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Channel responses to varying sediment input: A flume experiment modeled after Redwood Creek, California

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ABSTRACT

At the reach scale, a channel adjusts to sediment supply and flow through mutual interactions among channel form, bed particle size, and flow dynamics that govern river bed mobility. Sediment can impair the beneficial uses of a river, but the timescales for studying recovery following high sediment loading in the field setting make flume experiments appealing. We use a flume experiment, coupled with field measurements in a gravel-bed river, to explore sediment transport, storage, and mobility relations under various sediment supply conditions. Our flume experiment modeled adjustments of channel morphology, slope, and armoring in a gravel-bed channel. Under moderate sediment increases, channel bed elevation increased and sediment output increased, but channel planform remained similar to pre-feed conditions. During the following degradational cycle, most of the excess sediment was evacuated from the flume and the bed became armored. Under high sediment feed, channel bed elevation increased, the bed became smoother, mid-channel bars and bedload sheets formed, and water surface slope increased. Concurrently, output increased and became more poorly sorted. During the last degradational cycle, the channel became armored and channel incision ceased before all excess sediment was removed. Selective transport of finer material was evident throughout the aggradational cycles and became more pronounced during degradational cycles as the bed became armored. Our flume results of changes in bed elevation, sediment storage, channel morphology, and bed texture parallel those from field surveys of Redwood Creek, northern California, which has exhibited channel bed degradation for 30 years following a large aggradation event in the 1970s. The flume experiment suggested that channel recovery in terms of reestablishing a specific morphology may not occur, but the channel may return to a state of balancing sediment supply and transport capacity.

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1. Introduction

A river channel adjusts to its imposed sediment supply through changes in channel form, sediment storage and transport, bed texture, and flow dynamics. The degree of response to increased sediment input depends in part on the magnitude and caliber of the sediment input. Modes and rates of channel response are of interest to both researchers and land managers. The type and magnitude of channel change affect in-channel and off-channel resources, and understanding channel response to changes in sediment load is important for understanding sediment routing and the evolution of alluvial landforms. The magnitude, timing, and duration of channel responses in steep, gravel-bed river channels are still not well understood because adjustment processes may persist for decades, sediment transport rates vary in time and space, and channel processes are influenced by a multitude of physical factors.

Under the federal Clean Water Act of 1972, many rivers in the United States have been designated as "sediment-impaired" because the level of sediment in the river impacts beneficial uses, such as municipal water supply, cold freshwater habitat, flood conveyance, and estuarine habitat. For example, about 60% of the northern California region drains to rivers and streams that are impaired by too much sediment [State of California North Coast Regional Water Quality Control Board (NCRWQCB), 2006]. The U.S. Environmental Protection Agency is required to establish a total maximum daily load (TMDL) for sediment (that is, a sediment load allocation) in these river basins, but they also recognize a need for further research to determine levels of impairment and progress toward recovery (NCRWQCB, 2006). Questions remain as to how much sediment over what period can exceed water quality standards, and, conversely, how much sediment reduction is needed to restore the beneficial uses of a stream. Defining the relation between changes in sediment storage and sediment transport is central to addressing these questions.

In 1998, Redwood Creek in north coastal California was listed as sediment impaired under the Clean Water Act, based on documented

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increases in erosion rates (Nolan et al., 1995) and in sediment storage in the river channel (Madej, 1995). Large inputs of sediment from landslides, gullies, and bank erosion caused several meters of channel aggradation during 20- to 50-year floods in 1964, 1972, and 1975. Subsequently, during moderate flows, Redwood Creek has incised through these aggradational deposits, but some impacts from channel aggradation have persisted for more than 40 years.

Channel adjustments to variations in sediment loads in gravel-bed channels have been examined in field studies (Andrews, 1979; Lisle, 1982; Kinerson, 1990; Knighton, 1991; Lisle et al., 2000; Madej, 2001; Kasai et al., 2004; Hoffman and Gabet, 2007), but variations in sediment supply and the long periods often required to measure channel response can pose severe difficulties. Consequently, many field studies substitute space for time and investigate spatial variations in sediment supply rather than temporal changes in supply (but see Sawada et al., 1985; Pitlick, 1993; Lane et al., 1996; Wathan and Hoey, 1998; Wohl and Cenderelli, 2000; Sutherland et al., 2002; Gran and Montgomery, 2005). The problem here is the confoundment from a myriad of variables, including flow regime, lithology, and roughness elements such as riparian vegetation and large woody debris so that the sequence of change in any river cannot be specified.

Laboratory experiments thus become appealing for testing specific questions regarding sediment transport processes under varying supply. Physical modeling in flumes can control variables to provide a stricter experimental design, provided that hydraulics and sediment properties can be properly scaled. Such physical modeling can generate testable hypotheses for field studies and verify empirical and theoretical hypotheses (Douglass and Schmeeckle, 2007). Flume studies have elucidated relations between sediment supply and fluvial processes. Dietrich et al. (1989) and Lisle et al. (1993) demonstrated that a channel bed coarsens as sediment supply is reduced and sediment transport becomes confined to a progressively narrower active zone. Smith (2004) examined the transport capacity of a flume channel during both aggradation and degradation cycles and showed the role of channel morphology and armoring. Wilcock (2001) reviewed flume and field studies to explore flow/bed/transport interactions and investigated how bed mobility changes with sediment transport rates. Other experiments designed to investigate the evolution of sediment waves include data on channel response (Lisle et al., 1997; Cui et al., 2003). Experiments on adjustments in planform and gradient have been conducted by Eaton and Church (2004) and Ashmore (1991).

These experiments, as well as field studies, show that bed armoring is a common response to variations in sediment supply in gravel-bed channels. However, many related issues are unresolved, including (i) what sediment supply variations are associated with degrees of armoring; (ii) what sediment supply variations are associated with other channel changes, e.g., planform; (iii) how different responses interact in a channel in disequilibrium; and (iv) how combined effects of changes in flow and sediment supply affect channel response. For example, in the experiments described above, sediment supply was varied as discharge was held constant. This brings into question whether observed effects of sediment supply on armoring would persist under unsteady flow in natural rivers (Wilcock and DeTemple, 2005). However, model simulations by Parker et al. (2007) demonstrated that bed elevation and armoring tend to remain constant during hydrograph variation, but sediment supply still influences the degree of armoring and bed mobility.

Lisle and Church (2002) attempted to put channel response to sediment load in the context of sediment routing by regarding transport capacity as a dynamic mediator between sediment transport and storage. They proposed that sediment transport capacity in gravel-bed channels is a function of storage volume, which influences sediment mobility through variations in bed surface texture, channel gradient, and form. Their hypothesis is supported by observations in natural and experimental channels that were undergoing degradation. Lisle and Church (2002) used flume experiments and field data to examine relations between sediment transport capacity and sediment supply in degrading alluvial reservoirs, in which sediment transport was initially non-selective before bed mobility was decreased by bed armoring and form roughness.

The goal of this project is to examine how sediment transport capacity changes during aggradation as well as degradation in response to changing sediment loads, and to quantify the associated changes in bed texture, bed mobility and channel form. We use a flume to model channel response to changes in sediment input, storage, and output in Redwood Creek, California. Several measures of channel response to changes in sediment loads in the Redwood Creek basin are summarized in Madej (2000) and Madej and Ozaki (in press) and are the basis of comparison with flume results. Several types of channel responses are compared: channel bed texture, channel morphology, water surface slope, and sediment transport rates and particle sizes. These responses are used to explain variations in transport-storage relations during full cycles of aggradation and degradation.

2. Field area

Redwood Creek drains a 720-km^2 basin in northern California, USA. The basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Average hillslope gradient is 26%, and Redwood Creek ranges in gradient from 15% near the headwaters to 0.12% near the mouth. For most of its 100-km length, the gravel-bed channel is characterized by alternate bars (Fig. 1). The bedrock is part of the Franciscan assemblage of Jurassic and Cretaceous age (Cashman et al., 1995) and is pervasively sheared and fractured. Before the initiation of logging, about 90% of the basin was forested, primarily with redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menzeisii*). Extensive timber harvest began in the early 1950s, and by 2006, 80% of the forest was logged. As a result of the high precipitation, fractured bedrock, and land disturbances, the terrain is highly susceptible to mass movement and gullying.

Large floods in 1964, 1972, and 1975 with 20- to 50-year recurrence intervals (Coghlan, 1984) initiated widespread streamside landsliding, debris torrents, and logging road failures, which led to extensive aggradation and bank erosion in Redwood Creek. Public outcry resulted in Redwood National Park being established in 1968 and expanded in 1978 to protect old growth redwood trees in the downstream third of the basin from further flood damage. Subsequent channel surveys over the next three decades have documented erosion and redistribution of many flood deposits in Redwood Creek (Madej and Ozaki, in press). With the exception of a small aggradation event during a 12-year recurrence interval flood in 1997, most of the channel has been degrading since 1978.

Two reaches of Redwood Creek described by Lisle and Madej (1992) are used in this study (Fig. 1). Redwood Creek near Emerald Creek is 22 km from the mouth and Redwood Creek near Elam Creek is 10 km upstream of the mouth. Both reaches include discontinued gaging stations, cross-sectional and longitudinal transects that have been surveyed since 1973, and a bed facies map (Lisle and Madej, 1992; Madej, 1999). A useful contrast between the reaches for this study is that the Emerald Creek reach has degraded, while the Elam Creek reach remains aggraded.

Both reaches are weakly armored, but variations in armoring indicate an adjustment to sediment load (Lisle and Madej, 1992; Lisle et al., 2000). The median surface particle size ($D_{50\text{-surface}}$) in the Elam Creek reach was 14.7 mm, whereas in the Emerald Creek reach the channel bed surface was coarser ($D_{50\text{-surface}}$=22.2 mm). The armoring ratios ($D_{50\text{-surface}}$: $D_{50\text{-subsurface}}$) for these reaches were 1.57 and 1.23, respectively. However, based on pebble counts conducted at several cross-sectional transects in the Emerald Creek reach, $D_{84\text{-surface}}$ increased from 30 mm in 1979 to 75 mm in 2006, indicating surface

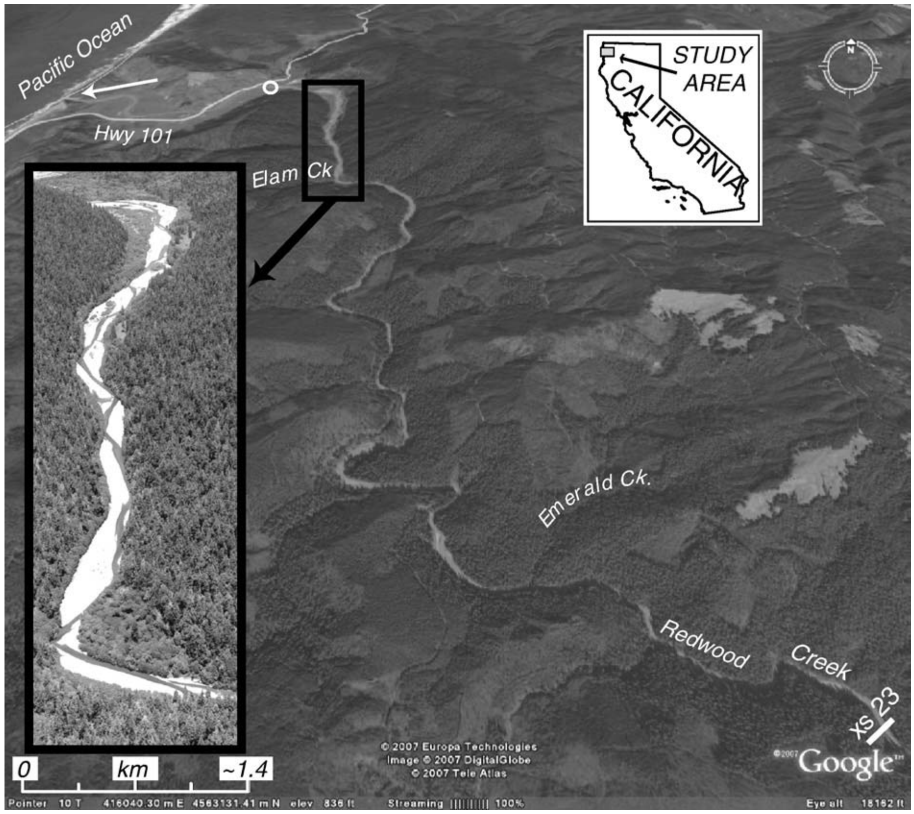

Fig. 1. Location map and view of lower Redwood Creek looking downstream. The inset shows a typical reach with alternate bars (Elam Creek reach) in 2000. Circle represents U.S. Geological Survey gaging station #11482500 at Orick, CA; white arrow points to the mouth of Redwood Creek; and location of cross section 23 at the upstream end of the Emerald Creek study reach is at the lower right-hand side of photo. Scale is variable on both the oblique image from Google Earth™ mapping service (available at earth.google.com) and on the inset photograph.

coarsening as the channel degraded (Madej and Ozaki, in press). Equivalent pebble count data were not available for the Elam Creek reach for this period.

The Emerald Creek reach is used as a prototype for the flume experiment. Based on analysis of historical photographs, this reach was a single-thread, armored channel with alternate bars before channel aggradation occurred in the 1960s and 1970s. All five cross sections in this 4-km reach exhibit similar patterns of aggradation following a large flood in 1975 and a gradual decrease in mean bed elevation of about 2 m since then. Longitudinal profile surveys of the channel in this reach documented a flat, shallow bed in the late 1970s when the channel was highly aggraded, with pool frequency and depths increasing as channel degradation progressed through the 1980s (Madej, 1999).

3. Laboratory materials and methods

Aggradation and degradation cycles in the Emerald Creek study reach were simulated using a 12-m long, 0.75-m wide, non-recirculating sediment-feed flume at Humboldt State University, Arcata, CA, USA. We attempted to scale hydraulic and sedimentologic conditions in the flume by Froude number and Shields stress according to bankfull conditions of the study reach (Lisle and Madej, 1992) (Table 1). We attempted to scale mean depth, width, and particle size by a factor of 1:100. However, viscous effects for small particles and the size of the flume required a relaxation of particle-size scaling, and slope was allowed to vary to achieve the hydraulic criteria. The minimum size class of flume bed material was truncated at 0.3 mm to avoid effects of the viscous sublayer on sediment transport. Therefore, we created a distorted Froude-scale model of the Emerald Creek reach or an undistorted model of a generic gravel-bed channel that is steeper and coarser. The slope of the flume was set at 1.2% and water discharge was held constant at 4.63 L/s. Width-depth ratios of 20 to 30 in the flume before sediment feed was started were similar to the ratio of 27 in the Redwood Creek study reach. Relative submergence [ratio of mean depth to median particle size (D_{50})] was less in the flume (20) than in Redwood Creek (100) but still in the range typical of gravel-bed rivers with alternate bars.

We used the same grain-size mixture for the original bed material and the sediment feed (D_{50} = 1.0 mm, D_{84} = 3.2 mm, D_{16} = 0.4 mm, D_{max} = 8 mm, where the subscript is the cumulative percentile of the particle-size distribution) (Table 2). Graphic standard deviation [$\sigma_g = (\varphi 84 - \varphi 16)/2$) (Inman, 1952)] was 1.6φ. Grain density was 2.67 g/cm^3. The feed entered the flume at 11 m upstream of the outlet. Sediment was not recirculated, simulating the condition of imposed sediment loads from hillslope sources.

Table 1
Comparison of values of modelling criteria in the flume with values in the simulated reach of Redwood Creek

Modelling criteria	Flume	Redwood Creek
Channel gradient	0.012	0.0024
Bankfull width (m)	0.3–0.74	60
Bankfull depth (m)	0.013–0.027	2.2
Width/depth ratio	20–30	27
D_{50} (mm)	1	22
Shields stress, τ^*	0.15	0.15
Froude number	0.6–1.0	0.6
Mean flow depth: mean particle size ratio	20	100
Sediment: fluid density ratio	2.67	2.65
Graphic standard deviation (φ)	1.6	1.4–1.8
Valley width: channel width ratio	1–3	1–3
Sinuosity	1.01–1.06	1.04

Table 2
Particle size distribution of sediment feed and initial channel bed

Size (mm)	Percent by weight	Cumulative percent
0.3–0.5	34	34
0.5–1	16	50
1–2	22	72
2–4	18	90
4–8	10	100

In the modeled reach (Redwood Creek near Emerald Creek), Shield's stress, τ^* (the dimensionless ratio of tractive and gravitational forces acting on bed particles) at bankfull flow is 0.15, which is indicative of intensive bedload transport. The flume parameters were scaled to have a τ^* of 0.15 as well, representative of a fully mobile gravel-bed channel. This initial value for the flume is based on the sediment mixture rather than the bed surface. Values of τ^* during the experiment were affected by varying hydraulic conditions and surface particle size distribution.

We induced two cycles of aggradation and degradation by varying sediment feed rates (Table 3). Each aggradational phase (runs A1 and A2) was followed by a degradational phase (runs D2 and D3) when the feed was stopped and sediment output declined to nearly zero. Beforehand, we screeded the bed material flat and ran the flume for 8 h without sediment feed until a stable channel with alternate bars formed (run D1). Run time was set to zero at the end of this period. In run A1, we used a moderate sediment feed (18 g/s) to cause channel filling without burying the alternate bars in order to model moderate aggradation in Redwood Creek after a 12-year flood. A higher feed rate in A2 (23 g/s) caused mid-channel bars to build and secondary channels to form, similar to the response observed in Redwood Creek after 20- and 50-year floods and associated landslide events.

A laser microtopographic scanner, which traversed a 10-m length of flume along overhead rails, output bed topography and elevation to a resolution of 1 mm in cross stream (x) and downstream (y) coordinates and 0.1 mm in elevation (z). Digital elevation models (DEMs, identified as maps A through M) were generated from the scanner data when flow was stopped periodically (Table 3). During the runs, cross sections were surveyed with point gages while the water was flowing, but accurate measurements of the submerged bed were difficult because of scour induced by the measuring device. In order to measure water surface slope, we quickly measured water surface elevations at about six locations down the length of the thalweg every 30 min. In addition, observers noted and mapped zones of active sediment transport and the approximate width of the transport zone along the length of the flume.

Each time the channel bed was scanned, channel facies were mapped into various categories (coarse: $D_{50}>1.5$ mm; fine: $D_{50}<0.5$ mm; mixed: $0.5<D_{50}<1.5$ mm; and bimodal). We used small scoops 25 mm wide to sample the top layer of sediment from three random samples of surface bed material from each facies unit. Samples were approximately as thick as the D_{90} of the sediment mixture (4 mm). They included more fine material in the near-surface than would a Wolman pebble count, but represent a uniform layer of the bed surface and have been used in flume experiments modeling gravel-bed channels (Dietrich et al., 1989; Lisle et al., 1993; Cui et al., 2003). Samples from a given facies category were combined and then sieved to obtain particle size distributions of the surface layer for that category. For each laser scan, the D_{84} and D_{50} for the entire flume bed and for the primary wetted channel were calculated from these facies maps using a weighted average based on facies area.

In field studies in Redwood Creek, roughness was quantified by the dimensions of bedforms contributing to form resistance (Madej, 1999) and by calculating Manning's n from flow measurements at gaging stations, which requires measurements of depth and velocity. The calculation of Manning's n in the flume proved to be problematic because it was difficult to measure water depth accurately during the flume run. The point gage induced scour of the channel bed and the associated turbulence around the gage obscured our view of the channel bed during much of the time. As an alternative method to quantify bed roughness, we calculated the rugosity, a dimensionless index of bed "wrinkling" or roughness (McCormick, 1994), using bed elevation data from the laser scans. First, the elevation of the thalweg at 1-cm intervals was calculated from the laser scans. The total length of this profile line, which included the vertical bed elevation variations, was divided by the straight-line thalweg length. To avoid inlet and outlet effects, rugosity was calculated for the length of flume bed 2 to 8 m from the outlet. For comparison, in Redwood Creek, rugosity was calculated in a similar manner based on thalweg profiles described in Madej (1999). In this case, we divided the length of the thalweg profile (encompassing pools and riffles) by the straight-line channel length.

Sediment transport was measured by collecting sediment at the flume outlet in 10- to 15-min increments throughout the experimental runs (A1-D3 in Table 3). Changes in sediment storage were computed by summing the differences between sediment output and feed during these time steps. Sediment samples were dried, weighed, and sieved to compute particle size distributions and transport rates. Graphic standard deviation [$(\varphi 84-\varphi 16)/2$] represents the spread within the particle size distribution, with higher values representing poorer sorting. In the case of the flume sediment, $\varphi 16$ was virtually the same throughout the runs because the initial size distribution had 34% of the material between 0.3 and 0.5 mm, so we use a modified sorting index, S_i, defined as ($\varphi 84-\varphi 50$). For each map, we calculated a mass-weighted average D_{84} and D_{50} of sediment output sampled between laser scans.

4. Results

4.1. Sediment output and storage

The DEMs of the channel bed illustrate changes in bed elevation and channel planform during the aggradational and degradational cycles. Fig. 2 shows examples of DEMs from the final scan in each cycle. Trends in sediment output, measured at the outlet of the flume, and channel-stored sediment are displayed in Fig. 3. When sediment feed was first started, a time lag of about 1 h was noted before the output rate began increasing. As expected, sediment output rates measured at the flume outlet were generally higher during aggradational periods when feed rate was high than during most of the degradational periods. The feed rate was 18 g/s during the 303-min A1 run, and output rates were not at equilibrium (that is, input was greater than output) for the duration of A1. The average output rate during A1 from 80–303 min was 13.9 g/s, well below the feed rate. The volume of channel-stored sediment increased throughout A1.

At the beginning of D2 (303–334 min in Fig. 3), moderate sediment output continued for about 30 min, despite cessation of sediment input at the upstream end of the flume. The first three samples after feed was shut off averaged 15 g/s, statistically indiscernible from the 13.9 g/s of A1 (within one standard deviation). When sediment transport at the flume outlet did slow down, it did so rapidly and output dropped to 1–2 g/s by minute 423. By 423 min (map G), sediment storage

Table 3
Sequence of experimental runs in flume

Run type	Feed rate (g/s)	Length of run (min)	Flume time (min)	Number of laser scans	Map name
Degrade 1 (D1)	0	480		1	A
Aggrade 1 (A1)	18	303	303	4	B, C, D, E
Degrade 2 (D2)	0	120	423	2	F, G
Aggrade 2 (A2)	23	472	895	4	H, I, J, K
Degrade 3 (D3)	0	210	1106	2	L, M

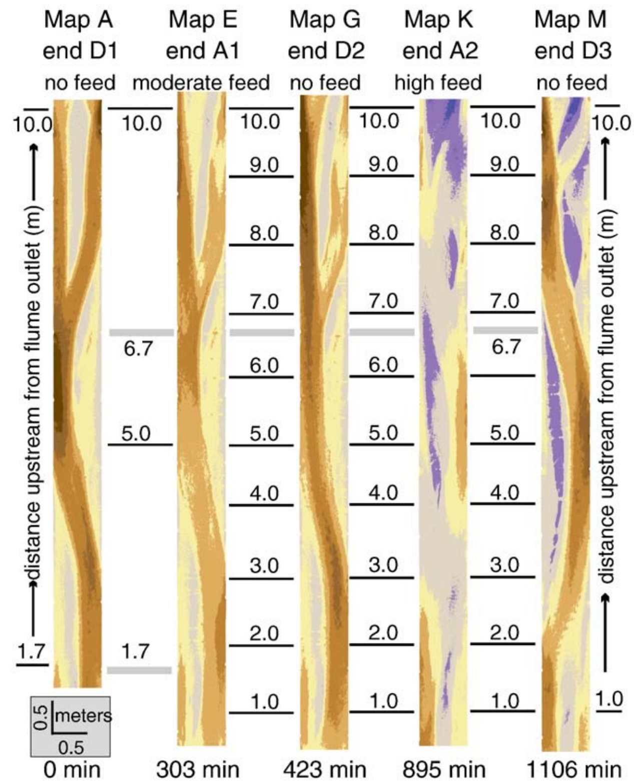

Fig. 2. Digital elevation maps of flume at the end of aggradational and degradational cycles. Tonal changes represent 1-cm elevation change with lighter tones representing higher elevations. Cross-sectional profiles at 6.7 m upstream from the outlet are plotted in Fig. 4A–D. "Minutes" refer to cumulative run time in the flume.

decreased to almost the initial (D1) condition of the flume run (map A, 0 min).

When sediment feed was increased to 23 g/s (run A2, starting at 423 min in Fig. 3), sediment transport at first followed a similar pattern to A1, with a lag time of about 70 min before sediment output increased, then a mild fluctuation around a mean of about 11 g/s for the next 300 min. When storage volume during A2 was about equal to the volume during A1 (at 500 and 300 min, respectively), transport capacity was also about the same (13 g/s). However, as channel aggradation continued, sediment output abruptly increased at 725 min to >25 g/s. This was the only period when sampled output exceeded the feed rate. During the remainder of A2, output fluctuated, but around a higher average (17 g/s) than the previous run. For the first half of the A2 run, sediment storage increased at a steeper rate than during A1. The rate of storage increase slowed during the last half of the A2 run as sediment output increased. During the final degradational cycle (D3), output rates again remained high for the first hour, when storage volume was still high (950 min). As with the first degradational cycle, once output rates began to decrease, they dropped quickly until the end of the run. The final storage volume was considerably greater than the pre-sediment feed condition, although sediment transport was negligible by 1100 min.

4.2. Channel morphology

Cross-sectional transects were used to quantify channel changes (channel fill or incision, or lateral bar accretion or erosion). Fig. 4A–D displays a typical pattern of channel change about one-third of the way down the flume during the runs. Map A represents the original channel bed, after alternate bars had formed but before sediment feed began. During the moderate sediment feed (A1), the thalweg and active channel bed filled at the upstream cross sections, with minor channel fill at the downstream cross sections. The flume-averaged cross-channel bed relief (the average difference between bar surface and thalweg elevations) became more subdued during A1 (map A to map E, Fig. 4A), as it dropped from 4.0 to 2.8 cm. The bars showed little change, and the channel planform remained the same (Fig. 2). During the subsequent D2 degradational cycle (maps E to G, Fig. 4B), the main channel incised to about the bed elevation before the feed was started (map A), and channel geometry and bed relief (4 cm) also became similar. Initially, channel response to the high (A2) sediment feed was similar to that of A1 (map H); but as sediment feed progressed, the channel completely filled in, then mid-channel bars and side channels formed, and at some locations the main channel shifted to the opposite side of the flume (maps I and K, Fig. 4C). The period of accelerated sediment transport

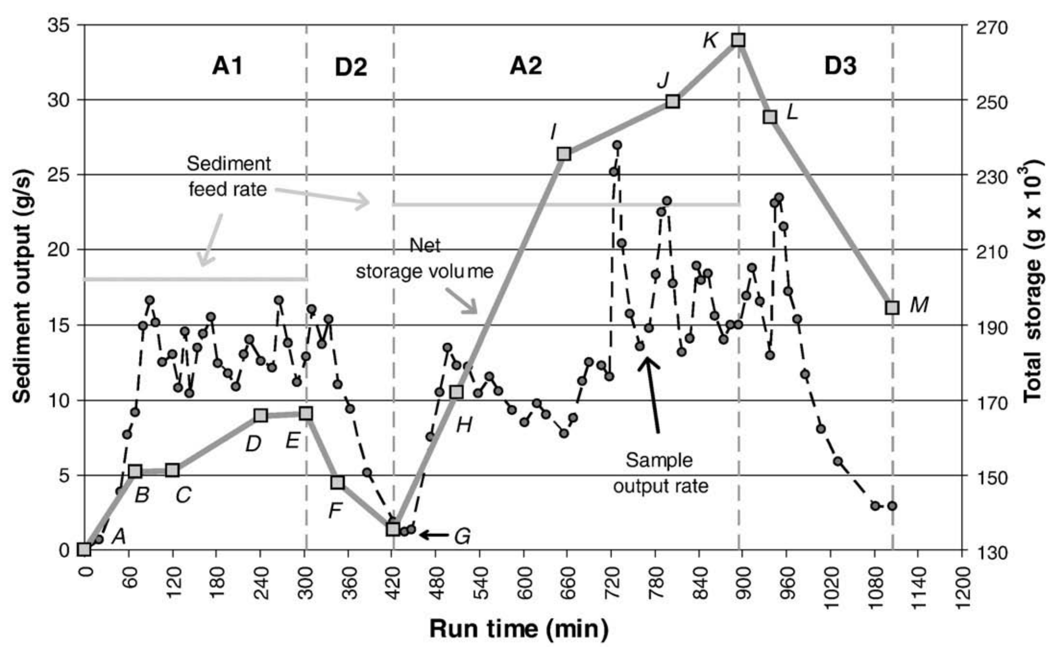

Fig. 3. Sediment output rates and sediment storage in the flume during aggradational and degradational cycles. Points (gray squares) on the net storage volume line are based on the timing of laser scans, starting with map A at time 0 and ending with map M at 1106 min.

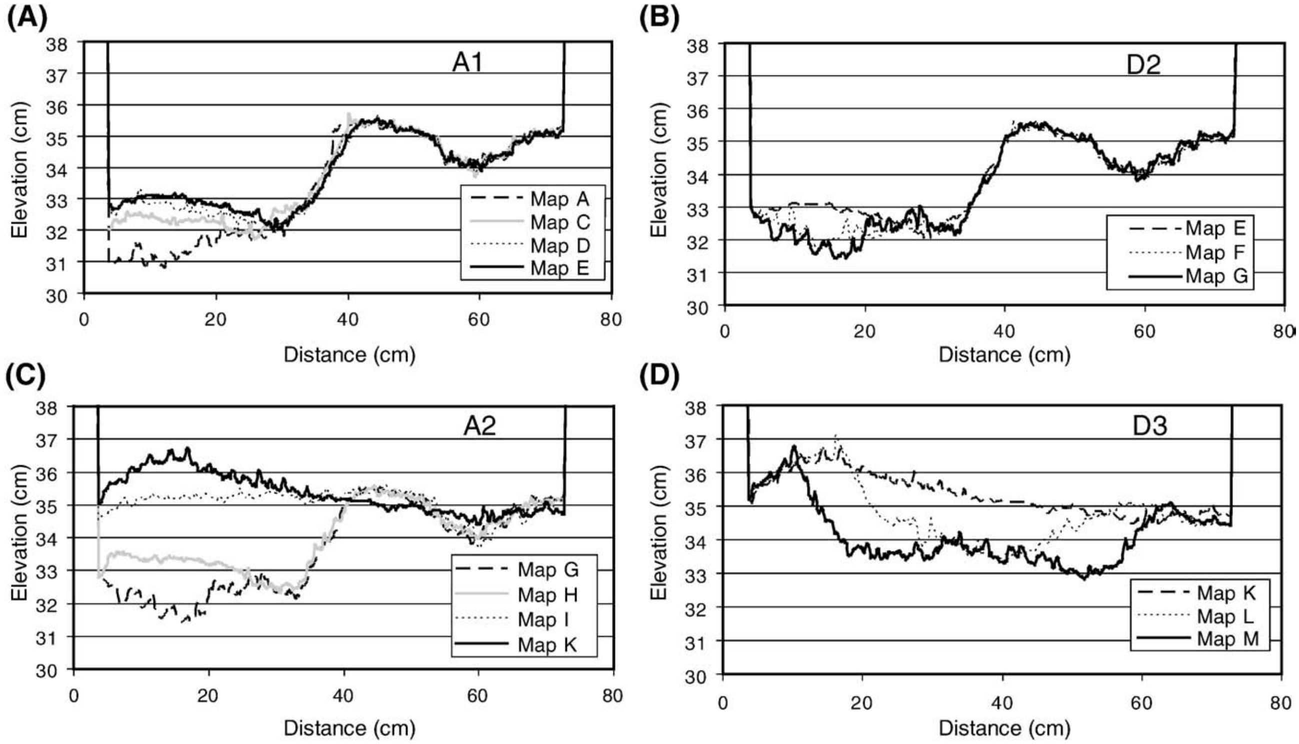

Fig. 4. (A–D) Typical cross-sectional changes during aggradational and degradational runs in the flume, measured at 6.7 m upstream of outlet.

(starting at about 725 min in Fig. 3) corresponds to the period of time between when the channel was filled and fairly flat (map I) and when mid-channel bars and secondary channels had formed (map K). Although mid-channel bars formed, the channel pattern never became fully braided. The flume-averaged cross-channel bed relief decreased from 4 cm at the beginning of A2 to 2.1 cm at the end of A2. During the final degradational cycle (D3), the channel first incised a single channel and then bars were eroded laterally (maps L and M, Fig. 4D). Although the channel at the end of D3 (map M) was wider than at the end of D2 (map G), the wetted cross-sectional areas at a flow of 4.63 L/s were similar (132 and 134 cm^2 at this cross section, respectively), and bed relief had returned to pre-aggradation values of 4 cm. At the end of D3, when sediment transport had declined to a negligible amount, the flume channel bed was still elevated along most of its length compared to the pre-aggradation (map G) value.

The extent of the channel bed that accommodated changes in sediment storage differed between moderate and high sediment supply runs. During moderate sediment feed, most change in sediment volume was accommodated across a limited channel area. For example, 80% of increased sediment storage volume occurred on only 22% of the channel bed area during A1 (Fig. 5). During the following degradation cycle (D2), the same area of the channel responded with 80% of the removed volume eroded from 22% of the channel bed. During A1, only 47% of the bed exhibited any fill. In contrast, during the high sediment feed of A2, 80% of the bed exhibited fill, and 80% of that fill volume occurred on 42% of the bed. The following degradational cycle D3 also involved more of the channel bed than in D2, but the scour area was more confined than the preceding fill area, with 80% of the scour volume derived from 36% of the bed (Fig. 5).

4.3. Channel bed slope, elevation and roughness

Fill and scour varied down the flume during aggradational and degradational cycles (Fig. 6). During A1, the greatest fill occurred mid-flume, 4 to 6 m upstream of the outlet (map E), while the downstream portion of the flume exhibited little change. In contrast, during A2, bed elevation increased most at 3 and 8 m upstream of the outlet (map K). During the degradational cycles, erosion in these areas accounted for most of the bed elevation change; however, at the end of the final degradational cycle (map M), the bed elevation remained higher than the original condition for most of the flume length.

During both aggradational runs, bed roughness (measured as rugosity) decreased during moderate and high sediment feeds (Fig. 7) and increased to 1.0031 during both degradational runs. These measurements are consistent with our observations of the smoothing of

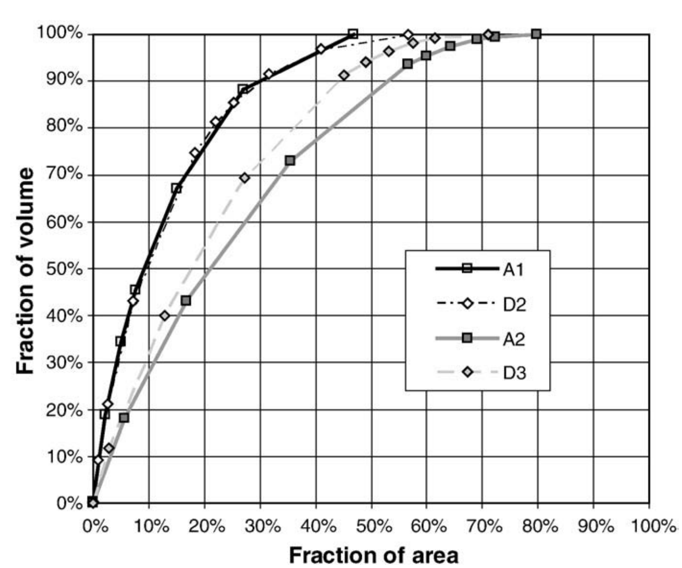

Fig. 5. Cumulative curves of channel bed areas exhibiting scour or fill during aggradational and degradational cycles.

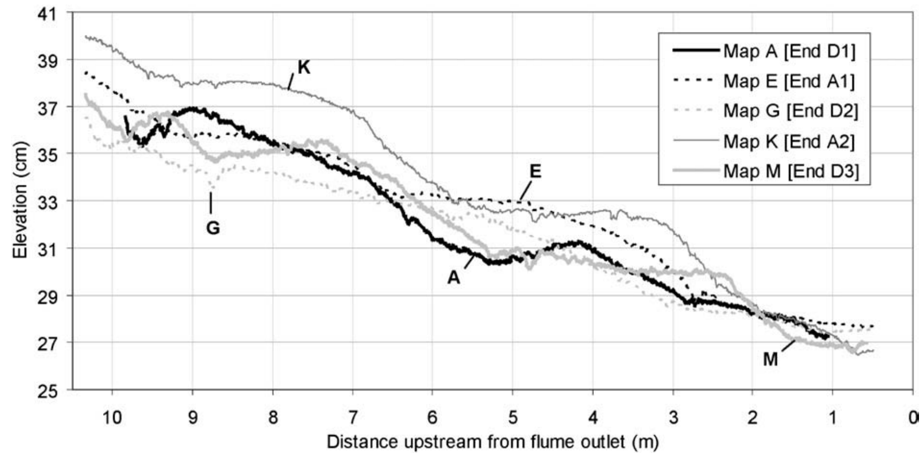

Fig. 6. Examples of longitudinal profiles of channel thalweg measured at the end of the aggradational and degradational runs.

bed microtopography in the flume during the aggradational cycles and a rougher bed during degradational cycles.

4.4. Water surface slope

Water surface slope is commonly used as a substitute for energy gradient (Dingman, 1984). As slope increases, boundary shear stress and bed material transport generally increase. During A1, water surface slope fluctuated slightly around the general slope of the flume (0.012 m/m) (Fig. 8). During D2, water surface slope decreased sharply to 0.0109 m/m after sediment feed was stopped. Water surface gradient increased steadily during A2 to a peak of 0.0132 at 845 min, and then decreased slightly near the end of the aggradational run to 0.0129. During D3, slope decreased farther to 0.0125. In general, increasing sediment output rate is associated with increasing water surface slope, and the trend is statistically significant ($p<0.010$) (Fig. 9). The trends exhibited a mild hysteresis during the aggradation–degradation cycles.

4.5. Textural response of channel bed

The bed surface became finer during aggradational cycles and coarsened during degradational cycles. Both the D_{84} and D_{50} of the bed surface decreased during A1, under moderate sediment feed, and then increased to about the initial (map A) values during D2 (Fig. 10). During the high sediment feed of A2, the bed again became finer, and the fining was more pronounced than during A1. Although the bed coarsened during D3, neither the D_{84} nor the D_{50} reached the values measured during D2, even though sediment transport was negligible at the end of each degradational run. During D2 and D3, the active transport zone was classified as “coarse” in the facies maps. At the end of D3, 8% of the full flume bed was still classified as “fine” (D_{50} about 0.3 mm) and 14% as ‘bimodal fine’ (D_{50} about 0.6 mm), but these fine facies units were isolated patches of fine sand on exposed bars and were not located in the active transport zone of the channel bed.

Fig. 10 also shows the lack of armoring of the channel bed during most of the flume runs. The sediment feed had a D_{84} and D_{50} of 3.2 and 1.0 mm, respectively. During each aggradational cycle, the weighted average of the surface bed particle size was finer than the sediment input. Although the bed coarsened somewhat during both degradational cycles, the armoring ratio ($D_{50\text{-surface}}$:$D_{50\text{-feed}}$) only exceeded 1 during D2 (maps F and G).

4.6. Sediment output

4.6.1. Selective transport

During most of the runs, the D_{84} of sediment transported out of the flume ($D_{84\text{-transport}}$) was considerably finer than the D_{84} of the sediment feed ($D_{84\text{-feed}}$) (Fig. 11), and this trend of selective transport of finer sediment was most pronounced during degradation phases. On the other hand, $D_{50\text{-transport}}$ fluctuated around the value of $D_{50\text{-feed}}$ (1.0 mm) during the aggradation phases (0.9–1.0 mm) and was only slightly finer during degradation phases (0.8 mm).

The degree of selective transport can be expressed by the ratio $D_{84\text{-transport}}$: $D_{84\text{-feed}}$. Wilcock (2001) showed that this ratio tends to increase at high flows and high transport rates. In the present flume experiment, however, the relation between particle sizes and transport rates was not clear (Fig. 12A). Selective transport was strongest at low transport rates, when mostly fines were transported. The transport

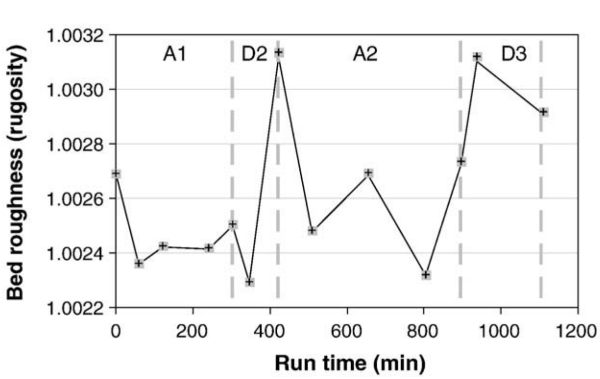

Fig. 7. Rugosity of flume channel thalweg during aggradational and degradational runs.

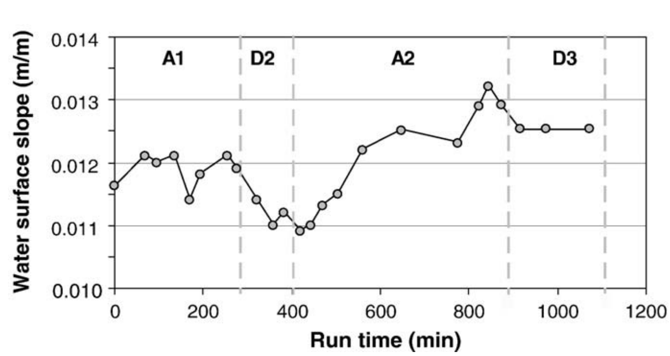

Fig. 8. Water surface slope measured along the thalweg between 2 and 10 m from the flume outlet.

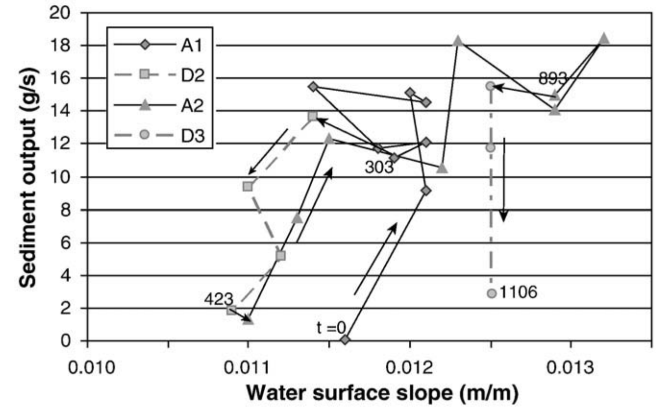

Fig. 9. Relation between sediment output from flume and water surface slope.

ratio generally increased as transport rates increased from 0 to 15 g/s, but the ratio fell at the highest transport rates (20 to 28 g/s).

4.6.2. Sorting of sediment output

If selective transport of certain size classes increases, the sediment transported out of the flume should become better sorted; that is, the spread of particle sizes in the output should narrow. Throughout the flume runs, the relation between our modified sediment sorting index and sediment transport rates was positive and relatively weak, but significant (r^2=0.15, p=0.0003) (Fig. 12B).

4.6.3. Migration of bedload sheets

Bedload sheets or low-relief bed waves, identified in previous flume and field studies (Bennett and Bridge, 1995; Kuhnle et al., 2006), also formed in this flume study during aggradational phases. They moved downstream at roughly 1 to 2 cm/s, measured through videography (Fig. 13). The leading edge of the sheets was typically several particles high, composed of the coarse fraction (>2 mm), and the surface of the sheets became somewhat finer in the upstream direction. The sheets were transported over finer bed material. The sampling interval used to measure sediment output from the flume (about 15 min) was too broad to quantify changes in sorting and transport rates related to the migration of individual bedload sheets.

4.7. Changes in channel transport capacity

The relation between sediment output and storage volume for the two aggradation–degradation cycles is summarized in Fig. 14. Transport capacity of the channel in terms of sediment output was dynamic and changed in response to storage volume. Although the relations between storage and transport for both the A1-D2 and A2-D3 cycles exhibited similar patterns early in the cycles, the two cycles differed in magnitude and patterns of response late in the cycles. During the beginning of the aggradational cycles, after a short lag time, sediment output rates increased sharply with relatively small increases in storage. In A1, output rates then fluctuated around 13 gm/s while storage steadily increased. When feed was shut off at 303 min, output rates initially increased as storage decreased and then decreased sharply with a moderate loss of stored volume by the end of the run at 423 min. In A2, after a steep increase in output rates, rates declined slightly as storage increased greatly, from about 150×10^3 to 250×10^3 g. As storage increased by about 300×10^3 g, output jumped rapidly and remained fairly high until the end of the run, even as storage continued to increase. At the beginning of D3 (893 min), in a similar pattern as D2, output rates were higher than at the end of the aggradation cycle as storage declined and the bed started to degrade. Finally, as in D2, sediment transport rates declined quickly as finer particles were selectively removed and the channel bed became armored. Sediment storage declined as well until the end of the run at 1106 min, but the channel was not able to evacuate all the added sediment because the armor layer prevented full channel incision to previous bed elevations.

4.8. Redwood Creek field measurements

Detailed field surveys of Redwood Creek provide data on river response to changing sediment loads. Following a period of aggradation from 1964 to 1975, bed profiles in the Emerald Creek reach have documented general streambed lowering of about 2 m. Individual pools have become deeper and more frequent, but bed elevations in intervening runs and riffles have also lowered along the length of the reach (Madej, 1999; Madej and Ozaki, in press). In areas with large flood deposits the channel first incised and then bars eroded laterally (Fig. 15). Even under peak aggradation conditions Redwood Creek did not become braided, but locally secondary channels formed around mid-channel bars. Mid-channel bars in Redwood Creek were evident in the 1973 to 1990 surveys (Fig. 15), but were gone by 2006. Bed slope decreased slightly from 0.0026 in 1977 to 0.0024 in 2006, which is within the range of field surveying error. Rugosity measured in the modeled reach, was 1.0001 in 1977 (near the peak of aggradation when the channel bed was virtually flat), 1.0031 in 1995, and 1.0058 in 2007 after 30 years of channel bed degradation and the development of many deep pools. In Redwood Creek, roughness (defined by the roughness coefficient Manning's n calculated from flow measurements) also increased as the channel degraded and bedforms became more prominent (Madej, 2001).

A data set equivalent to the flume, comparing grain size of the sediment input to sediment output, is not available for Redwood Creek; however, we can compare the D_{50} of bedload samples to bedload

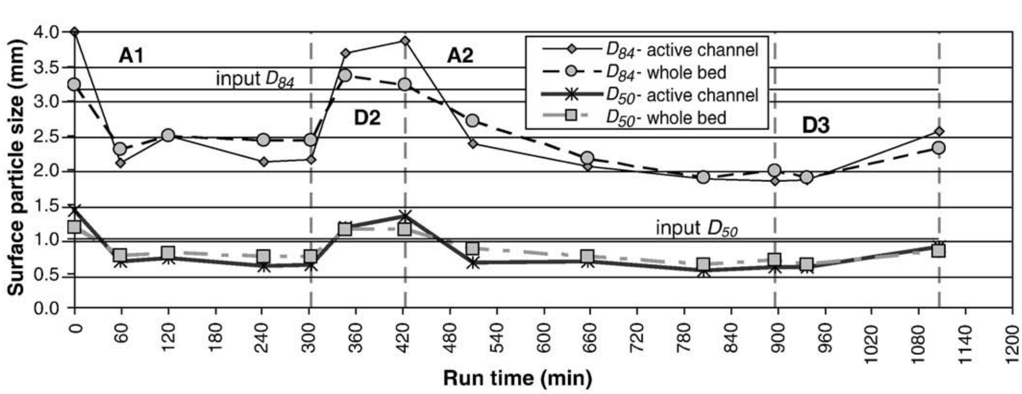

Fig. 10. Weighted average of dominant surface particle sizes (D_{84} and D_{50}) in entire flume bed and in active sediment transport zones (active channel) during aggradational and degradational cycles.

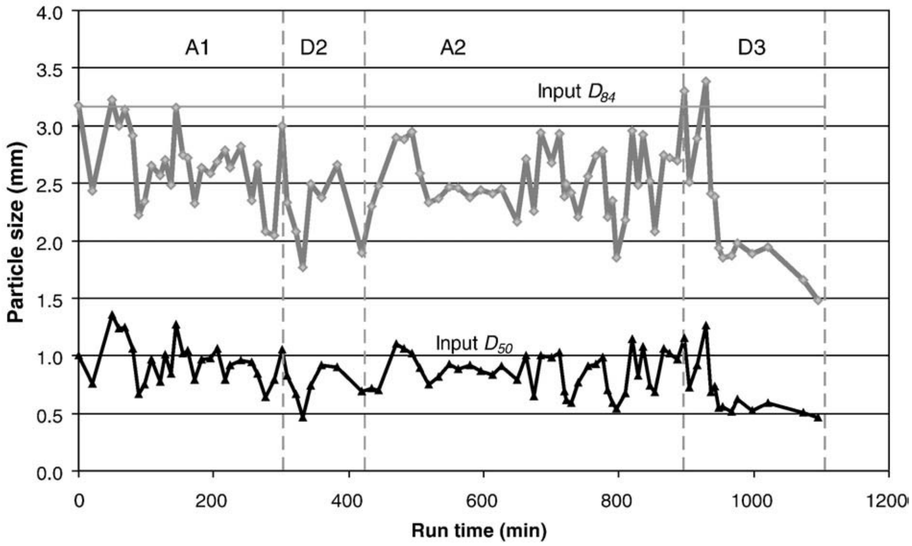

Fig. 11. Dominant particle sizes of sediment output from flume.

transport rates (Fig. 16A). For the data available (based on bedload samples collected in Redwood Creek at Orick from 1990 to 2002), the relation between $D_{50\text{-transport}}$ and bedload transport rates is positive and moderately strong (r^2=0.48, p<0.0001), and the proportion of coarse particles in transport increased with transport rates. The relation between Inman's sorting index for these bedload samples and bedload transport was also positive and moderately strong (r^2=0.46, p<0.0001) (Fig. 16B). Bedload samples were well sorted when bedload transport rates were low and became more poorly sorted under higher bedload transport rates.

5. Discussion

5.1. Comparison of flume and field results

Channel responses to varying sediment load that were observed continuously in the flume mirrored those observed at intervals in Redwood Creek (Table 4). Weakened armoring with increased sediment load and stronger armoring with decreased load are consistent with earlier experiments and field studies (see citations in Introduction). Planforms in the flume model and Redwood Creek prototype responded similarly by channel widening and medial bar formation during aggradation and formation of single-thread channels during degradation. As in the flume, channel roughness in Redwood Creek increased during degradation; scanter information suggests that roughness decreased during aggradation.

Of the flume runs, the changes observed in Redwood Creek from 1997 to present most resemble the flume runs of moderate aggradation followed by degradation (A1 to D2). During aggradation, the channel bed became finer and smoother. Steady transport rates in the final stages of aggradation indicate that transport capacity at this moderate feed rate had been nearly achieved, although large particles continued to accumulate in the flume. Increased transport rates were accommodated without an increase in energy gradient or a change in planform. During degradation, fine particles were selectively transported and the bed armored and became rougher as the channel planform remained essentially intact.

Changes observed in Redwood Creek from 1964 to 1997 most resemble the flume runs of maximum aggradation followed by degradation (A2 to D3). Channel changes in early stages of A2 were similar to those in A1, but further aggradation resulted in more widening and bar proliferation. Output rates increased, then plateaued at a higher level than during A1. This higher quasi-steady output could represent the transport capacity of a wider channel with mid-channel bars. As in D2, transport rates remained high at the beginning of the degradational run (D3) when bedforms were still migrating downstream, and then decreased rapidly. During most of the flume runs, D_{84} of the sediment output was considerably finer than the D_{84} of the sediment feed,

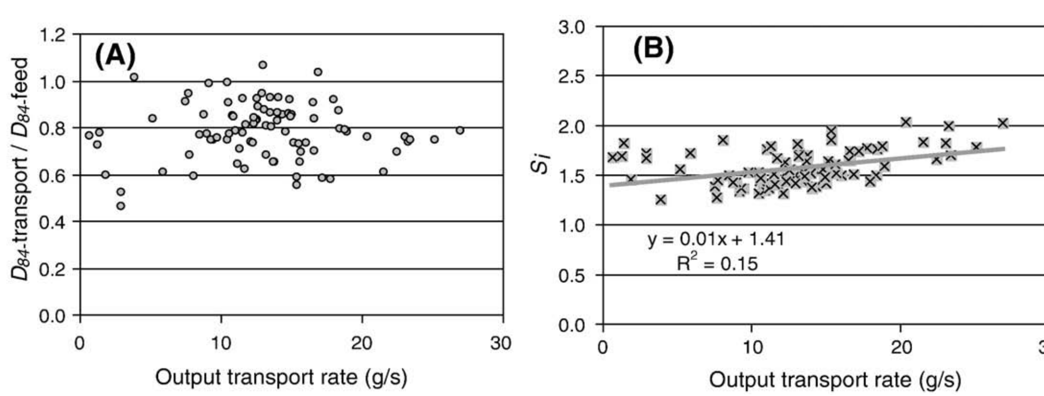

Fig. 12. (A). Transport ratio ($D_{84\text{-transport}}$: $D_{84\text{-feed}}$) of sediment output vs. sediment transport rates. (B) Relation between modified sorting index, S_i, of sediment output and output rate in flume.

Fig. 13. View is looking upstream in the flume at the coarse-grained leading edge of a bedload sheet (indicated by white arrow). Scale bar is divided into decimeter sections and is located about 3 m upstream of the flume outlet. (Photo by Thomas Dunklin.)

indicating that coarser particles accumulated in the flume bed. This must have further limited channel incision and as a result, residual storage increased with each cycle.

In contrast to flumes that typically are short and allow slope to adjust more freely, at the reach scale natural rivers generally have less freedom to vary slope. In A2 and unlike in A1 increased feed rate was accommodated in part by an increase in water surface slope by as much as 10%, to a maximum of 0.0132. After this peak, slope decreased slightly, which may indicate that the channel had reached the maximum accommodation needed to transport the high sediment feed. Slope decreased during the degradation cycles, and stabilized at 0.0125 at the end of the runs, 4% higher than the original bed slope of 0.012. In channels that are free to migrate across a floodplain, channel slope can adjust through both changes in bed elevation and sinuosity, and in these cases changes in slope can be a primary response variable (Eaton and Church, 2004). Increased sinuosity tends to maximize the resistance of the fluvial system (Eaton et al., 2004). However, sinuosity in the flume was low; typically 1.02 to 1.04, and channel migration was limited by the flume walls. Consequently, changes in slope were related to changes in bed elevation rather than sinuosity as sediment was stored or eroded. This is similar to the Redwood Creek example, in which sinuosity is low and a narrow valley is confined by steep banks. Over the long reaches studied in the field (>50 times the channel width), it is difficult to change slope significantly except in pronounced depositional zones or where the valley is wide enough that sinuosity can change.

Other similarities in response between model and prototype lend credence to conclusions about behavior that cannot be observed easily in the river. For example, facies mapping in the Emerald Creek reach in 1989 showed that lateral zones of coarse particles were beginning to form along the margins of this degrading reach (Lisle and Madej, 1992, Figure 13.3), but these zones were not contiguous. During degradational cycles in the flume, zones of coarser particles also formed along the channel margins and were immobile by the end of the runs. Bedload sheets were commonly observed in the aggrading reach of Redwood Creek during low flow when the sheets were immobile. They displayed the same particle-size patterns as in the flume, but the leading edge of the waves was about 10 coarse-particles high. Because the river was very turbid at high flow, the rate of movement of bedload sheets could not be observed. The relative relief ratios of the waves (water depth: height of wave) were similar for the flume (10) and Redwood Creek (7.5).

5.2. Transport-storage relations

Lisle and Church (2002) concluded that when viewed over wide ranges of variability of sediment stage, gravel channels can be expected to have some form of a positive relation between sediment transport and storage volume. In degrading experimental channels, these relations commonly exhibit two phases related to sediment transport conditions: phase I conditions are associated with initially high in-channel sediment supply and are typified by high mobility, weak armoring, and non-selective transport; phase II conditions are associated with decreased sediment supply and are typified by lower mobility, stronger armoring, and selective transport. Phase I is marked by widely fluctuating transport rates associated with migrating bedforms, and phase II is marked by steadily decreasing transport rates as armoring strengthens.

The flume experiment, which included both aggradational and degradational cycles, did exhibit an overall positive relation (Fig. 14), but in detail, relations for aggradation and degradation were inconsistent. Full aggradation–degradation cycles exhibited hysteresis whereby transport rates during aggradation plateaued after attaining phase I conditions and transitions in bar morphology, and initially increased and then decreased sharply during degradation as the channel armored (phase II). The pronounced changes in channel behavior when the feed rate was changed suggests that transport capacity responds immediately to changes in supply, mostly through selective transport of bed-surface material, although the response is conditioned at a larger scale by channel morphology associated with filling or evacuation of sediment storage. The shortness of the sediment-feed flume may have forced adjustments that were more rapid and pronounced than would occur in a natural channel.

The coarsening of the Redwood Creek and flume channels in response to lower sediment supply is comparable to coarsening in East Prairie River, Alberta where straightening of the channel increased transport capacity (Talbot and Lapoint, 2002a). Model simulations showed a downstream progression of degradation, coarsening, and reduced transport rates (Talbot and Lapoint 2002b).

Adjustments in armoring to sediment load in both Redwood Creek and the flume were limited by the degree of sorting of sediment (graphic standard deviation, φ, about 1.6). Consequently, the sensitivity of channel bed elevation to variations in sediment supply may be greater than that in channels with poorer sorting (Lisle and Church, 2002). Both cases exhibit evidence of phase I transport capacity, where high sediment loads severely weaken armoring, and further adjustments to high sediment loads would be expected to be accomplished through changes in gradient, channel morphology, and aggradation. In Redwood Creek, both the aggrading and degrading reaches have weak armoring, although surface particle size of the degrading reach has increased significantly over two decades. In the flume, armoring remained weak during both aggradation and degradation phases,

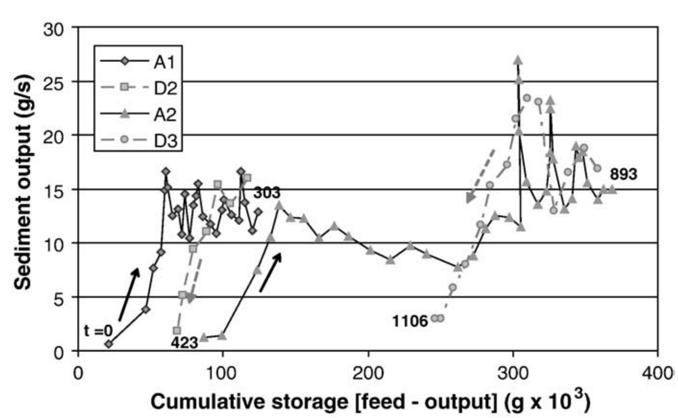

Fig. 14. Relation between sediment storage and transport capacity of flume channel during aggradational and degradational cycles. The direction of time is shown by arrows, proceeds from left to right during aggradational cycles as storage volume increases, and from right to left during degradational cycles as storage volume decreases. Cumulative time, in minutes, at the beginning and ending of the cycles are shown on the graph. The cumulative change in storage was computed as (sediment feed − sediment output).

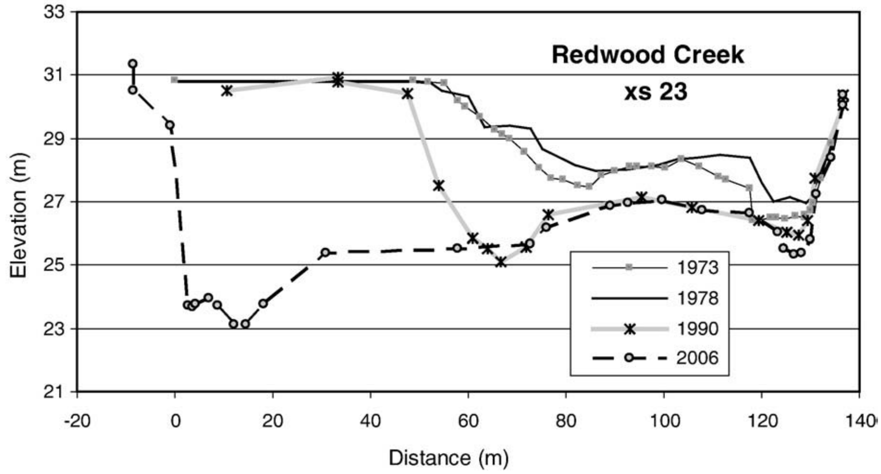

Fig. 15. Cross-sectional change in Redwood Creek near Emerald Creek, 1973 to 2006 at cross section 23 (xs 23).

although similarly, the bed surface coarsened after the load was reduced. The large range of aggradation and degradation (i.e., sediment stage) that has been observed in Redwood Creek and in the model experiment, but is uncommon in systems not having large and variable rates of sediment production, is consistent with the limited adjustment of bed mobility under phase I conditions.

However, bedload sheets provide another mechanism to enhance bed mobility. In our flume experiment, bedload sheets formed in the intense transport zones of the aggrading channel after the bed became finer and output rates were high. Bedload sheets are associated with high mobility of fine as well as coarse particles (Iseya and Ikeda, 1987; Whiting et al., 1988; Seminara et al., 1996), and their presence in both the flume and Redwood Creek is consistent with high transport capacity during phase I conditions. The presence of bedload sheets is apparently an easily identifiable indicator of high sediment loads in gravel-bed channels.

Erosion of sediment stored on floodplains and in terraces typically persists long after a channel has reestablished grade (James, 2006). This concept was examined by assessing how much of the flume bed exhibited aggradation or degradation under different sediment feed rates and how much sediment was evacuated during the degradation phases. The area of the channel bed involved in significant fill or scour differed during the runs. The area exhibiting degradation during D3, following a high-feed aggradational run, was greater than that during D2, following a moderate-feed run, although excess sediment was not fully removed during D3. Although more sediment was eroded from the flume bed during D3 (~72,000 g) than during D2 (~31,000 g) (Fig. 3), the D2 run removed a greater proportion of the aggraded material (85% vs. 55%). This sediment output is equivalent to an average bed lowering of 8 mm for D3 as opposed to 3.5 mm for D2. As the channel incised, the flow could no longer access sediment stored on the terrace remnants. Also, lateral erosion of flood deposits was limited by a lack of channel wandering and ceased entirely before sediment transport stopped as armoring strengthened. This implies that increases in sediment storage may persist long after large aggradational events and that the channel condition left after an aggradation–degradation cycle predisposes the channel response during the next cycle. Such long-term storage of off-channel deposits is documented in Redwood Creek (Kelsey et al., 1987) and other channels (Nakamura, 1986; James, 2006) and was observed as remnant terraces left after degradation of an experimental channel (Lisle et al., 1993). Residual storage manifests a poorly mixed sediment reservoir and a non-linear transport-storage relation (Nakamura and Kikuchi, 1996; Lancaster and Casebeer, 2007; Lisle, 2007).

5.3. Implications for river management

Water quality standards promulgated by regulatory agencies commonly include targets for median particle size diameter, and textural fining of a gravel-bed channel is commonly used as an index of sediment impairment (NCRWQCB, 2006.) Bed texture changes have biological as well as physical implications because the substrate provides spawning gravels for fish and habitat for benthic macroinvertebrates. Textural response to changing sediment supply was consistent in direction in both the flume and in Redwood Creek; however, the flume experiment also indicated that sequencing of events may be important. The channel bed during D3 did not coarsen as much as during D2, suggesting that after severe aggradation a

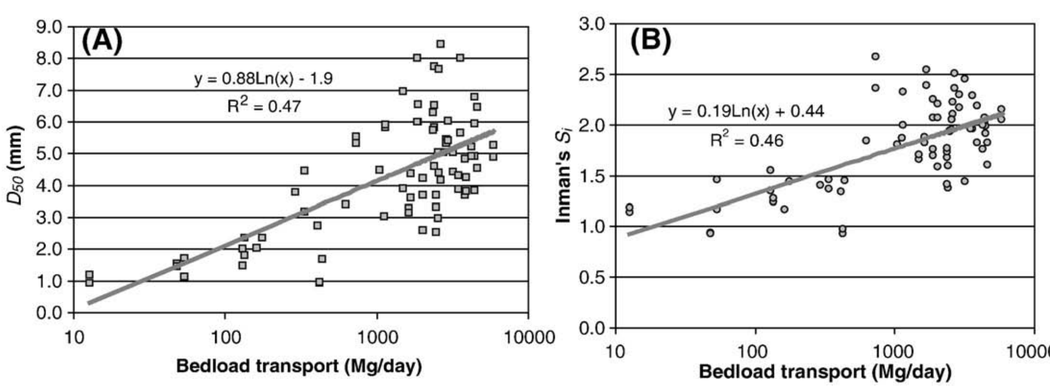

Fig. 16. (A). Relation between median particle size D_{50} of sediment output and bedload transport rates in Redwood Creek at Orick, CA. (B) Relation between Inman's sorting index of sediment output and bedload transport rates in Redwood Creek at Orick, CA.

Table 4
Channel responses during aggradational (A) and degradational (D) cycles. RWA and RWD refer to aggradation and degradation in Redwood Creek

Cycle	Channel storage	Output rate	Channel width (lateral erosion)	Planform	$D_{50\text{-transport}}$	$D_{84\text{-transport}}$	Bed texture	Water surface slope	Bed roughness	Bed relief
A1	Moderate increase	Moderate, < feed rate	Width ~constant	Single-thread channel	$\sim D_{50\text{-feed}}$	$< D_{84\text{-feed}}$	Unarmored	~Constant	Smoother	Subdued
D2	Moderate decrease	Moderate, then << feed rate	Width ~constant	Single-thread channel	$< D_{50\text{-feed}}$	$\ll D_{84\text{-feed}}$	Strongly armored	Decreased	Rougher	Increased
A2	Large increase	Moderate, then high, with wide fluctuations	Width increases	Mid-channel bars	$\sim D_{50\text{-feed}}$	$< D_{84\text{-feed}}$	Unarmored	Increased, peaked, then slight decrease	Smoother	Very subdued
D3	Moderate decrease	Moderate, then decreased rapidly	Channel remains wider	Single-thread channel	$\ll D_{50\text{-feed}}$	$\ll D_{84\text{-feed}}$	Armored	Decreased, then constant	Rougher	Increased
RWA	Large increase	Unknown	Width increases	Mid-channel bars	Unknown	Unknown	Unarmored	Constant	Smoother	Very subdued
RWD	Moderate decrease	Unknown	Channel remains wider	Single-thread channel	Unknown	Unknown	Weakly armored	Constant	Rougher	Increased

channel may not return to predisturbance conditions. Also, in the flume setting, $D_{84\text{-surface}}$ seemed more responsive to variations in sediment supply than $D_{50\text{-surface}}$, but regulatory targets usually only focus on the median particle size. The flume results, documenting the rapid decline in bedload transport and rates of channel incision as the channel bed became armored, suggests that stronger armoring in Redwood Creek will signal a stabilizing channel. Flume results coupled with field observations also suggest that other channel attributes such as channel planform and rugosity could be used to indicate earlier phases of channel recovery preceding increased armoring. Whatever indicator is used is probably more effective in establishing trends than in setting uniform target values that do not take into account background conditions such as geology that influence channels and sediment transport regimes.

Channel recovery following disturbances can be defined in several ways. Wolman and Gerson (1978) characterized recovery in terms of channel width following large storm events. A return to former channel bed elevation or grade has also been used (James, 1999). Regulatory agencies commonly employ a return to a low sediment transport rate or a specific dominant particle size as recovery targets. The present study shows that "channel recovery" following high sediment supply, using the definitions above, was not clear cut. Following the moderate aggradation cycle (A1), the experimental channel was able to recover in terms of bed elevation, channel width, dominant bed surface particle size, and sediment transport rates. If channel recovery is defined as a return to a previous bed elevation or channel width, the channel did not fully recover from the high sediment loading run (A2); but if recovery is defined as a return to an armored, single-thread channel with a similar cross-sectional area as the original and with low sediment transport rates, the channel did recover. This type of recovery can be defined as a return to a certain state related to sediment supply and transport capacity rather than a particular channel geometry.

6. Conclusions

Moderate and high levels of sediment loading initiated cycles of aggradation in a flume channel, and when sediment supply was subsequently decreased, the channel degraded. Transport rates varied between aggradation and degradation cycles, and changes in sediment feed rate were accommodated through bed texture and channel morphologic changes. Bed surface texture became finer under moderate feed rate and became even finer during high feed rate. The bed coarsened during both degradation cycles, but the coarsening was not as strong following major aggradation associated with high sediment feed. Bed textural changes in the flume mimicked those observed in Redwood Creek during aggradation and degradation.

Flume experiments modeled after natural channels can help confirm interpretations of observations that are limited by challenges of field conditions and allow exploration of processes in more detail. Similarities in observations of channel response to varying sediment loads in Redwood Creek and the flume give confidence in building conclusions from these two viewpoints. The similarities include (i) overall channel form and degree of armoring; (ii) bed-surface fining and bedform smoothing during aggradation, and coarsening and bedform roughening during degradation; (iii) greater selective transport during low transport rates. These similarities help to validate the applicability of observations seen only in the flume to Redwood Creek. The primary of these is that there is a positive relation between sediment transport rate to the volume stored, but conditions governing transport capacity at a given storage volume vary between aggradational and degradational phases.

The flume results provided a clear example of transport-storage relations during aggradational and degradational phases, and to a large degree they mimicked results from field studies. Transport capacity adjusted to the rate of sediment supply, with changes in storage and bed mobility as an outcome. The flume clearly showed an important connection between sediment feed rates and channel adjustments, and these experiments elucidate the importance of sediment inputs on channel conditions for biota. Future research will focus on the spatial relations among transport capacity, sediment storage, and bed mobility in various sediment reservoirs along a river, under a range of sediment sorting conditions. Understanding adjustments to varying sediment loads on a finer spatial scale will provide the basis for understanding degrees of channel recovery in different reaches of a river network.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geomorph.2008.07.017.

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