

Sediment pulses in mountain rivers:

1. Experiments

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[1] Sediment often enters rivers in discrete pulses associated with landslides and debris flows. This is particularly so in the case of mountain streams. The topographic disturbance created on the bed of a stream by a single pulse must be gradually eliminated if the river is to maintain its morphological integrity. Two mechanisms for elimination have been identified: translation and dispersion. According to the first of these, the topographic high translates downstream. According to the second of these, it gradually diffuses away. In any given river both mechanisms may operate. This paper is devoted to a description of three controlled experiments on sediment pulses designed to model conditions in mountain streams. Each of the experiments began from the same mobile-bed equilibrium with a set rate and grain size distribution of sediment feed. In one experiment the median size of the pulse material was nearly identical to that of the feed sediment. In the other two the pulse material differed in grain size distribution from the feed sediment, being coarser in one case and finer in the other case. In all cases the mode of pulse deformation was found to be predominantly dispersive, a result that constitutes the main conclusion of this paper. The pulses resulted in a notable but transient elevation of sediment transport rate immediately downstream. When the pulse was coarser than the ambient sediment, the bed downstream remained armored, and a migrating delta formed in the backwater upstream. When the pulse was finer than the ambient sediment, translation was observed in addition to dispersion. The presence of the finer material notably elevated the transport of ambient coarse material on the bed downstream. In part 2 [Cui *et al.*, 2003], the experimental results are used to test a numerical model. **INDEX TERMS:** 1803 Hydrology: Anthropogenic effects; 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); **KEYWORDS:** sediment transport, sediment pulses, sediment waves, mountain rivers

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1. Introduction

[2] In March 1995 a landslide with an estimated volume of 60,000 to 80,000 m³ ran into the Navarro River, a gravel bed mountain stream in northern California [Sutherland *et al.*, 1998; Hansler *et al.*, 1998, Sutherland *et al.*, 2002]. The landslide, shown in Figure 1, created a pulse input of sediment that temporarily blocked the river before being overtopped. Such pulse-like inputs are particularly common in mountain streams, which can receive them in the form of landslides or debris flows. While such events occur under purely natural conditions, their frequency and magnitude can be augmented by such anthropogenic factors as mining,

timber harvest and road building. How do rivers accommodate such sudden sediment inputs without losing their morphological integrity? Do they move downstream as identifiable sediment waves or instead gradually disperse away?

[3] Early literature on the subject may have been strongly influenced by the seminal paper by Gilbert [1917], who studied the effects of sediment produced by hydraulic mining on the American and Sacramento Rivers and their tributaries in California. His conclusions regarding pulse behavior suggest that pulses form downstream translating sediment waves: "The downstream movement of the great body of debris is thus analogous to the downstream movement of a great body of storm water, the apex of the flood traveling in the direction of the current."

[4] Benda and Dunne [1997] have developed a numerical model that predicts downstream-translating sediment waves. They acknowledge that dispersion may also occur, but

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Figure 1. A view of the landslide of March 1995 into the Navarro River, California. The direction of river flow is from top to bottom.

assign it a secondary role in describing the deformation of sediment pulses. Several field-oriented studies, however, have been more ambiguous in documenting significant translation [Roberts and Church, 1986; Knighton, 1989; Pitlick, 1993; Madej and Ozaki, 1996]. Here the terminology “sediment pulse” is used as a neutral term in preference to “sediment wave” or “sediment slug,” either of which may imply a translational behavior. The word “sediment pulse” is meant to encompass the full range of possible deformation, from fully dispersive to fully translational.

[5] It might be thought that a defining characteristic of bona fide translating waves is bed elevation that first rises and then falls not far downstream of the sediment input, with an analogous rise and fall occurring later at a point farther downstream, as illustrated in Figure 2. This is, however, not the case. Figure 2 illustrates that the same behavior can be observed regardless of whether the pulse is undergoing pure translation, pure dispersion or some combination of the two.

[6] The difference between translation and dispersion is of some practical significance. A sediment pulse undergoing pure translation will cause damage associated with bed aggradation followed by bed degradation to propagate far down the channel. This may include channel bank erosion,

floodplain deposition and the loss of bridges, pipeline crossings and adjacent roadways. On the other hand, in the case of a purely dispersive pulse, the damage to the channel can be expected to be more localized in the vicinity (both upstream and downstream) of the point of input, with the effect of the input decaying both upstream and downstream of this point.

[7] Some clues regarding the relative roles of translation versus dispersion are offered by Ribberink and van der Sande [1985] and Gill [1988]. They studied the solution to an equation of bed evolution obtained from a linearized version of the equations of sediment, water and momentum conservation over an erodible bed subject to the quasi-steady assumption. Sediment feed is impulsively augmented at time $t = 0$ and subsequently held constant at the augmented value. It is found that the aggradation so induced has a dispersive body ending in a translational front. As time passes dispersion becomes more dominant relative to translation. Because the sediment feed continues at an augmented rate for all time $t > 0$, however, the work does not provide a definitive answer to the question of sediment pulse deformation.

[8] Perhaps the first attempt to provide an unambiguous answer to the question of translation versus dispersion is the experimental and numerical study of Lisle *et al.* [1997]. In their experiment, they first formed an equilibrium mobile-bed channel with fixed banks in a recirculating flume with a length of 160 m. They then constructed a wedge-shaped pulse with a height of 4 cm over a 20 m reach of the flume, and recommenced the flow for over 16 hours. The result was both upstream and downstream dispersion of the pulse with essentially negligible translation. Here the upstream dispersion is caused by sediment deposition upstream of the pulse as a result of the backwater effect induced by the

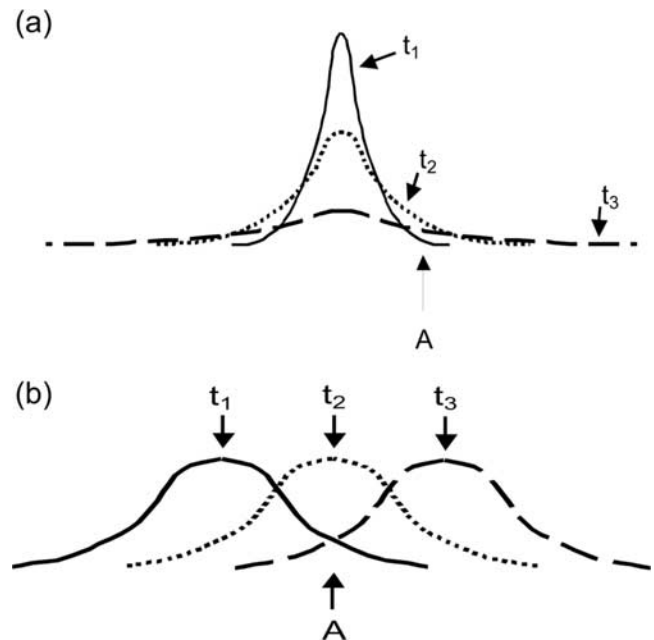


Figure 2. (a) The elevation at point A rises and then falls as the elevation profile of the sediment pulse undergoes pure diffusion. (b) The elevation at point A rises and then falls as the elevation profile of a sediment pulse undergoes pure translation from left to right.

pulse. It is important to remember that sediment feed at the prepulse rate was continued throughout the run. A fully nonlinear one-dimensional numerical model based on sediment of uniform size and the quasi-steady assumption reproduced this result. The model underlined the role of the flow Froude number Fr in determining the disposition of a sediment pulse; the higher the Froude number, the more dispersion tends to dominate translation. The value of Fr in the experiment in question was 0.90. It is useful to point out that the Froude number at flood stage in alluvial gravel bed mountain streams tends to be high, commonly ranging from 0.3 to 1.0.

[9] Inspired by the work of *Lisle et al.* [1997], *Cui and Parker* [1997] returned to the well-worn path of one-dimensional linear erodible-bed stability analysis [e.g., *de Vries*, 1965; *Gradowczyk*, 1968] to provide a more general clarification of the relative roles of translation versus dispersion for the case of spatially periodic pulses of infinitesimal height. In the absence of any lags between either shear stress and flow velocity or sediment transport rate and shear stress, such models predict that one-dimensional bed perturbations are universally stable, the decay of the pulse being caused by dispersion. They verified the essential role of the Froude number in determining the relative roles of translation versus dispersion. They furthermore found that when the pulse is long compared to the flow depth, dispersion dominates translation for all but the lowest Froude numbers.

[10] The present research represents an attempt to obtain a clearer picture of the fate of sediment pulses in mountain rivers. In particular, attention is focused on the evolution of pulses with grain size distributions that differ from that of either the bed material or the ambient bed load in the absence of pulses. In part 1, the results of a series of experiments on sediment pulses are presented. In part 2, the experimental results are compared with the numerical model of sediment pulses developed at field scale by *Cui et al.* [2003].

[11] The experiments presented in this paper pertain to straight rivers with resistant banks and are applicable only to streams that are competent to accommodate pulses of sediment. Some streams with extremely low transport capacity may not be able to rework the pulse material. By the same token, streams subjected to extremely coarse pulses, e.g., boulder-sized colluvium rolling in from the sides and blocking the channel, may not be able to rework the material. The experiments reported here do not apply to such cases.

[12] The review paper of *Lisle et al.* [2001] summarizes the sediment pulse research over the past several years and includes a brief introduction to the current work. This paper and its companion paper present the details of the experiments and the numerical simulation.

2. Experimental Setup and Procedure

[13] The experimental channel was built at St. Anthony Falls Laboratory expressly for the purpose of studying sediment pulses in mountain streams. The requirements of the study were as follows. The channel should be sufficiently long to allow for documentation of the downstream (and upstream) evolution of pulses. The channel should be sufficiently wide to allow for the formation of the alternate

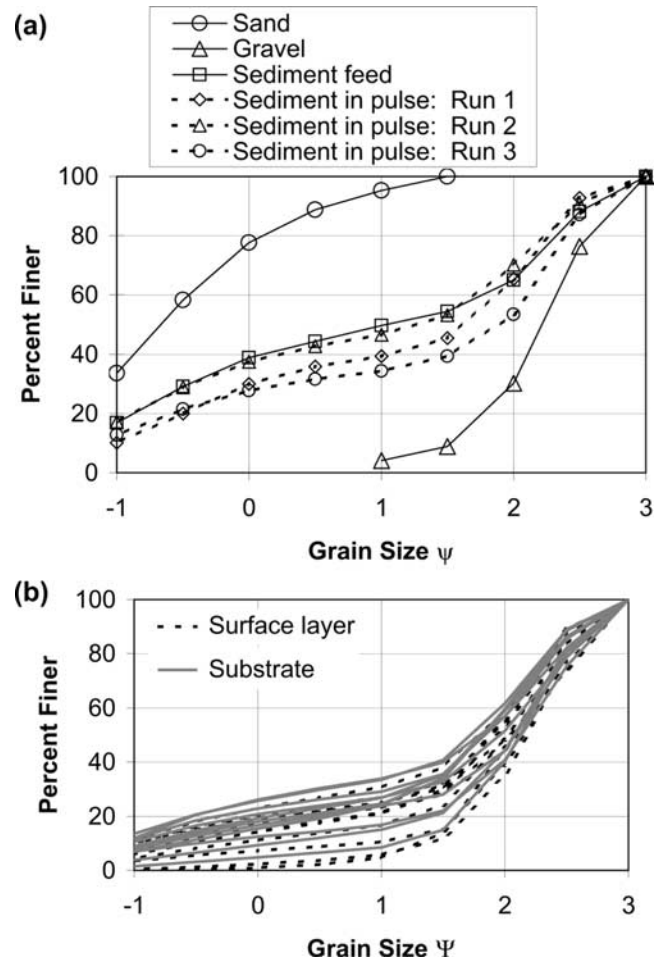


Figure 3. (a) Grain size distributions used in the experiment. The sediment in the pulses of runs 4a and 4b were identical to the “Sand” in the figure. (b) Grain size distributions in prepulse surface and substrate.

bars commonly observed in single-thread mountain gravel bed streams [e.g., *Colombini et al.*, 1987]. Finally, the channel should allow for the establishment of a definable and repeatable mobile-bed equilibrium in the absence of pulses.

[14] The channel is 45 m long, 0.5 m wide and 0.70 m deep. Water discharge is controlled at the upstream end by means of a valve and a manometer; sediment is introduced using a screw feeder. Water and sediment are allowed to flow freely out of the downstream end of the flume.

[15] In order to perform the experiments the following procedure was adopted. (1) The flume was allowed to reach a prepulse mobile-bed equilibrium. (2) The flow was temporarily halted to allow for a pulse of sediment to be installed toward the upstream end of the flume. (3) The flow was then recommenced, and the flume allowed to reequilibrate over time as the sediment pulse deformed. Five runs, runs 1, 2, 3, 4a and 4b were conducted in this way.

[16] The flume bed was nonerodible concrete. The flume was filled with sediment by allowing the sediment to gradually prograde downstream. The grain size distribution of the sediment used to fill the flume is labeled “Gravel” in Figure 3. It consisted of pea gravel ranging from 2 to 8 mm, with a small

admixture of sand, and had a median size near 4.6 mm. This gravel was used only as a convenient filler to establish the flume bed. Note that the parameter ψ in Figure 3 is a logarithmic grain size related to grain size D in mm as

$$D = 2^\psi \quad (1a)$$

The logarithmic grain size ψ is related to the more familiar ϕ scale as follows;

$$\phi = -\psi \quad (1b)$$

[17] The grain size distribution of the sediment feed used to establish the prepulse mobile-bed equilibrium was finer than that used to fill the flume. It consisted of a mixture of sediments with the “Gravel” and “Sand” size distributions shown in Figure 3a. Grain size ranged from under 0.5 mm to 8 mm, with a median size D_{f50} of 2.0 mm and a geometric mean size near 1.7 mm. This gravel-sand mixture was fed in for 170 hours in order to establish a prepulse mobile-bed equilibrium, allowing for copious amounts of sand to work its way into the substrate. The bed established under mobile-bed equilibrium conditions was mildly armored, with a median surface size of 3.14 mm and a median substrate size of 2.85 mm. The armoring was self-formed and in no way imposed experimentally. The substrate was found to be somewhat coarser than the sediment load. This may be partially due to the fact that the initial bed sediment was also somewhat coarser than the sediment load. It may also be partially associated with the self-evolution of the surface and substrate to equilibrium [Lisle, 1995]. The run 2 prepulse surface and subsurface grain size distributions are shown in Figure 3b.

[18] The use of a sediment feed that is half sand and contains gravel sizes only up to 8 mm does not necessarily provide the best model of a gravel bed river. This limitation was, however, necessitated by the experimental facility available to the authors.

[19] Three kinds of sediment were used to form pulses. In runs 1 and 2, the grain size distribution of the pulse was essentially identical to that of the feed sediment. The sediment pulse of run 3 was coarser than the feed sediment, as shown in Figure 3. The sediment pulses of runs 4a and 4b were formed solely from the “Sand” of Figure 3, and thus were finer than the feed. Here the grain size distribution of the pulse is compared to that of the feed sediment associated with the prepulse mobile-bed equilibrium rather than that of the equilibrium bed itself. This is because the prepulse equilibrium bed was characterized by a mobile-bed armor, such that the surface was coarser than the substrate. Feed sediment size distribution, then, becomes the distribution over which the experimenter has direct control.

[20] Prepulse conditions were established using a water discharge Q_w of 9 liters/s and a sediment feed rate G_s of 45 g/min. The channel was allowed to equilibrate for around 170 hours at these conditions before the first experiment was performed. The equilibrium bed slope S was found to average to 0.0108, and the equilibrium flow depth H averaged to 0.0325 m. Mean flow velocity U was thus 0.55 m/s, and the prepulse equilibrium Froude number Fr , given by the relation

$$Fr = \frac{U}{\sqrt{gH}} \quad (2)$$

Table 1. Scale-up of Model Parameters Based on a Scale Ratio of 1:80

Parameter	Units	Model	Prototype
S		0.0108	0.0108
B	m	0.5	40
H	m	0.0325	2.6
D_{f50}	mm	2	160
Q_w	m ³ /s	0.009	515

took the value 0.98. The equilibrium bed was characterized by three pairs of well developed alternate bars downstream of a development zone extending about 10 m downstream of the feed point. The bed was mildly armored, as outlined below. The dominant mode of sediment transport was bed load, although some suspension of the finer sand was also observed.

[21] The equilibrium conditions so established were loosely modeled after mountain gravel bed streams in northwestern California such as Redwood Creek and the Navarro River, where sediment loads are high, landslides entering channels are common, and bed load pulses have been documented [e.g., Madej and Ozaki, 1996; Sutherland et al., 1998; Hansler et al., 1998]. It needs to be clarified, however, that the equilibrium slope in the experiment is higher than the slopes normally found in the aforementioned gravel bed rivers (e.g., Redwood Creek or the Navarro River) due to the difficulty in creating a lower slope without using lighter material (e.g., walnut shell and coal) or working at a larger scale in a flume experiment. Gravel bed mountain streams with slopes of about 0.01 are, however, common in the field [e.g., Parker and Toro-Escobar, 2002]. The undistorted Froude scale-up of the model parameters with a sample scale ratio of 1:80 shown in Table 1 provides an indication of the type of field sub-bankfull to bankfull conditions that are represented by the experimental equilibrium.

[22] The sediment pulse of each run was emplaced by hand. In the case of runs 1, 2 and 3 the pulse was placed over a length of 7.5 m starting 8 m from the sediment feed point. In the case of runs 4a and 4b the pulse started at 6.8 m from the sediment feed point and had a length of 7.4 m. The upstream and downstream ends of the pulse were tapered to join smoothly with the ambient bed. The average initial pulse height was 2 cm in the case of run 1 and 3.5 cm in all subsequent runs.

[23] The observational technique used to study pulse deformation evolved with the experiments. In most experiments bed elevation was monitored by a crew of seven people using marked rulers. Each person recorded the lateral position and elevation of 3–6 points on a cross section, and then moved downstream two more times in 3-ft increments and repeated the measurements. In this way data for 21 cross sections could be obtained rapidly. These measurements were repeated frequently (i.e., in intervals of minutes) shortly after the commencement of a run, and then done with less frequency (i.e., in intervals of hours) as time passed.

[24] Sediment load was measured with uncalibrated samplers, each with a 2.5 cm square opening at the upstream end and a mesh basket at the back. Although the samplers were placed on the bed of the channel and collected mostly

bed load, some of the finer sand traveling in suspension was also captured by the samplers. In most cases two measurements were taken on each cross section. Sampling was performed opportunistically, judging by eye how to position the samplers and how long to keep them in to obtain a representative sample. Neither the measurements of bed elevation nor load were observed to have a notably intrusive effect on the flow and bed.

[25] A complete photographic record of bed evolution was taken during and at the end of each run. Between runs, the channel was allowed to reequilibrate for 48–72 hours. The flow was periodically turned off during each run to allow for sampling of the bed surface and substrate. The surface was sampled by removing the grains exposed on the surface, as well as smaller grains in their interstices, with a spoon. The substrate was similarly sampled with a spoon, but the layer sampled was several grains thick. The surface and substrate sediment was also sampled at the end of each run.

3. Overview of the Experiments

[26] Of the five experiments performed, detailed results are reported here only for runs 2, 3 and 4b. In the case of run 1, the initial pulse was so low in height that its evolution was difficult to measure. Run 2 was essentially identical to run 1, but with a higher initial pulse height. Run 4a was a trial run to test conditions for studying the evolution of a pulse consisting purely of sand. No data were taken for this run. Run 4b was essentially identical to run 4a.

[27] Runs 2, 3, and 4b were organized to allow for a study of the effect of pulse grain size distribution, and in particular the ratio D_{p50}/D_{f50} of pulse median size to feed median size on pulse deformation.

[28] 1. In run 2, the median size of the sediment in the pulse D_{p50} was nearly identical to that of the feed D_{f50} , i.e., 2.0 mm. Thus $D_{p50}/D_{f50} = 1.1$, allowing for study of a pulse with the same size distribution as the feed sediment. The pulse introduced for run 2 had a geometric mean grain size of 1.83 mm. The average prepulse surface and substrate geometric mean grain size for run 2 were 3.14 mm and 2.85 mm, respectively. Thus the pulse sediment was finer than both the surface and subsurface.

[29] 2. In run 3, the pulse sediment median size was 3.8 mm, and D_{p50}/D_{f50} was 1.9, so that the pulse was significantly coarser than the ambient sediment. The pulse introduced to run 3 had a geometric mean grain size of 3.05 mm. The average prepulse surface and substrate geometric mean grain size for run 3 were 3.43 mm and 2.58 mm, respectively. Thus the pulse sediment was finer than prepulse surface and coarser than prepulse substrate. This experiment loosely modeled the effect of the scree from a coarse landslide entering the river.

[30] 3. In run 4b, D_{p50}/D_{f50} was 0.31, so that the pulse was significantly finer than the feed sediment. Prepulse surface and subsurface sediment were similar to that of runs 2 and 3, and thus the pulse sediment was much finer than both the prepulse surface and subsurface sediment. This experiment loosely modeled the effect of a fine-grained debris flow entering from, for example, a steeper tributary.

[31] In runs 2, 3, and 4b the initial pulse height was 3.5 cm, as compared to an average flow depth of 3.25 cm. As a result, the pulse initially acted to partially block the flow, creating a backwater zone of reduced shear stress

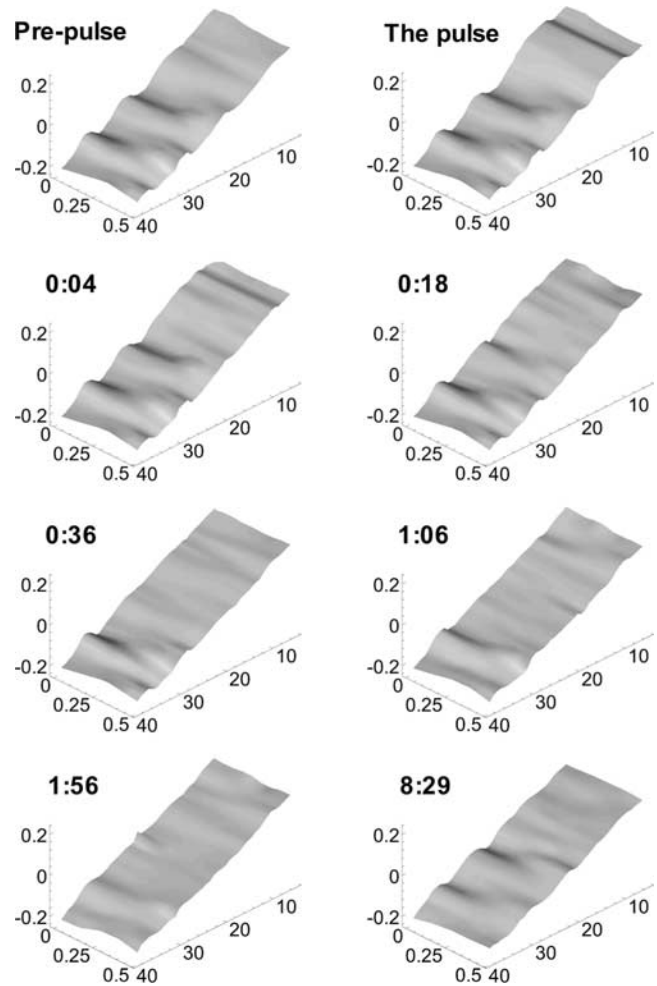


Figure 4. Three-dimensional plots of bed elevation for run 2 at various times given in (hour:min).

immediately upstream and a zone of accelerated slope, flow velocity and shear stress immediately downstream. This flow pattern is intimately connected to the subsequent evolution of the pulse, as described in more detail in the part 2.

4. Experimental Results

4.1. Run 2

[32] Three-dimensional plots of bed elevation are shown in Figure 4 for the prepulse equilibrium, just after pulse emplacement, and the following times after run commencement, the number to the left of the colon denoting hours and the number to the right denoting minutes; 0:04, 0:18; 0:36, 1:06, 1:56 and 8:29 hours. The pattern of alternate bars at prepulse equilibrium is readily apparent. The effect of the pulse was to gradually obliterate the surface expression of alternate bars, the process propagating downstream in time. By 1:56 hours, alternate bars had disappeared everywhere except at the distal end of the measuring reach. By 8:29 hours, the effect of the pulse had passed and the alternate bars were well on the way to reestablishment.

[33] Figure 5 shows the long profiles of cross-sectionally averaged bed elevation. Included are the ambient bed just before pulse emplacement, that of the initial pulse itself and

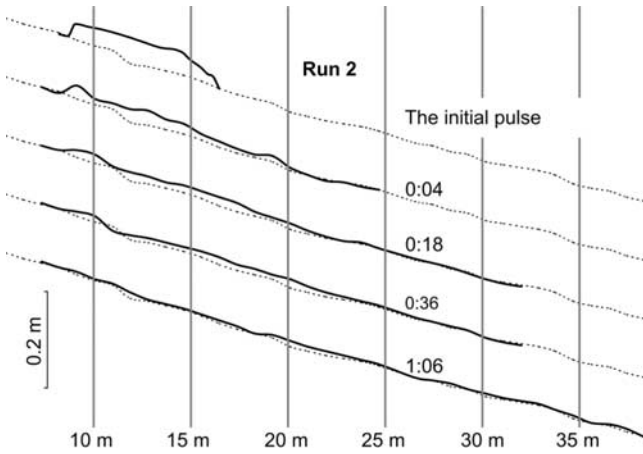


Figure 5. Long profiles of cross-sectionally averaged bed elevation for run 2 at various times. The times are in (hour:min).

the bed at 0:04 hours, 0:18 hours, 0:36 hours and 1:06 hours. Figure 5 documents the pulse as it is dissipated. The topographic expression of the pulse was negligible after 1:06 hours. While some tendency for translation can be observed in Figure 5, dispersion is clearly the dominant process.

[34] Figure 6 documents the measured cross-sectionally averaged sediment transport rate in g/min as a function of time and space. It should be recalled that the sediment samplers were uncalibrated, so that the measured values should be interpreted as order-of-magnitude estimates. This notwithstanding, the effect of the pulse on sediment transport rates was so strong that transport rate is plotted on a logarithmic scale in Figure 6. By 0:05 hours, the peak sediment transport rates, which were observed over the downstream half of the initial position of the pulse, were elevated over 15 times the feed rate (which remained equal to the ambient prepulse sediment feed rate). At 0:27 hours, the transport rate peaked at over 2000 g/min, or over 40 times the feed rate. As time passed the magnitude of peak transport rate declined, and the corresponding location shifted downstream, so that by 1:46 hours the peak transport

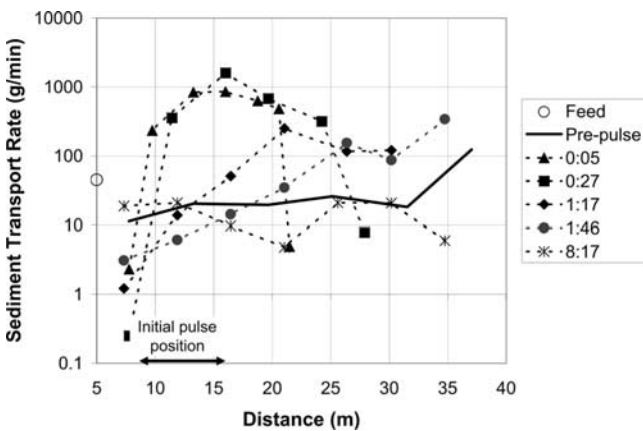


Figure 6. Sediment transport rates as functions of distance and time for run 2.

rate was only about 200 g/min, realized 11 m downstream of the downstream end of the initial pulse. By 8:14 hours transport rates had returned to near the prepulse values. It is also worth noting that the sediment transport rate immediately upstream of the pulse decreased by 1 to 2 orders of magnitude due to the backwater effect created by the introduction of the pulse. The sediment transport rate gradually recovered to the prepulse value as the magnitude of the pulse decreased and the backwater effect disappeared in time.

[35] Figures 5 and 6 illustrate an important point concerning pulse evolution. While the evolution of the elevation profile of the pulse itself is essentially dispersive rather than translational, the evolution of the sediment transport rate associated with that pulse shows stronger evidence of translation.

[36] Figure 7a shows the time and space variation of the arithmetic mean sizes on the Ψ scale, i.e., Ψ_m of the surface material; the corresponding variation for the substrate is shown in Figure 7b. It is obvious from Figures 7a and 7b that the introduced pulse sediment was finer than both the prepulse surface and substrate sediment. The geometric mean size D_g is obtained from the relation

$$D_g = 2^{\Psi_m} \quad (3)$$

[37] By 0:36 hours, the surface layer is seen to become significantly finer than the prepulse surface over a reach extending from the upstream end of the initial pulse position to about 10 m downstream of the downstream end of the initial pulse position. By 1:56 hours this surface fining has

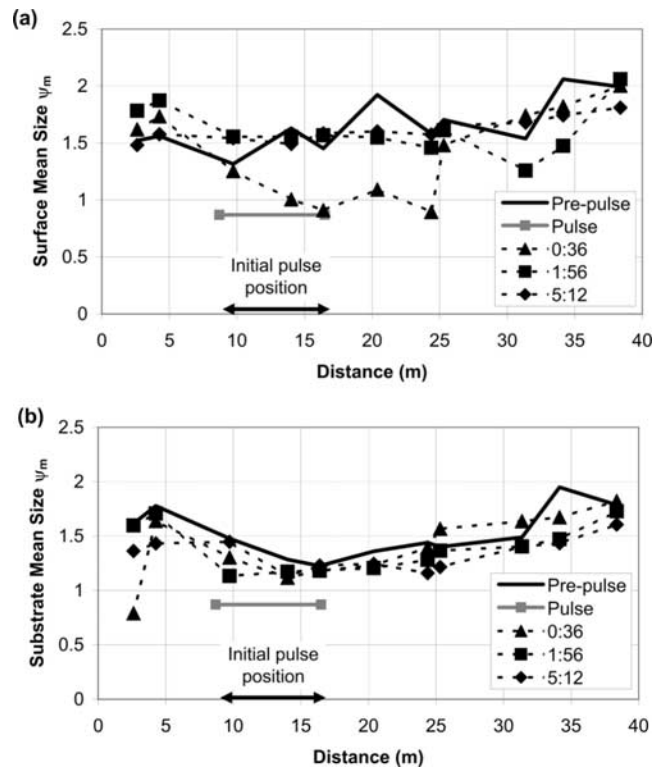


Figure 7. (a) Mean surface grain sizes for run 2. The times are in (hour:min). (b) Mean substrate grain sizes for run 2. The times are in (hour:min).

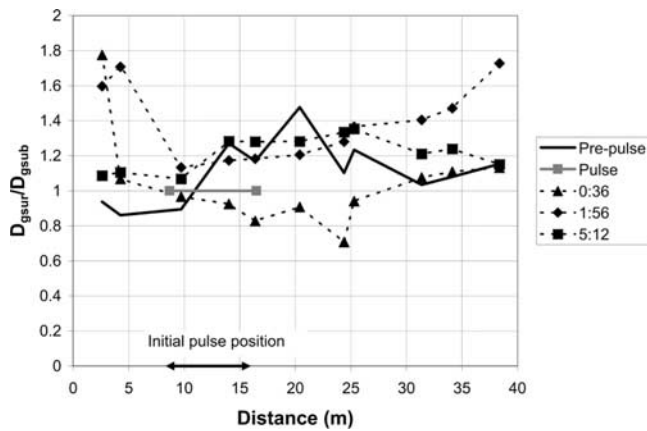


Figure 8. Ratio of surface geometric mean size to substrate geometric mean size for run 2. The times are in (hour:min).

become weaker and moved downstream. By 5:12 hours the surface has returned to its prepulse state. Figure 7b shows very little tendency for the substrate to become finer in response to the sediment pulse, the variations therein being within the error of the sampling. This is likely to be at least partially due to the fact that the pulse size distribution was identical to that of the feed.

[38] Figure 8 shows the evolution of the ratio D_{gsur}/D_{gsub} of the geometric mean size of the surface to that of the substrate. The prepulse bed is seen to have been mildly armored everywhere except at the extreme upstream end of the measuring reach, with the ratio typically in the range 1.1 to 1.5. Figure 8 documents a substantial fining of the surface layer by 0:36 hours, especially in the 10 m reach downstream of the downstream end of the initial pulse. At this time, the surface was finer than the substrate for most of the length of the measuring reach. That is, the armor had been eliminated either by destruction or burial. The armor had essentially recovered by 1:56 hours.

[39] Although not presented here for reasons of space, measurements of the geometric mean grain size of the measured sediment load showed prepulse values in the range 2.3–3.5 mm. These values declined substantially in the early stages of the run, with values in the range 1.9–2.1 mm at 1:46 hours. They eventually recovered as the run progressed.

4.2. Run 3

[40] As noted above, in this case the pulse sediment was substantially coarser than the feed sediment. The three-dimensional plots of bed elevation of Figure 9 document a tendency for the alternate bars to be subdued by the pulse, but the effect was considerably weaker than in run 2, and only extends about halfway down the measuring reach. The long profiles of cross-sectionally averaged bed elevation document the same essentially dispersive pattern as for run 2, with only weak translation. Whereas the topographic expression of the pulse took about an hour to dissipate in the case of run 2, it was still clearly evident after 7 hours in run 3. Evidently the relative immobility of the coarser material in the pulse slowed down its rate of dissipation.

[41] The pulse of run 3 deformed sufficiently slowly that it created substantial backwater upstream. This led to the

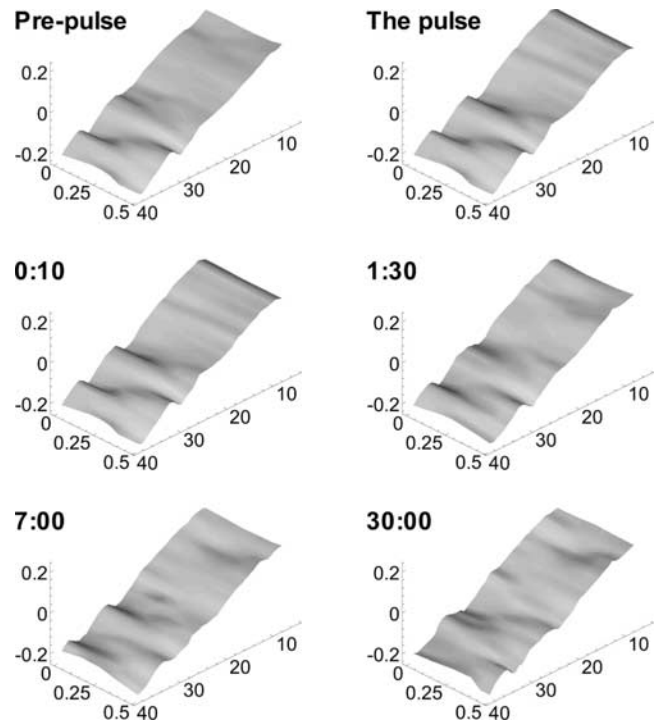


Figure 9. Three-dimensional plots of bed elevation for run 3 at various times given in (hour:min).

formation of a pool of slack water dammed by the pulse. At the upstream end of the pool, a delta formed from the ambient sediment feed and gradually migrated downstream. It can be seen at the far upstream end of the measuring reach at 7:00 hours in Figure 10. Figure 11 is a photograph of the sandy delta front. The front eventually merged with the main pulse and dissipated with it.

[42] Even this coarse pulse was associated with a substantial transient increase in bed load rate, as documented in Figure 12. The increase, however, is relatively short-lived, with only modestly elevated rates being realized by 1:05 hours. The highest recorded transport rate, about

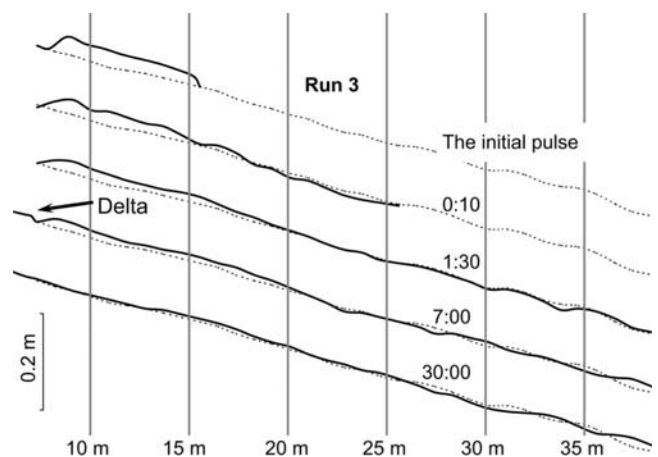


Figure 10. Long profiles of cross-sectionally averaged bed elevation for run 3 at various times. The times are in (hour:min).



Figure 11. View looking upstream at the delta of run 3. Channel width is 0.5 m.

18 times the ambient rate, was realized at 0:02 hours immediately downstream of the pulse. The high transport rate there was evidently associated with the increased energy slope as the water flowed off the pulse and on to the ambient bed downstream. Note that the sediment transport rate vanishes at the upstream end of the pulse due to the backwater there.

[43] The temporal and spatial variations of the arithmetic mean sizes Ψ_m of the surface and substrate are documented in Figures 13a and 13b, respectively. The pulse sediment is seen to be slightly coarser than the prepulse surface sediment and substantially coarser than the prepulse substrate. The prepulse bed was slightly more armored than the prepulse condition for run 2, possibly due to fine sediment infiltration into the substrate during run 2. The surface is seen to be noticeably coarser than the substrate throughout the experiment, neither showing much tendency to change

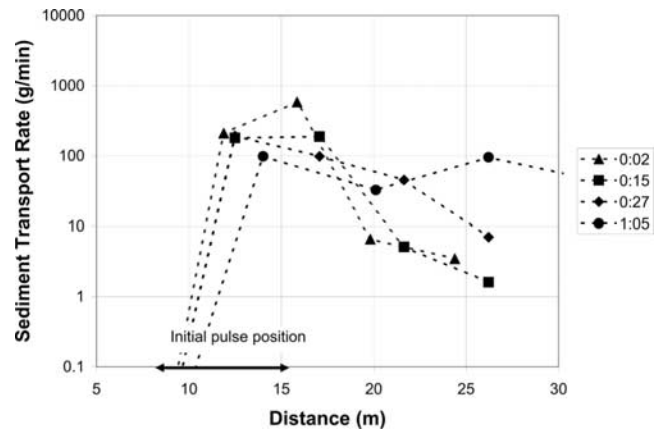


Figure 12. Sediment transport rates as functions of distance and time for run 3. The times are in (hour:min).

as the pulse dispersed. The variation in Figures 13a and 13b is within the error of the sampling.

4.3. Run 4b

[44] The evolution of this run, for which the pulse was composed entirely of sand, was very rapid. The three-dimensional plots of bed elevation are given in Figure 14. By 0:28 hours, the alternate bars had been completely buried. Figure 14 shows evidence of reappearance of the bars by 1:00 hours; this was confirmed by direct observation. Although not shown in Figure 14, the bars became progressively better defined as the sand worked its way out

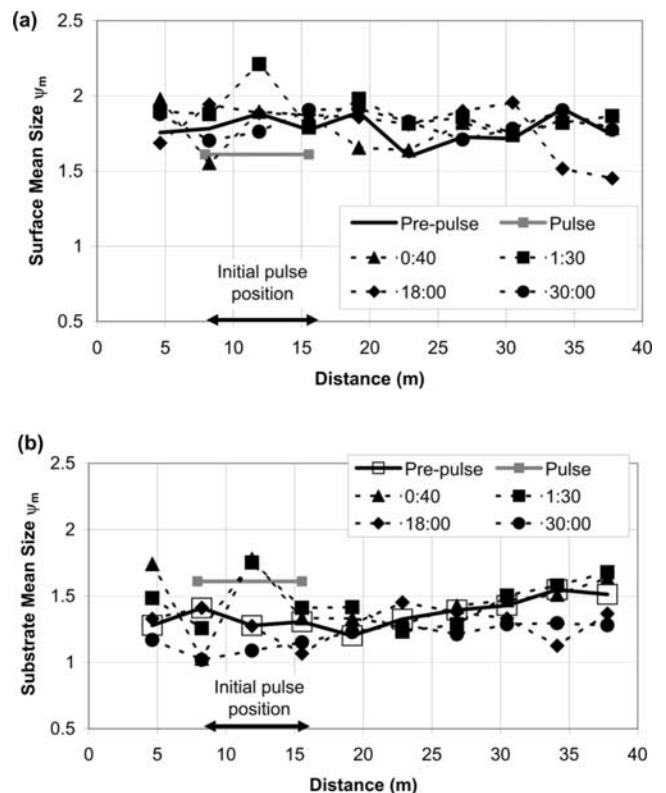


Figure 13. (a) Mean surface grain sizes for run 3. The times are in (hour:min). (b) Mean substrate grain sizes for run 3. The times are in (hour:min).

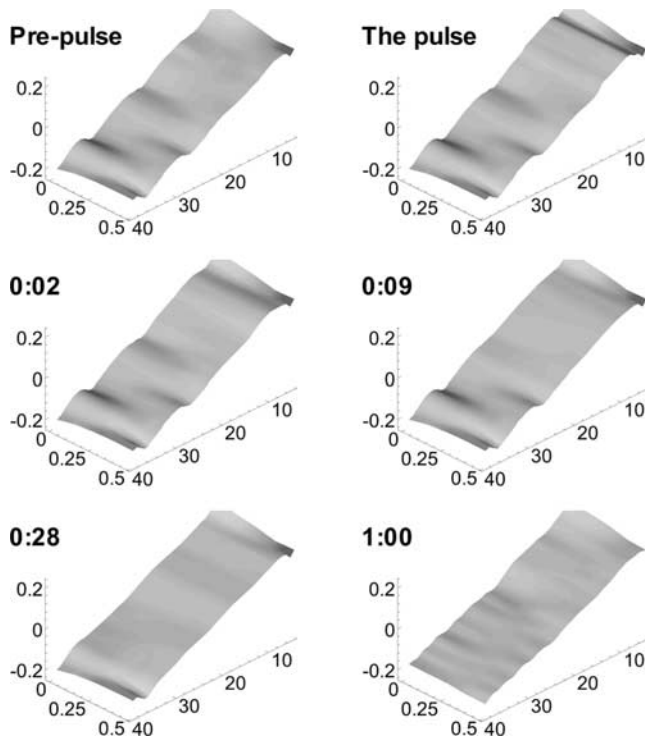


Figure 14. Three-dimensional plots of bed elevation for run 4b at various times given in (hour:min).

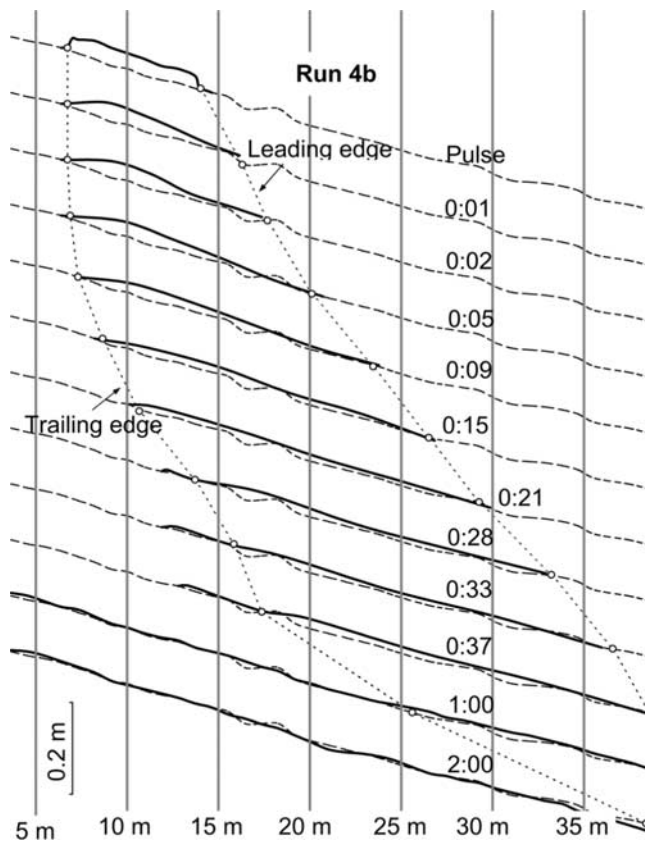


Figure 15. Long profiles of cross-sectionally averaged bed elevation for run 4b, showing the positions of the leading and trailing edges of the pulse. The times are in (hour:min).

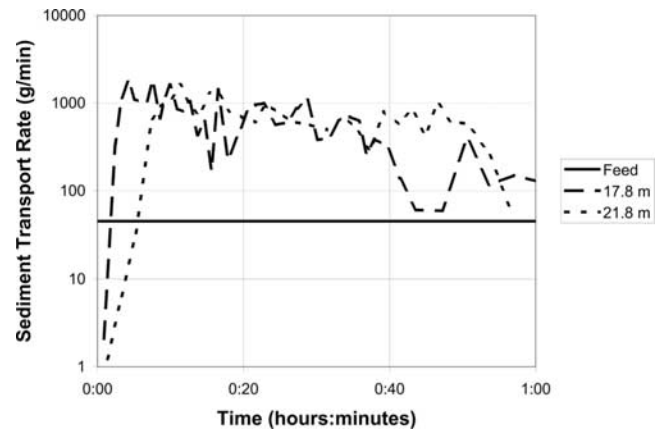


Figure 16. Plots of sediment transport rate against time for two stations in run 4b.

of the system. The long profiles of cross-sectionally averaged bed elevation of Figure 15 differ notably from those of runs 2 and 3 in that they document translation of the sand pulse. In particular, for at least the first hour of the run, the deforming pulse had a clearly defined leading and trailing edge, both gradually migrating downstream. For most of the run, the leading edge migrated downstream more rapidly than the trailing edge, indicating that translation was also accompanied by fairly strong dispersion.

[45] Figure 16 shows sediment transport rates as functions of time for two stations, one 3.6 m downstream of the downstream end of the initial pulse (17.8 m from the feed point) and the other 7.6 m downstream of the downstream end of the initial pulse (21.8 m from the feed point). At a point 3.6 m downstream of the downstream end of the initial pulse, sediment transport rates were elevated to over 1000 g/min within minutes after commencement of the run. They then decayed to values not far above the background value by 1:00 hours. Note that the sediment transport rate both peaked and then dropped off earlier at the upstream station than the downstream station.

[46] Figure 17 shows the percentage of sand in the load as a function of time for the same two stations as in Figure 16. Note that 50% of the ambient sediment feed was sand. This fraction quickly rose to above 90% in the first few minute-

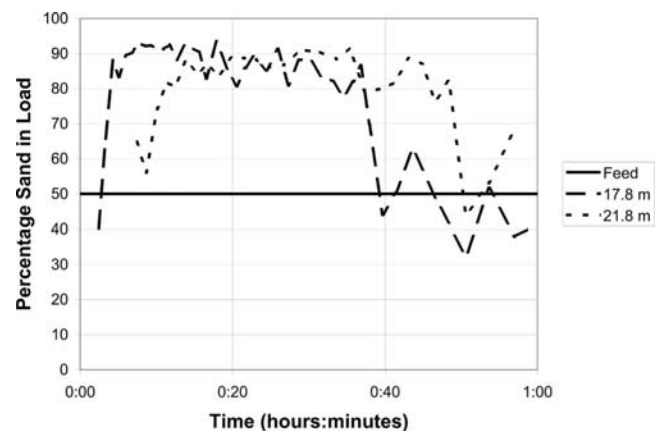


Figure 17. Plot of the percentage of sand in the load with time for two stations in run 4b.

sof the run, and then gradually decayed to near-ambient values by 1:00 hours. As was the case in Figure 16, the response of the downstream station lagged behind the upstream station.

[47] Figure 18 shows the mean grain size of the bed load Ψ_m on the Ψ scale as a function of time for the same two stations as in Figures 16 and 17. The arrival of the pulse is marked by a rapid, pronounced drop in Ψ_m from the gravel range to the sand range. This is followed by a much slower recovery back to the gravel range. The same pattern is displayed at both stations, but the response of the downstream station lags that of the upstream station in time.

[48] In Figure 19, sand and gravel transport rates measured 3.6 m downstream of the downstream end of the initial pulse (17.8 m from the feed point) are plotted as multiples of the corresponding ambient feed rates (22.5 g/min in both cases) for the first hour of the run. The extremely high transport rates of sand in the first 10 min of the run, i.e., as high as 75 times the sand feed rate, can be interpreted in terms of the high mobility of sand placed over a much coarser bed. The very high rates of gravel transport over the same period, i.e., as high as 18 times the gravel feed rate, however, require another explanation in that there was no gravel in the initial pulse. The initial peak in gravel transport rate apparent in Figure 19 is probably partially associated with the increased bed slope at the downstream end of the initial pulse, which likely increased the bed shear stress immediately downstream. This elevation signal is seen, however, to all but disappear by 21 min after run commencement, as seen from Figure 15. This notwithstanding, the gravel transport rate remains elevated above the feed rate by an average factor of five during the period from 20 to 40 min after run commencement. The experiment thus provides dramatic direct evidence that the addition of sand in amounts that are insufficient to completely bury the gravel can substantially increase gravel mobility for a period. Wilcock [1998] has reached the same conclusion in this regard via less direct evidence.

5. Interpretation of the Results

5.1. Run 2

[49] The grain size distribution of the pulse was essentially the same as that of the sediment feed and finer than

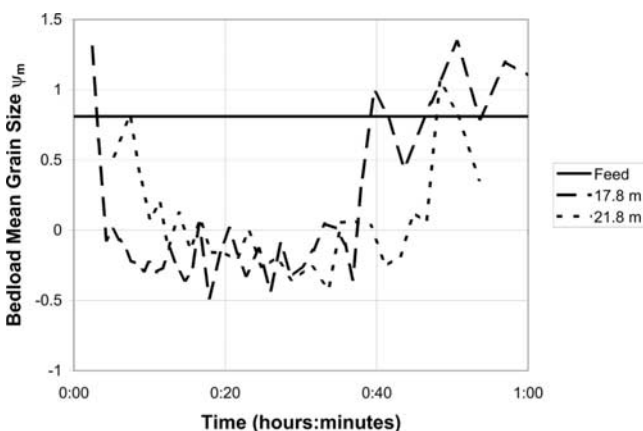


Figure 18. Plot of the arithmetic mean grain size of the bed load on the Ψ scale against time for two stations in run 4b.

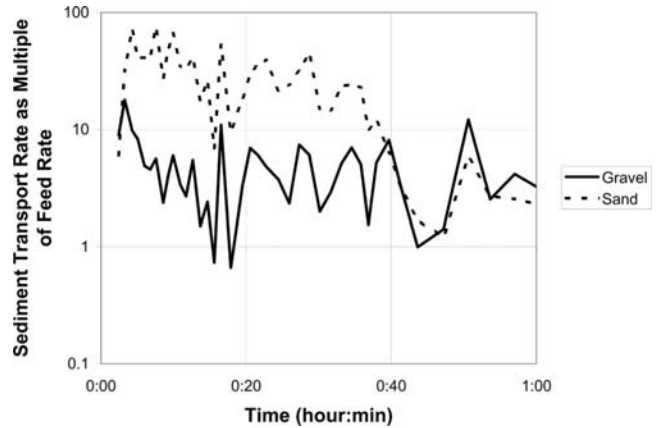


Figure 19. Plots of gravel and sand transport rates as multiples of the respective feed rates versus time for a station in run 4b.

both prepulse surface and substrate. The pulse was initially emplaced in an unarmored state, whereas the ambient bed was mildly armored. The experiment illustrates the effect of the armor in moderating sediment transport rates. The pulse initially buried the armor, at one point rendering the surface finer than the substrate over a substantial length of the channel. As it did this it tended to fill the pools of the alternate bar structure and thus eliminate the expression of bars. The presence of large amounts of fine material on the surface greatly increased the sediment transport rate over the pulse and up to 10 m downstream. It evidently rendered even the coarser surface particles more mobile than in the prepulse state. The essential mode of pulse deformation was strongly dispersive, showing no obvious evidence of translation. The topographic expression of the pulse was negligible after one hour. The sediment transport rates, surface armor and alternate bar pattern took longer to recover, but by 8 hours the state of the channel was close to the prepulse state.

5.2. Run 3

[50] Even though it was emplaced in an unarmored state, the coarseness of the pulse prevented the destruction of the armor layer. A tendency to flatten out the alternate bars was observed, but it was weaker and did not extend as far downstream as run 2. A transient elevation in sediment transport rates was observed, but it was not nearly as strong as run 2. Again the pulse deformation was strongly dispersive. The pulse dissipated much more slowly than that of run 2. It deformed sufficiently slowly that it created substantial backwater upstream. This backwater in turn caused the formation of a delta composed of sediment from the feeder. This delta eventually merged with the pulse and slowly dissipated with it.

5.3. Run 4b

[51] This sand pulse dissipated very rapidly, in the process completely wiping out the alternate bar pattern for a period. The fact that both a leading and trailing edge to the pulse could be visually discerned to migrate downstream indicates clear translational behavior. The fact that the pulse elongated substantially indicates fairly strong dispersive behavior as well. The pulse was associated with highly elevated transient transport rates of sand. As the pulse

thinned to the point that it no longer completely covered the gravel, it also had the effect of substantially elevating gravel transport rates for a period as well. This result coincides with the visual observation made during the run that the gravel armor layer ceased to exist as the sand pulse activated the surface gravel.

6. Conclusions

[52] The sediment pulses of all three runs proved to be strongly dispersive. This result is in agreement with the conclusions of *Lisle et al.* [1997] and in contrast with the conclusions of *Benda and Dunne* [1997]. The sediment pulses tended to suppress or even obliterate much of the alternate bar pattern of the ambient state for a period. They also resulted in sediment transport rates downstream of the pulse that were at first highly elevated, and then gradually declined back toward ambient values. These last two effects were most prominent when the pulse sediment was finer than the feed sediment and prepulse bed material. The time of recovery was shortest for the fine pulse and longest for the coarse pulse. In addition, the introduction of a sediment pulse into an otherwise equilibrium system reduces the sediment transport rate upstream of the pulse significantly (e.g., an order of magnitude reduction). The recovery of the reduced sediment transport rate upstream of the pulse is slower for the case the sediment pulse is composed of coarser sediment.

[53] When the pulse was finer than the prepulse bed material, it buried or completely destroyed the surface armor layer downstream for a period. This process was accompanied by sand transport rates that were orders of magnitude higher than the ambient rate. The sand on the bed also noticeably increased the rate of transport of gravel for a period. These effects were strongest for the fine pulse. When the pulse was coarser than the sediment feed and prepulse bed material the bed remained armored.

[54] The run with the coarse pulse was unique in that a downstream migrating delta formed in the backwater upstream. A very similar backwater zone and delta was observed after the landslide in the Navarro River of 1995 [*Sutherland et al.*, 1998].

[55] The run with the fine pulse was unique in that it exhibited significant pulse translation in addition to dispersion. The evidence for translation was embodied in clearly visible leading and trailing edges that migrated downstream. The sand from the pulse elevated the transport rate of the ambient gravel, a phenomenon earlier noted by *Wilcock* [1998]. The presence of the sand thus abetted a morphodynamic response similar to the "gravel sheets" observed experimentally by *Iseya and Ikeda* [1987] and *Whiting et al.* [1988] and studied theoretically by *Seminara et al.* [1996].

[56] In the companion paper, some of the experimental results are compared with the numerical model of *Cui and Parker* [2003] for field mountain streams.

Notation

B	channel width.
D _g	geometric mean grain size.
D _{gsur}	geometric mean size of the surface sediment.
D _{gsub}	geometric mean size of the substrate sediment.

D ₅₀	median grain size.
D _{f50}	median grain size of the sediment feed.
D _{p50}	median grain size of the sediment in the pulse.
Fr	Froude number of the flow.
g	gravitational acceleration.
G _s	mass sediment feed rate.
H	flow depth.
Q _w	water discharge.
S	bed slope.
U	cross-sectionally averaged flow velocity.
Ψ	grain size on the psi scale, $\Psi = \ln(D)$.
Ψ _m	arithmetic mean grain size on the psi scale, $\Psi_m = \ln(D_g)$.

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