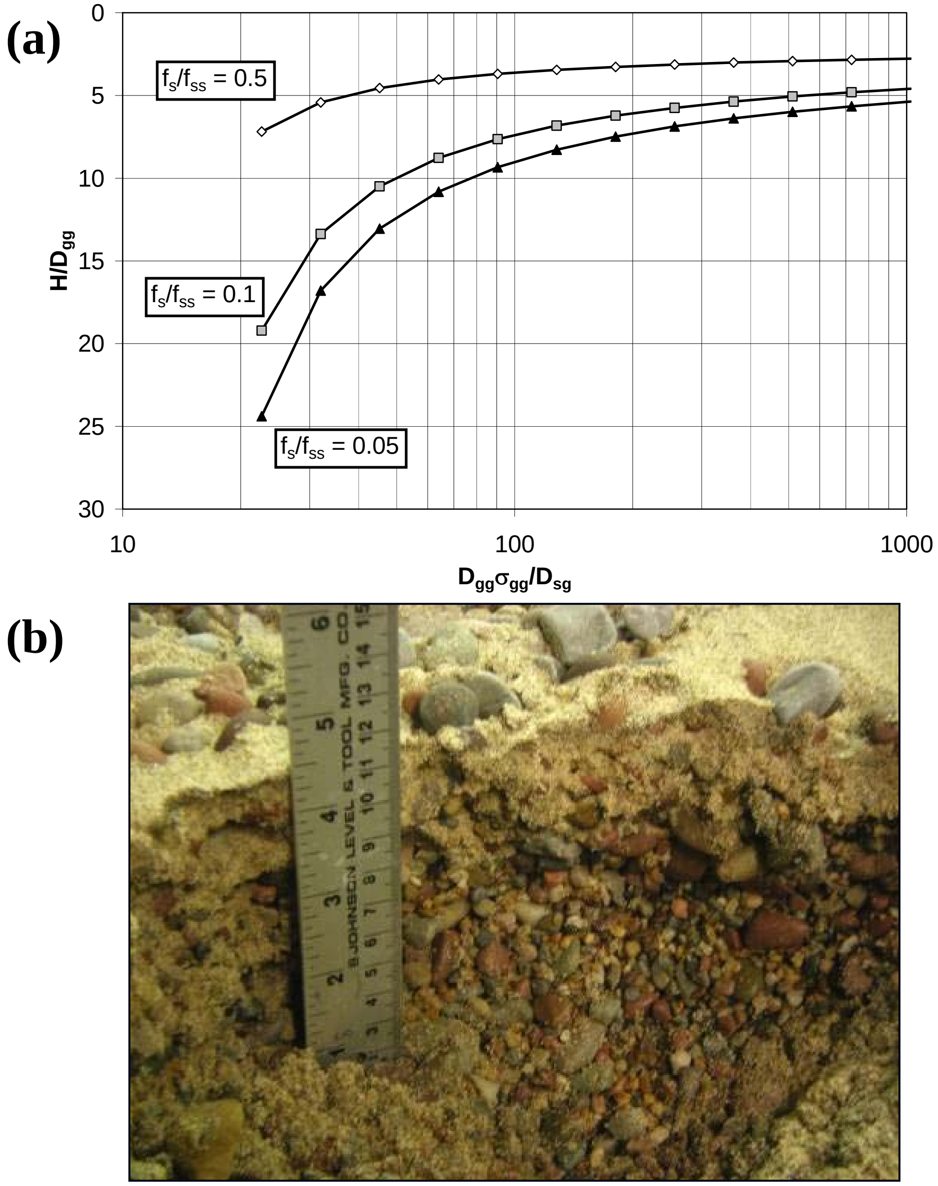

Figure 3-9. Decreased stable fine sediment fraction in depth (a) as a result of fine sediment infiltration based on the relation of Wooster *et al.* (2007b), assuming a geometric standard deviation of 3.0 for bed material; and (b) photograph taken following the experiment of Wooster *et al.* (2007b), showing decreased fine sediment content in depth. H denotes depth into the deposit; D_{gg} denotes bed material geometric mean grain size; σ_{gg} denotes bed material geometric standard deviation; D_{sg} denotes geometric mean grain size of the infiltrating fine sediment; f_s denotes fine sediment fraction; and f_{ss} denotes saturated fine sediment fraction. Because $\sigma_{gg}D_{gg}$ approximates bed material D_{84}, and D_{sg} approximates fine sediment D_{50}, and thus, the abscissa axis can be viewed as an approximation of bed material D_{84} to fine sediment D_{50} ratio. Diagram and photograph are adapted from Wooster *et al.* (2007b).

4 CONDITIONS NECESSARY TO CREATE MEANDERING CHANNELS: INFERENCES FROM FLUME EXPERIMENTS

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ABSTRACT

Stream restoration often involves reconstructing rivers as single-thread meandering channels; however, the morphology of the resulting channels is often unstable and the channel may eventually revert back to its pre-restoration condition. To increase success of channel reconstruction efforts, we set out to identify the underlying physical conditions necessary to create and maintain a single-thread channel that meanders across its floodplain. We hypothesize that, given the correct width-depth ratio, slope, and Froude number, meandering channels require three additional conditions to maintain their morphology: (1) bank strength, derived from cohesive sediment or vegetation, (2) fine sediment, which deposits at the downstream ends of point bars, attaching them to the floodplain, and (3) overbank flows, which function to attach bars to adjacent floodplains. We tested whether these conditions were sufficient to create a meandering channel in a laboratory flume using alfalfa sprouts and lightweight plastic material to model vegetation and fine sediment dynamics. The experiments were run with a simple two-stage hydrograph with a bankfull flow of 1.8 l/s and an overbank flow of 2.7 l/s. The initial channel was 40 cm wide and 1.9 cm deep, with an initial slope of 0.0046 and a Froude number equal to 0.57. Under these conditions, we were able to create and maintain a meandering channel with a granular bed in a laboratory flume. The channel maintained a meandering morphology for over 71 without braiding. The alfalfa sprouts slowed bank erosion enough to allow bars to grow to the elevation of the floodplain, and fine sediment plugged chutes at the upstream end of bars and deposited at the downstream end of bars. Channel width initially increased, but stabilized as the channel migrated. The width-depth ratio returned to its original value (21) just prior to a cutoff that forced more water overbank and increased the width-depth ratio to 25. These experiments indicate that vegetation should be integrated into stream restoration projects even where conditions such as slope, discharge, and channel dimensions are sufficient to maintain a meandering morphology.

4.1 INTRODUCTION

A single-thread meandering morphology is widely considered the ideal planform for restored river channels (Soar and Thorne 2001, Kondolf 2006, Wohl *et al.* 2005) because this morphology creates a wide diversity of aquatic habitats (Trush *et al.* 2000), but also for aesthetic reasons (Kondolf 2006). At sites where the goal is to maximize habitat for salmonids rather than restore the channel to its original condition, meandering channels are often built even where braided or low-sinuosity channels existed prior to human disturbance (*e.g.*, Kondolf *et al.* 2001, Wohl *et al.* 2005). Too often, however, the desired ecological benefits of channel restoration are not realized (Kondolf *et al.* 2001, Smith and Prestegaard 2005), in part because of the high value placed on subsequent channel stability. In particular, bank erosion is typically discouraged, often by armoring the outside of meander bends with rip rap, root wads, or other engineered structures (Kondolf 2006). As a result, many reconstructed channels have morphologies similar to natural channels, but do not sufficiently support the dynamic geomorphic processes necessary to restore the pre-disturbance ecological regime (Trush *et al.* 2000, Shields *et al.* 2003). Sometimes these designed channels cannot maintain their imposed morphology, such as when floods cause channel avulsions or a shift to a braided planform (*e.g.*, Kondolf *et al.* 2001). Restored channels fail for two primary reasons: (1) they are constructed in locations where current theory (*e.g.*, Leopold and Wolman, 1957) would not predict meandering channels to occur , or (2) they are constructed in locations where factors which have been qualitatively shown to affect channel morphology (*e.g.*, high sediment supply, weak banks, or flashy discharge) which are not included in current theory prevent development or maintenance of a meandering channel.

An ecologically beneficial design for single-threaded meandering channels would promote lateral migration, which results in point bar growth, floodplain deposition, meander loop cutoffs, and restoration of riparian vegetation dynamics and succession (Trush *et al.* 2000). This goal is particularly difficult to achieve downstream of dams where the supply of both water and sediment has been severely disrupted, and where channels are often laterally constrained by land use and development on the floodplain (*e.g.*, Ligon *et al.* 1995). An equally significant challenge in designing dynamic meandering channels is our limited scientific understanding of the factors that control the threshold between single- and multi-threaded channels (*e.g.*, Ferguson 1987) and the stable width of actively migrating channels (*e.g.*, ASCE Task Committee 1998).

Perhaps surprisingly, current theory does not allow us to predict the channel form based on the three fundamental independent variables: valley slope, discharge, and sediment supply (Ferguson 1987). Theoretical and empirical relationships that discriminate channel pattern do allow us to assess whether the slope and width-depth ratio are likely to promote a meandering or braided morphology (*e.g.*, Parker 1976); however, these relationships are difficult to apply in channel design because they use variables that can evolve in dynamic channels (Ferguson 1987). For example, bank erosion without adequate bar growth on the opposite channel margin can lead to channel widening and reduction in mean flow depth and local bed shear stress, with cascading effects on sediment mobility, bed texture, and morphology. Weak banks, as often occur in reconstructed channels before woody riparian vegetation becomes established, can permit runaway channel widening, formation of island bars and conversion to a braided morphology. The challenge in designing actively migrating channels is to create an initial condition that sets the river on a path toward an evolving morphology that maintains a stable average cross-sectional geometry and planform character, while channel migration and sediment transport occur.

Flume experiments are extremely valuable tools because they allow scientists to test the effects of individual variables while holding others constant, which is very difficult or impossible in natural rivers. Flume experiments can also simulate many years of floods on much shorter timescales than in the field, and they are essential for testing and developing models (*e.g.*, Wilcock *et al.* 2001, Cui *et al.* 2002). For these reasons, flume experiments are increasingly being used to address questions surrounding stream restoration (Parker *et al.* 2003, Leverich 2006, Venditti *et al.* 2006). One hurdle in stream restoration, however, is developing and testing models of self-formed channels. This hurdle arises because we have been unsuccessful in creating meandering channels in the laboratory that are scaled-down gravel- or sand-bedded streams. There have been recent advances, however, toward creating a meandering channel in the laboratory by Smith (1998) and Tal and Paola (2007) that have inspired us to conduct the experiment presented here.

The goal of this paper is to address the question of what conditions are necessary to create meandering (rather than braided) channels in the laboratory to better inform field application via restoration. We propose that the conditions necessary to create and maintain a meandering channel in the laboratory can be used to infer conditions necessary to create and maintain such channels in the field. The results of this experiment should therefore improve stream restoration project designs. In this paper, we first examine the hydraulic characteristics of meandering and single-thread channels from the field and the literature. We then present the scaling used to create our channels and our hypotheses for additional conditions necessary for meandering to occur. Following the results of the experiment, we discuss differences between the field and flume and the implications for stream restoration.

4.2 MEANDERING RIVER DATA SET

To better understand the conditions necessary for meandering rivers to form, we have assembled a data set of slope, grain size, bankfull width, bankfull depth, and discharge at bankfull conditions for 74 single-thread, gravel-bedded, meandering rivers described in the literature. Rivers were included in the meandering data set if they had a median grain size greater than 2 mm and were described as meandering or as having sinuosity greater than 1.25. The meandering data set may also include channels that have a sinuous form, but do not migrate (the channels with width-depth ratios <10), however, based on the information available, we were not able to separate these sites.

For the meandering river data set, Froude numbers are typically around 0.5 at bankfull flow, while Reynolds numbers are on the order of 10^5–10^6 (Figure 4-1). In these analyses, the velocity used to calculate the Froude and Reynolds numbers was assumed to equal bankfull discharge (Q_{bf}) divided by bankfull width (B) and bankfull depth (H). These data indicate that gravel-bedded meandering rivers occur over a wide range of slopes and channel sizes. The mean valley slope was 0.0055, but meandering, gravel-bed rivers were found at slopes ranging from 0.0003 to 0.022. The mean width-depth ratio is 21 for the meander data set and ranged between 5 and 64.

Meandering gravel-bed rivers reported in the literature often are reworking material derived from Pleistocene deposits (*e.g.*, Nanson 1980, Leopold and Emmett 1997) or even fine-grained deposits originating from human activity (see Walter and Merritts, 2008). These older deposits can either be a source for fine, cohesive material (Nanson 1980; Walter and Merritts, 2008) or gravel (Leopold and Emmett 1997).

4.3 BACKGROUND

A challenge for previous laboratory experiments and channel reconstruction projects has been to maintain a single-thread morphology following construction. There are many models for discriminating between meandering and braided morphology (Leopold and Wolman 1957; Schumm 1960, 1985; Parker 1976; Ferguson 1987; van den Berg 1995; Xu 2004a, b; Church 2006), but no current model can be used to predict whether a designed channel will maintain its morphology once the channel has been constructed and bars begin to grow and banks begin to erode. The most commonly cited model to discriminate between meandering and braiding systems is from Leopold and Wolman (1957), which differentiates meandering and braided streams based on the channel slope and bankfull discharge. Their model loses its power if valley slope is used rather than channel slope because braided rivers have a much lower sinuosity (Ferguson 1987); it also misclassifies many streams when additional data is added to the data set (Xu 2004b). Other models assume that the channel has reached equilibrium, and cannot be used to predict whether a constructed channel (in the flume or the field) will maintain that morphology. These models have discriminated between meandering and braided systems based on channel width and slope (Xu 2004a), median grain size versus stream power (Xu 2004b), or median grain size versus the potential stream power, which assumes a channel width based on the discharge (van den Berg 1995). Parker (1976), predicts the threshold for meandering and braiding based on the following equation:

$$\frac{S}{Fr} = \frac{H}{B} \tag{1}$$

where S is slope and Fr is Froude number. Braiding occurs when S/Fr>>H/B and meandering occurs where S/FR<<H/B (Figure 4-2). Channels tend to be straight and free of bars when H/B is less than 0.1 (Figure 4-2). We have plotted the meandering data set onto Figure 4-2, and most data lie within the meandering portion of the plot. The data that do not lie in the meandering realm likely represent a gradual

transition between meandering and braiding (*e.g.*, Parker 1976, Ferguson 1987), or data where bankfull conditions do not correspond to the channel-forming discharge.

The parameter space outlined by Parker (1976) is necessary for meandering to occur, but assumes that the channel has reached an equilibrium morphology. This raises problems for channel restoration design because width and depth can change in channels that can erode their banks and grow bars. For example, if bank erosion occurs faster than bar growth, the channel will widen and shallow. This will cause H/B to decrease, and the channel can move from a meandering to a braided region on Figure 4-2. A similar phenomenon has also occurred in flume experiments, but on a much faster time scale. Experiments conducted by Eaton and Church (2004) and Peakall *et al.* (2007) lie within the meandering portion of Figure 4-2, but they were unable to maintain the meandering morphology and their morphology evolved toward a braided condition. This evolution indicates that other factors likely affect the equilibrium width and depth of rivers and hence channel pattern.

Two commonly cited controls on channel pattern are sediment supply and bank strength. Channel pattern has been qualitatively shown to be a function of sediment supply (Ferguson 1987, Schumm 1985, Church 2006), with braided streams typically associated with high supply and meandering streams typically associated with lower supply. Bank strength has also been proposed as a control on channel pattern with higher bank strength associated with meandering (sinuous) rivers and lower bank strength associated with braided (straight) rivers (Schumm 1960, Schumm and Lichty 1963, Church 2006). This bank strength can be derived from either cohesive sediment (Schumm 1960), vegetation (Millar 2000), or bank revetment in altered channels. Thresholds between braiding and meandering in response to supply or bank strength have not been quantified, so they provide little guidance in the design of restored channels.

Vegetation supplies additional bank strength to channels by increasing the near-bank roughness and also by increasing the strength of the soil (Millar 2000). If banks fail, herbaceous vegetation can help maintain the integrity of failed blocks, which also serves to prevent subsequent bank erosion (Micheli and Kirchner 2002a; G. Parker, *pers. comm.*). Reduction in vegetation has been shown to alter a channel from a meandering to braided morphology (Schumm and Lichty 1963). Vegetation can act as a major control on bank erosion rates (Micheli and Kirchner 2002a, ASCE Task Committee 1998) and bank strength (Micheli and Kirchner 2002b), but the interaction between vegetation and bank erosion is very complex, with some vegetation types increasing bank erosion rates relative to unvegetated banks, and other types decreasing bank erosion rates (ASCE Task Committee 1998). Vegetation also promotes bar growth in natural channels (Dietz 1952) and reduces the braiding index of laboratory channels (Gran and Paola 2001, Tal and Paola 2007).

Ideally, we would test the degree to which bank strength and sediment supply affect channel morphology in flume experiments where we could control each variable and measure channel response. This is not possible, however, because we have been unable to create freely migrating, meandering rivers in laboratory flumes. Flume experiments on channels with granular beds and cohesionless banks eventually braid (Friedkin 1945, Parker 1976, Eaton and Church 2004), and meandering experiments to date have often consisted of a sinuous thalweg with relatively straight banks where bars to not emerge from the flow to create new floodplain deposits (Schumm and Khan 1972). Based on the importance of bank strength to meandering channels in the field, previous experiments in the literature (*e.g.*, Friedkin 1945, Eaton and Church 2004), and preliminary experiments conducted by our group, we hypothesize that experimental channels braid because bank strength in the laboratory is not sufficient to allow bars to grow vertically and chutes that develop behind the bar eventually enlarge and promote braiding.

Researchers have been increasing bank strength by various means in an effort to create meandering channels in the laboratory (*e.g.*, Friedkin 1945, Schumm and Khan 1972, Smith 1998, Tal and Paola 2007). Bank strength has been increased by using cohesive sediment (Schumm and Khan 1972, Smith

1998, Peakall *et al.* 2007), or vegetation (Gran and Paola 2001, Tal and Paola 2007), or a combination of the two (Leverich 2006). Peakall *et al.* (2007) created an actively migrating channel in a laboratory flume using mildly cohesive ground silica to provide bank strength. Their channel eventually destabilized and became a single bend down the length of their flume. Gran and Paola (2001) used alfalfa sprouts as surrogates for riparian vegetation to decrease the number of channels in a braided river, and Tal and Paola (2007) used alfalfa sprouts to transform a braided channel to a single-thread channel. Leverich (2006) used alfalfa sprouts to examine the effects of peak flows on the morphology of a low-amplitude bend. Smith (1998) created the first truly meandering channels with point bars in steep (slope = 0.015), small channels (< 4 cm wide) in diatomaceous earth and kaolinite clay. Because of the cohesive nature of the materials used by Smith (1998), it is difficult to extrapolate his results to gravel-bed meanders in the field. The previous alfalfa experiments (Gran and Paola 2001, Leverich 2006, Tal and Paola 2007) showed that vegetation is likely the key to developing stable meanders, but these experiments were limited by the size of their flume basins.

In experiments using sand (model gravel) without alfalfa, a chute often develops behind the bar (Figure 4-3) and the development of the bar downstream of the bar apex is much weaker than upstream of the bar apex (Parker 1976, Eaton and Church 2004). With time, these chutes can enlarge and lead to the development of large secondary channels that promote island-bar formation. Studies of gravel-bed meanders show that the chutes are typically filled by finer sediments (mostly sand) in the field (Leopold and Wolman 1960, Bluck 1971, McGowen and Garner 1970, Nanson 1980). Similarly, in sand-bedded channels, fine sand tends to deposit at the downstream end of bars (Jackson 1976, Dietrich and Smith 1984). This occurs because coarse and fine particles follow different paths around point bars, with coarse sediment staying toward the outside of the bend downstream of the apex, while fine sediment is transported toward the point bar (Dietrich and Smith 1984, Julien and Anthony 2002, Clayton and Pitlick 2007). Previous experiments modeling meandering streams have generally been conducted using unimodal sediment. In these experiments, gravel is typically scaled to sand to allow the model channels to be a reasonable size. To maintain consistent scaling, sand would therefore have to be scaled down to silt, where cohesion and differences in critical shear stress make scaling very difficult.

Natural channels typically experience variable flow. Overbank flows may be critical for attaching bars to floodplains or to fill in chutes. This is supported by the work of Yen and Lee (1995), who found that high, short-duration peaks increased the height of bar deposition in experiments in a fixed bend.

Based on previous research in the laboratory and the field, we hypothesize that to maintain a meandering channel in either the laboratory or the field, channels must not only plot within the meandering space defined by Parker (1976) (Figure 4-2), but the following additional requirements must also be met.

1. Bank strength from fine sediment or vegetation (to reduce near-bank velocity, increase bank strength, and armor the bank toe);
2. Fine sediment (sand in gravel-bed rivers) must be supplied to fill chutes and deposit at the downstream end of bars; and
3. Overbank flows are required to deliver fine sediment to the bars.

We assumed that these hypotheses were correct when planning and conducting these experiments. They will be systematically tested in future experiments.

4.4 FLUME EXPERIMENTS

We conducted experiments from September to November 2006 in the large basin at UC Berkeley's Richmond Field Station. The large basin is 6.1-m wide and 17-m long (Table 4-1). The slope of the basin is set to 0.01, but was adjusted to 0.0046 by creating a sediment wedge (*i.e.*, the sediments are thicker at the downstream end of the flume than the upstream end). In these experiments, alfalfa sprouts provided bank strength and lightweight plastic sediment was used as model sand.

Table 4-1. Initial conditions for flume experiments.

Parameter	Value
Flume length	17 m
Flume width	6.7 m
Slope	0.0046
Initial channel width	40 cm
Initial channel depth	1.9 cm
Floodplain/channel D50	0.8 mm
Coarse feed D50	0.8 mm
Fine feed D50	0.35 mm
Fine feed specific gravity	1.5

4.4.1 Scaling the flume experiments

We based the initial channel geometry in the flume on five conditions: the ratio of the channel width to the experimental basin length, Froude number, Reynolds number, excess Shields stress, and the width-depth ratio (Table 4-2). During preliminary experiments, we determined that minimizing the Froude number while still maintaining turbulent flow (Reynolds number >2,000) was critical for maintaining a meandering channel. In preliminary experiments where the average Froude number >0.7, the channel tended to develop bends and then straighten. We set the Shields stress at the designed bankfull discharge to be 1.5 times critical (assumed to be approximately 0.03 based on preliminary experiments) because we assumed that the bars and bends would provide some roughness, and wanted high enough stress to drive bank erosion at bankfull flow.

Although we started with a channel with only one bend at the upstream end of the flume, we wanted to ensure that there was enough space in the flume to allow at least five bends to develop. Because bend spacing is determined by channel width (Leopold *et al.* 1964), we set the initial channel width to allow at least five bends within the flume length, while having a width-depth ratio between 20–30. We assumed that approximately 5 m of the flume length would be controlled by the boundary conditions at the upstream and downstream ends of the flume. We therefore required an initial channel width of approximately 40 cm to accommodate five bends in the remaining length of the flume. Based on these constraints, we used the Manning's and Shields equations to determine the initial slope, median grain size, and flow depth. The initial slope of 0.0046 is close to the median value of the meandering data set.

Table 4-2. Scaling criteria and initial conditions used in the flume experiments.

Parameter	Condition	Initial flume value
Froude number	<0.7	0.56
Reynolds number	>2,000 (Fully turbulent)	4,500
Channel width	0.4 m	0.4 m
Channel depth	Calculated using $\tau_{bf}^*/\tau^*_{crit}=1.5$	.019
B/H	20-30	21
τ^*/τ^*_{crit}	1.5 at bankfull flow	1.5
S/FR	<0.03	0.008

4.4.2 Experimental measurements

Water was supplied from a large storage basin and passed through a V-notch weir used to calculate discharge. Coarse and fine sediment were fed from separate Vibrascrew Accufeed feeders. Bed topography was measured using a laser sheet photographed by an oblique camera while the flume was dry. Overhead photographs were taken every minute to record the position of the channel during the run. Water-surface elevations were measured with a point gauge, and water velocity was measured using a float and stopwatch. Sediment was collected at the downstream end of the flume, but due to a malfunction of our sediment trap, we do not have measurements of sediment ouflow with time.

We would typically run the flume for 10–14 hours over the course of 2–3 days, by which time the alfalfa sprouts started to die because they had been submerged for an extensive period. We would then replant the alfalfa and allow it to grow for 7–10 days, depending on the air temperature and light conditions in the building. Six metal halide lights suspended over the flume provided light to the alfalfa after it sprouted. During the course of preliminary experiments, we found that the best way to maintain alfalfa was to provide water to the roots but not the leaves. We therefore maintained a low flow to promote alfalfa growth and survival during the growth period. During the course of these experiments, we seeded alfalfa five times. Alfalfa was seeded while the irrigation flow was on, to prevent vegetation encroachment into the channel. The irrigation flow was not sufficient to transport sediment, although some minor adjustments did occur during low flow periods.

A 0.4-m wide, 0.019-m deep channel was carved with an initial bend, but was otherwise straight (Figure 4-4). This configuration promotes sinuosity development and was used by Schumm and Khan (1972) and Eaton and Church (2004). Our flood hydrographs were a simple two-stage hydrograph consisting of bankfull flow (1.8 l/s) and an overbank flow (2.7 l/s). The bankfull flow was run for 5.5 hours for every 1.5 hours of the overbank flow. We conducted three high-flow tests of 3.7, 4.2, and 4.4 l/s (Figure 4-5) to try to promote deposition of sediment behind the bar and test the effects of higher flows on bank erosion rates. The longest test was 30 minutes.

The median grain size of the coarse sediment was 0.8 mm, and the distribution was based on a mixture of commercially available sand (Figure 4-6). The grain-size distribution of the coarse sediment was bimodal. The fine sediment was Plasti-Grit 40/60 Urea (Type II) plastic sediment with a median grain size of 0.35 mm and a specific gravity of 1.5. We painted the coarse sediment feed blue, to contrast with the tan sediment that made up the floodplain and the white plastic sediment feed. Sediment supply during both discharges was initially determined using Wong and Parker (2006), substituting a critical stress of 0.03. Although the Wong and Parker equation specifies a different critical Shields stress, using a critical Shields stress of 0.03 accurately predicted sediment transport in experiments with a single, low-amplitude bend (Leverich 2006). During the experiments, we adjusted the coarse feed to minimize bed aggradation at the upstream end of the flume.

The floodplain on the right side of the channel (looking downstream) was approximately 1 cm lower than the floodplain on the left side of the channel due to difficulties in leveling a 6.7-m wide floodplain. This caused overbank flows to be deeper on the right floodplain than on the left floodplain.

4.5 RESULTS

We successfully created a meandering channel in the laboratory that maintained a relatively constant width and migrated across its floodplain and maintained its morphology (Figure 4-4). The channel adjusted its morphology following a chute cutoff 52 hours after the beginning of the experiment, but maintained a relatively stable width and depth (Figure 4-4). We were able to develop and maintain a meandering geometry in a laboratory flume. The channel maintained a meandering morphology for over 71 hours, after which its morphology stabilized, with no sign of braiding by the experiment's end.

Chutes formed behind bars but were sealed off from the channel on their upstream ends (Figure 4-7) and the water within them was still. This prevented the chutes from enlarging and allowed the channel to continue to meander. The lightweight plastic sediment also deposited at the downstream edge of bars and the margin of the thalweg (Figure 4-4). The plastic sediment was transitional between bedload and suspended load, and was too heavy to plug the downstream end of chutes, but a thin layer of plastic did deposit in the chutes as the bar grew. The high discharge tests did not succeed at promoting deposition in the chutes. Bank erosion was relatively rapid during these tests (best seen in time-lapse movies of the experiment, available at http://eps.berkeley.edu/~xian/), but due to their short duration, the total erosion was small relative to the rest of the experiments. The channel had steep banks on the outside of bends and a gradual sloping point bar on the inside of bends. The channel bank on the outside of the bend was able to hold a much steeper slope, than in preliminary experiments without alfalfa. Cross sections show that, in general, point bars grew as the bank eroded (Figure 4-8), which helped maintain a single-thread channel.

The first bar downstream of the entrance never completely connected to the floodplain; this helped promote the chute cutoff, which occurred behind the bar after 52 hours (Figure 4-4). This bar grew laterally very fast, and we hypothesize that two factors prevented it from attaching to the floodplain: cross-stream flows were suppressed due to proximity to the entrance, and frequent aggradation upstream of the bar kept the water-surface elevation high at this point, preventing deposition of the suspended sediments.

We therefore had to reduce the feed rates dramatically from the predictions made by the modified Wong and Parker (2006) equation. Once bends developed, sediment fed from the upstream end backed up behind the first bend, likely due to the suppressed cross-stream flow at the first bend. Because we considered the initial bend to be a boundary condition, we tried various methods to overcome this, including excavating sediment, and eventually settled on decreasing the sediment feed. Sediment was still supplied by erosion of the bed upstream of the first bend and by bank erosion. Because the painted feed sediment is almost completely absent downstream of the first bend prior to the cutoff (Figure 4-4), we can infer that bars were built via sediment derived from bank erosion rather than sediment fed from upstream. Bars were built as the sinuosity of the upstream bend increased during periods of bank erosion.

We calculated the channel width, average depth, and the difference between the bar elevation and floodplain elevation at nine cross sections between 5.9 m and 13.9 m downstream of the flume inlet during each survey (Table 4-3; Figure 4-9 and Figure 4-10a-f). The cross sections were chosen to be outside of the boundary-influenced area of the flume. If the cross section had multiple, active flow channels separated by islands, it was excluded because it was difficult to define the boundary between the channel and the floodplain. This exclusion only affects channel morphology early in the experiment at the upstream end of the flume. Channel width was calculated as the distance, perpendicular to flow, from the bank top to the top of the bar if the chute behind the bar was isolated, if not, the width was measured from bank top to bank top. The median width initially peaked at 81 cm between 36 and 42 hours, then decreased to between 29 and 36 cm (Figure 4-10a). The average channel depth (the difference between the floodplain and the average bed elevation) was much more stable, ranging between 10 and 20 mm (Figure 4-10b). The depth decreased slightly at the beginning of the experiments as the channel widened, and then remained relatively stable throughout the experiments. Following the cutoff of the first bar downstream of the entrance, the median depth initially increased from 1.7 to 1.8 cm, then decreased to 1.5 cm. Because the depth was relatively stable, and the width was variable, the width-depth ratio increased as the width increased (to a maximum of 99) at 42 hours, and then decreased as the bars vertically accreted to a median value between 18 and 25 for the last 25 hours of the experiment. The width-depth ratio increased to 25 during the last time step due to increased width in the straight reaches of the channel.

Table 4-3. Summary of channel morphology conditions at selected times during the experiments.

Parameter	Initial Value	Pre-cutoff (52 hours)	Final condition (71.2 hours)
Slope	0.0046	0.0037	0.0043
Channel width	40 cm	32.8 cm	36.2 cm
Channel depth	1.9 cm	1.7 cm	1.5 cm
Width-depth ratio	21	20.9	27.7
Floodplain elevation-bar elevation	n/a	-0.1 cm	-0.2 cm
Sinuosity	1.02	1.23	1.11

The median elevation of the bar top increased during the first 42 hours of the experiments, and then stabilized at a value approximately equal to the elevation of the right floodplain (Figure 4-10d). The stabilization in bar elevation corresponded to the stabilization of the width and the development of bends throughout the length of the flume (Figure 4-4).

The decrease in width after 42 hours was accompanied by a decrease in bed slope (Figure 4-10e). Bed slope initially increased, then decreased to a minimum of 0.0037 just prior to the cutoff. After the cutoff, the slope increased due to decreased sinuosity and aggradation at the upstream end of the flume. The sinuosity increased from 1.0 to 1.23 and then the channel straightened via a chute cutoff (at 52 hours) to a sinuosity of 1.08 and finished at 1.11 (Figure 4-10f). After the cutoff, much of the water was flowing on the floodplain because the channel had previously narrowed. The final morphology of the flume plots well within the meandering space on Figure 4-2.

4.6 DISCUSSION

These experiments successfully maintained a single-thread channel with meandering morphology by limiting the rate of bank erosion and promoting conversion of the point bar to the floodplain. There are several differences, however, between processes observed in the flume and processes in the field that are discussed below. The alfalfa sprouts decreased the bank erosion rate and allowed the bars to eventually grow at the same rate that the bank eroded. Pollen and Simon (2006) found that the root size and density of alfalfa scale reasonably well to young riparian vegetation in the field, but because cohesion cannot be scaled, alfalfa is not simply scaled-down vegetation. While the banks of the flume channel typically eroded by transport of individual grains, bank failure in the field is far more complex (ASCE Task Committee 1998). Banks with fine-grained, cohesive deposits may fail by rotational or cantilever slumps driven by erosion of the bank toe or bank hydrology. The type of bank failure likely influences channel geometry, but would not alter our hypotheses regarding the necessary conditions for meandering to occur. Often slump failures leave a large deposit at the toe of the bank, and the bank erosion rate is limited by the rate at which the slump is removed (ASCE Task Committee 1998).

Although dimensionless numbers such as the bankfull Shields number relative to critical Shields number, Froude number, and the width-depth ratio were similar between our experiments and the field data discussed in Table 4-2, there is a large difference between the Reynolds number in the flume and in natural channels. While our flows were turbulent, the Reynolds number was 2–3 orders of magnitude lower than field values (Figure 4-1). This is a common occurrence in experiments scaled by the Froude number, but likely affects the results, particularly for the transport and deposition of suspended sediments.

We believe that at higher Reynolds numbers, more sediment would be transported in suspension and delivered to the chute. In addition, our experiments use scaled-down gravel and sand, but do not include scaled-down silt, which is the material that often makes up the overbank deposits of gravel-bed meanders (*e.g.*, Leopold and Wolman 1960).

Although qualitative classification schemes indicate that sediment supply should affect channel morphology, for these experiments bedload was primarily supplied by bank erosion. We found that the channel banks supply most of the sediment that builds bars, an observation also made by Friedkin (1946) and Pryce and Ashmore (2005) during their flume experiments. The degree to which this is an artifact of flume experiments is not clear. Because of the difficulty in transporting sediment around the first bend, which limited our ability to control sediment supply, we hypothesize that secondary circulation was not sufficient to transport sediment towards the outer bank at the top of the flume. Field observations, however, indicate that sediment is transported around bends rather than just from bar to bar (Dietrich and Smith 1984, Julien and Anthony 2002, Clayton and Pitlick 2007). Visual inspection of sediment transport during the experiments, indicate that some sediment is transported around bars in the lower end of the flume, and that lack of painted sediment past the first bar may be an artifact of the upstream boundary condition.

We hypothesized that meandering rivers required variable flow to allow bars to attach to the floodplain. These experiments were therefore designed with a simple two-stage hydrograph with a designed bankfull flow and an overbank flow. Due to in-channel adjustments, however, both discharges resulted in overbank flows on the right floodplain. Variable flows may be important for other reasons in the field that are not important in the controlled environment of the laboratory, such as establishing and maintaining riparian vegetation, providing refugia for aquatic organisms during high flows, and transporting fines from the streambed to the floodplain. In addition, Leverich (2006) found that during overbank flows, pools deepen and bars grow higher than during bankfull discharge, although the degree to which this is controlled by the hydrograph or sediment supply is not clear. We therefore expect that overbank flows increase habitat diversity in streams.

4.7 APPLICATIONS TO STREAM RESTORATION

Our experimental results showed that meandering channels could be maintained by the addition of bank strength through vegetation, overbank flows, and fine sediment to isolate chutes and promote vertical accretion on the downstream end of bars, assuming that their geometry lies within the meandering region in Figure 4-2. These hypotheses were not systematically tested, and the degree to which overbank flows are necessary, versus bank strength and fine sediment, is unknown. We have also not quantified the increase in bank strength required to maintain a stable geometry. Taken together with the previous experiments shown in Figure 4-2, our experiments indicate that simply building a channel with a geometry sufficient to promote a meandering morphology is likely not sufficient to create a channel that migrates across its floodplain and maintains a stable width.

Although riparian vegetation may provide sufficient bank strength to maintain a meandering morphology, conditions downstream of dams may not be sufficient to promote and maintain riparian vegetation. Many restoration projects occur where dams have altered the timing and magnitude of the hydrograph. Dams can disrupt linkages between seed release of native riparian species and recession flows necessary for establishment of some species (Stella *et al.* 2006). These sites may require planting and irrigating of riparian species in addition to natural recruitment to maintain vegetation that provides strength.

Simply adding riparian vegetation may not be sufficient to create a meandering channel for channel designs that lie within the meandering region in Figure 4-2. Our literature review indicated that gravel-bed meandering channels often are reworking material deposited during the Pleistocene (*e.g.*, Nanson

1980, Leopold and Emmett 1997) and, therefore, historical conditions may be very important for determining the proper channel morphology, and the historical morphology of the restoration site may provide clues to the processes that promoted the pre-disturbance morphology.

4.8 CONCLUSIONS

These experiments show that by using a few simple scaling rules that place channels in the meandering space on Figure 4-2, and by the addition of bank strength, fine sediment, and overbank flows, a meandering channel can be created in the laboratory. These represent the first successful experiments to create a meandering channel using granular material as bedload. During the experiments, bars were built with sediment derived from erosion of upstream banks. The increased strength from alfalfa allowed the banks to be nearly vertical and slowed the pace of bank erosion. Slower bank erosion provided sufficient time the bars to vertically accrete to the level of the floodplain as the channel migrated. The channel width initially increased, but eventually stabilized until a cutoff formed at the upstream end of the flume. Even following the cutoff, changes in channel morphology were relatively minor.

We did not explicitly test our hypotheses that fine sediment and overbank flows were necessary for channels to maintain a meandering morphology. We also did not test the degree to which bank strength was required to maintain a meandering morphology. These questions can be examined in subsequent experiments.

These experiments and the river data set reviewed here indicate that examining independent variables such as valley slope, sediment supply, and discharge may not be sufficient to predict channel pattern. Channel pattern is also dependent on factors such as bank strength (from vegetation or fine material), and discharge patterns. Restoration projects therefore cannot rely on designed channel geometry or even the three driving variables (valley slope, discharge, and sediment supply) to maintain meandering channels.

These experiments indicate that both increased bank strength and fine sediments are necessary to maintain meandering gravel-bed channels. The degree of additional bank strength required likely varies based on the conditions found at individual sites, and some locations may not be suitable to maintain a meandering morphology regardless of the amount of vegetation because of flashy hydrographs, high sediment supply, or conditions that will not allow the channel morphology to reach the conditions outlined in Parker (1976) and Figure 4-2.

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4.11 FIGURES

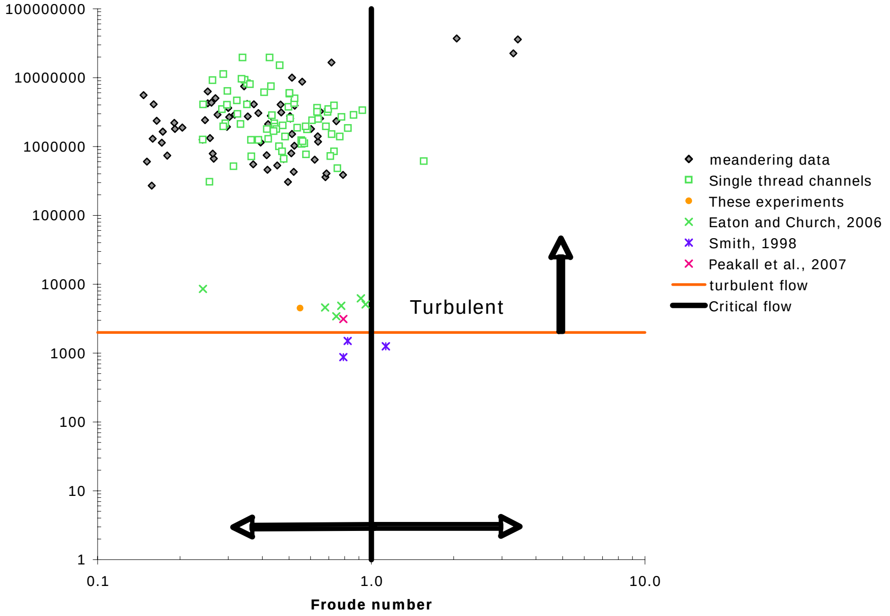


Figure 4-1. Froude number versus Reynolds number for both the meandering and single-thread datasets. We have also plotted various experiments that attempted to create meandering channels. The experimental data typically have higher Froude numbers and much lower Reynolds numbers than natural channels.

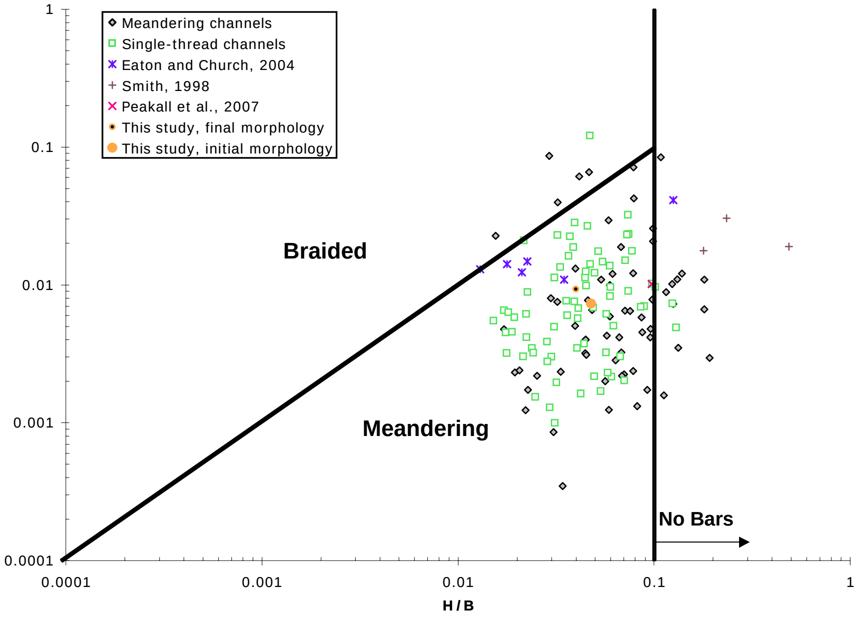


Figure 4-2. The criterion for meandering, braided, and straight channels defined by Parker (1976). Parker notes that the transitions are more gradual than shown in the figure. The majority of the field data plots within the meandering realm (some of the data plots in the realm with no bars). Flume experiments that eventually braided plot within the meandering portion of the plot. The experiments by Smith (1998), plot in the region with no bars, but point bars did develop in his experiments.

Figure 4-3. Chutes behind bars in experiments conducted by Parker (1976) prior to the channel braiding. The limited sediment deposition at the downstream end of bars is typical of meandering experiments conducted in sand. Photo courtesy of Gary Parker.

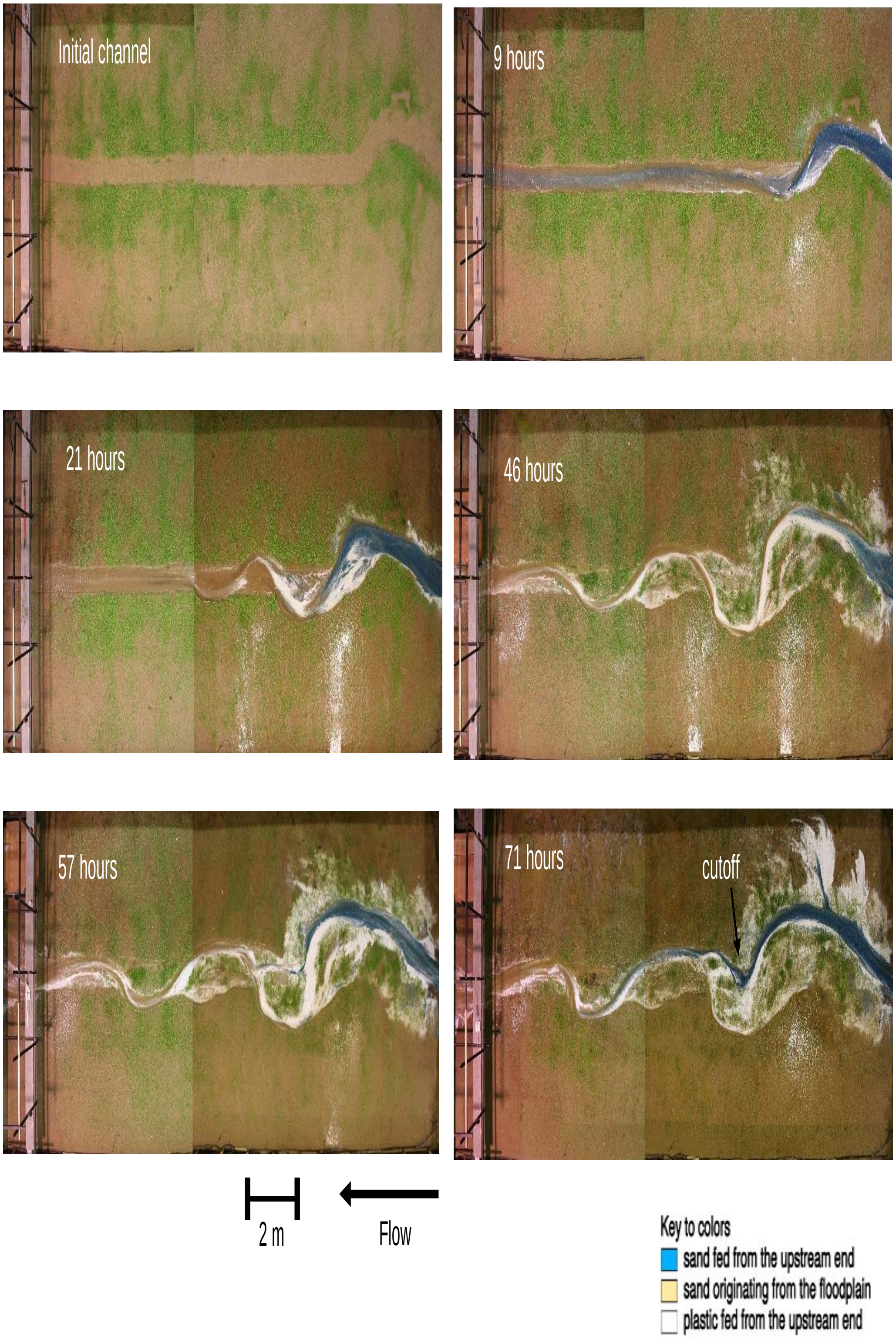


Figure 4-4. Overhead pictures of the flume through time. The fed sediment (blue) does not extend past the first bar until the cutoff shown at 71.3 hours.

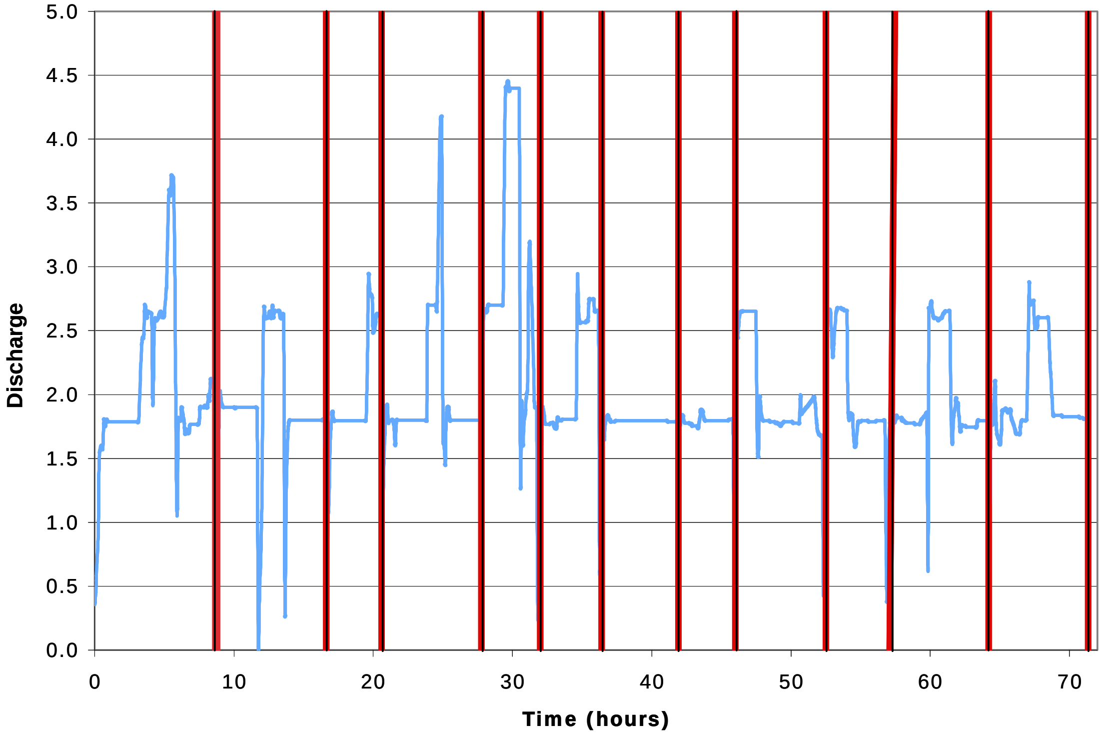


Figure 4-5. Discharge for the flume run. The vertical lines correspond to topographic surveys. The dips in discharge below 1.8 l/s correspond to periods where the discharge was turned on or off.

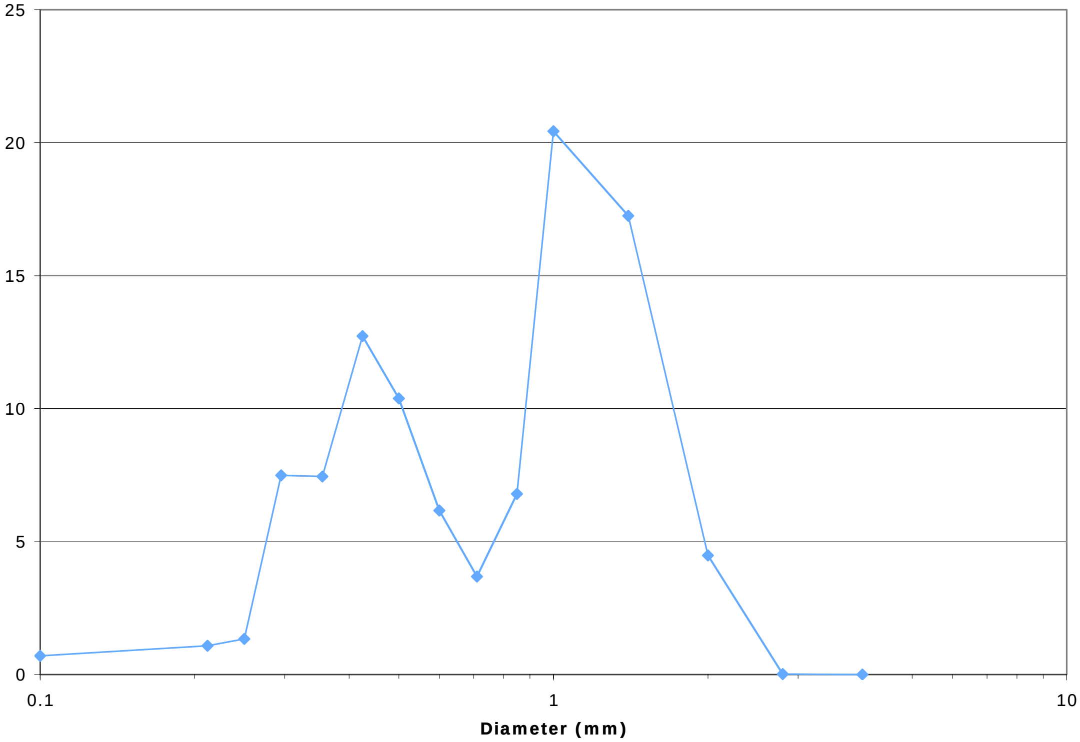


Figure 4-6. Grain size distribution of the coarse sediment used to fill the basin and for the coarse feed.

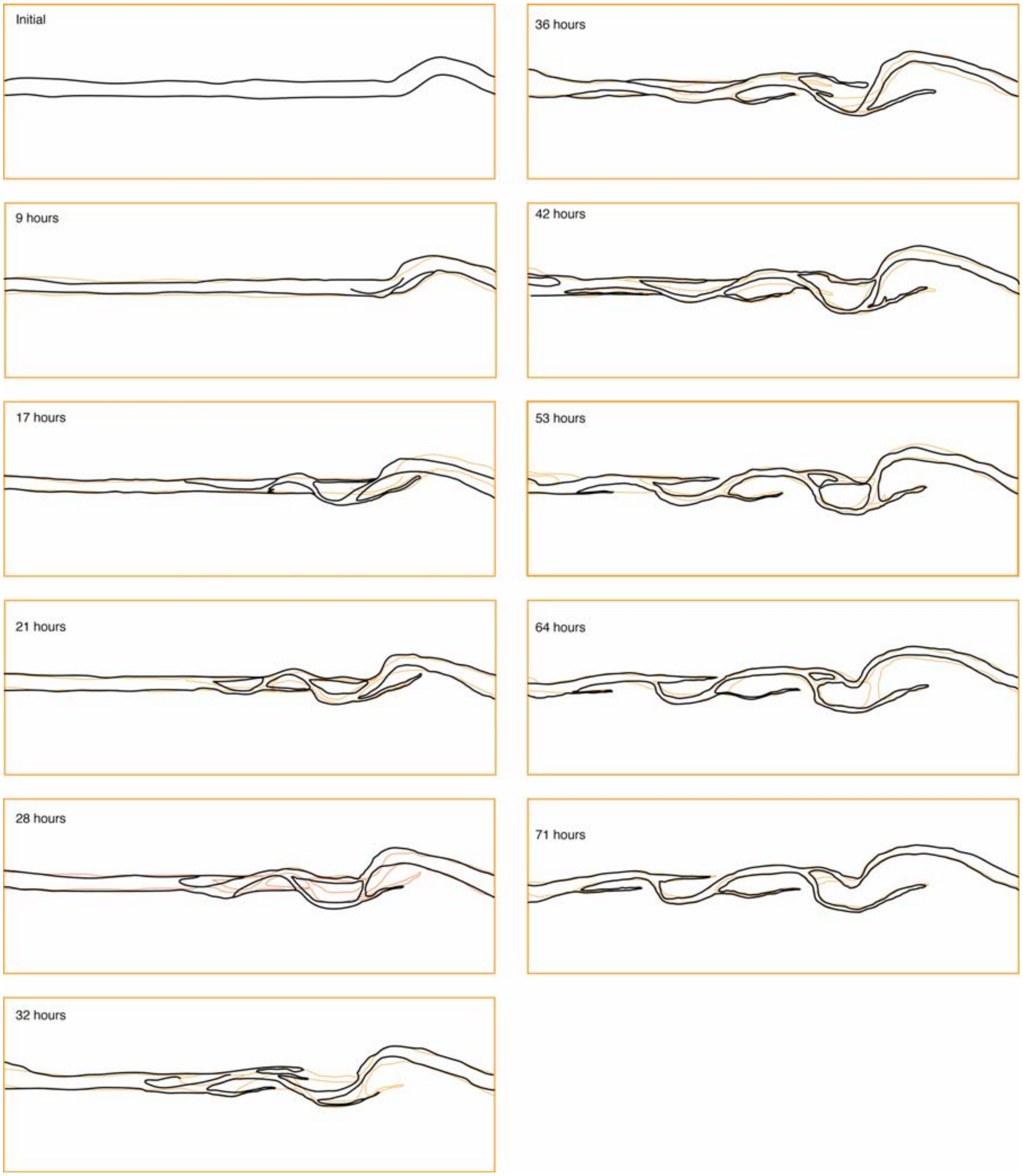


Figure 4-7. Trace of channel margin through time. The light orange lines indicate the channel margin during the previous time step.

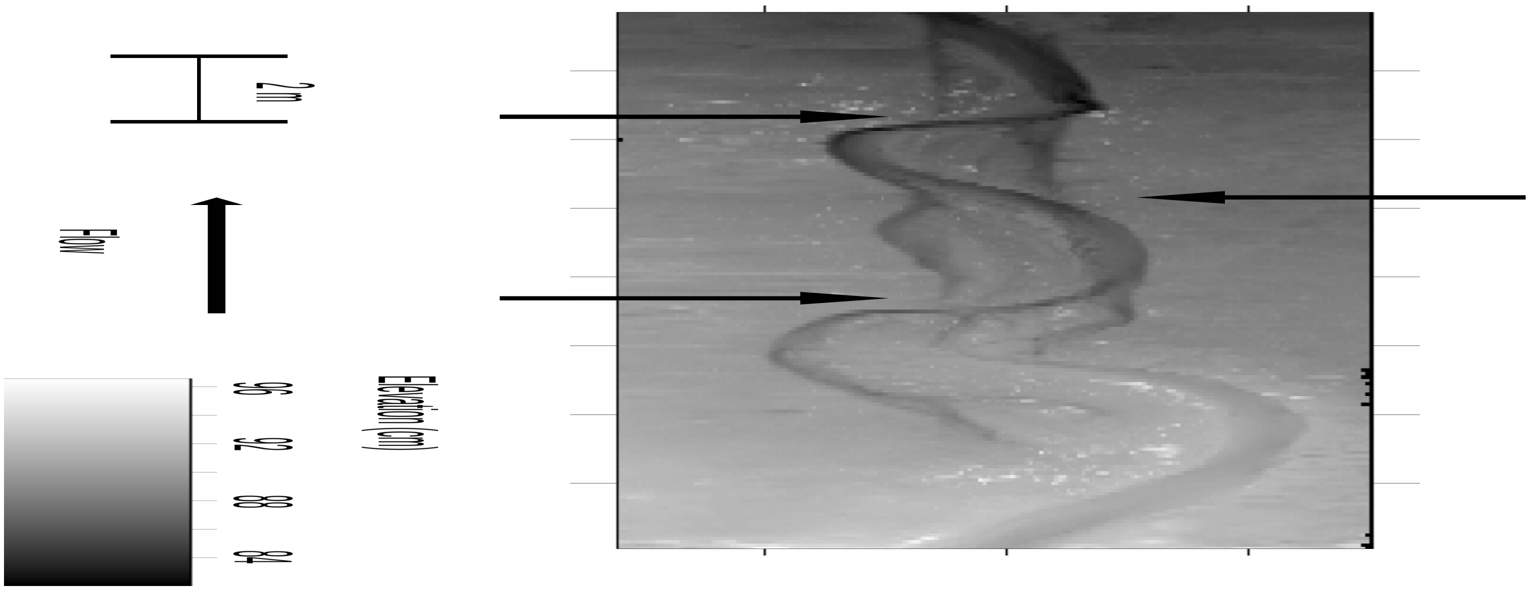
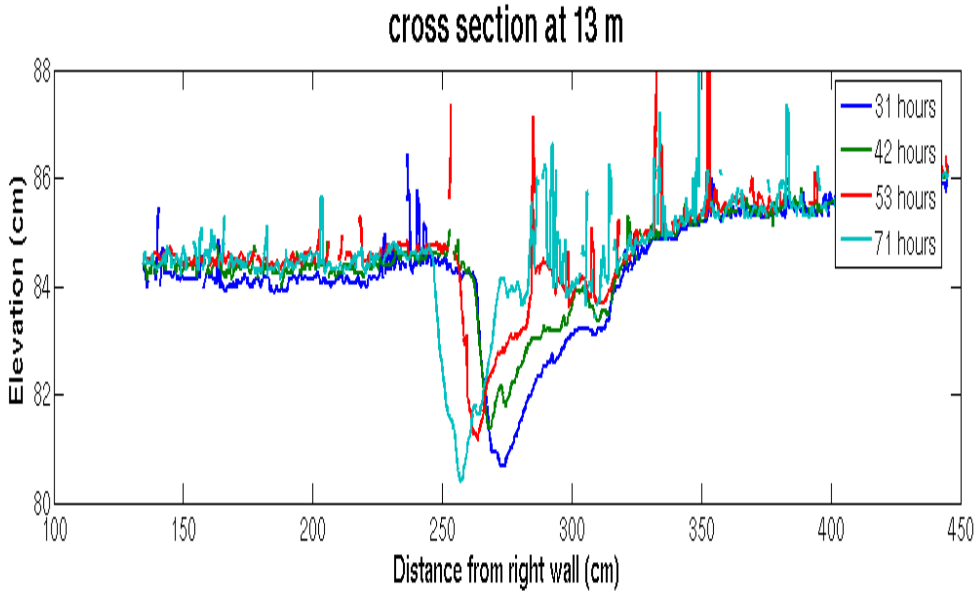


Figure 4-8. Grayscale image of topography in flume at the conclusion of the experiments. The black arrows indicate the sealed upstream area of chutes.

A. upstream of bar apex



B. downstream of bar apex

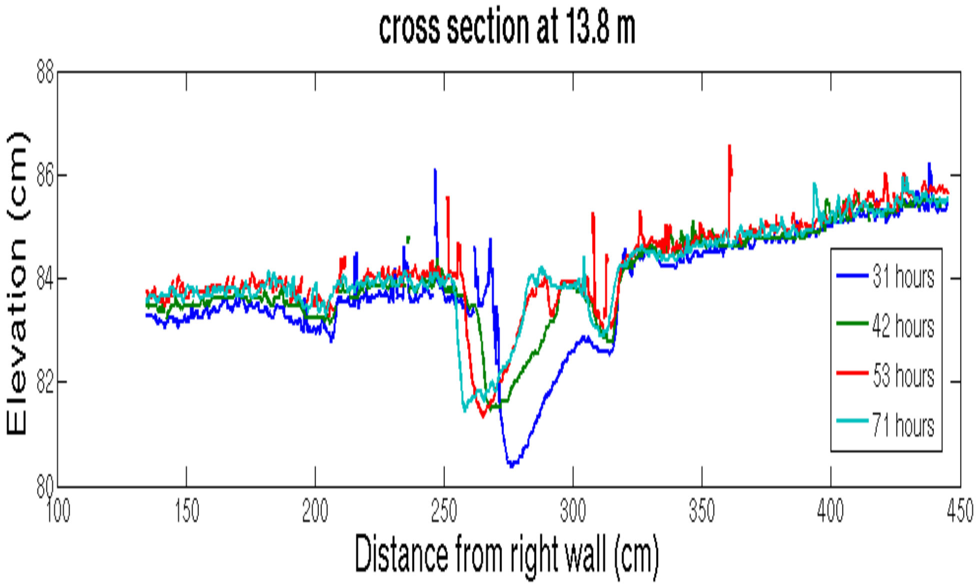


Figure 4-9. Cross section changes through time 13 and 13.8 m downstream of the flume inlet. The point bar is attached to the channel upstream of the bar apex, but a small chute remains downstream of the bar apex.

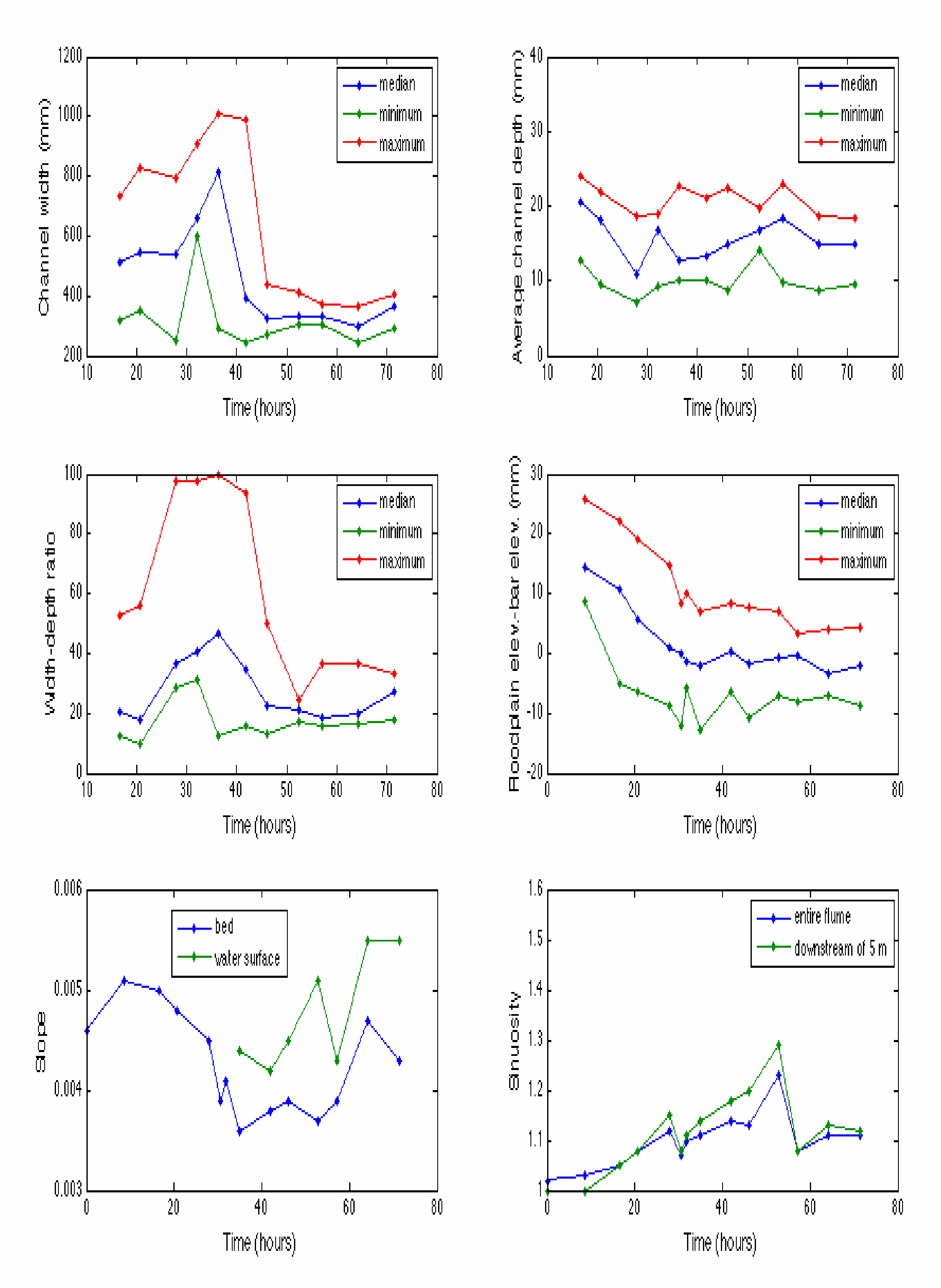


Figure 4-10. Changes in channel morphology through time. The curves in figure 10a-10d show the median, minimum, and maximum of width, average channel depth, width-depth ratio, and bar elevation, respectively. The data are taken from cross sections oriented perpendicular to flow spaced at 1-m intervals between 5 and 15 m from the upstream end of the flume.