WATER RESOURCES RESEARCH, VOL. 45, W08439, doi:10.1029/2008WR007346, 2009

Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams

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Received 7 August 2008; revised 8 April 2009; accepted 2 June 2009; published 28 August 2009.

[1] The effectiveness of gravel augmentation as a river restoration strategy depends on the extent and duration of the topographic and bed texture changes created by the pulse of added sediment. Previous work has emphasized the strong tendency for natural sediment waves to propagate primarily by dispersion; however, pulse translation may occur for gravel additions to armored channels downstream of dams where added sediments are finer than the preexisting bed material. 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 gravel pulses of various volumes and grain sizes. The introduced sediment waves evolved by a combination of translation and dispersion, with a significant translational component. 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 preexisting bed topography. Translation was most evident for smaller volumes of added sediment. Pulses of finer-grained gravel moved through the flume more rapidly, resulting in a larger magnitude but shorter duration of bed fining. More work is needed to understand the influence of bar-pool topography and flow magnitude and duration before the grain size and volume of gravel additions can be selected to achieve optimal patterns of pulse propagation.

Citation: Sklar, L. S., J. Fadde, J. G. Venditti, P. Nelson, M. A. Wydzga, Y. Cui, and W. E. Dietrich (2009), Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams, *Water Resour. Res.*, *45*, W08439, doi:10.1029/2008WR007346.

1. Introduction

[2] 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; *Schmidt and Wilcock*, 2008]. Gravel augmentation (or ‘‘replenishment’’), the artificial supply of bed load–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; *Merz and Ochikubo Chan*, 2005; *Elkins et al.*, 2007]. 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 [*Pasternack et al.*, 2004; *Sklar et al.*, 2005; *Merz et al.*, 2006; B. Harvey et al., Key uncertainties in gravel augmentation: Geomorphological and biological research needs for effective river restoration, 2005, CALFED Science Program, Sacramento, California, available at http://www.science.calwater.ca.gov/events/workshops/workshop_gravel.html, hereinafter referred to as Harvey et al., unpublished report, 2005].

[3] Effective design of gravel augmentation projects requires accurate prediction of the temporal and spatial extent of beneficial changes to the channel bed and associated aquatic habitat characteristics for a given set of design parameters [e.g., *Wheaton et al.*, 2004a, 2004b]. 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, 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

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0043-1397/09/2008WR007346$09.00

[*Pasternack et al.*, 2004; *Elkins et al.*, 2007]. At present, project designers tend to focus primarily on biological considerations and do not commonly make use of scientifically based analytical approaches [e.g., *Pasternack et al.*, 2004; *Wheaton et al.*, 2004a, 2004b] to make design choices that optimize the use of limited budgets for purchasing and delivering gravel and can meet predetermined goals for habitat restoration [Harvey et al., unpublished report, 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. Despite some notable successes [e.g., *Merz and Setka*, 2004; *Elkins et al.*, 2007], postimplementation monitoring often reveals that projects have performed poorly, with limited habitat restoration benefits [*Lutrick*, 2001; *Kondolf et al.*, 1996; *Wohl et al.*, 2005; *Alexander and Allan*, 2007].

[4] Sediment supply is naturally episodic, varying 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 [*Madej*, 2001; *Sutherland et al.*, 2002; *Kasai et al.*, 2004; *Bartley and Rutherford*, 2005; *Hoffman and Gabet*, 2007], flume experiments [*Lisle et al.*, 1997; *Cui et al.*, 2003a] and numerical modeling [*Pickup et al.*, 1983; *Benda and Dunne*, 1997a, 1997b; *Lisle et al.*, 2001; *Cui et al.*, 2003b; *Cui and Parker*, 2005; *Greimann et al.*, 2006]. 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 [*Sutherland et al.*, 2002] and debris flows [*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 incoming sediment upstream and enhanced sediment transport capacity downstream, which together cause the topographic waveform on the bed to remain fixed in place while being reduced in magnitude [*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 preexisting bed, when the Froude number is high ($\sim$1), and where downstream fining occurs because of selective transport and particle abrasion [*Lisle et al.*, 2001].

[5] 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 preexisting bed, and are likely to have a relatively narrow spread in the size distribution [Harvey et al., unpublished report, 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 coarse sediment from upstream is negligible, and channels may lack the well-developed bar-pool topography that promotes pulse dispersion [*Lisle et al.*, 1997, 2001]. In addition, there may be many channel settings downstream of dams where added sediments are more commonly mobilized under relatively low Froude number conditions because of the combined effects of reduced flood frequency and magnitude, reduction in channel slope, or increased roughness from bed coarsening, vegetation encroachment or other postdam morphologic adjustments [e.g., *Williams and Wolman*, 1984; *Brandt*, 2000].

[6] 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; *Bartley and Rutherford*, 2005], 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., unpublished report, 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 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 preexisting channel conditions.

[7] 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. 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 potential implications of these experimental results for design of gravel augmentation projects and the challenges in scaling up from the laboratory to the field.

2. Experimental Methods

[8] The gravel augmentation experiments were conducted in a 28 m long, 0.86 m wide, 0.8 m deep flume, located at the University of California, Berkeley, Richmond Field Station. Water is recirculated in the flume while sediment is fed at the upstream end by three separate motor-driven auger feeders. Sediments exit the flume into a tipping bucket-type bed load trap suspended from a load cell that measures the weight of accumulated submerged bed load material; the flux out of the flume is calculated from the rate of change of sediment mass over time. At regular intervals, sediments are tipped into a

submerged hopper and pumped out to a dumpster, and are not recirculated. The flume bottom has a slope of 1%, but for these experiments was filled with a gravel wedge to create an initial bed slope of 0.5%. The bed was composed of a unimodal, lognormally distributed gravel mixture with a median size of 8 mm, a geometric standard deviation of 2, and was truncated at 2 and 32 mm. In the experiments, the bed slope was allowed to evolve through differential erosion and deposition.

[9] The experiments were designed to focus on the influence of sediment supply and grain-to-grain interactions on gravel augmentation pulse evolution and bed texture response. We used a low width-to-depth ratio ($\sim$4) to suppress bar development and maintain an approximately planar bed on which pulse evolution could occur. We maintained a constant discharge (0.205 m^3/s) to focus on the effect of spatial and temporal variations in sediment supply without the complications introduced by hydrographs. The Froude number was within the subcritical regime (0.6 to 0.7), and the flow was fully turbulent in terms of the Reynolds number and hydraulically rough. The hydraulic conditions were selected to maintain approximately 1:4 Froude scaling with prototype field channels.

[10] We began the experiments by recreating the sequence of bed texture changes that typically follow dam construction, by shifting from active bed load 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, and a wide grain size distribution to provide sufficient coarse grains to form the immobile armor. We first established an equilibrium active bed by feeding the initial size distribution at 120 kg/h for 16 h, and then sequentially reduced the sediment supply to the channel in four steps, to feed rates of 80, 47, and finally 0 kg/h. At each feed rate, the supply was held constant until the flux at the downstream end of the flume matched the upstream supply rate and we observed no further changes in the bed slope or bed texture. With the elimination of sediment supply, sediment flux exiting the channel dropped to 1–2 kg/h, and the bed slope declined to 0.4%. The median grain size of the armored bed was $\sim$12.5 mm, creating an armoring ratio of $\sim$1.6, which is comparable to some field settings with dam-impaired sediment supply [e.g., *Lisle et al.*, 2000]. Detailed analysis of the response of the bed surface to the stepped reduction of sediment supply is reported by *Nelson et al.* [2009].

[11] 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. Larger pulses corresponded to the volume required to cover the entire flume bed with a layer of sediment one bed material D_{50} diameter thick, for the 8 mm median diameter of the predam 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" pulses, respectively.

[12] 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 predam 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.*, 2005]. For each pulse, we ran the flume for a time sufficient to allow the pulse mass to move completely through the flume, 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.

[13] Table 1 lists the experimental conditions for each run, encompassing the four combinations of pulse volume and grain size. Note that we report results taken from two replicate small-volume, fine-grained pulses (runs 9 and 21d), because the frequency of successful topographic scans for run 9 was not sufficient to capture the pulse evolution. Note also that we have retained the original run numbers for consistency with papers where results of other concurrent experiments will be reported; those runs focused on effect of supply on bed texture during armoring [*Nelson et al.*, 2009], lateral sorting and patch development [*Nelson et al.*, 2008], and infiltration and flushing of fine sediment [*Wydzga et al.*, 2006].

[14] Each pulse of added gravel was painted a different color to facilitate documentation of the pulse movement and to distinguish added sediments from the preexisting 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 160 kg/h, at a location 5 m downstream of the flume entrance to avoid the zone of flow acceleration.

[15] The flume is equipped with a computer-controlled, motorized instrument cart, which moves along horizontal rails supported by an independent frame. We measured the evolution of the bed and water surface topography during active flow with an echo sounder and an ultrasonic distance meter, respectively. Both devices have a vertical precision of ±1 mm in this application. Topographic scans of the bed and water surface were made as frequently as possible; a complete scan took 8 min however most scans were spaced about 50 min apart. Sediment flux out of the flume was monitored continuously during the experiments at 0.1 Hz [*Venditti et al.*, 2005]. We also hand mapped the position of the leading edge and the tail of the pulse of painted grains through time.

[16] 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. The grains

Table 1. Experimental Conditions

	Large Coarse	Large Fine	Small Coarse	Small Fine	
Run Type[a]	Run 7	Run 10	Run 23	Run 9	Run 21d[b]
Pulse grain size, D_{50} (mm)	8.0	2.8	8.0	2.8	2.8
Pulse mass (kg)	267	267	68	68	68
Pulse input feed rate (kg/h)	160	160	134	160	160
Sediment feed duration (min)	100	100	30	25	25
Total run duration (min)	1165	1383	1269	1210	1042
Bed slope (%)	0.41	0.41	0.37	0.42	0.40
Water depth (m)	0.23	0.23	0.24	0.23	0.24
Mean flow velocity (m/s)	1.06	0.99	0.98	1.03	0.98
Froude number	0.71	0.64	0.63	0.69	0.63
Mean bed shear stress[c] (Pa)	8.6	9.3	8.3	9.0	9.1
Prepulse bed grain size, D_{50} (mm)	11.9	11.7	11.9	12.9	NA
Prepulse bed Shields stress, τ^*	0.053	0.050	0.047	0.047	NA
Pulse sediment Shields stress, τ^*	0.073	0.23	0.071	0.22	0.22
Pulse transport stage, τ^*/τ^*_c[d]	1.6	5.0	1.6	4.9	4.9
Pulse grain paint color	dark blue	pink	light blue	red	green

[a]Run type gives volume and grain size.
[b]Fourth pulse in a multiple pulse run. NA means not applicable.
[c]Sidewall corrected using *Williams* [1970] correction.
[d]Critical Shields stress, $\tau^*_c = 0.047$.

removed were rinsed to remove any adhesive, dried and sieved to obtain an area-by-weight grain size distribution, which was converted to a volume-by-weight using the method of *Kellerhals and Bray* [1971]. Second, to avoid disturbing the bed and potentially affecting the experimental outcome, grain size distributions were measured from point counts on digital photographs taken during the experimental runs. The camera was mounted on the instrument cart and each photo was taken at the same elevation above the bed, which we controlled using a laser distance scanner. All photos were calibrated using the distance between the flume walls. Point counts of grain diameters were made using a 100-point grid superimposed on the center 75 cm of each image. We estimated radial distortion in the images to be insignificant, on the order of 1 mm across the measurement area. These point counts are similar to a Wolman count, which produces a grain size distribution similar to a volume by weight [*Kellerhals and Bray*, 1971; *Bunte and Abt*, 2001]. Comparisons between photo results and the volume-by-weight converted hand samples showed agreement within detection limits [*Fadde*, 2007]. Replicate point counts on seven photos by three different individuals showed that the 95% confidence interval around the median diameter was less than 0.2 mm.

3. Conceptual Framework for Pulse Evolution

[17] Sediment waves in the field can be difficult to identify, much less quantify [e.g., *Lisle et al.*, 2001], in part because prepulse 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 is not diagnostic of pulse translation or dispersion. With field data, they quantified pulse evolution using the ratio of the height to length of the topographic deviation from preexisting conditions, and showed that in nearly all cases the wave aspect ratio declines over time. Here we define translation as the downstream migration of both the center and trailing edge of the pulse volume and quantify the extent of pulse translation and dispersion by comparing the relative time rates of change of the location of the center of the pulse and the longitudinal spread of the topographic wave form.

[18] Figure 1a shows a hypothetical pulse that evolves purely by translation. The pulse waveform was generated using a gamma function for the spatial distribution of bed elevation [*Walpole and Myers*, 1978]. Figure 1b shows the downstream-cumulative distribution of bed elevation changes from the prepulse bed topography, for the case of pure translation depicted in Figure 1a. Figures 1a and 1b 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 1b) does not change. This can be considered diagnostic of pure translational pulse evolution. Note that because there is no upstream sediment supply, and we assume in this illustration that there is no erosion of the underlying prepulse bed, the total area under the curve remains constant until the pulse begins to exit the flume.

[19] In contrast, Figure 1c shows a dominantly 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 1d shows the cumulative distribution of the elevation for this dispersive pulse. Unlike the case of pure translation (Figure 1b) 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.

[20] Most sediment pulses have both translational and dispersive properties [*Lisle et al.*, 2001]. Figure 1e shows an example of a pulse that evolves with simultaneous translation and dispersion, with the cumulative distribution shown in Figure 1f. Combining the diagnostic properties of the two

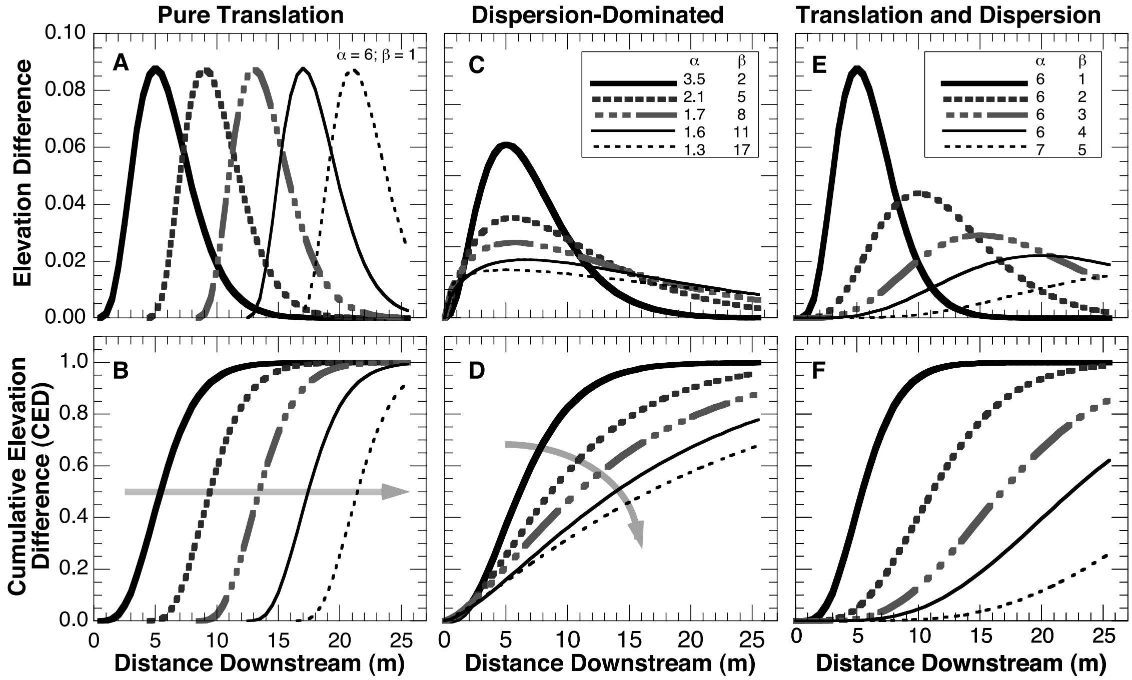

Figure 1. Hypothetical examples of pulse evolution showing difference between bed elevation and prepulse bed elevation and downstream-cumulative elevation difference (CED) for cases of (a and b) pure translation, (c and d) dispersion-dominated evolution, and (e and f) mixed translation and dispersion. Pulse shape is described by gamma distribution with parameters α and β. Pulse translation is characterized by a slope-parallel downstream shift in the CED curve (Figure 1b), whereas pulse dispersion is characterized by clockwise rotation of the CED curve (Figure 1d).

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.

[21] 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 longitudinal spread of the pulse (Figure 2). Here we use the nonparametric statistics of the distribution of elevation deviations from the prepulse bed, with the pulse center represented by the median and the spread of the pulse distribution represented by the interquartile range (IQR). For a purely translational pulse (Figure 1b) we would expect a steady increase in the median location with no increase in the IQR in Figure 2. In a sediment wave that is dominantly dispersive (Figure 1d) there would be little 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 2, for the dispersion example of Figure 1d, the IQR increases steadily while the median location only changes very slightly. Finally, for the mixed case in Figure 1f, both the median location and the IQR increase with time (Figure 2). Note that as the pulse begins to exit the flume the IQR will decrease because the leading edge 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 Figures 1 and 2 to identify translational and dispersive behavior in the evolution of the experimental gravel augmentation pulses.

4. Experimental Results

4.1. Qualitative Overview of Pulse Propagation

[22] Each pulse was fed into the flume over a finite duration, 25 and 100 min for the small and large volumes,

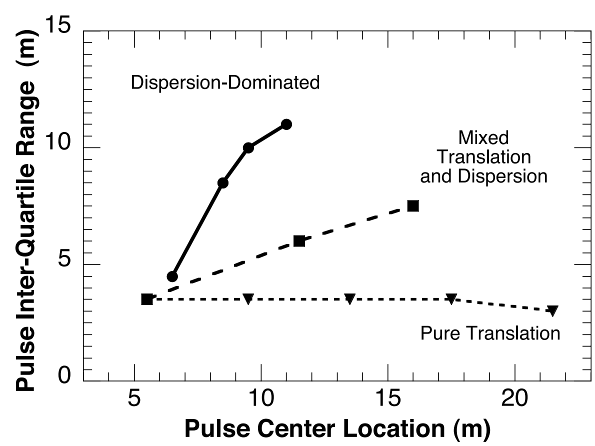

Figure 2. Pulse evolution depicted with nonparametric statistics of downstream-cumulative distributions of elevation differences for the three theoretical cases shown in Figure 1. Pulse interquartile range is the length enclosing the central 50% of the pulse volume, and pulse center location is the median (50th quartile) in the elevation difference curve. Points omitted where less than 80% of pulse remains in flume.

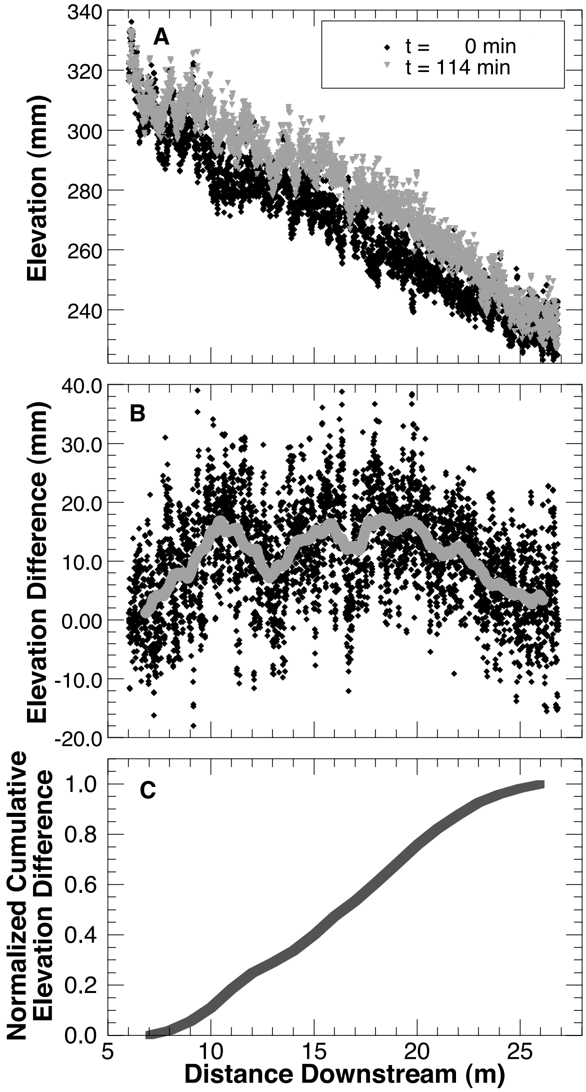

Figure 3. Method for detrending and smoothing bed topography scans. (a) Raw topographic data for large-volume, coarse-grained pulse (run 7) just prior to and 144 min after beginning of sediment feed. (b) Elevation difference between scans at 0 and 144 min at 5 mm intervals (solid symbols) and smoothed by Gaussian-weighted moving-window average (2σ = 0.85 m, thick gray line). (c) Cumulative elevation differences for smoothed curve, normalized by total.

respectively (Table 1). A clearly visible leading edge of the pulse of painted grains began 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 centerline of the flume, forming a convex downstream facing front 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) gravel 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 reexposing the preexisting coarse armor. The tail of the pulse then visibly migrated downstream, distinguishable as the upstreammost zone with active transport of the painted added gravel. The added gravel caused mobilization of the previously static armor, resulting in scour of the armor layer and net degradation of the bed upstream of the pulse tail [*Venditti et al.*, 2005]. Eventually, each of the 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.

[23] 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 echo sounder 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 surface material.

4.2. Topographic Evolution of the Bed

[24] The pattern of pulse propagation is best revealed by the topographic evolution of the bed surface. We focus on longitudinal profiles along the centerline of the flume, measured with the echo sounder scans, which are composed of elevation measurements spaced 5 mm apart. Figure 3a shows the raw data for two scans, taken from the large-volume, coarse-grained pulse (run 7). The first scan was made just prior to the introduction of the pulse material while the second scan was made 114 min 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 visualization and analysis of the bed topography, we calculated the deviation in elevation from the prepulse bed profile for each scan, and then smoothed the resulting profile using a Gaussian-weighted running average, scaled by the flume width (2σ = 0.85 m). The resulting raw and smoothed elevation difference profiles are shown in Figure 3b for the run 7 scan at the end of the pulse input. Figure 3c shows the cumulative elevation difference (as in Figures 1b, 1d, and 1f) for the smoothed profile, normalized by the total cumulative elevation difference (CED). In this and subsequent figures the CED curves are normalized to simplify comparisons between runs. Below, we use the CED of the smoothed profiles to evaluate the topographic evolution of the bed for the four single pulse runs, considering first the two small-volume pulses (fine and then coarse grained) and second the two large-volume pulses (fine and then coarse grained).

[25] The full set of eight elevation difference scans for the small-volume, fine grain size pulse (run 21d) is shown in Figure 4a. During the sediment feed (scans at 9 and 17 min, indicated by dashed lines), the leading edge of the topographic change can be seen moving downstream, reaching the 20 m location at 26 min, shortly after completion of the pulse input. At 34 min, the leading edge the pulse reached 23 m while topographic tail of the pulse can be seen moving downstream (at ~11 m). The scan at 42 min shows that the pulse wave form had translated downstream, with a sharp leading edge at 25 m and a break in slope between the main pulse body and a trailing wedge of slower-moving material at ~17 m. At this time about 80% of the pulse material was confined within an 8 m segment of the flume, fully 12 m downstream of the input location. By 50 min after initiation of the feed, the leading edge had exited the flume, and by

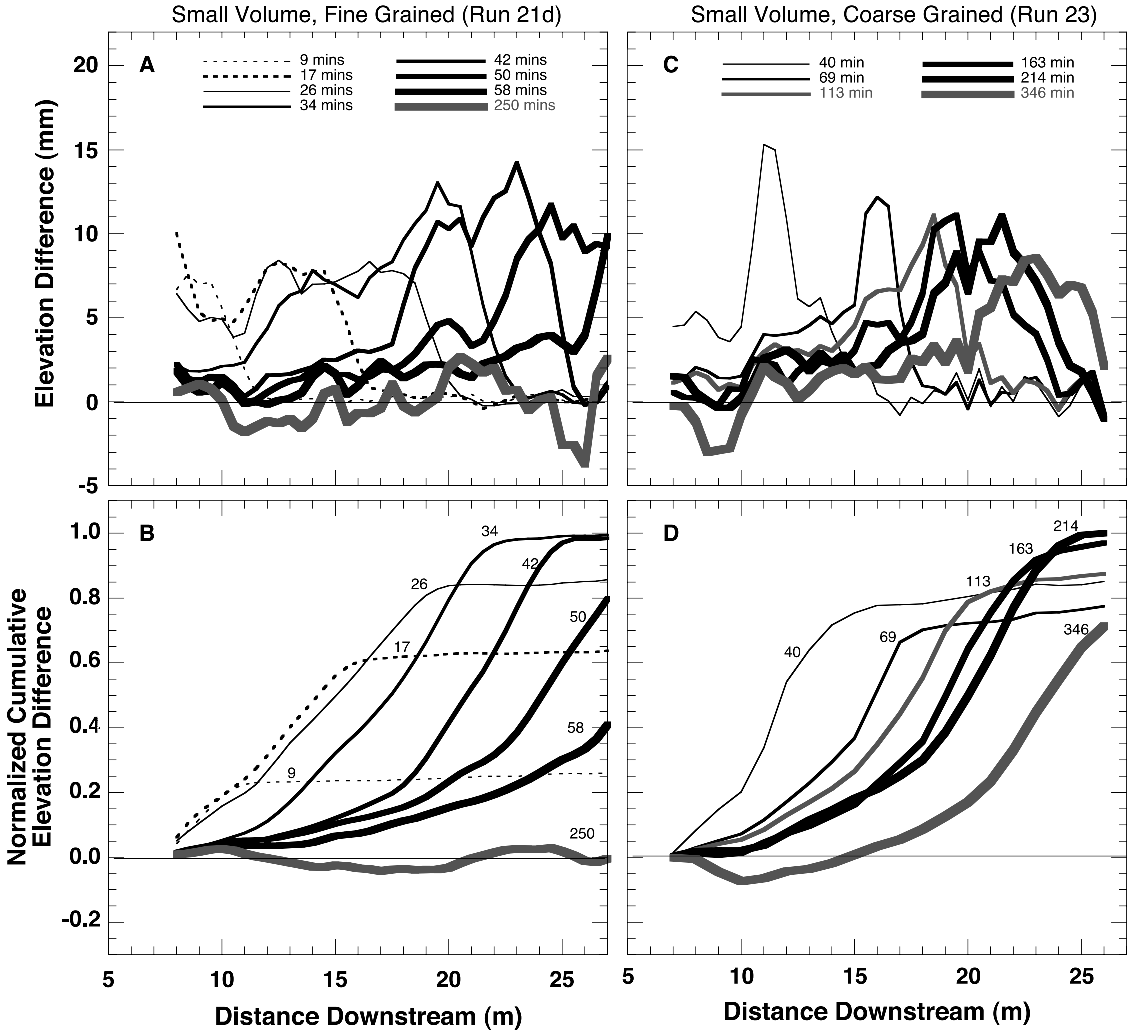

Figure 4. Topographic evolution of small-volume pulses, coarse grained (run 23) and fine grained (run 21d). (a and c) Elevation difference from prepulse bed and (b and d) downstream-cumulative elevation difference normalized by maximum for each run. Dashed lines indicate sediment feed still in progress.

58 min nearly the entire topographic wave had passed through the flume. The scan at 250 min shows that bed returned to approximately the initial condition, with residual elevation differences no larger than a single grain diameter (~3 mm).

[26] The cumulative elevation difference curves for the same run (small-fine) are plotted in Figure 4b, and provide a simpler depiction of the propagation of the pulse through the flume. As the pulse material was added to the flume during the feed period (scans at 9 and 17 min), the peak in the cumulative elevation difference (CED) increased accordingly. The peak in the CED curve continued to grow because of entrainment of mobilized prepulse bed material (26 and 32 min) but then declined as the pulse material exited the flume (50 min).

[27] Pulse translation is clearly seen by comparing the curves for 26, 34 and 42 min, which are essentially parallel but offset downstream. Some dispersion of the pulse tail can be inferred from the clockwise rotation of the CED curves after the pulse had begun leaving the flume.

[28] Figures 4c and 4d shows the elevation difference and cumulative elevation difference profiles for the other small-volume pulse (run 23), which had a coarse median grain size of 8.0 mm. This pulse migrated through the flume with a pattern similar to the small-fine pulse, although with a lower celerity. The roughly parallel slopes of the CED profiles (Figure 4d), for all but the trailing 25% of the CED, are clear evidence for significant pulse translation. Dispersion of the pulse tail is also evident in the decline in the lower (upstream) portion of the CED profiles, particularly for scans between 40 and 163 min.

[29] Considering next the large-volume, coarse-grained pulse (run 7), shown in Figures 5a and 5b, we see a similar characteristic pattern of pulse translation in the parallel downstream motion of the CED profiles for the two scans made when the entire pulse was within the flume (114 and 122 min). Because of difficulties with the instrument cart, the next scan for this run was made only after 80% of the pulse volume had left the flume, however the rotation of the CED profiles of the pulse tail for scans at 170 and 277 min is consistent with dispersion of the pulse tail.

[30] Plotted in Figures 5c and 5d are the elevation difference and CED profiles for the large-volume, fine-grained pulse (run 10). Unfortunately, we were unable to obtain a

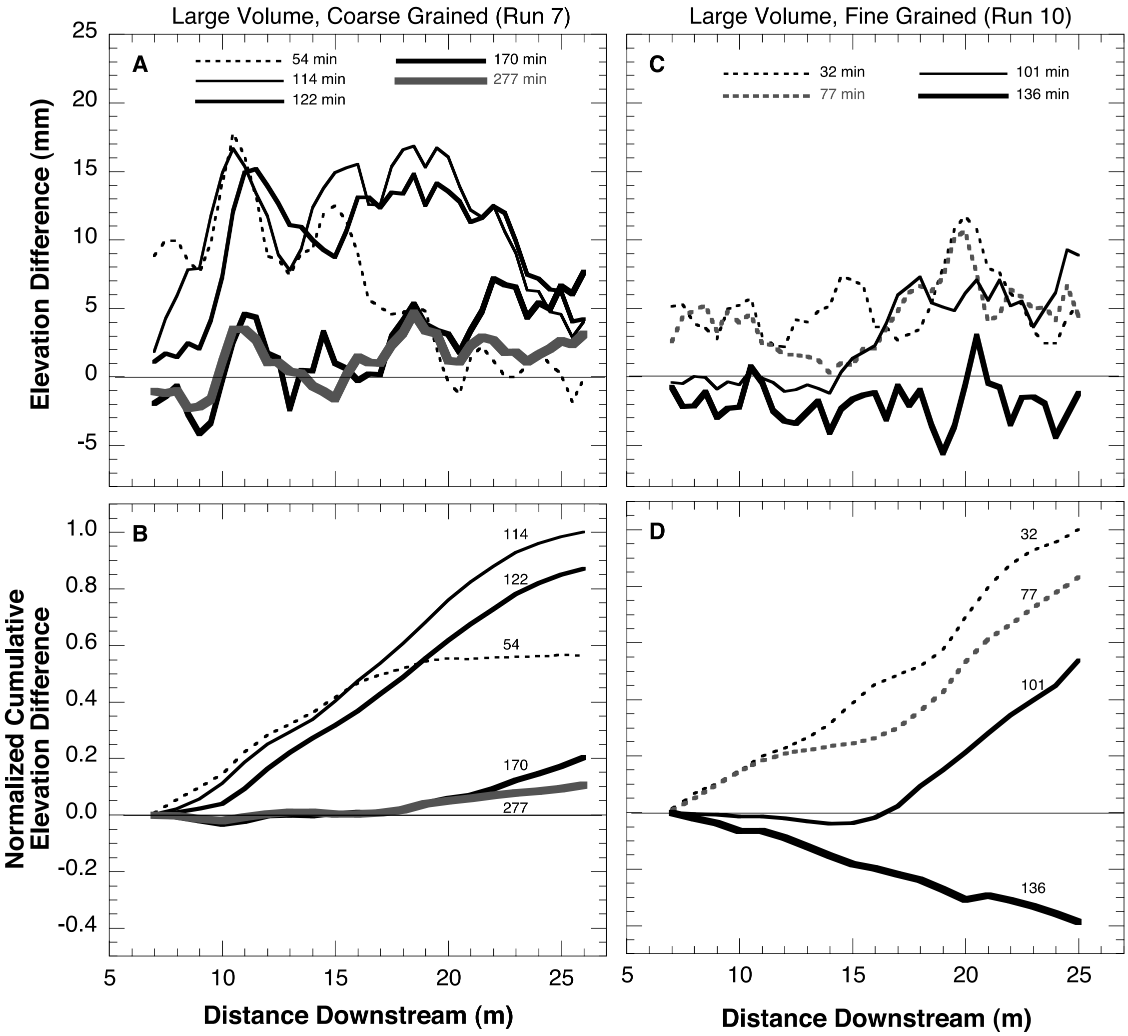

Figure 5. Topographic evolution of large-volume pulses, coarse grained (run 7) and fine grained (run 10). (a and c) Elevation difference from prepulse bed and (b and d) downstream-cumulative elevation difference normalized by maximum for each run. Dashed lines indicate sediment feed still in progress.

scan of the complete topographic wave form for this pulse because the leading edge traversed the entire flume and began exiting before the sediment input was completed. The available scan profiles are consistent with a dominantly translational pattern of pulse propagation for this run. Note in particular the similarity of the CED profile slope for the scan at 101 min to the two earlier scans (32 and 77 min), and the lack of a dispersive lower-slope wedge of tail material.

[31] To compare the topographic evolution of the set of pulses we plot in Figure 6a the longitudinal spread of the central 50% of the topographic wave (interquartile range, IQR) as a function of the pulse center location, as in the illustrative hypothetical pulse propagation example shown in Figure 2. Only points representing times when the entire pulse volume was within the flume are included in Figure 6, precluding inclusion of the large-fine pulse (run 10). Because the duration of the sediment feed was longer for the large-volume pulses, the absolute IQR will be larger for those runs (compare runs 7 and 23 in Figure 6a). Similarly, for a fixed pulse volume, the higher celerity of the finer-grained pulses will result in a more elongated initial pulse and a higher IQR (compare runs 21d and 23). To facilitate comparison between pulses, Figure 6b shows the pulse IQR normalized by the initial IQR, obtained from the first scan after the end of the sediment feed, plotted against the distance moved by the pulse center since that initial postfeed scan.

[32] The dominantly translational behavior of the small-volume pulses (runs 23 and 21d) is clearly evident in the horizontal progression of the pulse plotting position across the graph (Figure 6b). In contrast, the large-volume, coarse-grained pulse (run 7) shows a more pronounced increase in pulse length, consistent with a mixed translational-dispersive pattern of evolution. The slope of a linear trend fit to the curves plotted in Figure 6b can be used as a metric for the ratio of pulse dispersion to translation, analogous to the inverse of the Peclet number derived from analytical expressions for sediment wave motion [*Lisle et al.*, 2001]. For example, the IQR of the large-coarse pulse grew by 50% as the pulse

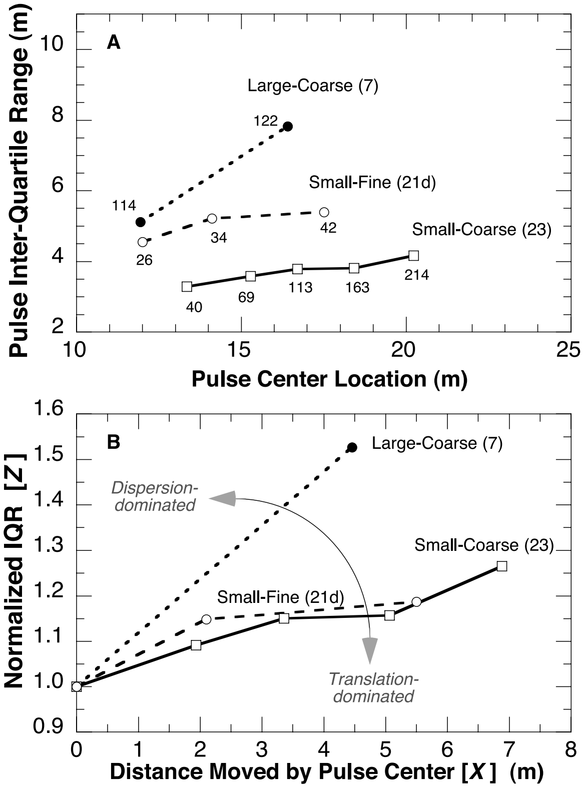

Figure 6. (a) Pulse statistics of downstream-cumulative elevation difference distributions (as in Figure 2) for experimental runs shown in Figures 4 and 5; scan times indicated. (b) Pulse interquartile range (IQR) and center position normalized by initial values. Scans during sediment feed and after pulse began leaving the flume are not included.

center moved 5 m (normalized IQR increased to 1.5 from 1.0). With normalized IQR represented by Z and the distance moved by the pulse center location by X, for the large-coarse pulse $dZ/dX = 0.1$/m. As listed in Table 2, $dZ/dX = 0.04$/m for both small-volume pulses, indicating that these pulses translated 2.5 times further for same extent of pulse dispersion. For comparison, the dZ/dX values for the hypothetical pulse propagation patterns in Figure 2 are 0.0/m for pure translation, 0.4/m for the dominantly dispersive example, and 0.1/m for the mixed translation and dispersion case. Using this heuristic metric we interpret the small-volume pulses (runs 21d and 23) as being dominantly translational and the large-coarse pulse (run 7) as mixed translational-dispersive.

4.3. Celerity of Leading and Trailing Edges

[33] 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 7 shows the mapped position of leading and trailing edges of the mobile pulse material as a function of time for each of the four pulse types. (Note that we use data from run 9 for the small-volume, fine-grained pulse because run 21d had the same paint color as runs 21a–21c making it difficult to map pulse edges.) To clarify how celerity is indicated by the data, we have annotated Figure 7a, for the large-volume, coarse-grained pulse. Each of the edges bounding the pulse begins at the feed location at 5 m and moves up across the graph to the downstream end of the flume at 28 m. The average celerity of a pulse edge 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, for a dominantly dispersive wave lacking any upstream sediment supply, the curve for the trailing edge would be approximately horizontal. For a dispersive wave with upstream supply and deposition on the upstream side of the pulse the trailing edge curve would have a negative slope (i.e., moving upstream).

[34] The celerity plots shown in Figure 7 reveal five general features of the pattern of pulse propagation observed in these experiments. 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, translation is more dominant for the smaller-volume pulses, as indicated by the slower rate of increase in horizontal distance between leading and trailing edge curves as the pulse moves up the graphs (i.e., downstream). Fourth, 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.

[35] Table 2 lists the mean celerity for the leading and trailing edges for each pulse, divided into two phases, an

Table 2. Experimental Results

	Large Coarse	Large Fine	Small Coarse	Small Fine	
	Run 7	Run 10	Run 23	Run 9	Run 21d
Slope of line, dZ/dX[a] (1/m)	0.10	-	0.04	-	0.04
Leading edge celerity, initial (m/min)	0.29	1.0	0.19	0.61	-
Leading edge celerity, later (m/min)	0.08	0.39	0.04	0.36	-
Trailing edge celerity, initial (m/min)	0.23	0.28	0.06	0.14	-
Trailing edge celerity, later (m/min)	0.02	0.04	0.04	0.06	-

[a]See Figure 6b.

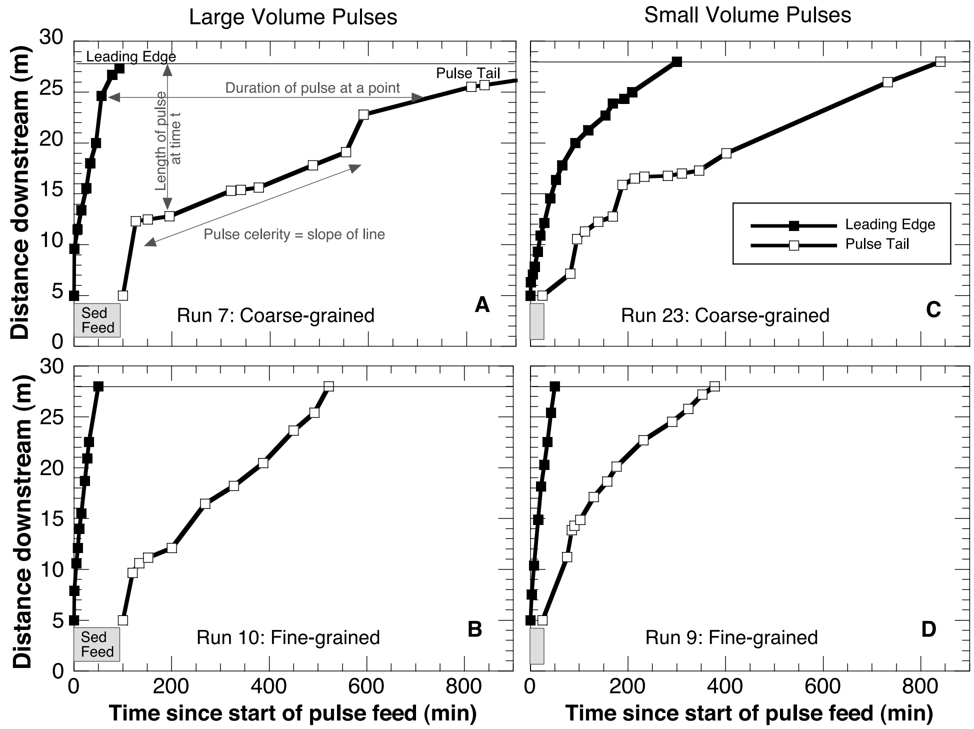

Figure 7. Pulse leading edge and tail celerity from change in hand-mapped pulse edge locations over time. Horizontal distance on graph between leading edge and tail curves indicates duration of pulse occupation at a location along the flume; vertical distance between curves (or flume exit at 28 m) indicates length of pulse at a moment in time. Celerity indicated by slope of line.

initial phase of more rapid movement, and a later phase of generally slower movement. Comparing equal pulse volumes, the most rapid movement of both the leading and trailing edges occurred with the fine-grained pulses. Comparing equal grain size, greater pulse volume corresponded with higher leading edge celerity but lower trailing edge celerity, consistent with a greater tendency for dominantly translational movement for the smaller-volume pulses.

4.4. Bed Texture and Grain Size Evolution

[36] 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 grain size distribution. 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, focusing on the surface median grain diameter (D_{50}).

[37] Figure 8 shows the evolution in both time and space of the bed D_{50} for each pulse, with symbols representing measured grain size superimposed on the celerity plots from Figure 7. The prepulse armored bed had a median grain size between 11 and 13 mm (Table 1), however, as the pulse passed through the flume a transient fining of the bed occurred. For the large-volume, coarse pulse (Figure 8a) the bed fined to ~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 prepulse bed. Part way through the rearmoring period (625 min), the grain size measurements show a downstream fining pattern that reflects the downstream propagating armor development. By the end of the run a more uniformly coarse bed was reestablished.

[38] The rapid passage of the large-volume, fine-grained pulse (run 10) is clearly shown in Figure 8b, which, after the pulse exits the flume, is followed by a similar transient downstream fining pattern and eventual reestablishment 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 8c), but because of the initially rapid translation of the pulse (Figures 5a and 5b) the bed upstream had already coarsened by the time of the first set of postpulse bed measurements (350 min). 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 8d. At 50 min 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 rearmoring by 800 min shows a net coarsening for the upstream locations and a downstream fining pattern.

[39] 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 a preferred spawning gravel size 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 9 shows this range as an unshaded 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

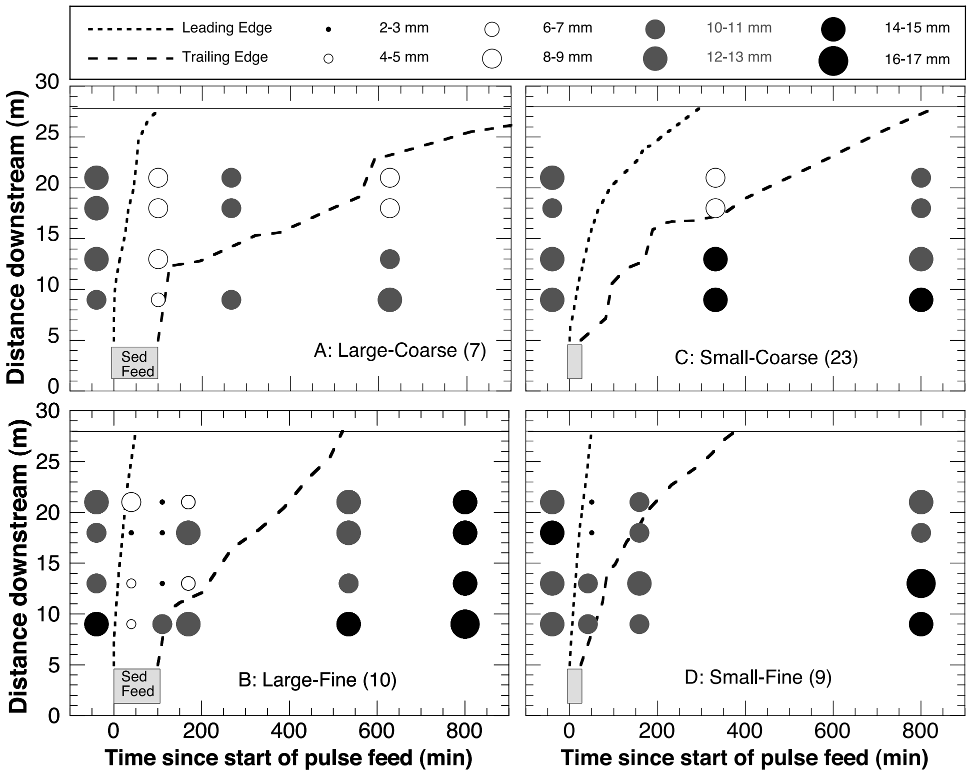

Figure 8. Changes in bed surface median grain size (D_{50}) over time for various positions along the flume. Grain size indicated by size and shading of circle. Pulse leading edge and tail also shown, as in Figure 7.

because it is far from the upstream boundary where entrance conditions might affect the results. Figure 9 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 rearmoring at or above the preexisting armor D_{50}.

5. Discussion

5.1. Pulse Translation and Dispersion

[40] The 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 6 and 7). Pulse translation was also evident in the downstream movement of the zone of most significant bed fining (e.g., Figure 8d). Translational behavior occurred most significantly in the small-volume pulses (Figures 4 and 6), while pulse grain size appears to have a secondary influence.

[41] Some dispersion was also evident in each pulse. Pulses tended to disperse by spreading more on the trailing edge than the leading edge, in effect by leaving material behind (e.g., Figure 4c). 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.

[42] A major limitation of our experiments 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 7a

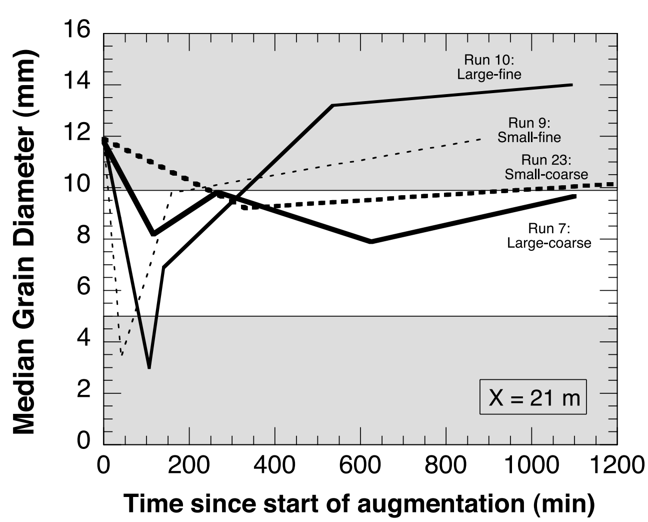

Figure 9. Change in bed surface median grain diameter with time for each run at position 21 m downstream of flume inlet. Unshaded area represents hypothetical range of potential spawning grain sizes (1:4 scaling).

and 7b). Similarly, the bulk of the fast-moving, fine-grained, small-volume pulse had left the flume within 20 min of the end of the sediment feed. Our most accurate documentation of pulse evolution is where we have the highest frequency of topographic scans, for the small-volume pulses run toward the end of the experimental program (runs 21d and 23). Given that these pulses also showed the strongest translational behavior, we conclude that our primary finding of significant pulse translation is robust despite the constraints of the flume length.

[43] The pulse translation observed here confirms previous predictions that translation can occur when a sediment pulse has a low height-to-length ratio, the grain size is smaller than the preexisting bed, and the pulse has a narrow grain size distribution [*Lisle et al.*, 1997, 2001; *Cui et al.*, 2003a, 2003b]. Our results further suggest that translation is favored by volumes of sediment addition that are small relative to channel dimensions and where upstream sediment supply is lacking. The above conditions are characteristic of many gravel augmentation projects downstream of dams. The mobilization of some of the prepulse surface armor layer by the pulses of finer gravel [*Venditti et al.*, 2005] also contributed to the translational behavior because newly mobilized material was added to the pulse volume at the leading edge, somewhat compensating for loss of pulse material left behind as the pulse moved downstream. Partial armor mobilization may also account for the slowing of the celerity of the pulse leading and trailing edges (Table 2 and Figure 7) because of coarsening of the mobile pulse grain size distribution. Despite the significant component of translation, however, 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 commonly occur in gravel bedded rivers.

5.2. Uncertainties in Scaling From Flume to Field

[44] These experimental results cannot be directly scaled up for application to design of gravel augmentation projects in the field. Much work remains to understand how the spatial complexity of natural channels and the temporal variability of flow and entrainment of added gravel can influence patterns of sediment pulse propagation. Our experiment conditions are most representative of a straight reach of armored plane bed channel located a short distance downstream of a point of sediment injection. Because we created pulses by supplying gravel at a steady rate for a finite duration, rather than placing gravel directly on the flume bed during low flow, these experiments cannot capture the dynamic evolution of placed gravel additions, such as the significant in situ consolidation and ''deflation'' of artificial gravel bars documented by *Merz et al.* [2006].

[45] We intentionally used a low width-depth ratio ($\sim$4) to focus on grain-to-grain interactions in the process of armor mobilization and formation of patches [*Venditti et al.*, 2005; *Nelson et al.*, 2008]. Increasing the width-depth ratio above $\sim$12 would lead to formation of alternate bars and lateral shear stress divergence and topographic steering of sediment transport, with associated effects on the pattern of pulse propagation. Even with the narrow flume configuration we observed development of some transient zones of persistently elevated bed topography, suggestive of nascent bar formation, particularly for the more dispersive large-volume pulses (Figure 5). Temporary sediment storage sites provided by bar-pool topography should promote pulse dispersion but may also have the effect of narrowing and fining the size distribution of mobile sediment, enhancing conditions for translation of a reduced volume pulse downstream [*Lisle et al.*, 2001]. The effect of forced bar-pool topography on pulse propagation dynamics was the focus of a later component of our experimental program [*Wooster et al.*, 2006]; those results will be reported in detail elsewhere.

[46] By holding discharge constant we implicitly are simulating a single flow event such as might occur during a controlled release from a dam. For Froude-scale modeling, *Yalin* [1971] used dimensional analysis to show that the time scale for motion of individual sediment grains, and thus the celerity of the pulse leading edge, scales with the square root of the ratio between the prototype and model length scale. However, the time scale for vertical changes in bed elevation due to downstream sediment flux divergence scales with the 1.5 power of the length scale. Assuming a prototype-to-model length scale of 4:1, and characteristic model pulse propagation time scales of between 100 min (small-fine pulse) and 1000 min (large-coarse pulse), our experiments represent between 3 h and 5 days of field-scale elapsed time.

[47] Constant discharge also results in a limited range of excess shear stress conditions explored here (Table 1). A rich parameter space of variable shear stress, pulse grain size relative to armor size, and frequency and sequencing of both discharge and sediment supply events remains to be explored. A recent set of experiments exploring the effect of hydrographs of various peak magnitudes on sediment pulse propagation through a forced bar-pool topography [*Humphries et al.*, 2008] suggests that pulse translation is favored by high excess shear stress and steep recession limbs. Understanding the influence of flow variability on gravel augmentation pulse evolution is particularly important for settings where discharge can be manipulated along with sediment supply to achieve river restoration goals.

5.3. Potential Implications for River Restoration

[48] Despite the large uncertainties in scaling up the flume results to field settings, some potential implications for the use of gravel augmentation in river restoration downstream of dams can be identified. These interpretations are valid only to the extent that future work shows potential for significant pulse translation of small-volume, fine-grained sediment additions in complex natural channels.

[49] Whether pulse dispersion or translation is the preferred outcome depends on whether the beneficial changes to bed texture and topography are intended for the local reach where sediments are added or for channel segments downstream of the input location. For a given time scale of pulse propagation, pulse dispersion will produce the longest-lasting benefits at the input reach, while pulse translation will result in short-lived local benefits. As noted by previous studies [e.g., *Lisle et al.*, 2001], and illustrated by the experiments reported here, dispersive pulse evolution is favored by coarser sediment inputs, wider grain size distributions, and larger input volumes. Gravel placement rather than injection also allows for shaping of bars and other topographic features that may promote gravel retention, in addition to providing direct habitat benefits.

[50] For target reaches downstream of the sediment input location, for example where access points are limited, pulse translation may sometimes be a preferred outcome. For a

given volume of input gravel, sediments will arrive at the target downstream reach at a higher rate if the pulse retains a more compact form because of a more translational pattern of evolution. In contrast, a dominantly dispersive pattern, where the pulse evolves by elongation and thinning, will result in lower rates of sediment delivery to downstream reaches, spread over a longer time period. These differing influences on downstream reaches are illustrated schematically in Figure 7a, which shows the tradeoff between the spatial concentration of added sediment and duration of pulse occupation at a given location. The differences in magnitude and duration of effect, between dominantly translational versus dispersive pulses, will be more pronounced with increasing distance downstream. There are other tradeoffs between the conditions that favor pulse translation and potential restoration effectiveness. Smaller input volumes, which our experiments suggest favor pulse translation, may arrive at downstream reaches as discrete sediment waves, but may not be of sufficient magnitude to create biologically meaningful changes to channel conditions. Similarly, gravel pulses composed of smaller grain sizes, and thus more likely to have a significant translational pattern of propagation, will move downstream with greater celerity, arriving at, but also passing through, downstream reaches more quickly. Where a fine gravel pulse is primarily intended to cause mobilization of static armor, rapid and far-reaching translation may be the most effective outcome, although entrainment of coarser bed materials should tend to suppress the tendency for further pulse translation. One ideal outcome of pulse translation would be supply from upstream of finer gravel to a downstream target reach, whereupon the pulse propagation pattern shifts to dominantly dispersive, allowing both large-magnitude and long-duration beneficial changes to occur.

[51] The experimental results also suggest tradeoffs between the potential spatial and temporal benefits of using fine- or coarse-grained sediment inputs. 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 prepulse armor [*Venditti et al.*, 2005]. As Figure 9 illustrates, it is possible to overshoot the ecologically beneficial grain size range by augmenting with finer-grained gravel [e.g., *Kondolf and Wolman*, 1993; *Phillips et al.*, 1975]. Moreover, the coarse-grained pulses produced a net fining, comparing the prepulse and postpulse 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]. More work is needed to explore the effect of alternating fine- and coarse-grained gravel additions, or using a distribution intermediate between the two end-members we tested in these experiments.

6. Conclusions

[52] We conducted a series of flume 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. Patterns of pulse propagation can be determined from a time series graph of the downstream-cumulative elevation differences (CED) from the prepulse bed topography. We quantify the extent of pulse translation versus dispersion from the rate of change in the interquartile range of the CED for a unit distance of travel downstream by the pulse center of mass. All experimental gravel augmentation pulses evolved through a combination of translation and dispersion, with a significant translational component, particularly for small augmentation volumes. These results are consistent with previous predictions [e.g., *Lisle et al.*, 2001] that translation is favored for sediment additions finer than the preexisting bed, and suggest that some component of pulse translation may be a common outcome for gravel augmentation pulses in armored channels below dams.

[53] Bed texture response to gravel augmentation pulses depends on the grain size of the preexisting 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. More research is needed to understand how the spatial complexity of natural channels and the temporal variability of discharge can influence patterns of propagation of small-volume pulses of finer-grained gravel in armored channels.

[54] **Acknowledgments.** We are grateful to Skye Corbett, Stuart Foster, John Potter, Kurt Yaeger, and Neto Santana for laboratory assistance; Chris Ellis, Jim Mullin, Brett Otteson, and Chris Paola of the University of Minnesota Saint Anthony Falls Laboratory for instrument cart development; Peter Downs, Scott Dusterhoff, Craig Fixler, and Frank Ligon of Stillwater Sciences for project leadership and management; and the project scientific advisory panel members Tom Lisle, Scott McBain, Gary Parker, Kris Vyverberg, and Peter Wilcock for insightful discussions. We also extend our thanks to Greg Pasternack and three anonymous reviewers for thoughtful and detailed comments on a previous version of the manuscript. Funding for this research was provided by CALFED Ecosystem Restoration Program (grant ERP-02D-P55) and by the STC program of the National Science Foundation (NSF) via the National Center for Earth Surface Dynamics (NCED) under agreement EAR-0120914.

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