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Key Points:

- Width variation controls the location of and relief between riffles and pools
- A sediment pulse evolved primarily through dispersion rather than translation
- Under steady flow, sediment supply does not influence riffle-pool relief

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Morphodynamic response of a variable-width channel to changes in sediment supply

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Abstract River channels commonly exhibit downstream variations in channel width, which can lead to the development of alternating shallow and deep areas known as riffle-pool sequences. The response of these channels to variations in sediment supply remains largely unexplored. Here we investigate the morphodynamic response of a variable-width channel to changes in sediment supply through laboratory experiments conducted in a straight flume in which we imposed sinusoidal variations in width. We first developed equilibrium conditions under a constant sediment supply and then eliminated the sediment feed to create a degraded, armored bed. This sediment-starved bed was subjected to two types of sediment supply increases: a return to the initial constant supply, and the introduction of a well-sorted sediment pulse (analogous to gravel augmentation). Riffles and pools formed in wide and narrow areas, respectively, and the location of and relief between riffles and pools remained the same throughout all experimental runs, regardless of the sediment supply. The primary channel response to changes in supply was adjustment of the overall slope. The sediment pulse evolved primarily through dispersion rather than translation, which contrasts with prior gravel augmentation experiments conducted in constant-width channels and suggests that width variation and resulting riffle-pool topography enhances pulse dispersion. Our results indicate that width variation is a primary control on the location and relief of riffles and pools in straight channels, and sediment supply changes are unlikely to affect riffle-pool morphology when bank geometry is fixed and water discharge is steady.

1. Introduction

River channels commonly exhibit downstream variations in channel width. Frequently associated with these changes in width are downstream variations in bed topography and flow depth known as riffle-pool sequences. Riffle-pool sequences are characteristic of straight and meandering gravel-bed rivers of <2% slope [e.g., *Leopold et al.*, 1964; *Montgomery and Buffington*, 1997; *Knighton*, 1998]. Riffles tend to be colocated with locally wide portions of the channel or valley [*Richards*, 1976; *Montgomery and Buffington*, 1997; *White et al.*, 2010], while pools are often forced by constrictions or local obstructions such as boulders or debris jams [*Keller and Swanson*, 1979; *Lisle*, 1986; *Montgomery and Buffington*, 1997; *Thompson et al.*, 1999; *Harrison and Keller*, 2007; *MacVicar and Roy*, 2007a,2007b].

In channels where both width and depth are free to adjust to flow, downstream perturbations in width can induce changes in bed topography or vice versa [e.g., *Parker et al.*, 2011; *Luchi et al.*, 2012; *Eke et al.*, 2014a]. The relative time scales of bed evolution and bank erosion and deposition influence the development of channel geometry and sinuosity [e.g., *Eke et al.*, 2014b]. In circumstances where bank erosion is slow with respect to bottom evolution, as may occur in channels with banks that are strongly vegetated or composed of cohesive sediment or bedrock, the planimetric configuration of the river is essentially steady and downstream variations in width will force changes in depth and/or velocity [e.g., *Repetto et al.*, 2002].

This latter condition, where local planimetric controls force the development of riffles and pools, can be readily explored through flume experiments or modeling studies. Experiments conducted in straight flumes with sinusoidal width variations, using a constant discharge and single grain size, have found that narrow parts of the channel develop pools and wide parts of the channel develop shallow "central" or "side" bars (topographic highs near the channel centerline or near the banks, respectively), depending on the wavelength and amplitude of the width variation [*Bittner et al.*, 1995; *Repetto and Tubino*, 1999; *Repetto et al.*, 2002; *Wu and Yeh*, 2005]. Recent studies using a one-dimensional morphodynamic model have shown that riffles and pools are predicted to emerge spontaneously at locations that are wide and narrow, respectively [*de Almeida and Rodríguez*, 2012]. While these studies have provided valuable insight on the influence of width variation on equilibrium bed topography, the effects of changes in sediment supply on the morphodynamics of variable-width channels has not been investigated.

Sediment supply has been shown to be an important factor controlling the morphology of gravel-bed rivers. Rivers can experience increases and decreases in sediment supply due to bank erosion and cutoffs which naturally occur during channel migration [e.g., *Zinger et al*., 2011], or due to natural or anthropogenic effects such as postfire sedimentation [e.g., *Benda et al*., 2003], dam installation, dam removal [e.g., *Grant*, 2001; *Pizzuto*, 2002], or land use change [e.g., *Wolman*, 1967; *Trimble*, 1997]. Experiments conducted in straight, constant-width flumes where a stepwise reduction in upstream sediment supply is imposed have shown that, with decreased supply, channels become coarser and exhibit less bed surface patchiness than under conditions of high sediment supply [e.g., *Dietrich et al*., 1989; *Lisle et al*., 1993; *Nelson et al*., 2009]. Additional flume experiments have shown that the presence or absence of alternate bars in gravel-bed rivers is partly dependent upon the sediment supply [*Venditti et al*., 2012; *Podolak and Wilcock*, 2013].

In some areas, where sediment starvation due to dams has caused the bed to coarsen and become unsuitable salmonid spawning and rearing habitat [e.g., *Kondolf*, 1997; *Buffington and Montgomery*, 1999], river managers have employed passive gravel augmentation; i.e., the addition of gravel to the channel downstream of a dam, to rejuvenate spawning habitat and restore geomorphic activity [*Bunte*, 2004; *Pasternack et al*., 2004; *Harvey et al*., 2005]. Gravel augmentation and natural sources of episodic sediment supply such as landslides or debris flows create a pulse of locally high sediment supply. Sediment pulses have received considerable attention in recent years, including field studies [*Madej*, 2001; *Sutherland et al*., 2002; *Kasai et al*., 2004; *Bartley and Rutherfurd*, 2005; *Hoffman and Gabet*, 2007], flume experiments [*Lisle et al*., 1997; *Cui et al*., 2003a; *Sklar et al*., 2009; *Venditti et al*., 2010a, 2010b; *Humphries et al*., 2012], and numerical modeling [*Pickup et al*., 1983; *Benda and Dunne*, 1997a,1997b; *Lisle et al*., 2001; *Cui et al*., 2003b; *Cui and Parker*, 2005; *Cui et al*., 2008; *Maturana et al*., 2013]. These studies have shown that sediment pulses evolve through some combination of dispersion and translation, but generally pulse evolution is dispersion-dominated [*Lisle et al*., 1997; *Cui et al*., 2003b; *Lisle*, 2008].

Flow conditions, the volume of the sediment pulse, and the grain size of the sediment pulse material have been shown to influence whether a sediment pulse is more likely to evolve through dispersion or translation. The flume experiments and numerical modeling presented in *Lisle et al*. [1997, 2001] suggested that sediment pulses in gravel-bed rivers are much more likely to be dispersive than translational, and their work indicated that significant pulse translation requires a low Froude number and low sediment wave amplitude. The experiments of *Cui et al*. [2003a] also found pulse dispersion to predominate, although one experiment using fine pulse material exhibited pulse translation, suggesting that finer pulse sediment relative to the ambient bed material may promote translation. Both of these experiments had high Froude numbers (0.90 and 0.98), and the sediment pulses were added to the channel as triangular waves with apex heights on the order of the mean flow depth. The experiments also maintained a sediment supply upstream of the location of the addition of the sediment pulse, and this may have contributed to pulse dispersion. In this scenario, the relatively large height of the added wedge of pulse material produces a backwater effect encouraging deposition from the upstream sediment supply while enhancing sediment transport on the downstream face of the pulse, which causes the pulse to become effectively stationary as its amplitude decreases and its upstream and downstream ends spread away from the pulse center [*Cui et al*., 2003a].

Pulses in channels with no upstream sediment supply, as is likely to occur in a gravel augmentation, have been investigated in recent experiments by *Sklar et al*. [2009] and *Humphries et al*. [2012]. *Sklar et al*. [2009] conducted experiments in a straight, rectangular flume under constant discharge, and documented sediment waves evolving by a combination of translation and dispersion, with a significant translational component. The average Froude number in the *Sklar et al*. [2009] experiments ranged from 0.63 to 0.71; this, along with the absence of a sediment feed, likely contributed to the translational nature of the sediment pulses. *Humphries et al*. [2012] performed experiments in the same flume, but they fixed stationary alternate bars in the flume bottom and imposed both constant flow and repeat hydrographs. They observed that flow perturbations due to the bed topography caused the leading edge of the sediment pulse to progress downstream in an episodic pattern, and they found that constant flows tend to produce dispersion with some

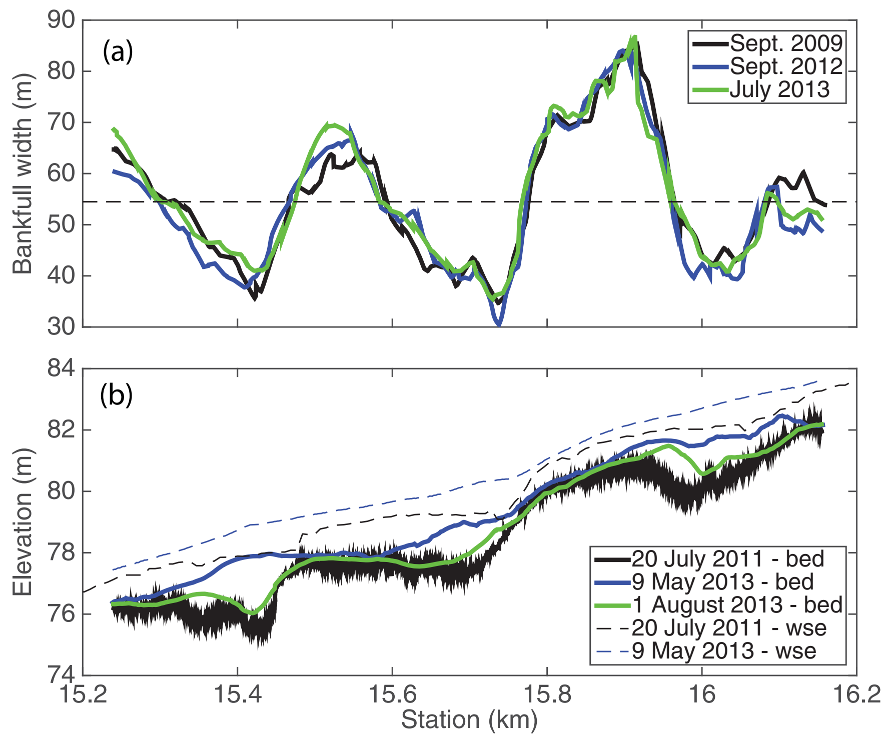

Figure 1. (a) Bankfull width for the middle reach of the Elwha River, Washington, USA, as measured using Google Earth imagery. Imagery dates provided in the legend. (b) Centerline bathymetry and water surface profiles before (20 July 2011) and after (9 May 2013 and 1 August 2013) dam removal.

limited translation, while small hydrographs produce primarily dispersion, and large hydrographs cause pulse translation. *Cui et al*. [2008] report steady-flow sediment pulse experiments conducted over the same stationary alternate bars used in the *Humphries et al*. [2012] experiments, and show that a one-dimensional model was able to capture much of the reach-averaged pattern of aggradation and degradation.

Much of our understanding of the effects of sediment supply on gravel-bedded rivers is based on work in channels of constant width, and it is not clear how a variable-width channel will respond to either sustained or temporary (pulse) changes in sediment supply. Here we present experiments conducted in a variable-width flume where the sediment supply has been manipulated under constant water discharge. In our experiments, the channel planform and downstream width variations are fixed and impose a control on the development of riffles and pools. We are interested in understanding how width variations affect bed morphology under conditions of equilibrium sediment supply, zero sediment supply (i.e., before and after the installation of a dam), and we investigate how the sediment-starved channel responds to a steady and pulsed increase in sediment supply.

2. Methods

2.1. Flume Configuration

Flume experiments were conducted at the hydraulics laboratory at the Colorado State University Engineering Research Center. The flume slope, geometry, and grain size were designed and scaled to be characteristic of the middle reach of the Elwha River, Washington, USA. This reach is just downstream of the former Glines Canyon Dam, a 64 m high dam that had accumulated 16 ± 2.4 million m^3 of sediment in its reservoir [*East et al*., 2015]. Glines Canyon Dam was removed in stages between 2011 and 2014, releasing an estimated 6 million m^3 of sediment during the first 2 years of removal. Flows were low during this period, and the 2 year recurrence interval discharge was not exceeded [*East et al*., 2015], so flows were likely confined to the main channel. The bankfull width in the middle reach of the Elwha River has a mean of about 55 m and varies downstream in a sinusoidal pattern with a wavelength of about 300 m (Figure 1) [*Brew et al*., 2015]. Prior to

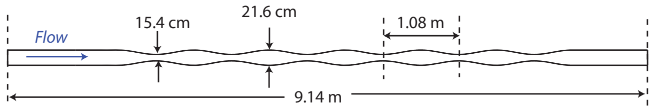

Figure 2. Planform geometry of the experimental channel.

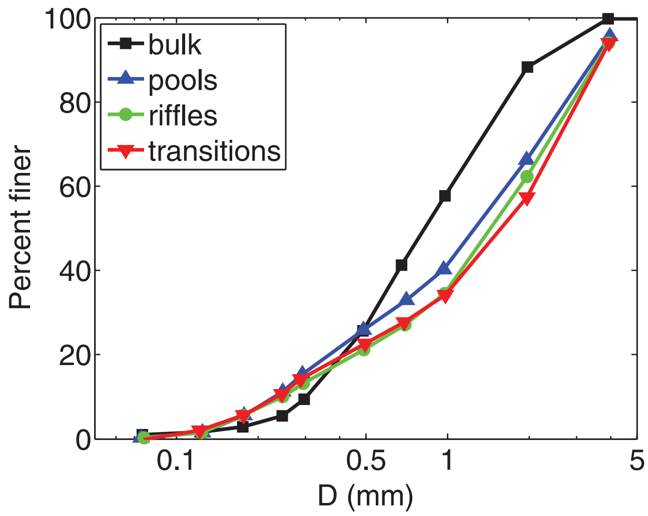

Figure 3. Grain size distributions of the bulk sediment and of surface samples collected on riffles, pools, and transitions at the end of Run 2.

dam removal, the river bed was composed of a mean grain size in the large cobble to small boulder range [*East et al.*, 2015]. The slope of the river at this location prior to dam removal was 0.0063 [*Brew et al.*, 2015].

The experiments were conducted in a 9.14 m long, 21.6 cm wide, and 38.1 cm deep rectangular flume. In the central portion of the flume, downstream of a 1.58 m straight entrance reach and upstream of a 1.08 m straight exit reach, we imposed sinusoidal width variations by installing walls fabricated from flexible fiberglass mounted to wooden supports attached to the outer flume walls (Figure 2). The six sinusoidal channel constrictions we installed had a wavelength of 1.08 m, which is 5 times the maximum (riffle) width to be characteristic of natural settings [*Leopold and Wolman*, 1957] and matches the approximate scaled wavelength of width variations in the middle reach of the Elwha. The width of the narrowest sections was set to 15.4 cm, 60% of the width of the wide sections (21.6 cm), which is similar to conditions in the middle reach of the Elwha (Figure 1).

The grain size distribution of the bed material, the initial bed slope, and the water discharge were selected so that (a) all grain sizes in the distribution would be mobile and transported primarily as bed load and (b) the width-to-depth ratio in the wide sections would be about 15, which is representative of the fairly wide, shallow flow characteristic of riffles [e.g., *Richards*, 1976; *Milan*, 2013]. The bed material was a unimodal mixture of sand and fine gravel, ranging from 0.08 to 4 mm in diameter, with a median diameter (D_{50}) of 0.84 mm and a geometric standard deviation of 2.15 (Figure 3). The initial bed was screeded flat and set to a slope of 0.007, which is about the slope of the middle reach of the Elwha and is in the characteristic range of natural gravel-bed rivers with riffle-pool morphology [e.g., *Montgomery and Buffington*, 1997]. Using the rationale presented in *Parker et al.* [2003], the flume channel geometry and sediment scale to approximately the same conditions as the middle reach of the Elwha: with a scaling factor of $\lambda = 250$, the D_{50} scales to 210 mm and the riffle width scales to 54 m; with a scaling factor of $\lambda = 150$, the D_{50} scales to 126 mm and the riffle width scales to 32 m.

A constant discharge of 0.91 L/s was used in all of the experiments. Given our slope and grain size distribution, we determined that this discharge would produce dimensionless boundary shear stress ($\tau^* = \tau/(\rho_s - \rho)gD_{50}$, where τ is the dimensional boundary shear stress, ρ_s and ρ are the densities of sediment and water, and g is gravitational acceleration) approximately 2 times the critical value for the median grain size ($\tau_c^* \approx 0.045$), which according to *Wilcock and McArdell* [1993] would mobilize the entire range of grain sizes. Water was pumped into a head box at the flume inlet and entered the straight entrance reach through a set of stacked 1/4 in. (6.35 mm) diameter PVC pipes, which acted as flow straighteners and allowed uniform flow to develop.

The flow was frequently stopped during the experiments to facilitate bed surface measurements. Care was taken to ensure that bed adjustments due to stopping and restarting the flow were minimized. Bed surface measurements were collected using a camera and laser system similar to those used in other flume experiments [e.g., *Wu and Yeh*, 2005; *Rowland et al.*, 2009; *Braudrick et al.*, 2009], where a digital SLR camera and a laser level were mounted to a movable platform spanning the flume width. The laser was oriented vertically so that it projected a laser sheet across the channel bed. A photograph of the laser line, distorted by the cross-sectional topography, was taken with a digital SLR camera from an oblique angle, and this image was processed with a MATLAB script to extract the pixels corresponding to the laser line and relate those pixels to actual elevations, essentially measuring a cross section. These photographs were taken every 2 cm in the downstream direction. The data from all of the images for a given scan were combined and used to generate a digital elevation model of the bed with 2 cm longitudinal resolution and 1 mm horizontal resolution.

At the end of each experimental run, water surface profiles were measured along the flume centerline with a point gage mounted to the platform; these measurements were collected with a spacing of 37 cm. Bed load flux was measured approximately every 15 min by using a #200 sieve with square 0.075 mm openings to capture all sediment exiting the flume for 60 s. The collected sediment was later dried and weighed to determine the transport rate. The bed surface grain size distribution was generally not sampled because sorting was not obvious and we did not want to disturb the bed; however, at the end of Run 2 (described below), samples were collected at several locations along the flume centerline using a flour paste adhesive sampling technique [*Bunte and Abt*, 2001].

2.2. Experimental Procedure

The overall experiment consisted of five runs, designed to simulate equilibrium (predam) conditions, dam installation, and a subsequent constant or pulsed sediment supply increase.

Run 1 established equilibrium conditions under constant water discharge and sediment supply. Throughout this run, the bulk sediment was fed to the upstream end of the flume by adding 150 g of sediment every 60 s. We arrived at this sediment feed rate of 150 g/min by using several bed load transport relations [*Ashida and Michiue*, 1972; *Fernandez Luque and van Beek*, 1976; *Engelund and Fredsøe*, 1976; *Wong and Parker*, 2006] to estimate transport rates for our flume geometry and discharge and using the average of the calculated values. The run lasted for a total of 13 h, at which point the system appeared to have adjusted to an equilibrium condition and the bed load flux exiting the flume had been equal to the sediment feed rate for about 3 h.

The bed at the end of Run 1 formed the initial condition for Run 2, which simulated the installation of a dam by cutting off the sediment supply. Run 2 lasted for 23.6 h, during which time the flume was stopped and restarted seven times so that bed topographic measurements could be collected. By the end of the run, the bed load flux exiting the flume approached zero, and the bed topography was unchanging.

Run 3 explored the channel's response to a scenario where the predam sediment supply is returned to the sediment-starved bed at a constant rate. The bed from the end of Run 2 served as the initial condition for Run 3, and the initial feed rate of 150 g/min was supplied at a constant rate for the duration of the run, which lasted 4.5 h. The flow was stopped and started approximately every hour to measure bed topography, and by the end of the run the sediment flux exiting the flume was approximately equal to the supply rate.

Runs 4 and 5 constituted another sequence of sediment starvation and resupply. In Run 4, the sediment supply was once again terminated and the flume was run for 28.6 h to create a sediment-starved bed. Run 5 investigated the dynamics of a well-sorted sediment pulse supplied to this system. This run was designed to be as analogous to the work presented in *Sklar et al.* [2009] as possible so that the effects of channel width variation on sediment pulse evolution might be inferred. The volume of the sediment pulse was calculated to be that which would completely fill in the pools present at the end of Run 4 and cover the resulting plane bed with a carpet of sediment with a thickness of one D_{50} of the pulse material, similar to the "large pulse" experiments of *Sklar et al.* [2009]. This calculation yielded a pulse material mass of 15.7 kg. The pulse material had a uniform grain size of 0.83–1 mm, which was approximately the D_{50} of the original bulk mixture, and was finer than the D_{50} of the armored bed surface (Figure 3). As in the *Sklar et al.* [2009] experiments, the pulse was added by hand at the upstream end of the flume at a rate 4 times the "predam" equilibrium rate (150 g/min in Run 1). Thus, in Run 5, the pulse material was supplied at a rate of 600 g/min for 27 min. Visual observations of the location of the sediment pulse front were recorded every 60 s until it reached the flume outlet. At that point, bed load measurements were taken every 5 min to monitor pulse response. To capture the dynamics of the pulse, topographic scans were collected more frequently during Run 5 than in the previous runs; initially, the flume was stopped every 5 min to collect a scan, but this frequency was reduced to 10 min, 20 min, and eventually several hours as the pulse signature became less

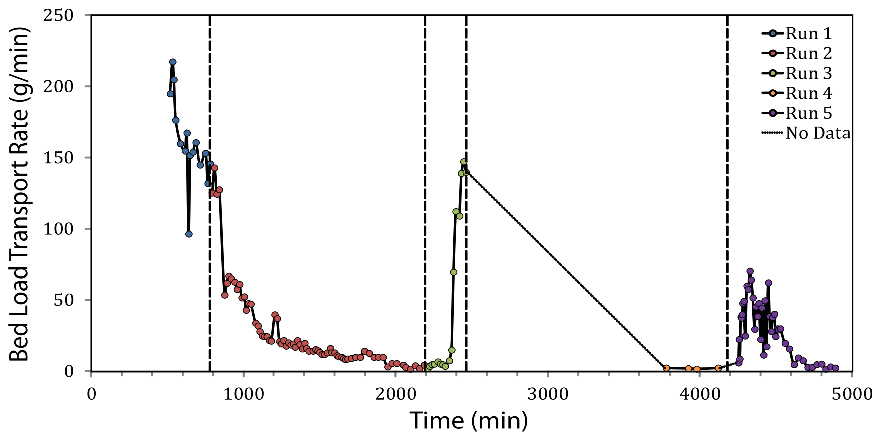

Figure 4. Time series of bed load transport collected at the flume outlet. Dashed vertical lines distinguish transitions between experimental runs.

distinct. The experiment was run for 711 min, by which point nearly the entire pulse of sediment had been evacuated from the system.

3. Results

3.1. Bed Load Transport

Figure 4 shows the bed load transport rate measured at the flume outlet for all five runs of the entire experiment. During Run 1, the flume adjusted to a constant supply of 150 g/min in approximately 12.5 h, equilibrating transport at the outlet with the provided supply. In Run 2, the sediment feed was eliminated, and the bed load flux precipitously dropped and asymptotically approached zero. At the end of Run 2, after approximately 25 h with no sediment supply, bed load was exiting the flume at approximately 2 g/min.

During Run 3, when the upstream sediment supply was reinstated at 150 g/min, the bed load at the end of the flume remained below about 5 g/min for 120 min. After that point, the sediment flux rapidly increased, and after another 4 h it had reached the feed rate of 150 g/min.

By the end of the second period of sediment starvation, Run 4, the bed load flux exiting the flume once again leveled out at around 2 g/min for several hours. The pulse material added in Run 5 began to reach the outlet of the flume 70 min after the beginning of the run, and the bed load flux increased to a maximum of 70.4 g/min 150 min into Run 5. After that point, the flux gradually declined until it once again reached about 2 g/min at the end of the run. During all of Run 5, 13.1 kg of sediment exited the flume, which is approximately 84% of the mass of the sediment pulse.

3.2. Bed Morphology

3.2.1. Equilibrium Supply (Run 1)

During Run 1, the bed evolved from its initial flat state to one with distinct riffles in the wide sections and pools in the narrow sections (Figures 5 and 6). Figure 5a shows the bed topography at the end of Run 1, and Figure 5b shows the residual bed elevation after subtracting out the mean bed slope so that riffles, pools, and bars are emphasized. The riffles developed so-called "side bars" [*Wu and Yeh*, 2005], where the local topographic high points were closer to the channel walls than the center.

The average flow depth at the end of Run 1 was 1.9 cm, and the average bed slope was 0.0067 (Figure 6c). During Run 1, the Froude number ranged from 0.47 to 0.82, with an average value of 0.61 (Figure 6b). For all runs, the average relief between riffles and pools was calculated by first computing the "reach-averaged" (in the sense of *Cui et al*. [2008]) bed elevation as the average elevation of all measured bed topography points in a moving window with a width of one width-variation wavelength. This reach-averaged bed profile was then subtracted from the cross-sectionally averaged bed profile (e.g., Figure 6c) to generate a profile of residual elevation (e.g., Figure 6d). The difference between consecutive local maxima and minima of this residual elevation for the three central riffle-pool sequences (e.g., between about 3000 and 6000 mm

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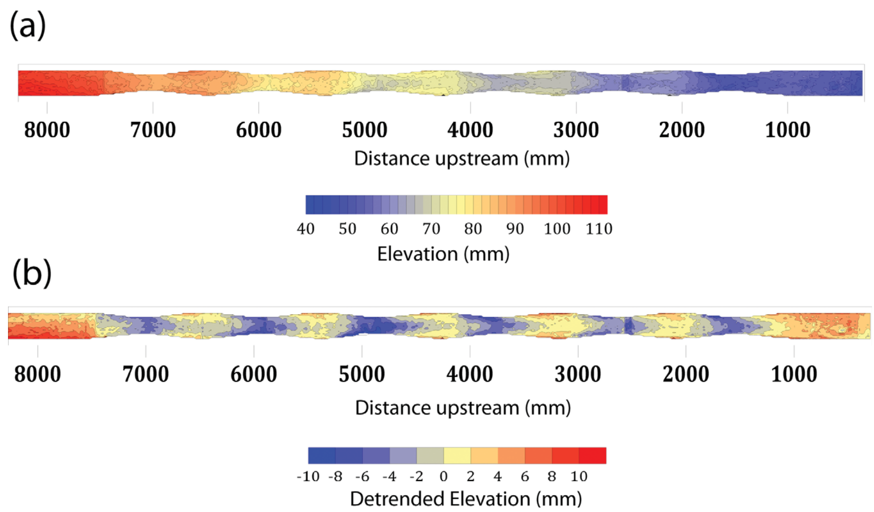

Figure 5. Bed topography at the end of Run 1. (a) Digital elevation model of the bed surface. (b) Bed surface topography detrended by subtracting the mean channel slope.

upstream from the outlet) were measured and averaged to calculate the characteristic riffle-pool relief for each run. These data are presented in Table 1. The average riffle-pool relief at the end of Run 1 was 8.2 $\pm$ 0.9 mm.

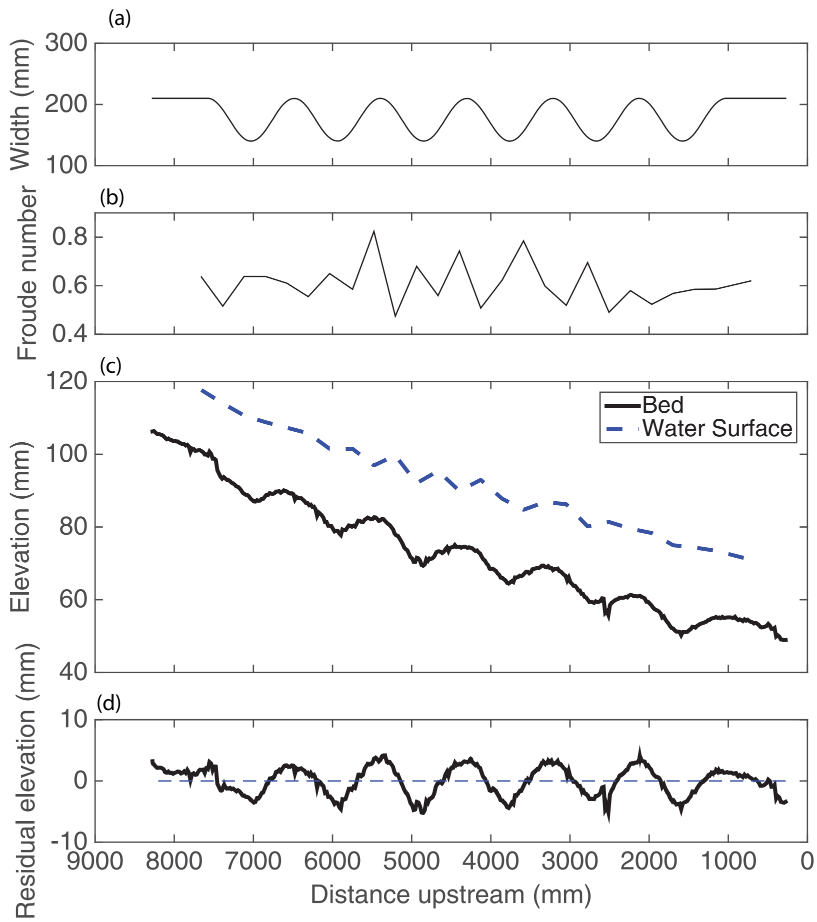

Figure 6. Bed topography at the end of Run 1. (a) Channel width. (b) Froude number. (c) Longitudinal profiles of bed and water surface elevation. Bed elevation is the average at each cross section. (d) Bed topography detrended by subtracting the average elevation over a single wavelength of width variation from the local cross-section-averaged bed topography.

Table 1. Average Relief Between Riffles and Pools, Computed by Subtracting the Cross-Sectionally Averaged Bed Elevation From the Local "Reach-Averaged" Bed Elevation

Run	Relief (Mean $\pm$ 1σ) (mm)
Run 1 (end)	8.2 $\pm$ 0.9
Run 2 (end)	8.9 $\pm$ 0.1
Run 3 (end)	7.7 $\pm$ 0.1
Run 4 (end)	8.4 $\pm$ 0.4
Run 5 (27 min after pulse started)	8.4 $\pm$ 0.2
Run 5 (86 min after pulse started)	8.2 $\pm$ 0.2

3.2.2. Armoring (Runs 2 and 4)

Upon eliminating the sediment supply at the end of Run 1, the bed began to coarsen and the bed slope declined. At the end of Run 2, the bed was nearly uniformly coarse: the D_{50} of the riffles was 1.55 mm and that of the pools was 1.38 mm (Figure 3). Figure 7c shows the evolution of the longitudinal profile of the channel during Run 2: the slope steadily declined from its initial value of 0.0067 to a final value of 0.0038. Erosion was not concentrated in wide or narrow sections of the flume, but progressed fairly uniformly from upstream to downstream (Figure 7d). The bed had essentially finished evolving after 15.2 h of no feed, as the scans taken at that time and 9 h later were nearly identical. The average flow depth at the end of Run 2 was 2.0 cm. Although the slope declined by nearly a factor of two from the beginning to the end of Run 2, the relief between the riffles and pools was 8.9 $\pm$ 0.1 mm, remaining largely the same as at the end of Run 1 (Table 1).

Bed conditions at the end of the two armoring runs (Run 2 and Run 4) were very similar (Figure 8). The bed at the end of Run 4 also had a mean slope of 0.0038, and the riffle-pool relief was 8.4 $\pm$ 0.4 mm. The

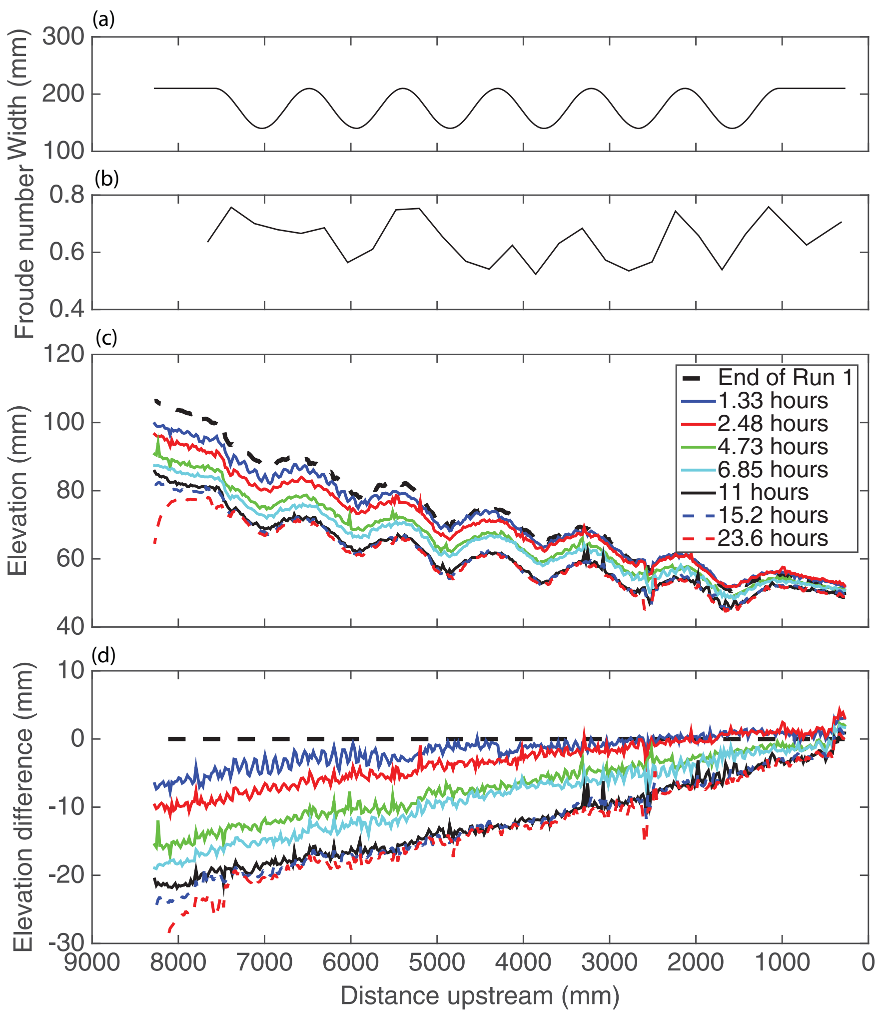

Figure 7. Longitudinal profiles of mean bed elevation during Run 2. (a) Channel width. (b) Froude number at the end of Run 2. (c) Longitudinal profiles of mean cross-sectional bed elevation during Run 2. Times shown in the legend indicate the amount of time elapsed since the end of Run 1, when the sediment feed was eliminated. (d) Change in elevation relative to conditions at the end of Run 1.

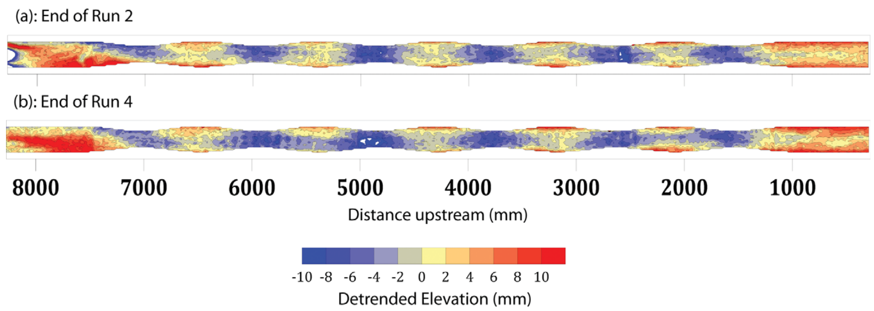

Figure 8. Bed topography (detrended by subtracting the mean channel slope) at the end of the two runs without sediment supply: (a) Run 2 and (b) Run 4.

primary difference between the beds at the end of these runs is the scour that occurred during Run 4 on the right side of the channel at the upstream end (between 5000 and 6000 mm upstream). This phenomenon probably resulted from entrance effects, and areas further downstream did not experience scour of this nature.

The flow at the end of Run 2 was subcritical throughout (Figure 7b), with Froude numbers ranging from 0.52 to 0.76 with a mean of 0.64. These conditions, which are representative of the prevailing flow before the sediment additions of Run 3 and Run 5, are on the low end of the Froude numbers reported by *Sklar et al*. [2009], and are considerably lower than those in the sediment pulse experiments reported in *Lisle et al*. [1997] and *Cui et al*. [2003a].

3.2.3. Constant Sediment Supply Increase (Run 3)

Figure 9b shows the evolution of the longitudinal profile after the sediment supply was returned to 150 g/min in Run 3. The bed responded to the increased supply with deposition at the inlet, and this deposition migrated downstream over time (Figures 9c and 10). At 1.17 h after the supply returned, the

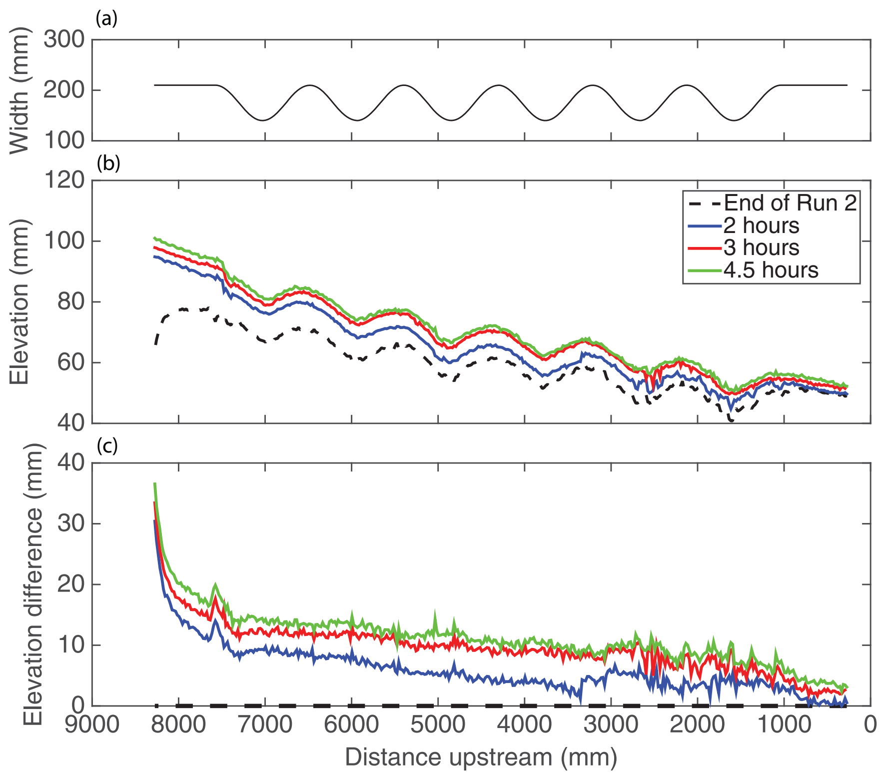

Figure 9. Longitudinal profiles of mean bed elevation during Run 3. (a) Channel width. (b) Cross-sectional average bed elevation. Times shown in the legend indicate the amount of time elapsed since the end of Run 2, when the sediment supply was restored to 150 g/min. (c) Change in elevation relative to conditions at the end of Run 2.

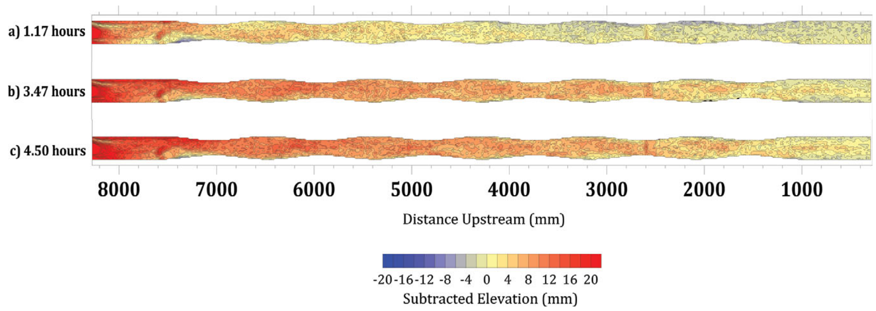

Figure 10. Maps of topographic change during Run 3. The time since the end of Run 2 is shown on the left of each map. Topographic change is calculated by subtracting the topography from the end of Run 2 from the high-resolution scans taken during Run 3. Thus, elevation differences >0 indicate deposition, and values <0 indicate erosion.

upstream part of the flume had begun to aggrade, but, downstream of about $x = 4000$ mm, the bed remained largely unchanged from the end of the armoring run. By the time the next bed scan was collected, 3.47 h after the feed resumed, the entire bed had aggraded. By this time, the sediment flux exiting the channel had also increased dramatically (Figure 4). After 4.5 h with the supply returned, the bed had steepened to an average slope of 0.0056 (Figure 9). At the end of Run 3, the relief between riffles and pools was 7.7 ± 0.1 mm (Table 1).

3.2.4. Pulse Morphodynamics (Run 5)

Figure 11 shows maps of topographic change as the pulse moved through the channel during Run 5, and Figure 12 shows the evolution of the mean longitudinal profile. The front of the pulse steadily moved down the channel with an average celerity of 90 mm/min (Figure 13). While the pulse was being added (over the first 27 min of Run 5), the upstream end of the channel aggraded nearly 30 mm, and the two upstream riffle-pool sequences steepened dramatically such that the average slope between $x = 8200$ mm and $x = 5000$ mm at 27 min was 0.013 (Figure 12). Between 27 and 47 min into Run 5, after all of the pulse

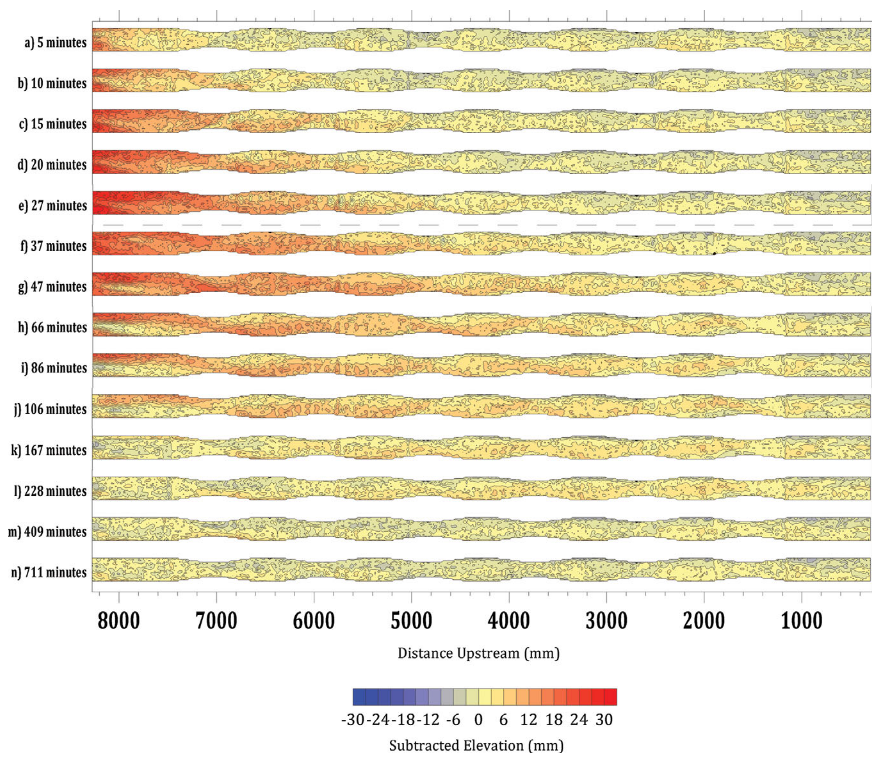

Figure 11. Maps of topographic change during Run 5. The time since the end of Run 4 is shown on the left of each map. Topographic change is calculated by subtracting the topography from the end of Run 4 from the high-resolution scans taken during Run 5. Thus, elevation differences >0 indicate deposition, and values <0 indicate erosion.

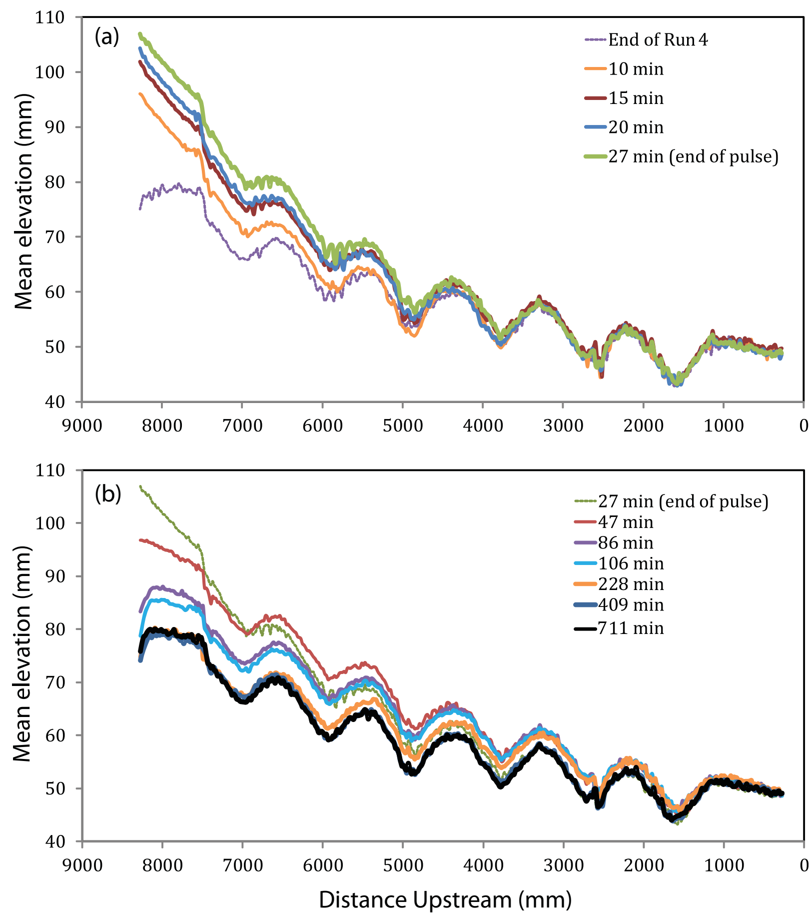

Figure 12. Longitudinal profiles of mean bed elevation during Run 5. Figure 12a shows profiles collected during the first 27 min of Run 5, during which time pulse material was still being added. Figure 12b shows profiles collected after 27 min, as the pulse evolved but no additional sediment was being supplied at the upstream end of the channel.

material had been added to the flume, the upstream-most riffle-pool sequence began to degrade while the second and third riffle-pool sequences continued to aggrade.

The longitudinal profiles and maps of erosion and deposition give some sense of how the pulse evolved, but do not provide a good assessment of the degree to which the pulse displays translation and dispersion. A useful metric for quantifying pulse translation and dispersion was presented by *Sklar et al.* [2009]. They define a purely translational pulse as one where the center and trailing

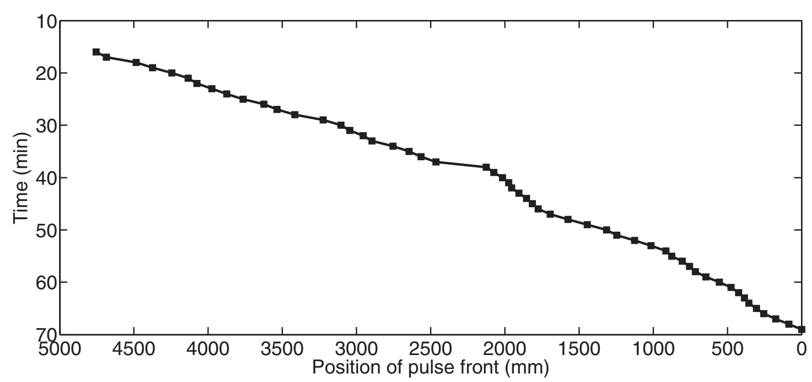

Figure 13. Temporal evolution of the position of the front of the pulse of added material during Run 5.

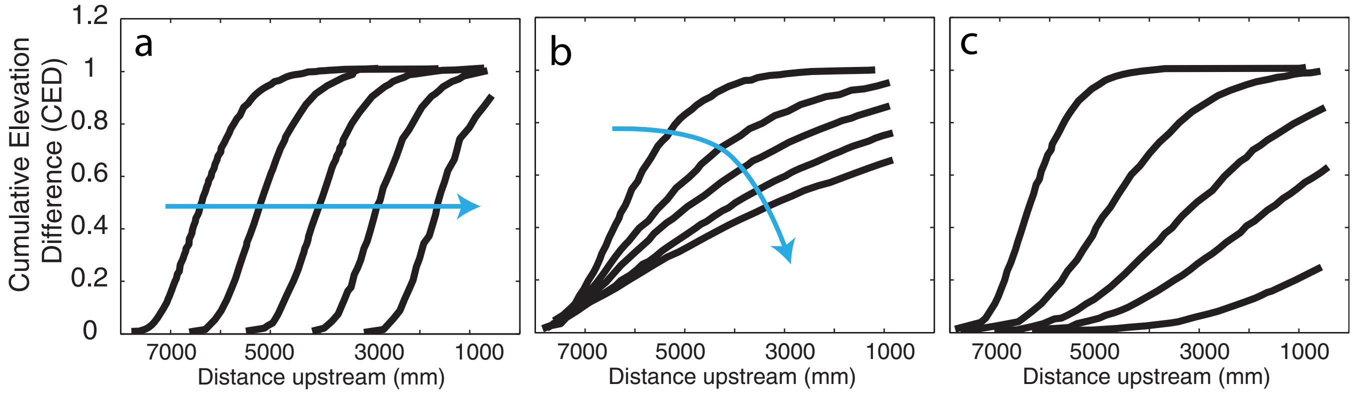

Figure 14. Cumulative elevation difference (CED) curves for hypothetical sediment pulses that are (a) purely translational, (b) dispersion-dominated, and (c) mixed dispersion and translation. See *Sklar et al*. [2009] for details on how these curves were generated.

edge advance downstream at the same rate, and they define a purely dispersive pulse as one where the center and trailing edge do not migrate downstream and the pulse length grows. The relative degree of translation and dispersion can be assessed by plotting the downstream cumulative distribution of bed elevation changes (CED) from the prepulse bed topography. Figure 14 shows hypothetical CED curves for purely translational, dispersion-dominated, and mixed translational and dispersive pulse evolution. In a purely translational pulse, the waveform is not altered by downstream translation, and the slope of the CED curve does not change. In a dispersion-dominated pulse, the CED curve rotates clockwise and fades as the pulse exits the flume. The CED curve for a pulse that displays both translation and dispersion will show both a progressive translation to the right and a rotational decline in the slope of the curve.

The relative dispersion and translation of a pulse can be further quantified by plotting the longitudinal spread of the pulse (characterized by the distance occupied by the central 50% (interquartile range, IQR) of downstream cumulative elevation deviations) against the position of the center of the pulse (characterized by the location of the median (50th percentile) of the downstream cumulative elevation deviation) [*Sklar et al*., 2009]. Figure 15 shows these relationships for the hypothetical CED curves shown in Figure 14. The purely translational pulse shows steady downstream migration of the pulse center with no increase in the IQR; the dispersion-dominated pulse shows slight change in the location of the pulse center (due to dispersive erosion of the pulse deposit) and a steady increase in the IQR; and in the mixed translation and dispersion pulse the median location moves downstream while the IQR increases.

Figure 16a shows the evolution of the bed elevation changes from the end of Run 4, and Figure 16b plots the downstream cumulative elevation differences (CED). As the pulse material was added to the flume (the first 27 min, indicated by dashed lines in Figure 16), the peak in the CED increased as well. Throughout Run 5, the pulse is very strongly dispersion-dominated. The CED curves show rotation of the slope about the sediment input location throughout the experiment, which is characteristic of dispersion-dominated pulse behavior (Figure 14b).

Figure 17 shows the evolution of pulse IQR (length of the central 50% of the CED) and the pulse center (location of the median of the CED). The figure uses data collected up to 106 min after the pulse was introduced; after this time, too much of the pulse had exited the flume to provide meaningful results for this analysis. Over this time, the IQR length increases from about 1000 to 2800 mm as the pulse center migrates from about $x = 7300$ to $x = 5500$ mm. The slope of this line is 1.0. For comparison, the slopes of the hypothetical pulses in Figure 15 are 1.3 for the dispersion-dominated pulse, 0.0 for the translational pulse, and 0.5 for the mixed-behavior pulse. Additionally, *Sklar et al*. [2009] report slopes of 0.60 m/m for their "large-coarse" pulse and 0.15 m/m for their "small-fine" and "small-coarse" pulses, all of which exhibited a substantial translational component. Using this metric, we interpret the pulse in our experiment to be dominantly dispersive.

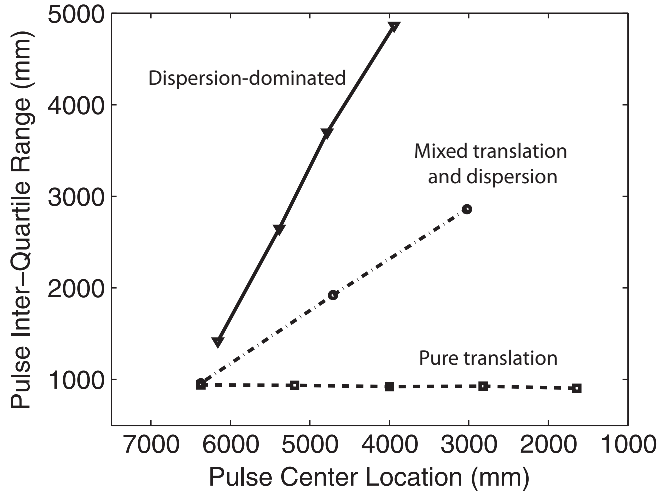

Figure 15. Pulse evolution depicted through nonparametric statistics of downstream cumulative elevation differences (CED) for the three hypothetical curves shown in Figure 14. The pulse center location is the median (50th percentile) of the CED curve; the pulse interquartile range is the length enclosing the central 50% of the CED.

4. Discussion

4.1. Width Variation and Riffle-Pool Topography

In our experiments, the development of shallow areas (riffles) and deep areas (pools) in channel expansions and constrictions, respectively, agrees with prior field [e.g., *Richards*, 1976; *Montgomery and Buffington*, 1997; *White et al*., 2010], flume [e.g., *Repetto et al*., 2002; *Bittner et al*., 1995; *Wu and Yeh*, 2005], and numerical modeling [e.g., *de Almeida and Rodríguez*, 2012] observations. These studies have indicated that width variations play an important role in developing steady state riffle-pool morphology, but how these width variations interplay with changing sediment supply has not been previously addressed. Sediment supply can be an important control on channel-scale bed forms, as *Venditti et al*. [2012] showed in their experiments where alternate bars washed out to a plane bed condition upon elimination of the upstream sediment supply.

The development of side bars during the experiments was not affected by the sediment supply rate (Figures 5 and 8). Although they did not investigate sediment supply effects, *Wu et al*. [2011] used a two-dimensional morphodynamic model to systematically explore equilibrium morphology in channels with sinusoidal

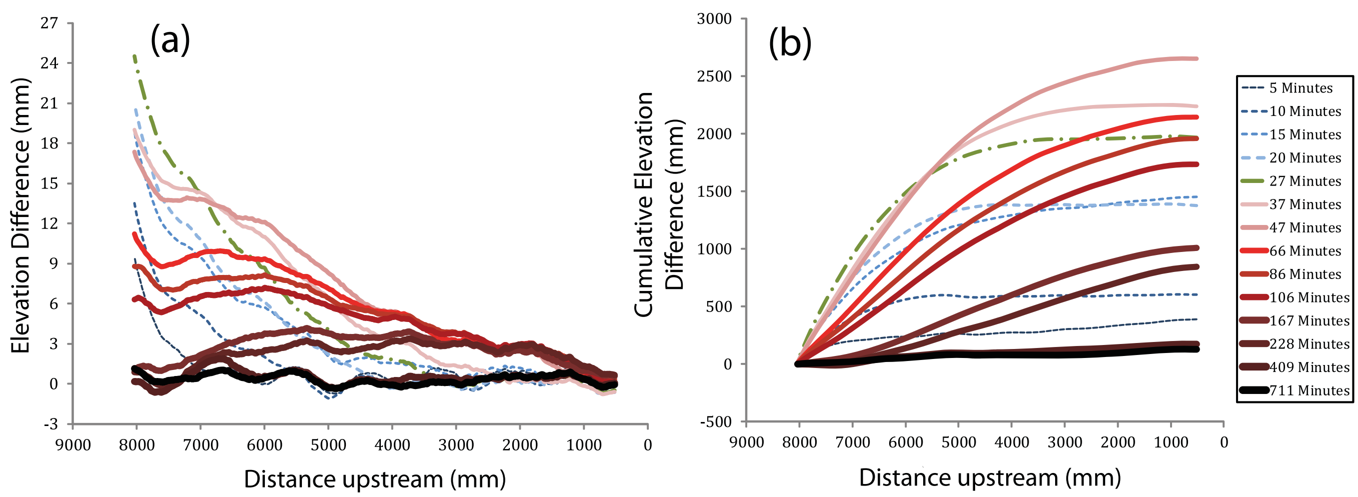

Figure 16. (a) Downstream profiles of elevation differences during Run 5, as depicted in the maps in Figure 11. (b) Downstream cumulative elevation differences (CED) of the data shown in Figure 16a. In both plots, dashed lines represent elevation differences during the first 27 min while pulse material was still being added to the flume. Elevation differences after 27 min, when the addition of pulse material had ceased, are shown as solid lines that become darker as time increases.

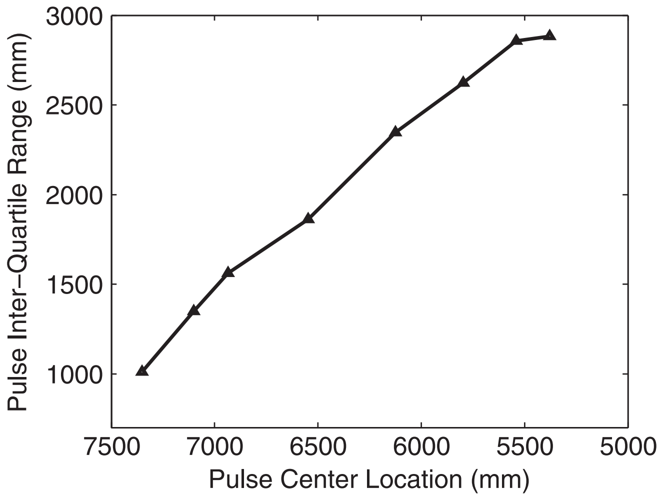

Figure 17. Pulse evolution during Run 5 represented by the pulse center (location of the 50th percentile of downstream cumulative elevation differences) and the pulse interquartile range (the length enclosing the central 50% of the CED curve).

variations in width, and determined that channels with a dimensionless wave number λ_c ($\lambda_c = 2\pi B_0/L_c$, where B_0 is the mean channel width and L_c is the wavelength of width variations) greater than 0.2 developed side bars while channels with $\lambda_c < 0.2$ tended to develop central bars. Our observations of side bars agree with these findings, as λ_c in our experiments (which does not depend on sediment supply) was 0.5.

In our experiments, regardless of the sediment supply condition, the location of and relief between riffles and pools remained spatially and temporally persistent. The channel responded to changes in sediment supply by adjusting its overall slope, but the nature of the riffles and pools did not change either transiently or at equilibrium (e.g., Figures 6, 7, 9, and 12 and Table 1). Thus, at least under conditions of constant water discharge and fixed, inerodible banks, width variations appear to control the location and relief of riffles and pools, and sediment supply does not play an important role in the development of these features. This may not always hold in natural channels because bed and bank evolution can occur simultaneously, and excessive aggradation may lead to overbank flows which can change patterns of erosion and deposition; however, field studies have shown riffle locations to remain constant despite changes in channel slope and prevailing hydrology [e.g., *Carling and Orr*, 2000; *White et al*., 2010]. After the removal of Glines Canyon Dam, pools in the middle reach of the Elwha River aggraded under extremely high sediment loads, but quickly returned to their predam-removal locations, which were colocated with local minima in channel bankfull width (Figure 1) [*Brew et al*., 2015]; the experiments presented here support the idea that in this scenario, relatively low flows were confined to the bankfull channel geometry, and downstream variations in channel width helped to enforce the persistent location of riffles and pools despite large changes in sediment supply.

Given the importance of sediment supply on the development [*Venditti et al*., 2012] and morphology [*Erwin*, 2012] of alternate bars, it is somewhat surprising that the riffle-pool relief did not change throughout the experiments. In the field, the amount of fine sediment in pools has been used as an indicator of sediment supply [*Lisle and Hilton*, 1992]. In our experiments, however, the pools never filled in, even during the introduction of the pulse in Run 5 when the channel was subject to very high rates of sediment supply (Figure 12). This suggests that increased sediment supply alone is insufficient to cause filling of pools, and that unsteady flow and a wide range of grain sizes in the sediment supply, which we did not have in our experiments, are probably necessary to cause changes in riffle-pool relief. Filling of pools likely occurs primarily during the receding limb of a hydrograph as fine material that is transported either in suspension or as bed load under low stress is deposited in pools. This sediment is then scoured out of the pools during the rising limbs of subsequent hydrographs [e.g., *Keller*, 1971; *Lisle and Hilton*, 1992; *Humphries et al*., 2012]. Without hydrographs or relatively fine material in the sediment supply, pools do not fill in and riffle-pool relief does not change with sediment supply. Future experiments are necessary to fully understand how unsteady flow and sediment supply interact and affect riffle-pool dynamics.

4.2. Pulse Evolution and Potential Implications for River Restoration

The relative amount of translation and dispersion that occurs as a sediment pulse evolves plays an important role in understanding and predicting the downstream effects of natural and anthropogenic changes in sediment supply. The size of the sediment pulse (relative to the channel dimensions), the Froude number of the flow, and the size of the pulse material have been shown to influence how sediment pulses evolve [*Lisle et al*., 1997; *Cui et al*., 2003a; *Lisle*, 2008]. Natural episodic sediment inputs due to hillslope failures, landslides, debris flows, or similar phenomena can supply enough sediment to the channel to create a temporary dam, which enhances dispersion (rather than translation) of the sediment pulse because as the downstream face of the sediment pulse is eroded and transported downstream, sediment supplied from upstream is caught in the backwater effect caused by the pulse material and deposits on the upstream end of the pulse. Flume experiments conducted in near-critical flows with high Froude numbers, in which large sediment pulses (relative to the flow depth) are supplied to channels with an upstream sediment supply, have shown that dispersion is by far the dominant progression process for these conditions [*Lisle et al*., 1997; *Cui et al*., 2003a; *Lisle*, 2008]. In contrast, experiments with lower Froude numbers and no upstream sediment supply, where the pulse is small relative to the depth, have documented a significant translational component of pulse evolution, particularly for pulses composed of material finer than the bed surface [*Sklar et al*., 2009; *Humphries et al*., 2012]. These conditions are more representative of those associated with gravel augmentation river restoration practices.

Run 5 of our experiment represents an extension of these latter experiments. The average Froude number during Run 5 (0.64) was slightly lower than those in the experiments of *Sklar et al*. [2009], and the scaling of the pulse size and pulse feed rate was similar to that in the *Sklar et al*. [2009] experiments. Although the conditions of our experiment seem to have been set up to favor pulse translation (low Froude number, a small pulse composed of sediment that is finer than the bed material, with no upstream sediment supply), the pulse evolution was dispersion-dominated, more so than any of the experiments reported in *Sklar et al*. [2009]. Although we cannot directly quantify the influence of variable width on the pulse evolution in our experiment, we suspect that the width variation tended to enhance the relative dispersion of the sediment pulse, and we are designing additional experiments to verify this hypothesis.

Gravel augmentations are generally designed to improve spawning and rearing habitat by fining the bed, either by burying the coarse bed with a desired grain size [*Bunte*, 2004; *Harvey et al*., 2005] or by mobilizing the coarse bed surface to reveal finer subsurface material below [*Venditti et al*., 2010b]. Dispersion is likely to be favored when the bed material is too coarse to be mobilized, when the subsurface sediment is not appropriate for habitat, or when increased sediment supply downstream is likely to be detrimental to ecosystems or increases flood risk [*Sklar et al*., 2009; *Humphries et al*., 2012]. Pulse translation is likely to be preferred when channel access is limited or when it is desirable for the effects of gravel augmentation to be felt over a long downstream reach. Our results from Run 5 suggest that channel width variations associated with riffle-pool topography may enhance the dispersion of sediment added to the channel in gravel augmentations.

The dominance of dispersion in our experimental pulse was probably influenced by feedbacks between the irregular channel boundary and the flow field. Downstream variations in channel width induce local convective accelerations, which lead to spatial variations in sediment transport and the development of riffles and pools. Local backwater effects due to width and depth variations, and eddies in local expansions, likely trapped some of the pulse material locally and limited its overall magnitude as it spread downstream, causing it to evolve in a highly dispersive manner. This idea is supported by recent work by *Maturana et al*. [2013], who suggested that prepulse stream topography may enhance the importance of dispersion of sediment pulse material. Our observations are consistent with *Lisle et al*.'s [2001] conclusion that persistent sediment wave migration does not commonly occur in gravel-bed rivers, which inherently experience width variations and are consequently more likely to exhibit dispersion dominance.

The persistence of the riffles and pools in our experiments, regardless of the sediment supply, is potentially informative for channel design in river restoration, where these features may be desired for ecological benefit [e.g., *Brookes and Sear*, 1996; *Wade et al*., 2002; *Rhoads et al*., 2008]. The "biological drift" of macroinvertebrates dislodged from coarse riffle substrate into the flow makes these areas critical feeding habitat for larger predators [*Allan and Castillo*, 2007]. Pools provide deep, slow moving water that protects fish from predation and creates a refuge that requires minimal energy expenditure. Our results suggest that for channels that do not experience large overbank flows or much variation in discharge, which may be expected downstream of a dam where restoration is more likely to be needed, channel design that explicitly includes forced width variation can encourage the development of persistent riffle and pool features.

5. Conclusions

We conducted a series of flume experiments to explore how a channel with downstream variations in width responds to changes in sediment supply. Channel width can be a primary control on the development of pools, which formed in narrow portions of the channel, and riffles, which formed in wide parts of the channel. Changes in sediment supply were mainly accommodated through adjustment to the channel slope, and the location of and relief between pools and riffles persisted regardless of the sediment supply. Pools in our experiment did not fill in during high-supply runs, which suggests that unsteady flow and fine material in the supplied sediment may be necessary for pools in natural channels to fill in under conditions of high sediment supply. The addition of a gravel augmentation sediment pulse to the channel led to a transient response where the pulse material evolved primarily through dispersion rather than translation. While prior experimental studies simulating gravel augmentation below dams have suggested that small, fine-material pulses like this are likely to exhibit a component of translation when Froude numbers are low, the largely dispersive evolution of the sediment pulse in our experiment suggests that downstream variation in channel width and riffle-pool topography may have enhanced dispersion of the sediment pulse. Our experiments point to the important role that width variations play in the morphodynamics of gravel-bed rivers, and suggest that further research is needed to better understand how the magnitude of these width variations, along with unsteady flow effects, influence bed morphology and sediment pulse dynamics.

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