FINAL TECHNICAL MEMORANDUM

Physical Modeling Experiments to Guide River Restoration Projects:

Gravel Augmentation Experiments

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Prepared by

Stillwater Sciences
Berkeley, California

Department of Earth and Planetary Science
University of California, Berkeley, California

and

Department of Geosciences
San Francisco State University, San Francisco, California

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1 INTRODUCTION

California Bay-Delta agencies have identified a number of strategies for restoring Bay-Delta tributaries. Three such strategies include: 1) injecting gravel to compensate for the loss of coarse sediment trapped behind dams and mined from the channel; 2) removing diversion dams to open 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 implementers 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 Experiments to Guide River Restoration Strategies’ (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 floodplain-channel redesign. The experiments were conducted at the University of California Richmond Field Station (RFS) 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 project from both 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 technical memorandum describes the key points from the gravel augmentation experiments. Two other memoranda that describe the key points from the dam removal and channel-floodplain redesign experiments are also being submitted concurrently. The purpose of this memorandum is to provide a brief discussion of the experimental questions, the experimental design, and summarizes the results, analysis, and key findings/implications for both the physical and numerical modeling associated with the gravel augmentation experiments. Detailed discussions of the entire gravel augmentation experimental program can be found in several manuscripts that are in preparation for submission to professional scientific journals. Attached to this memorandum is a copy of a manuscript, currently undergoing internal peer-review prior to submission for potential publication in a scientific journal that details one set of comprehensive gravel augmentation experiments (‘Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation downstream of dams,’ see Attachment). The rest of the manuscripts dealing with the gravel augmentation experiments are listed later in this document.
1.1 Impetus for Gravel Augmentation Experiments and Experimental Questions

Effective design of gravel augmentation projects requires accurate prediction of the temporal and spatial extent of beneficial changes to channel bed and associated aquatic habitat characteristics for a given set of design parameters. Project designers must select the volume of augmented gravel, the grain size distribution of augmented gravel, the frequency and timing of augmentation, and the method of sediment delivery (e.g., placement or injection). 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 upstream factors such as the availability of flows capable of mobilizing bed sediments and supply of both coarse and fine sediments. At present, project designers do not have sufficient scientifically-based analytical tools with which to make design choices that optimize the use of limited budgets for purchasing and delivering gravel and can meet pre-determined goals for habitat restoration. 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.

To assist in developing a stronger scientific basis for gravel augmentation project design, the gravel augmentation experiments were specifically focused on the following issues:

1. **Spatial and temporal evolution of discrete sediment pulses.** Gravel augmentation creates a pulse of relatively mobile sediment, analogous in some ways to a landslide or other episodic sediment delivery event. Recent work on sediment waves due to landslides has shown that large pulses predominantly disperse and do not translate downstream. Gravel augmentation pulses, however, may be more likely to translate because of they are typically small volumes and composed of well-sorted sediments designed to be finer than the bed to which they are added. Understanding the factors that control translation and dispersion of gravel augmentation pulses, and the rates of pulse evolution, will help improve models for predicting the location, magnitude and duration of beneficial changes to channel conditions.

2. **The potential for mobilization of armored channel beds by additions of finer gravel.** Beds downstream of dams are generally armored with a coarse layer of immobile sediments. Gravel augmentation projects commonly seek to reduce the grain size on the bed by burying the immobile armor under a layer of appropriately-sized gravel thick enough to support salmonid spawning. A potentially more cost-effective strategy would be to augment with gravel finer than the intended spawnable grain size distribution where the added gravel is capable of mobilizing the existing armor and exposing the finer sub-surface bed sediments. Previous flume experiments have suggested that this strategy may be effective, however it has not been systematically investigated.

The key experimental questions that were addressed by the gravel augmentation experiments conducted within this project were as follows:

1. How do the volume and grain size of gravel augmentation pulses influence the degree of pulse translation and dispersion and the magnitude and duration of beneficial bed texture changes? How does bar-pool topography influence the pattern of gravel augmentation pulse propagation? What is the difference between the pattern of gravel augmentation pulse evolution when combined with constant flow versus a variable flow in the form of a flood hydrograph?

2. To what extent can pulses of finer gravel mobilize previously immobile armored beds? What grain size and augmentation volume are most efficient in armor mobilization?
To address these questions, an armored channel bed was created in the long, gravel-transporting flume at the RFS, and then subjected to numerous pulses of gravel of various volumes and size distributions. The evolving bed topography and grain size distribution were monitored, along with the rate of sediment transport at the downstream end of the flume. We compared augmentation pulse behavior in channels with plane-bed and forced bar-pool topography, and with constant flow and variable flow hydrographs. The following sections succinctly describe the experimental design, the analysis of physical and numerical modeling results, and highlight the important findings and implications for restoration design and implementation associated with gravel augmentation. Detailed descriptions and discussion of the gravel augmentation experiments and results can be found in the following manuscripts (which will be posted at http://flume.stillwatersci.com):


2 OVERVIEW OF THE EXPERIMENTS AND ANALYSIS

2.1 Translation and Dispersion of Gravel Augmentation Sediment Pulses

We designed a series of flume experiments to examine the evolution of bed topography and texture in response to pulses of added sediment. The experiments were conducted in the 28-m long, 0.86-m wide and 0.9-m deep gravel-transporting flume at the Richmond Field Station (RFS). The flume was completely refurbished and instrumented as part of this project. To create an armored bed similar to those downstream of dams, we first simulated a natural, pre-dam condition by feeding a wide grain size distribution at a high supply rate and established an equilibrium active transport bed in which the sediment flux out of the flume balanced the sediment input rate. We then reduced the sediment supply in a series of steps, holding the discharge constant, eventually shutting off the sediment feed entirely. As sediment supply declined, we documented a decrease in the bed slope, a coarsening of the bed texture, and a reduction in the spatial variability of bed grain size distribution. The specific details of the analysis of the effects of the reduction in sediment supply on bed texture and mobility can be found in the manuscript ‘Response of bed surface patchiness to reductions in sediment supply.’

Once the bed was fully armored, and the sediment flux out had declined to less than 5% of the equilibrium value, we imposed a sequence of sediment supply pulses, varying pulse volume, grain size and frequency independently. After each gravel augmentation pulse run, we restored the initial armored bed by running the flume without sediment supply until the sediment flux out returned to a negligible rate. We used two well-sorted grain size distributions for the sediment pulses; one with the same median diameter as the equilibrium feed (8 mm) and the other with a smaller median diameter of 2.8 mm. We used two gravel augmentation volumes for these experiments; a large ‘unit’ pulse, equivalent to the amount of sediment required to cover the flume bed with a layer one median grain diameter thick, and a small pulse with 25% of the unit volume. Runs included single pulses with all four possible combinations of grain size and augmentation volume, and sequences of small volume pulses that were repeated without allowing the bed to fully re-armor. Replicate experiments were run under three sets of channel and flow conditions; a planar bed with constant flow, a forced bar-pool channel with constant flow, and a forced bar-pool channel with variable flow hydrographs. This three-step approach allowed us to incrementally build in complexity so that our experimental results can be interpreted at the field scale. The forced bar-pool topography was created by installing sand bags and immobile cobbles at a five-channel-width spacing, alternating between the left and right sides of the flume. Two flood hydrographs were used, each with a time-integrated water volume equal to the constant discharge over the same run duration; the hydrograph peaks were approximately 1.5 and 2.0 times the constant flow magnitude of 20 l/s. A total of eight hydrograph runs were conducted.

During each pulse we made frequent topographic surveys of the bed, using a submerged sonar instrument while flow was active, and a laser scanner when the bed was dry. We also measured bed grain size distribution by hand sampling the surface and with point counts taken from high resolution digital photographs. At the downstream end of the flume, we monitored bedload sediment flux with a tipping-bucket sediment trap suspended from a load cell. For each run, the augmented gravels were painted a different color, facilitating mapping of the leading and trailing edges of the evolving pulse. We analyzed the extent of pulse translation and dispersion using a new graphical method in which the centroid of the topographic deviation from the pre-pulse bed is plotted against the longitudinal distance encompassing the central 50% of the pulse mass. The time series of bed median grain size was analyzed to determine the magnitude and duration of the bed fining that results in bed sediment within the range of spawnable gravel, when scaled to a prototype river channel.
The major findings from these experiments are provided in the summary section below. The specific details of these experiments and associated analyses can be found in the attached manuscript (‘Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation downstream of dams’) and in the manuscripts ‘Variable flow influences on sediment pulse dynamics in a forced-bar morphology experimental channel’ and ‘Channel response to fine and coarse sediment pulses at varying spatial scales in a flume with forced pool-riffle morphology’.

2.2 Mobilization of Static Armor by Augmentation Pulses of Fine Gravel

The plane-bed gravel augmentation pulse runs described above were also used to study the mobilization of static armor by sediments finer than the pre-pulse bed grain size distribution. Within these experiments, armor mobilization was measured in several ways. First, we tracked the mass balance of bed sediments through each run, and inferred that mobilization had occurred when the time-integrated sediment flux out at the downstream end exceeded the sum of the mass of added gravel combined with the time-integrated background sediment flux rate measured prior to pulse addition. Second, we observed a spike in sediment flux out prior to the arrival at the downstream end of the leading edge of the painted augmented gravel, indicating that armor mobilization occurred along the pulse leading edge and that mobilized grains traveled downstream more rapidly than the added gravel. Third, we developed a sediment budget for the flume bed surface layer by sorting the sediment grains that exited the downstream end of the flume according to their color, and we also sorted the sediments removed in surface grain size samples and in point counts of digital photos. We then used the bed sediment budget to calculate the extent of armor mobilization and exchange of augmented gravel with the pre-pulse surface layer.

The major findings from these experiments are provided in the summary section below. The specific details of the analysis of the mobilization of the static armor by augmentation pulses can be found in the manuscripts ‘Mobilization of coarse surface layers by finer gravel bedload’ and ‘Sediment pulses in gravel bedded rivers: pulse sediment size effects on bed mobility’.

3 SUMMARY OF MAJOR FINDINGS RELATED TO GRAVEL AUGMENTATION AND IMPLICATIONS FOR GRAVEL AUGMENTATION PROJECT DESIGN

A summary of major findings are provided below while details of the results can be found in the five manuscripts listed earlier.

- Gravel augmentation pulses evolve through a combination of translation and dispersion, with translation becoming dominant for small augmentation volumes and fine gravel 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 a 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 rather than gravel placement in the channel bed.

- Pulse evolution is more dispersive in forced bar-pool topography than in 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.

- Gravel augmentation using relatively fine gravel is capable of mobilizing static armor due to a hydrodynamic smoothing effect on the channel bed. 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 volume pulses of gravel sizes four times smaller than the median diameter of the armor were most efficient in mobilizing the static surface layer. To prevent long-term re-armoring and maintain enhanced bed mobility, fine gravel augmentation pulses intended to mobilize armor should be followed by augmentation of gravel in the target size distribution for spawning habitat. 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 in gravel purchasing. 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.
APPENDIX A

Translation and Dispersion of Sediment Pulses in Flume Experiments Simulating Gravel Augmentation below Dams
Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams

Leonard S. Sklar¹, Jessica Fadde¹,², Jeremy G. Venditti²,³,⁴, Peter Nelson³, M. Aleksandra Wydzga⁵, Yantao Cui², and William E. Dietrich³

Abstract: Gravel augmentation is an increasingly common river restoration strategy for armored channels downstream of dams, however, few analytical tools are available to assist river managers in selecting the appropriate sediment volumes and grain sizes to achieve specific geomorphic and ecological outcomes. Coarse sediment additions are typically intended to improve habitat for spawning salmonids by altering stream bed grain size distributions, and increasing the frequency of bed mobilization and the diversity of channel morphology. Here we report results of a laboratory investigation in which we created an immobile, armored bed and documented the spatial and temporal evolution of the bed topography and bed texture in response to pulses of added finer, mobile gravel. The initial armored bed was created by first achieving an active transport equilibrium slope and then shutting off the sediment feed and allowing the bed to coarsen and degrade until the transport rate became negligible. We then introduced gravel pulses of various volumes and grain sizes, and used sonar bed topography surveys, hand mapping of the leading and trailing edges of the pulse, and grain size distribution measurements, to track the propagation of the wave of added sediment as it moved through the flume. We find that the introduced sediment waves evolve by a combination of translation and dispersion, with a significant translational component, particularly for small-volume sediment additions. Pulse translation and dispersion can be readily discerned on a graph of the time evolution of the downstream-cumulative distribution of elevation differences from the pre-existing bed topography. We also find that pulses of fine-grained sediments moved through the flume more rapidly, resulting in a larger magnitude but shorter duration of bed fining. Our results suggest that gravel augmentation projects can be designed to take advantage of the potential for pulse translation, particularly where a long downstream reach has significant restoration potential but lacks convenient access for artificial sediment delivery.

INTRODUCTION

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

Effective design of gravel augmentation projects requires accurate prediction of the temporal and spatial extent of beneficial changes to channel bed and associated aquatic habitat characteristics for a given set of design parameters. Project designers must select the volume of gravel to supply to the channel, the grain size distribution of the sediments, the frequency and timing of augmentation, and the method of delivery.

¹ Department of Geosciences, San Francisco State University, San Francisco, California, 94132, USA
² Stillwater Sciences, 2855 Telegraph Ave. Suite 400, Berkeley, California, 94705, USA
³ Department of Earth and Planetary Sciences, University of California, Berkeley, California, 94702, USA
⁴ Department of Geography, Simon Fraser University, Burnaby, BC V5A 1S6 Canada
⁵ Department of Earth Science, University of California, Santa Barbara, California, 93106, USA
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 upstream factors such as the availability of flows capable of mobilizing bed sediments and supply of both coarse and fine sediments. At present, project designers do not have sufficient scientifically-based analytical tools with which to make design choices that optimize the use of limited budgets for purchasing and delivering gravel and can meet pre-determined goals for habitat restoration [e.g. Harvey et al., 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 upstream tributaries. Gravel augmentation creates an artificial pulse of locally-enhanced sediment supply, which might be expected to evolve much the 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., 2003a; Lisle, et al., 1997] and numerical analysis [e.g. Cui et al., 2003b; Lisle et al., 2001]. These studies have shown that sediment pulses tend to disperse in place and rarely form mobile sediment waves that translate downstream. Dispersion is favored over translation in particular when pulse volumes are large relative to the channel dimensions. Large volumes of added sediment, as occur in landslides [e.g. Sutherland et al., 2002] and debris flows [e.g. Gabet and Hoffman, 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 incoming sediment upstream and enhanced 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., 2003a]. Dispersion of the sediment pulse is also favored when the size distribution of added sediment has a large spread and includes sediments coarser than the pre-existing bed, and when the Froude number is high (~1) [e.g. Lisle et al., 2001].

Gravel augmentation pulses often do not share these characteristics of natural sediment pulses, and thus may have a stronger tendency to evolve through translation as well as dispersion. The volumes of added sediments are typically small relative to the channel dimensions and may not cause significant change in the water surface topography. Gravel augmentation pulses 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 spread in the size distribution [Harvey et al., 2005]. Moreover, channels downstream of dams can differ in important ways from natural conditions where sediment pulses have been studied. For example, directly below dams, the supply of sediment 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 more commonly be mobilized under relatively low Froude number conditions.

Whether gravel augmentation pulses evolve by dispersing in place or by propagating downstream as a translating wave (or some combination of the two), has significant implications for predicting and achieving the intended aquatic habitat improvements. In contrast to the mostly negative disturbances to the bed caused by large natural sediment pulses [Lisle et al., 2001; Cui, et al., 2003a], the bed fining and enhanced bed mobility created by gravel augmentation is most beneficial when it persists for a long time and affects a long reach of river [Bunte, 2004; Harvey et al., 2005]. Slow dispersion without significant translation may be preferable to avoid scour of salmonid redds and when unique local conditions limit the potential benefits of enhanced sediment supply downstream. Conversely, translation may be a desired outcome when access points for sediment delivery are limited but a long downstream reach could...
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potentially benefit from the added gravel. In either case, the fundamental challenge is to predict the magnitude and temporal and spatial extent of changes to the bed for a specific set of gravel augmentation design parameters and pre-existing channel conditions.

Here we report the results of a set of laboratory experiments in which we explored the influence of pulse volume and grain size on the evolution of bed topography and texture during pulse propagation in a physical model of an armored channel downstream of a dam. These experiments were part of a larger program to investigate the response of gravel-bedded channels to episodic sediment supply; other contributions will focus on bed texture changes during channel armoring [Nelson et al., in prep.], mobilization of coarse armor by pulses of finer gravel [Venditti et al., in prep.], and the influence of forced bar-pool topography [Cui et al., in review; Wooster et al., in prep.] and flood hydrographs [Humphries et al., in prep.] on pulse propagation dynamics. In this paper we focus on the case of a planar, immobile armored bed subjected to pulses of finer gravel under constant flow conditions. We present a new metric for quantifying pulse translation and dispersion and document significant pulse translation, particularly for small pulse volumes. We then discuss implications of these experimental results for design of gravel augmentation projects.

EXPERIMENTAL METHODS

The gravel augmentation experiments were conducted in a 27 m long, 0.86 m wide, 0.8 m deep flume, located at the University of California, Berkeley, Richmond Field Station. Figure 1 shows a plan-view and a side-view schematic of the flume and the associated infrastructure. Water is recirculated at discharges ranging from 3 to 330 l/s. Sediments are supplied at the upstream end by up to three separate motor-driven auger feeders and are removed at the downstream end by a tipping bucket-type bedload trap that is suspended from a load cell. Submerged bedload sediment flux can be calculated from the time rate of change of the weight of the bedload trap. After weighing, sediments are tipped into a hopper and pumped out to a dumpster, and are not recirculated. The flume bottom was set to a slope of 1% and then filled with a wedge of sediment to create an initial bed slope of 0.5% (Figure 2a). In the experiments, the bed slope was allowed to evolve through differential erosion and deposition.

The flume is equipped with a computer-controlled, motorized instrument cart, which moves along horizontal rails supported by an independent frame (Figure 2b). To measure the evolving bed topography during active flow, we used a submerged sonar scanner (JSR ultrasonic pulser) with a vertical precision of 1.0 mm. We also measured the water surface topography with a sub-aerial sonar distance meter (MassaSonic M-5000/220). The instrument cart was also equipped with a Keyence laser scanner for making high resolution topographic scans (<1mm precision) of the flume bed when dry. Also mounted on the cart was a digital camera for documenting the bed texture when there was no water flowing in the flume.

The sediments used to create the initial bed and in the gravel augmentation pulses were obtained from local suppliers of well-rounded river gravel and mixed to achieve the desired size distributions. Each pulse of added gravel was painted a different color to facilitate documentation of the pulse movement and to distinguish added sediments from the pre-existing bed material in samples of the bed surface and the flux out the downstream end of the flume. The acrylic paint and sediments were tumbled together in a cement mixer until dry to prevent grains from sticking together. Sediments used to create the initial bed were supplied to the flume by the motorized sediment feeders but for the gravel augmentation pulses we fed the sediments by hand at a constant rate, at a point sufficiently downstream of the flume entrance to avoid the zone of flow acceleration.

We used two techniques to measure the bed surface grain size distribution during the experiments. First, we hand-collected samples of bed material at five locations along the flume (5, 10, 15, 20 and 25 m
downstream of flume entrance) at the beginning and end of each experimental run. To make sure we collected all grains exposed at the surface, we placed a piece of cardboard with a 25 by 25 cm square opening cut out in the center of the flume. We then lightly spray-painted the grains and removed each partially-painted grain by hand and with an adhesive coated cloth (Figure 3a). The grains removed were rinsed to remove any adhesive, dried and sieved to obtain the gravimetric grain size distribution. We used a second technique, point counts from digital photographs, to measure the bed size distribution during the runs to avoid disturbing the bed and potentially affecting the experimental outcome. The photos were calibrated using rulers placed across the bed (Figure 3b) and were always taken from the same elevation above the bed, which we controlled using the laser distance scanner. Point counts of grain diameters were made using a 100-point grid superimposed on the photo. We used the method of Kellerhals and Bray [1971] to convert the areal distribution to a gravimetric grain size distribution. Comparisons between photos taken prior to hand sampling showed excellent agreement.

During the gravel augmentation pulse experiments, we monitored the topographic evolution of the bed surface with frequent scans using the submerged sonar scanner. We also mapped by hand the position over time of the leading edge and the tail of the pulse of painted grains.

**EXPERIMENTAL DESIGN**

The scaling of the hydraulic conditions (Table 1) and sediment size distributions was guided by several goals. First, these experiments were intended to focus on the influence of sediment supply and grain-to-grain interactions on gravel augmentation pulse evolution and bed texture response. We therefore used a low width-to-depth ratio (~ 4) to suppress bar development and maintain an approximately planar bed on which pulse evolution could occur. We also used a constant discharge (205 l/s) to focus on the effect of spatial and temporal variations in sediment supply. Froude number was kept below one (~ 0.7) to maintain sub-critical flow. Second, we sought to recreate the sequence of bed texture change following dam construction by shifting from active bedload transport to an immobile armored bed solely by eliminating the sediment supply. This required a shear stress well in excess of the threshold of motion for the active bed (achieved for this discharge with a bed slope of 0.5%) and a wide grain size distribution to provide sufficient coarse grains to form the immobile armor. The grain size distribution for the initial, pre-dam condition had a median diameter of 8 mm and a graphical standard deviation of 1.7. This size distribution corresponds to a 1:4 model-to-prototype ratio for a typical gravel bedded river with a median grain size ($D_{50}$) of 32 mm [Parker, 1990], and also maintains a fully hydraulically rough flow condition, facilitating scaling between the model and prototype channel beds.

To create an immobile armored bed, as is commonly found downstream of dams, we first simulated the pre-dam condition of a quasi-equilibrium bed formed by active bedload transport in which the flux out is equal to the sediment supply from upstream. Starting with a bed slope of 0.5%, we fed the initial size distribution at 120 kg/hr for 16 hours, until the flux out matched the supply rate and we observed no further changes in the bed slope or bed texture. We then reduced the sediment supply in three steps (to 80, 47 and 0 kg/hr), documenting the change in slope and bed texture once a new steady state bed was established. With the elimination of any sediment supply at the end of the third step-down, we ran the flume for 100 hours until the flux out reached a negligible rate of 1-2 kg/hr. During this time the bed slope declined to 0.4% and the median grain size of the armored bed was 13 to 14 mm, creating an arming ratio of approximately 1.7. A detailed account of the bed armoring in response to sediment supply reduction for these experiments, will be provided by Nelson et al. [in prep.].

Once the immobile armored bed was established, we simulated a sequence of gravel augmentation pulses to investigate the influence of pulse grain size and volume on pulse evolution and bed texture response. Here we focus on four single-pulse runs in which we varied grain size and volume independently. To explore the effect of variations in pulse volume we used two volumes that differed by a factor of 4. The
larger volume was equivalent to that required to cover the entire flume bed with a layer of sediment one grain diameter thick, for the 8 mm median diameter of the pre-dam equilibrium sediment supply. This corresponded to a pulse mass of 270 kg. The smaller pulse volume had a mass of 68 kg. These two pulse volumes are referred to hereafter as the ‘large’ and ‘small’ pulse respectively. To investigate the effect of the grain size of added sediments on pulse evolution, we used two well-sorted size distributions, with median diameters that differed by a factor of about 3. The ‘coarse’ distribution had a median diameter of 8 mm, the same as the D$_{50}$ of the pre-dam equilibrium feed distribution and representative of the intended target distribution for restored spawning conditions. The ‘fine’ distribution had a median diameter of 2.8 mm, which was selected to test the hypothesis that additions of fine gravel can mobilize static armor [Venditti et al., in prep.]. For each pulse, we ran the flume for a time sufficient to allow the pulse to fully evolve, and for the bed to return to an immobile armored state where the flux out at the downstream end was reduced to a negligible value (~1 to 2 kg/hr). Table 1 lists the experimental conditions for these four runs.

**CONCEPTUAL FRAMEWORK FOR PULSE EVOLUTION**

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 known well and because small topographic and grain size disturbances are difficult to measure reliably. Laboratory experiments allow control over initial and boundary conditions and facilitate more detailed and frequent measurements, and are more readily compared to numerical simulations [Lisle et al., 1997; Cui et al., 2003a]. Lisle et al. [1997] provided graphical 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. Here we quantify the extent of 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 4a shows a theoretical pulse that evolves purely by translation. The pulse waveform was generated using a gamma function for the spatial distribution of bed elevation:

$$z = \frac{x^{\alpha-1}e^{-x/\beta}}{\beta^\alpha(\alpha-1)},$$  \hspace{1cm} (1)

where $z$ is the bed elevation, $x$ is the downstream distance along the flume, $e$ is the base of natural logarithms and $\alpha$ and $\beta$ are parameters that control the shape of the distribution. Figure 4b shows the cumulative distribution of bed elevation changes from the pre-pulse bed topography, for the case of pure translation depicted in Figure 4a. Both figures show a translational pulse that marches downstream at a constant speed and exits the flume. Because the waveform itself is not altered by downstream translation, the slope of the curve in the cumulative plot (Figure 4b) does not change. This can be considered diagnostic of translational pulse evolution. Note that because there is no upstream sediment supply, and we assume in this simulation that there is no erosion of the underlying pre-pulse bed, the total area under the curve remains constant until the pulse begins to exit the flume.

In contrast, Figure 4c shows a purely dispersive wave, again generated with a gamma function. The pulse appears stationary and gradually fades away as sediment is transported downstream and out of the flume. Figure 4d shows the cumulative distribution of the elevation for this dispersive pulse. Unlike the case of pure translation (Figure 4b) the cumulative curve for the dispersive case rotates clockwise and fades as the pulse exits the flume. This rotation of the cumulative curve can be considered diagnostic of dispersion-dominated pulse evolution.
Most sediment pulses have both translational and dispersive properties [Lisle et al., 2001]. Figure 4e shows an example of a pulse that evolves with simultaneous translation and dispersion, with the cumulative distribution shown in Figure 4f. Combining the diagnostic properties of the two previous examples, the cumulative curve shows both a progressive displacement toward the right, indicating translation, and a rotational decline in the slope of the curve, indicating dispersion.

The full range of possible combinations of translation and dispersion in sediment pulse evolution can be plotted on the same graph by comparing the position of the center of the pulse with the lateral spread of the pulse. Here we use the non-parametric statistics of the distribution of elevation deviations from the pre-pulse bed, with the pulse center represented by the median and the spread of the pulse distribution represented by the inter-quartile range (IQR). For a purely translational pulse we would expect a steady increase in the median location with no increase in the IQR. This behavior is shown in Figure 5 for the example pulse of Figure 4b. In a sediment wave that is purely dispersive there would be no change in the location of the center of the pulse. Because we are concerned with the case of no sediment supply from upstream, dispersive erosion of the transient sediment deposit would have the effect of slightly shifting the location of the centroid downstream. As shown in Figure 5, for the dispersion example of Figure 4d, the IQR increases steadily while the median location only changes very slightly. Finally, for the mixed case in Figure 4f, both the median location and the IQR increase with time (Figure 5). Note that as the pulse begins to exit the flume the IQR will decrease because the tail of the pulse is no longer within the elevation distribution of the flume bed. Thus, this method can only be used to identify pulse evolution behavior when the bulk of the pulse is still within the flume. Below, we use the patterns illustrated in Figure 4 to identify translational and dispersive behavior in the evolution of the experimental gravel augmentation pulses.

EXPERIMENTAL RESULTS

Qualitative overview of pulse propagation

Each pulse was fed into the flume over a finite duration, 25 and 100 minutes for the small and large volumes respectively. A clearly visible leading edge of the pulse of painted grains begin migrating downstream immediately after the feed began. Although the added sediments were spread evenly across the flume width during the feed, the leading edge advanced most rapidly along the center line of the flume, forming a convex-downstream facing plume of altered bed color, texture and topography. The pulse spread across the width of the flume, more completely for the slower moving coarse (8 mm) added sediments than for the fine (2.8 mm) gravel. After the sediment feed was complete, transport of material from the input location thinned the accumulated deposit of painted gravel, eventually re-exposing the pre-existing coarse armor. The tail of the pulse then visibly migrated downstream, distinguishable as the upstream-most zone with active transport of the painted added gravel. As discussed in detail by Venditti et al. [in prep.], the added gravel caused mobilization of the previously static armor, resulting in scour of the armor layer and degradation of the bed upstream of the pulse tail. Eventually, each of the mappable pulse components, the leading edge, the central portion of the pulse mass, and the pulse tail, exited the flume. Sediment transport continued at a declining rate until returning to a negligible level at the conclusion of the run.

In the following sections, we provide a detailed quantitative description of the pulse dynamics, focusing first on the topographic evolution of the bed, as revealed by the sonar scans, then on the celerity of the leading edge and tails of the pulses, and finally on the pattern of changes in grain size distribution of the bed material.
Topographic evolution of the bed

The pattern of pulse propagation is best revealed by the topographic evolution of the bed surface. We focus on center-line longitudinal profiles from the sonar scans, which are composed of elevation measurements spaced 5 mm apart. Figure 6a shows the raw data for two scans, taken from Run 7, the large volume, coarse-grained pulse. The first scan was made just prior to the introduction of the pulse material while the second scan was made 114 minutes after the beginning of the pulse feed, and shortly after the feed was completed. Although the increase in bed elevation due to the addition of the pulse material is apparent, it is difficult to clearly see the shape of the topographic wave form from this representation of the data. To aid in visualizing and analysis of the bed topography, we calculated the deviation in elevation from the pre-pulse bed profile for each scan, and then smoothed the resulting profile using a running average with a window 1.5 meters long. The resulting raw and smoothed elevation difference profiles are shown in Figure 6b for the Run 7 scan at the end of the pulse input.

Below, we use the smoothed profiles to evaluate the topographic evolution of the bed for the four single pulse runs, considering first the two large volume pulses (coarse- and then fine-grained) and second the two small volume pulses (coarse- and then fine-grained).

The full set of six elevation difference scans for the large volume, coarse grain size pulse (Run 7) is shown in Figure 7a. During the pulse input (scans at 7 and 54 minutes), the leading edge of the topographic change can be seen moving downstream, reaching the end of the flume (at 27 meters) just after completion of the pulse input (114 minutes). At 122 minutes, the topographic tail of the pulse can be seen moving downstream (at ~9 m), while through the center of the pulse, the peak elevation differences can be seen to decline between scans at 114 and 122 mins. By 170 mins, most of the pulse material has left the flume, and scour below the pre-pulse bed elevation has occurred at the upstream end of the flume. However, long after the pulse has exited, significant deviations from the pre-pulse topography persist, notably elevated zones centered at 12, 18 and 22 meters downstream of the flume inlet.

The cumulative elevation difference curves for the large, coarse pulse (Run 7) are plotted in Figure 7b, and provide a simpler depiction of the propagation of the pulse through the flume. As the pulse material is added to the flume during the feed period (scans at 7, 54 and 114 minutes), the peak in the cumulative elevation difference increases accordingly. Evidence for pulse translation is seen by comparing the curves for 114 and 122 mins, which are essentially parallel but offset downstream by about 2 meters. The peak in the 122 minute curve is lower because the leading edge of the pulse has exited the flume, reducing the total volume of pulse material remaining in the flume. Evidence for some dispersion of the pulse tail can be inferred from the volume of added material remaining in flume after the pulse has exited the flume.

Figure 8 shows the elevation difference and cumulative elevation difference profiles for the other large volume pulse (Run 10), which had a fine grain size of 2.8 mm. This pulse migrated rapidly through the flume, showing clear evidence of translation in the parallel slopes of the cumulative elevation difference profiles (Figure 8b) in the downstream half of the flume for the scans at 32, 77 and 101 minutes. Pulse dispersion is also evident in the division of the pulse into two major lobes, separated by a topographic low point at ~15 m in the 77 minute scan (Figure 8a). Enhanced armor mobilization due to the small grain size in this run is reflected in the widespread bed degradation along the length of the flume once the pulse has left the flume (136 min.).

Considering next the small volume, coarse-grained pulse (Run 23), clear evidence for both translational and dispersion elements of pulse evolution are visible in the plots of elevation difference (Figure 9a) and cumulative elevation difference (Figure 9b). The peak of the topographic wave form migrates downstream and declines in height as the topographic wave form widens (Figure 9a). The bulk of the
pulse shows primarily translational propagation in the slope-parallel advance of the cumulative difference curve (Figure 9b), with the dispersive component visible in the gradual rotation of the tail portion of the pulse.

The small volume, fine grained pulse (Run 9) moved through the flume so quickly that only one of the three available scans can be used to evaluate the topographic evolution of the bed (at 32 mins.), shown in Figures 10. However, the pattern is consistent with a primarily translating wave leaving some material behind as it moves down the flume, as indicated by the break in slope of the cumulative curve at 21 m, with the steeper slope downstream and the more gradual slope upstream. The pulse had completely exited the flume by the time of the second scan, which reveals bed degradation due to armor mobilization.

To compare the evolution of the set of pulses we plot in Figure 11 change over time in the width of the central 50% of the topographic wave as a function of the pulse centroid location, as in the theoretical example shown in Figure 5. (Note that the small, fine-grained pulse could not be plotted because at least two scans are needed to show pulse evolution using this method). The primarily translational behavior of the small, coarse pulse (Run 23) is clearly evident in the horizontal progression of the pulse across the graph. The two large-volume pulses (Runs 7 and 10) are more difficult to evaluate because most of the available scans were taken while the pulse was still being added to flume. However, once the pulse feed ended, neither large volume pulse showed significant dispersion before the bulk of the pulse began to exit the flume.

**Celerity of leading and trailing edge**

The celerity of the wave of added sediment, as it moved through the flume, provides another way to evaluate the propagation and evolution of the sediment pulse. Figure 12a shows the mapped the position of leading and trailing edges of the mobile pulse material as a function of time for the large volume, coarse-grained pulse (Run 7). Each of the edges bounding the pulse begins at the feed location at 6 m and moves up across the graph to the downstream end of the flume at 28 m. The average celerity is represented by the slope of the line, faster wave speed corresponds to a steeper line because less time is required to reach the end of the flume. For any position along the flume (vertical axis), the duration of the pulse passage is represented by the horizontal separation of the two curves. Similarly, for any moment in time (horizontal axis), the length of the flume occupied by the pulse material is shown by the vertical distance between the tail curve and the leading edge or the flume end when the leading edge has already exited the flume. For a purely translational wave, the celerity of the leading and trailing edges would be the same, and the two curves would be parallel. Conversely, the curve for the trailing edge would be approximately horizontal for purely diffusive wave, for the case of no upstream supply, and would have a negative slope (moving upstream) for a diffusive wave with deposition on the trailing limb due to active supply from upstream.

Comparing the celerity plots for the four runs (Figure 12), several observations can be made. First, each pulse translates downstream in that the pulse tail advances downstream and does not stay fixed at the sediment input location. Second, each pulse disperses in that the tail celerity is always less than the leading edge celerity, such that the duration of pulse occupation increases downstream. Third, translational behavior was most dominant early in the pulse evolution, with a larger dispersive component occurring in each case further downstream as the tail celerity declined with time. Finally, celerity depends on both pulse volume and grain size, with the most rapid movement of both the leading and trailing edges occurring for the fine-grained pulses. The slowest leading edge celerity occurred during the small volume, coarse-grained pulse, unlike the slowest trailing edge celerity which occurred during the large volume, coarse-grained pulse.
Bed texture and grain size evolution

The most common goal of gravel augmentation projects is reducing the median grain size of the bed material, so perhaps the most important aspect of the pulse propagation is the evolution of the bed $D_{50}$. Following the same sequence as the previous two sections, we next present results of the bed sampling and photo-based point count grain size measurements for the two large and then the two small volume pulses.

Figure 13a shows the time evolution of the bed $D_{50}$ for four locations along the length of the flume, for the large volume, coarse-grained pulse (Run 7). The pre-pulse armored bed had a median grain size between 11 and 13 mm, but as the pulse passed through the flume the bed fined to about 8 mm, the size of the pulse material. After the passage of the pulse, the bed coarsened to approximately 10 mm, resulting in a small but significant net fining compared to the pre-pulse bed. Part way through the re-armoring period (650 minutes), the grain size measurements show a downstream fining pattern that reflects the downstream propagating armor development. By the end of the run, (1100 minutes) a more uniformly coarse bed was re-established.

The rapid passage of the large volume, fine-grained pulse (Run 10) is clearly shown in Figure 13b, which, after the pulse exits the flume, is followed by a similar transient downstream fining pattern and eventual re-establishment of the coarse immobile armor. The small volume, coarse-grained pulse (Run 23) produced a long-lasting bed fining in the downstream portion of the flume (Figure 13c), but due to the initially rapid translation of the pulse (Figure 9) the bed upstream had already coarsened by the time of the first set of post-pulse bed measurements (350 minutes). Rapid initial pulse translation is also responsible for the pattern of bed fining for the small volume, fine-grained pulse (Run 9) shown in Figure 13d. At 50 minutes after the start of the augmentation the bed in the downstream portion of the flume is dominated by the pulse material, while upstream the bed has coarsened. Full re-armoring by 900 minutes shows a net coarsening for the upstream locations and a downstream fining pattern

How ecologically significant these patterns of bed fining are depends on the duration that the bed is within a target median grain size range. For example, if the target range for the $D_{50}$ is between 20 and 50 mm, and our model sediments are scaled down from the prototype by a factor of 4, then a gravel augmentation pulse that produced bed fining in the range between 5 and 10 mm would be considered successful. Figure 14 shows this range as a shaded block imposed on a plot of the time evolution of the bed $D_{50}$ for the four experimental pulses, at the location 21 m downstream of the flume inlet. This location provides a good point to compare the various pulses because it is far from the upstream boundary where entrance conditions might affect the results. Figure 14 shows that the coarse-grained pulses shift the bed $D_{50}$ into the target range, and persist for a longer duration than the fine-grained pulses. Moreover, the fine-grained pulses overshoot the lower boundary of the target range as the bulk of the pulse passes through and lead eventually to re-armoring at or above the pre-existing armor $D_{50}$.

DISCUSSION

Pulse translation and dispersion

Our simulated gravel augmentation pulses evolved through a combination of translation and dispersion. For each pulse, translation was evident in the downstream migration of all three of the basic components of the pulse: the leading edge, the centroid of added material, and the trailing edge (Figures 11 and 12). Pulse translation was also evident in the downstream movement of the zone of most significant bed fining (e.g. Figure 13d). Translational behavior occurred most significantly in the small volume pulses (Figures 9b and 10b). Pulse grain size appears to have less of an influence on translation, with the coarse-grained pulse (Run 23) having the lowest ratio of leading edge to trailing edge celerity. The translation observed
here is consistent with previous observations that translation can occur when a sediment pulse has a low height to length ratio, the grain size is smaller than the pre-existing bed, and the pulse has a narrow grain-size distribution [Lisle et al., 1997, 2001; Cui et al., 2003a, 2003b].

Significant dispersion was also evident in each pulse. Pulses tended to disperse primarily along the trailing portion of the translating wave, in effect by leaving material behind (e.g. Figure 10b), and by breaking into multiple smaller pulses (e.g. Figure 8a). Overall pulse dispersion is most evident when comparing the difference between leading edge and trailing edge celerity, however, the downstream-cumulative elevation difference graphs reveal more accurately how pulse mass is distributed as the pulse spreads and migrates downstream. Despite the significant component of translation, the simultaneous dispersion of these pulses is consistent with the fundamental conclusion of Lisle et al. [2001] that persistent sediment wave migration over long distances does not occur in gravel bedded rivers.

A major limitation of our experiments, however, is the short length of the flume relative to the size and celerity of the pulses. For example, the large volume pulses (Runs 7 and 10) spanned the length of flume, such that the leading edge exited the flume before the sediment feed was complete (Figures 12a and 12b). Similarly, the bulk of the fast-moving, fine-grained, small volume pulse had left the flume within 20 minutes of the end of the sediment feed, leaving insufficient time to complete a second scan to capture the movement of the centroid. Our most accurate documentation of pulse evolution is where we have the highest frequency of topographic scans, the small-volume, coarse-grained pulse (Run 23). Given that this pulse also showed the strongest translational behavior, we conclude that our findings are robust despite the constraints of the flume length.

**Implications for river 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 stretches of rivers may be more likely to succeed than has been previously thought [Harvey et al., 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 frequent deliveries of small pulses will be more effective than fewer larger pulses. Supply of gravel to the channel by dumping gravel off the edge of a high bank or terrace to form a talus cone (often referred to as ‘gravel injection’) [Bunte, 2004; Harvey et al., 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 material was left behind as pulses translated downstream. 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 longest duration of beneficial grain size changes occurred in the downstream portion of the flume, due to the difference in celerity between the leading and trailing edges (e.g. Figures GG and HH). 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 anticipated. Where project goals call for maximizing pulse dispersion, large pulse volumes should be used, although major changes to local water surface slope, such as in the case of landslide
inputs [e.g. Sutherland, et al., 2001], may degrade habitat quality by reducing upstream flow velocity and trapping fine sediments.

In each run, the most significant bed fining occurred during the passage of the peak of the pulse, where the bed texture was dominated by added pulse material. For any given location along the flume, the transition from the pre-existing bed grain size distribution was abrupt, as the leading edge of the pulse formed a distinct, advancing wave of painted finer gravel. In contrast, the trailing edge was considerable more diffuse, so that the transition to the post-pulse bed texture was more gradual. For the fine-grained pulses, which moved through the flume more rapidly, the transition to the post-pulse bed texture was more rapid than for the coarse-grained pulses.

For the restoration goal of maximizing 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 (14 mm to 3 mm), and were more effective at mobilizing the pre-pulse armor [Venditti et al., in prep.]. As Figure 14 illustrates, it is possible to overshoot the ecologically beneficial 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-finishing, comparing the pre- and post-pulse median grain size, while the fine-grained pulses resulting in no net fining and even net coarsening, as has been observed in the field following large volume 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.

CONCLUSIONS

We conducted a series of experiments simulating gravel augmentation in a plane-bed, armored channel downstream of a dam, to explore the influence of the volume and grain size of added material on the style and rate of evolution of the resulting sediment wave. Key findings with implications for gravel augmentation project design include the following.

All experimental gravel augmentation pulses evolved through a combination of translation and dispersion, with the most significant translation occurring for small augmentation volumes. Translational pulse propagation has the potential to provide bed texture and mobility benefits over a longer downstream distance than dispersive pulses, but also results in shorter duration of bed improvements locally. 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 rather than gravel placement in the channel bed.

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, because fine-grained pulses are more effective in mobilizing pre-existing armor and mixing with the pre-pulse sub-surface sediments, alternating fine- and coarse-grained additions may be maximize the duration and spatial extent of beneficial bed texture changes.
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### Table 1. Experimental conditions.

<table>
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<th>Run 10</th>
<th>Run 23</th>
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<td>Small, Fine</td>
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Figure 1. Plan-view and side-view schematics of flume.

Figure 2. Photographs of flume, (left) looking upstream with unarmored initial bed, (right) looking downstream from sediment feed platform during run; note instrument carriage midway down flume.
Figure 3. Bed grain size distribution measurement methods, (left) Surface sample taken by hand from 25x25cm square, and (right) point counts from photos calibrated with rulers.

Figure 4. Theoretical examples of pulse evolution showing elevation difference between bed elevation and pre-pulse 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).
Figure 5. Pulse evolution depicted with non-parametric statistics of downstream-cumulative distributions of elevation differences for the three theoretical cases shown in Figure 4. Length enclosing 50% is calculated as the interquartile range, and pulse centroid location is the median point in the elevation difference curve.

Figure 6. Method for de-trending and smoothing bed topography scans. (A) raw topographic data for large-volume, coarse-grained pulse (Run 7) just prior and 144 minutes after beginning of sediment feed. (B) Elevation difference between scans at 0 and 144 minutes at 5 mm intervals, solid symbols, and smoothed by averaging over 3 meter window, thick grey line.
Figure 7. Topographic evolution of large volume, coarse-grained pulse (Run 7). (A) elevation difference from pre-pulse bed, and (B) downstream-cumulative elevation difference.
Figure 8. Topographic evolution of large volume, fine-grained pulse (Run 10). (A) elevation difference from pre-pulse bed, and (B) downstream-cumulative elevation difference.
Figure 9. Topographic evolution of small volume, coarse-grained pulse (Run 23). (A) elevation difference from pre-pulse bed, and (B) downstream-cumulative elevation difference.
Figure 10. Topographic evolution of small volume, fine-grained pulse (Run 9). (A) elevation difference from pre-pulse bed, and (B) downstream-cumulative elevation difference.
Figure 11. Pulse statistics of downstream-cumulative distributions (as in Figure 6), for experimental runs shown in figures 7, 8 and 9. Run 9 not plotted because only one scan captured pulse in flume.

Figure 12. Celerity of pulse leading and trailing edges.
Figure 13. Change in bed median grain size over time for various positions along the flume.

Figure 14. 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.