

# Transport and storage of bed material in a gravel-bed channel during episodes of aggradation and degradation: a field and flume study

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**ABSTRACT:** The dynamics of sediment transport capacity in gravel-bed rivers is critical to understanding the formation and preservation of fluvial landforms and formulating sediment-routing models in drainage systems. We examine transport-storage relations during cycles of aggradation and degradation by augmenting observations of three events of channel aggradation and degradation in Cuneo Creek, a steep (3%) gravel-bed channel in northern California, with measurements from a series of flume runs modeling those events. An armored, single-thread channel was formed before feed rates were increased in each aggradation run. Output rates increased as the channel became finer and later widened, steepened, and braided. After feed rates were cut, output rates remained high or increased in early stages of degradation as the incising channel remained fine-grained, and later decreased as armoring intensified. If equilibrium was not reached before sediment feed rate was cut, then a rapid transition from a braided channel to a single-thread channel caused output rates for a given storage volume to be higher during degradation than during aggradation. Variations in channel morphology, and surface bed texture during runs that modeled the three cycles of aggradation and degradation were similar to those observed in Cuneo Creek and provide confidence in interpretations of the history of change: Cuneo Creek aggraded rapidly as it widened, shallowed, and braided, then degraded rapidly before armoring stabilized the channel. Such morphology-driven changes in transport capacity may explain the formation of flood terraces in proximal channels. Transport-storage relations can be expected to vary between aggradation and degradation and be influenced by channel conditions at the onset of changes in sediment supply. Published in 2011. This article is a US Government work and is in the public domain in the USA.

**KEYWORDS:** bed material transport; sediment storage; aggradation

## Introduction

Sediment eroded from hillslopes and delivered to valley bottoms is sculpted by erosion and deposition to give form and structure to fluvial features. Episodic sediment production in mountainous terrain creates highly variable sediment supply, but downstream transfer is moderated by the capacity of the flow to access and transport sediment stored in terraces, floodplains, channel bars, and channel beds (Kelsey *et al.*, 1987; Benda and Dunne, 1997; Brierley and Fryirs, 1999; Lisle and Church, 2002; Coulthard *et al.*, 2005; Wilkinson *et al.*, 2006). Suspended sediment commonly comprises most of the total sediment load and is stored primarily in floodplains, but erosion and deposition of bed material, as well as bank accretion by suspended sediment, mold the channels that transfer all sizes of sediment through the system and from channel to floodplain. Herein we focus on bed material, whose movement is limited by transport capacity in most dispersive systems. Transport capacity is defined by Gilbert (1914, p. 35) as ‘the maximum load of a given kind of debris which a given stream can transport’. Lisle and Church (2002) interpret ‘kind of debris’ to specify properties such as grain-size distribution that influence sediment mobility; they approach natural flow variability by focusing on sediment rating

relations that operate under the existing flow regime. In gravel-bed channels, this necessarily involves the competence as well as the capacity of flow of variable magnitude to entrain and transport particles of a wide range of sizes. Transport capacity, as codified by relations between transport rate and a parameter for the impelling force, has been assumed to be constant in some sediment-routing models (e.g. Pickup *et al.*, 1983; Benda and Dunne, 1997; but see Cui and Parker, 2005). However, this assumption is suspect because variables that quantify channel morphology and texture and appear in bed load transport formulae (e.g. depth, velocity, gradient, roughness) have been observed to respond to variations in imposed load (Andrews, 1979; Lisle, 1982; Dietrich *et al.*, 1989; Madej, 2001; Parker *et al.*, 2008; Pitlick *et al.*, 2008; Eaton and Church, 2009; Nelson *et al.*, 2009). Study of the dynamics of sediment transport is motivated by the need to improve predictions and interpretations of the downstream effects of large sediment inputs in disturbed systems, and sediment routing in general.

Lisle and Church (2002) suggest approaching basin-scale sediment routing by using the conceptual model of Church (1983), wherein a channel network is composed of a series of sediment reservoirs with uniform hydraulic and geomorphic characteristics. Lisle and Church (2002) do not present a routing

model *per se*, but indicate an approach that could guide the selection of computational nodes. A sediment reservoir contains sediments of the channel, floodplain and modern terraces. As sediment supply varies, changes in storage and transport from one reservoir to the next are mediated by dynamic transport-capacity conditions that are unique to each reservoir. Transport capacity does not respond functionally to storage volume or channel elevation, but rather to changes in channel attributes influencing mobility, as changes in load force adjustments in transport, erosion, and deposition. These attributes include armoring, channel morphology, planform, and local gradient. Field studies and laboratory experiments analyzed by Lisle and Church (2002) are limited to degrading channels with decreased sediment supply. In their examples, variations in flow were insignificant or their effects on transport rate could be resolved analytically. Under these conditions, storage and transport rates decrease exponentially with time (approximately), implying a positive linear relation between transport rate and storage.

Two distinct phases of transport can be recognized in transport-storage relations of degrading reservoirs (Lisle and Church, 2002). Phase I occurs in early stages of degradation of a filled channel with high sediment supply, and is typified by weak armoring. Changes in supply are accommodated by small changes in average transport rate and large changes in storage. The absence of armoring has been used as an indication of the achievement of transport capacity by sediment supply (Dietrich *et al.*, 1989). In Phase II, mobility is reduced by development of channel armor, surface structure, and increased form roughness. Transport-storage functions during Phase II take the form of a generally positive linear relation. Transport rates are high at the maximum storage volume at the onset of degradation and then decrease as armoring and surface structure strengthens and roughness increases.

In this paper, we investigate transport-storage relations during full cycles of aggradation and degradation in an experimental channel that models a natural channel where such cycles are documented by repeated topographic surveys. We find that although transport-storage relations are generally positive during both aggradation and degradation, the trends do not follow the same pattern and are contingent on channel conditions leading from one state to the other. Shallowing of the flow during advanced stages of aggradation can suppress transport capacity and promote deposition; incision during early stages of degradation can enhance transport capacity and rapidly deplete storage. The resulting hysteresis in transport-storage relations is consistent with observations of deep aggradation and rapid incision in the prototype channel. Our results have implications for interpreting stratigraphic records of sediment reservoirs and for formulating sediment-routing models that employ reservoir theory. This study is most relevant to gravel-bed channels that receive large sediment pulses.

## Field Study

### Site conditions and history

Cuneo Creek is a steep gravel-bedded stream, draining 10.8 km<sup>2</sup> of the northern California Coast Range in the Bull Creek watershed, which is the downstream-most major tributary to the South Fork of the Eel River. The study reach of 1 km represents a single sediment reservoir with active channel, floodplain, and terraces. It lies downstream of the junction of three major tributaries and extends to the junction with Bull Creek (Figure 1). Channels upstream of the study reach are steeper and more confined and show much less capacity for sediment storage. Channel gradient varies around 3% as the channel aggrades and degrades. Armored bed material includes cobbles and boulders but flood deposits are much finer. Active channel width varies widely

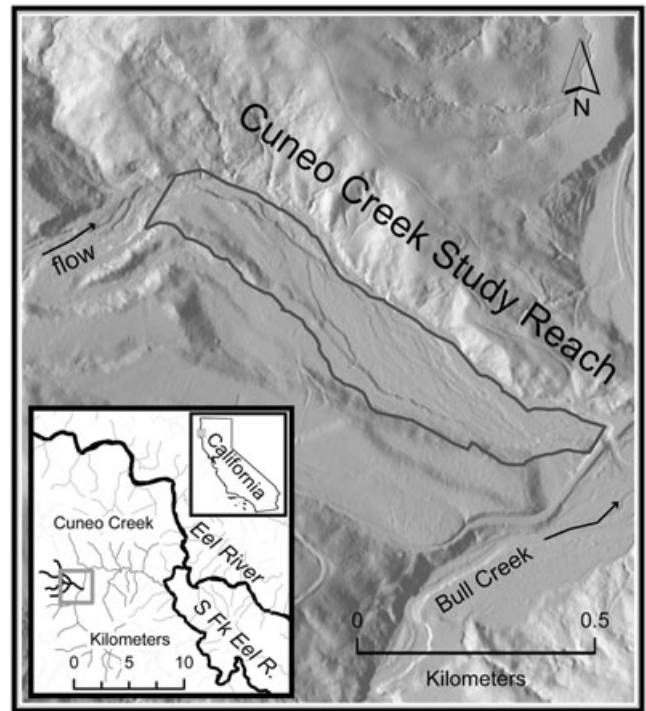


**Figure 1.** Location of study reach in Cuneo Creek, California. LiDAR survey was performed in summer 2002.

from about 10 to 50 m with transitions between single-thread and braided planforms.

The Eel River drainage basin has some of the highest rates of sediment production in the coterminous United States as a result of steep topography generated by high uplift rates and erodible, weakly consolidated sedimentary rock of the Franciscan and Yager terrains combined with high rates of precipitation concentrated in the winter months (Brown and Ritter, 1971). The location of Bull Creek near the zone of highest uplift rates in the basin (Merritts and Bull, 1989; Lock *et al.*, 2006) and evidence of extensive erosion and sedimentation (LaVen, 1987; Short, 1993) indicate that Bull Creek is among the sub-basins responsible for the exceptional sediment yield of the Eel River.

Upper portions of the Bull Creek watershed, including Cuneo Creek were cleared for grazing and farming by the mid-twentieth century, and much of the remaining old-growth forest of Douglas fir (*Pseudotsuga menziesii*) and coastal redwood (*Sequoia sempervirens*) was depleted by extensive clear-cutting and wildfires from 1946 to 1966 (Short, 1993). Large regional floods in 1955, 1964 and 1997 produced extensive mass wasting and gullying, and channels aggraded and widened throughout regional river systems (Kelsey, 1980; Madej and Ozaki, 1996, 2009; Sloan *et al.*, 2001) and caused three episodes of aggradation in Cuneo Creek (Lowdermilk, 1961; LaVen, 1987; Short, 1993; Smith, 2004).

The 1955 flood overloaded the channels with landslide-derived sediment and caused widespread channel aggradation and widening (Short, 1993). Cuneo Creek was one of the largest sources of sediment in the Bull Creek watershed (Lowdermilk, 1961) and was severely affected (Figure 2), aggrading approximately 2.4 m (Thorp, 1959). Dense vegetation was stripped from the stream channel and floodplain.

The 1964 storm again delivered large volumes of hillslope sediment to channels such that the 1955 deposits were mobilized or buried (Figure 2). The combined aggradation from the 1955 and 1964 storms totaled 5 m at the Cuneo Creek bridge just upstream of the junction with Bull Creek (Short, 1993).

The peak flow in 1964 remained the highest on record in Bull Creek (US Geological Survey Gauge # 11476600) until

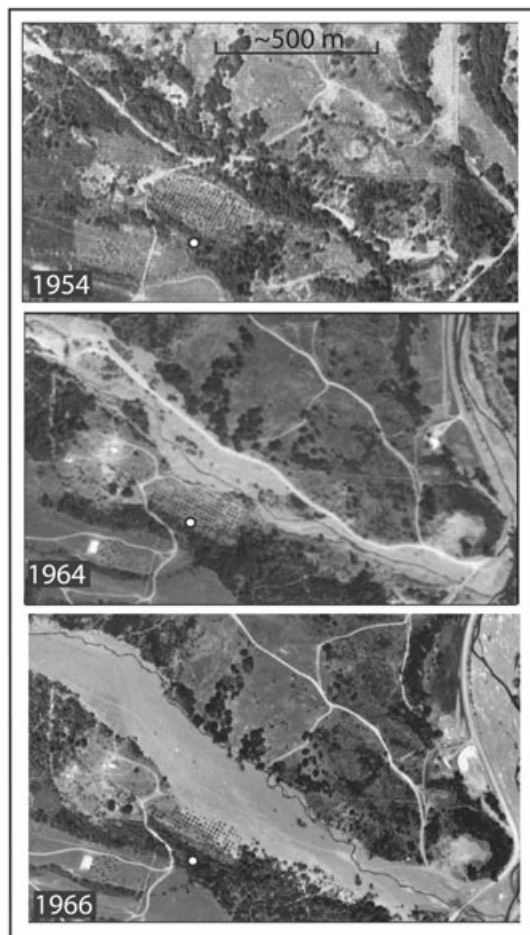


**Figure 2.** Aerial photographs of the vicinity of the study reach taken in 1954, 1964, and 1966.

December 31, 1996 (Figure 3). In the intervening period, the Cuneo channel degraded (Short, 1993) despite the occurrence of several large storms, particularly those in 1974 and 1983 (as recorded in Bull Creek). The 1997 storm had a larger peak flow than the 1964 flood, but sediment delivery was significantly lower and caused aggradation within the limits of the 1964 flood deposits (Hall, 2000).

These three major storms resulted in three cycles of aggradation and degradation. Degradation is apparently continuing at the time of this writing as indicated by new exposures of stumps and old cohesive floodplain deposits pre-dating 1955. Each cycle was unique in initial conditions (channel geometry and

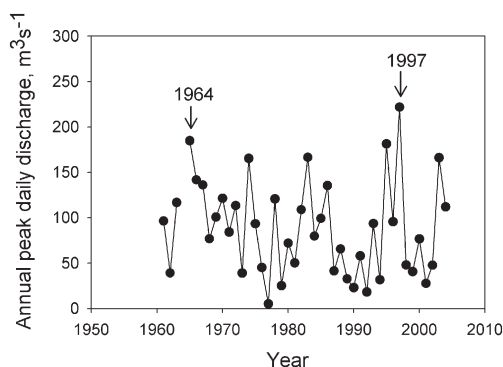


**Figure 3.** Annual maximum daily discharge in Bull Creek (US Geological Survey Gauge # 11476600) water years 1961–2004. The gauge is approximately 3 km downstream of the junction with Cuneo Creek. The arrows mark aggradational events in calendar years 1964 and 1997.

planform, surface texture, and slope), as well as the magnitude of sediment delivery and aggradation.

## Methods

Data available to document channel change in the first cycle (1955–1964) are limited to qualitative information except for Thorp's (1959) estimate of aggradation depth. The initial storage volume left by the 1964 flood cannot be measured directly due to a lack of post-1955 surveys, but maximum aggradation can be estimated by interpolating between remnant terraces and assuming that the valley fill was essentially planar, as indicated by aerial and ground photographs. LaVen (1987, p. 26) describes Cuneo Creek in 1976, after it had already degraded significantly, as a 'poorly defined, braided stream flowing over massive, nearly level alluvial fill'. In 1976, the California State Department of Parks and Recreation classified and surveyed 11 channel cross-sections over a 1-km reach of Cuneo Creek upstream of its mouth. Ten of these were resurveyed in 1982, 1983, 1985, 1986, 1998, 2001, and 2003 (LaVen, 1987; Short, 1993; Hall, 2000; Smith, 2004). Maximum levels of aggradation in 1997 were reconstructed from channel surveys of remnant flood terraces in 1998 (Hall, 2000). Together with mapping of stream terraces in 2003 (Smith, 2004), these data are used to quantify changes in channel morphology and sediment storage between 1964 and 2003.

Development of a transport–storage relation requires measurements of stored sediment volume and rate of bed-material transfer from a sediment reservoir. Stored volume is measured at the beginning of each time period, and transport is represented by the rate of loss of stored sediment. These quantities were computed by differencing topographic surfaces, including channel, floodplain and terraces, at each time step. Digital elevation models were built from cross-section data, surveys of remnant stream terraces and aerial photographs (Smith, 2004).

Bed-material transport includes both the net sediment taken from storage as well as throughput material (sediment that entered and exited the reach within the time period). For this study, throughput was neglected and computed transport only includes the net volume of sediment removed from the study reach during each time period (the 'bed material transfer' volume). This approximation is supported by the strong shift in sediment sources after episodes of aggradation from hillslopes to sediment reservoirs, of which the study reach is the most voluminous. Bed-material transfer rate is computed by dividing bed-material transfer volume by the number of days of 'geomorphically significant discharge' (flows capable of fully mobilizing the stream bed) and expanding the time scale to years. A minimum geomorphically significant discharge was estimated with bedload transport and water discharge measurements in Cuneo Creek in water year 2001, and the flow record was expanded to the study period by using the flow record of the Bull Creek gauging station and correlating values of discharge measured in Cuneo and Bull Creeks in water year 2002. The computed discharge in Cuneo Creek is  $2.3 \text{ m}^3 \text{ s}^{-1}$  and has an exceedance probability of 10% from 1960 to 2002. It was capable of moving particles as large as 50 mm ( $> D_{84}$ ), and the grain size distribution (GSD) of the bedload was roughly equivalent to the bed material GSD measured at cross-section 25 +68 (Table I), indicating that the bed was fully mobile.

Changes in bed-surface particle size are used to quantify the response of armoring to changes in sediment supply. The degree of channel armoring is computed as the ratio of the median particle size of the bed surface ( $D_{50\text{sur}}$ ) to the median size of the subsurface, or bed-material ( $D_{50\text{sub}}$ ) (Dietrich *et al.*, 1989). Surface GSDs were measured in 1986 before the 1997 event (Short, 1993) and three times afterward in 1998 (Hall,

**Table 1.** Particle size of surface and subsurface bed material in Cuneo Creek.

| Year              | 15+00           |               |                                     | 25+68               |               |                                     | 38+71         |               |                                     |
|-------------------|-----------------|---------------|-------------------------------------|---------------------|---------------|-------------------------------------|---------------|---------------|-------------------------------------|
|                   | $D_{50}$ (mm)   | $D_{84}$ (mm) | $D_{50\text{sur}}/D_{50\text{sub}}$ | $D_{50}$ (mm)       | $D_{84}$ (mm) | $D_{50\text{sur}}/D_{50\text{sub}}$ | $D_{50}$ (mm) | $D_{84}$ (mm) | $D_{50\text{sur}}/D_{50\text{sub}}$ |
| <i>Surface</i>    |                 |               |                                     |                     |               |                                     |               |               |                                     |
| 1986 <sup>a</sup> | —               | —             | —                                   | —                   | —             | —                                   | 32            | 128           | 1.3                                 |
| 1998 <sup>b</sup> | 8.3             | 106           | 0.6                                 | 5.6/16 <sup>c</sup> | 80/76         | 0.7/1.9                             | 19            | 40            | 0.8                                 |
| 2001              | 27              | 199           | 1.8                                 | 23                  | 104           | 2.6                                 | 39            | 138           | 1.6                                 |
| 2004              | 38              | 342           | 2.5                                 | 45                  | 202           | 5.3                                 | 51            | 155           | 2.1                                 |
| <i>Subsurface</i> |                 |               |                                     |                     |               |                                     |               |               |                                     |
| 1999              | 15 <sup>d</sup> | 126           | —                                   | 8.4 <sup>e</sup>    | 36            | —                                   | 24            | 74            | —                                   |

Note: Sizes smaller than 0.5 mm are excluded from subsurface samples.

<sup>a</sup>Short (1993).

<sup>b</sup>Hall (2000).

<sup>c</sup>Sampled at 20+95 and 29+68.

<sup>d</sup>Sampled 60 m upstream of cross-section 15+00.

<sup>e</sup>Average of three samples from 20+96 to 29+68.

2000), 2001 and 2004 (Smith, 2004). Locations of the counts were not exactly duplicated partly due to lateral channel migration, but differences between locations are not significant enough to affect comparisons between data sets (Smith, 2004). Subsurface bed material was sampled at three locations distributed longitudinally in the study reach (cross-sections 13+00 and 38+71 and between cross-sections 20+95 and 25+46; Smith, 2004). Bulk samples were taken from bar deposits left by the 1997 flood, which we use to represent the bed material load. Sizes < 0.5 mm are not included in GSDs.

## Results

### Changes in channel storage

The largest decrease in sediment storage occurred in the first 12 years following aggradation (1964–1976). Bed elevation decreased across most of the valley width, leaving only isolated remnants of the 1964 surface on the edges of the valley bottom (Figure 4). Depth of degradation varied across the surface and generally decreased downstream. Between 1976 and 1982, degradation continued, with deep incision (> 3 m) extending over most of the reach. Thirteen percent of the volume change was positive (fill); 87% was negative (scour). Between 1982 and 1986, channel incision declined and lateral migration became dominant in storage depletion (Figure 5). Channels scoured and filled during this period but no significant changes in channel morphology occurred.

Net sediment removal was interrupted by another aggradation event in water year 1997. Aggradation was greatest (2–3 m) within the channel between cross-section 10+00 and cross-section 29+68 and decreased to < 1 m downstream of cross-section 29+68 (Figure 4). Adjacent valley walls and earlier flood deposits were eroded. The following year (1998), the Bull Creek stream gauge recorded nearly the same volume of runoff as the previous water year, but peak flows were smaller. Approximately 92% of the net storage gained in Cuneo Creek from the 1997 event was removed in 1998. However, eroded material was not limited to the 1997 flood deposits; rather, the channel avulsed and a new channel was cut through older deposits from just upstream of cross-section 20+95 to cross-section 35+00. Subsequent surveys showed no significant change in channel shape from 1999 to 2002. During water year 2003, high water inundated and mobilized the 1997 aggradation surface. Significant channel widening and lateral migration was observed in eight of the 10 measured cross-sections, with more than 15.2 m of lateral erosion occurring over 67% of the channel length. A primary lane of transport appears to have been

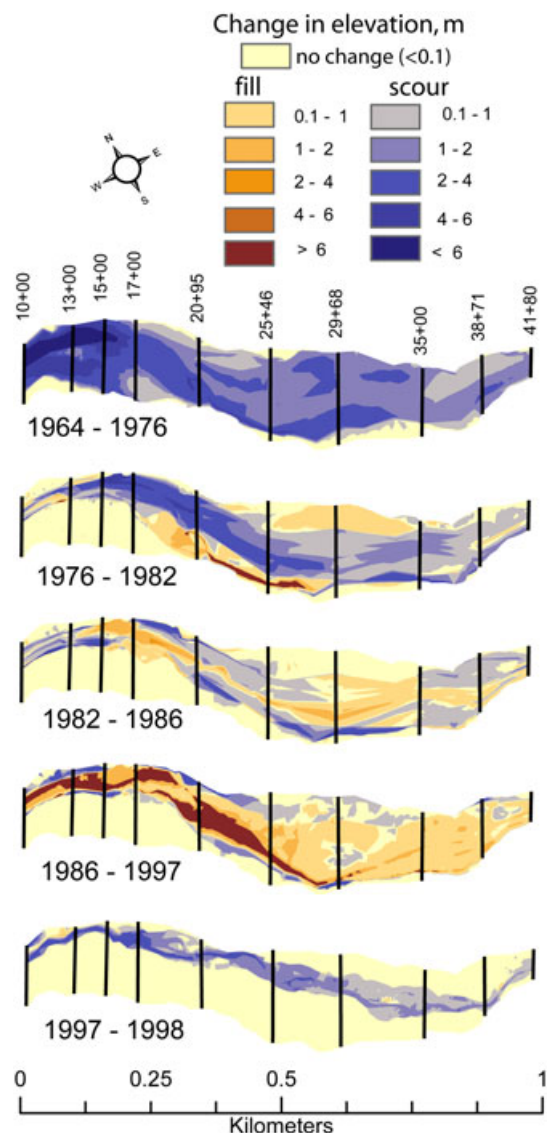


**Figure 4.** Changes in sediment storage in the Cuneo Creek study reach, 1964–1986.

maintained, and average bed elevation of the thalweg through the reach decreased by only 0.024 m, which is approximately equal to the dominant grain diameter of the subsurface.

Changes in elevation generally decreased downstream as the aggradational wedges measured from terraces dating from 1964

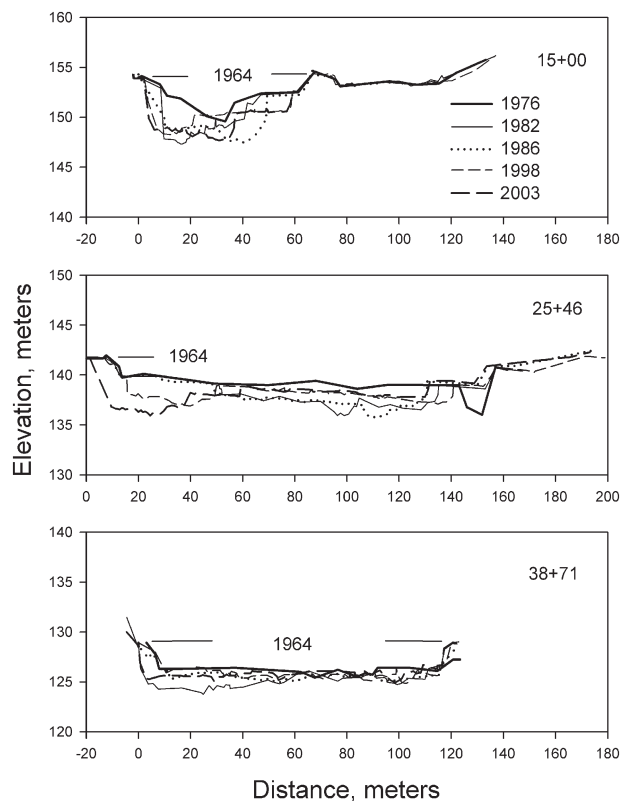


**Figure 5.** Representative Cuneo Creek cross-sections, 1976–2003. Cross-section names are distances downstream in feet. Data provided by LaVen (1987), Short (1993), Hall (2000), Smith (2004). The 1964 terrace levels are indicated.

to 1998 and 1997 to 1998 degraded (Figure 6). Longitudinal terrace profiles are weakly concave, but linear fits indicate a decrease in average gradient of 26% from 1964 to 1998 and 14% from 1997 to 1998.

#### Particle size

Aggradational deposits exposed in cut banks are dominated by fine to medium gravel in a sandy matrix and appear much finer than the cobble- and boulder-dominated surfaces of channels cut in reworked material. This difference indicates that selective transport during incision led to formation of much coarser active channel surfaces. Bulk samples and pebble counts bear this out (Table I). The bed surface was generally coarser than the subsurface but the degree of armoring ( $D_{50\text{sur}}/D_{50\text{sub}}$ ) decreased after

the 1997 flood and then mostly recovered by 2001. Differences in  $D_{84}$  between surface and subsurface material show similar variations. Between 2001 and 2004, the surface at cross-section 15+00 coarsened by one  $\phi$  size class for both  $D_{50\text{sur}}$  and  $D_{84\text{sur}}$ , while the surface at cross-section 38+71 showed no change in  $D_{50\text{sur}}$  and a slight fining of  $D_{84\text{sur}}$  (0.5  $\phi$  size class). The greater coarsening of the upstream location can be correlated with deeper degradation from 1998 to 2004 (Figure 5).

Disintegration of weakly indurated gravel on bars upon exposure to wetting and drying cycles can lead to a fining of the bed surface and increased mobility when the bar is inundated by the next flood. The disintegration of large surface particles probably contributes to the weak armoring observed on flood terraces in Cuneo Creek, but the fragments are apparently winnowed from the annually inundated channel.

#### Transport–storage relations

The total volume of sediment stored in Cuneo Creek cannot be determined precisely due to the lack of a recognizable datum such as valley geometry prior to the 1955 storm. Deposits from the 1955 and 1964 storms are indistinguishable and are collectively called 1964 deposits. These deposits represent the maximum volume of stored sediment in Cuneo Creek, and serve as a datum to examine the pattern of sediment removal. The decrease in sediment storage with time starting with an arbitrary storage volume corresponding with the 1964 datum appears to be exponential during the study period, except for a small peak in 1997 (Figure 7A). An initial storage volume of 400 000 m<sup>3</sup> in the 1-km study reach decays to approximately zero.

Only three points are available to define the transport–storage relation for the degradation period following the 1964 flood (1964–1986), and the points do not show a close fit to a linear relation (Figure 7B). We offer two interpretations. If an exponential decay in sediment storage is assumed, then plots of transfer rate versus storage volume define a linear relation with a slope equal to the exponential coefficient ' $K$ ' (Lisle and Church, 2002), and the scatter in points can be attributed to unmeasured inputs from upstream and differences in flow magnitude that are not accounted for in our exclusion of flows that are judged not to be geomorphically significant. Alternatively, the apparent inflection in the relation is real and indicates a transition from weakly armored conditions (Phase I, sub-horizontal limb) to armoring conditions (Phase II, sloping limb) in the early 1980s. Bed armoring is evident by 1986 (Table I), but considering the long-time period (22 years) since peak aggradation and the nearly featureless channel observed at that time, weak armoring in 1964 could have persisted for some years afterward. Observations of

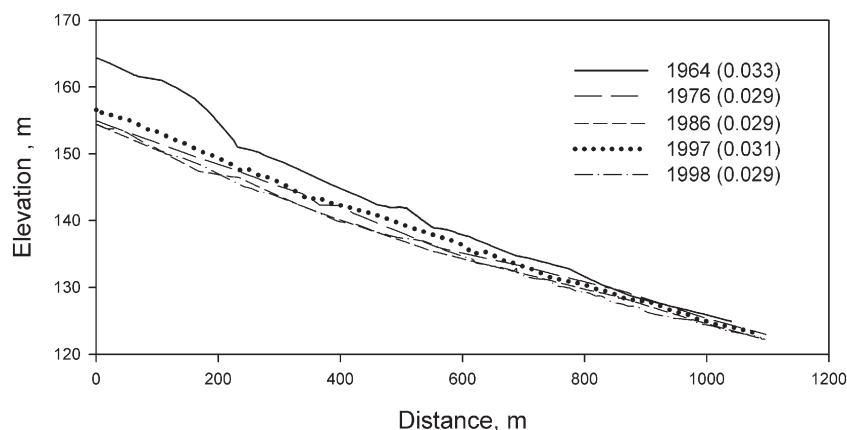


**Figure 6.** Longitudinal profiles of depositional surfaces in Cuneo Creek. Values in parentheses are channel gradients computed from 230 m to 1040 m, excluding the depositional wedge from 0 m to 230 m in 1964.

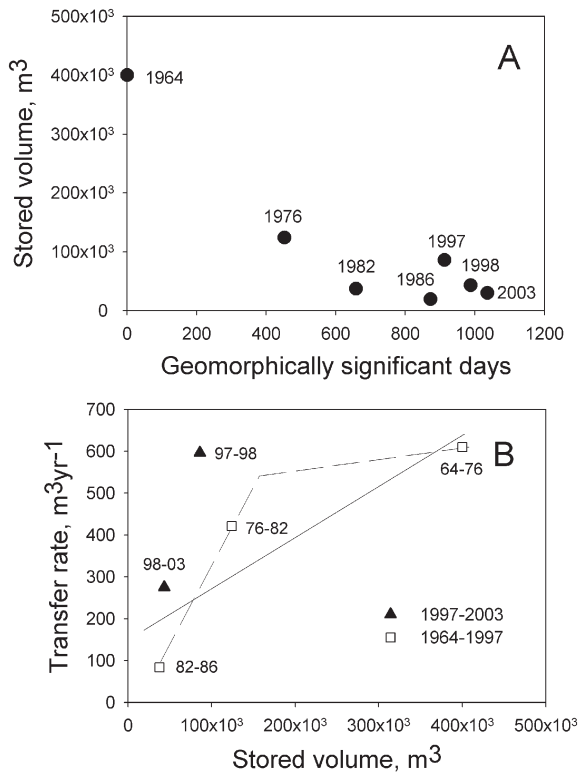


**Figure 7.** Temporal variations in stored sediment in Cuneo Creek: (A) changes in stored volume from 1964 to 2003 [time is measured in geomorphically significant days (cumulative days with discharge exceeding  $2.3 \text{ m}^3 \text{ s}^{-1}$ )]; (B) variation in bed material transfer rate with stored volume. Bed material transfer rate is the net change in stored volume between cross-section surveys divided by the number of geomorphically significant days and expanded to periods measured in years. Solid line represents linear transport-storage model; dashed line denotes two-stage model reflecting initial unarmored (Phase I) conditions followed by armored (Phase II) conditions.

sediment-transport conditions in the flume experiments reported later are intended to test these models.

Transport-storage relations for the last aggradation-degradation cycle (1997–2003) do not conform to those of the previous cycle (Figure 7B). In 1998, the bed was poorly armored and bed-material transfer rates were high and similar to those estimated between 1964 and 1976, when Phase I conditions may have occurred, but the peak storage volume in 1997 was less than it was in 1964. Small changes in storage and significant channel coarsening between 1998 and 2001 suggest that armoring had strengthened by the onset of the water year 1999. Transfer rates decreased in 2002–2003 and the observed armoring is consistent with Phase II conditions then and in 1986. The slope of a transport-storage relation defined by these two points is similar to that of the relation for 1976 to 1986, when Phase II conditions were evident. Higher transfer rates after 1997 may be due to rejuvenation in bed mobility caused by the smaller aggradational episode, as well as noise in either of the relations and errors in the data or scaling of time.

## Flume Experiment

Results of the field study appear to be consistent with transport-storage models developed by Lisle and Church (2002), but data are insufficient to rigorously define the form of a transport-storage function and to investigate adjustments in transport capacity during full aggradation-degradation cycles. Therefore, a simplified scale model of Cuneo Creek was constructed to

examine in detail the transport and storage changes that occur during aggradation events and intervening degradation periods. The experiment consisted of delivering pulsed sediment inputs to the channel while holding a constant discharge that models a moderate transporting flow.

## Experimental procedure and methods

A sediment feed flume 12 m long and 0.76 m wide at the Environmental Resources Engineering Department at Humboldt State University, Arcata, California, was utilized in the experiments. An approximate undistorted Froude model (Smith, 2004) was used to scale discharge and grain size. Scaling of sediment requires a small scale factor to maintain a practical minimum particle size, while optimal discharge scaling requires a larger scale factor to accommodate modeling a channel that is formed within an alluvial bed, rather than a flume-wide channel. A scale factor of 21 yielded a model discharge of  $68 \text{ l min}^{-1}$  ( $2.3 \text{ m}^3 \text{ s}^{-1}$  field equivalent) and a model  $D_{50\text{sub}} = 1 \text{ mm}$  (21 mm field equivalent) with a geometric standard deviation of 1.8 $\phi$ . The range of particle sizes in the sediment feed and flume bed material ranged from 0.25 to 11.2 mm (5–235 mm field equivalent). Grains less than 5 mm in the Cuneo bedload GSD were represented with a 0.25 mm grain in the flume. The field equivalent median grain size is within the range of that measured in Cuneo Creek, but is somewhat coarser than the thickest deposits sampled in the middle of the reach (Table I). The Froude number computed in Cuneo Creek at  $2.3 \text{ m}^3 \text{ s}^{-1}$  is 0.8. Froude numbers computed in the flume ranged from 0.4–0.9 when the channel was single-thread.

The fact that peak flow in Bull Creek in 1964 was equaled or exceeded in later years without such large-scale aggradation indicates that sediment supply to Cuneo Creek controls changes in sediment storage. Accordingly, we varied feed rate to force aggradation and degradation while keeping discharge constant. The feed rate could not be directly scaled due to lack of knowledge of sediment input rates from tributaries of Cuneo Creek. Therefore, sediment feed rates and durations were determined by creating responses in the flume that resembled those observed in the field. In some cases, this resulted in forcing steeper slopes in the flume than were measured in the field.

## Experimental runs

Seven complete aggradation-degradation cycles were modeled (Table II). Aggradation runs were terminated at different degrees of disequilibrium or equilibrium to evaluate the effect of the initial state on subsequent degradation runs. Disequilibrium was allowed because the rapidity of aggradation in Cuneo Creek indicates that equilibrium was not reached throughout the study reach before the channel began to degrade. Degradation runs lasted until equilibrium in sediment input and output was reached in order to mimic conditions that were approached in Cuneo Creek between large sediment pulses and to observe full development of armor layers. The first five sets of runs were used to examine the sensitivity of the transport-storage relation to variations in sediment feed and conditions at the onset of degradation. The last two sets (Runs 6 and 7) were designed to model two cycles of aggradation and degradation between 1955 and 1997. Initial conditions modeled channel conditions before the 1955 event: single-thread, armored, and at equilibrium with a low sediment supply rate (Run 5D). Aggradation in 1955 was simulated with a high feed rate (Run 6A) that ran until all surfaces in the flume were mobilized and/or aggraded, as occurred in Cuneo Creek. The feed rate to model degradation from 1955 to 1964 (Run 6D) was set low enough to initiate channel incision but high enough to model elevated sediment inputs from upstream reaches. This feed rate was

**Table II.** Experimental runs in chronological order.

| Run | Feed rate<br>(cm <sup>3</sup> s <sup>-1</sup> ) | Duration<br>(hours) | Equilibrium<br>(yes/no) | Model<br>period |
|-----|-------------------------------------------------|---------------------|-------------------------|-----------------|
| 1A  | 21.3                                            | 4.2                 | no                      | NA              |
| 1D  | 0                                               | 9.2                 | yes                     | NA              |
| 2A  | 21.3                                            | 6.0                 | no                      | NA              |
| 2D  | 0                                               | 11.8                | yes                     | NA              |
| 3A  | 9.0                                             | 5.7                 | no                      | NA              |
| 3D  | 0                                               | 12.3                | yes                     | NA              |
| 4A  | 6.7                                             | 5.5                 | yes                     | 1997            |
| 4D  | 0                                               | 3.0                 | yes                     | post-1997       |
| 5A  | 9.0                                             | 15.5                | yes                     | NA              |
| 5D  | 2.2                                             | 4.0                 | yes                     | NA              |
| 6A  | 12.0                                            | 5.2                 | no                      | 1955            |
| 6D  | 6.5                                             | 2.75                | yes                     | 1955–1964       |
| 7A  | 12.0                                            | 3.6                 | no                      | 1964            |
| 7D1 | 6.5                                             | 9.3                 | yes                     | 1964–1987       |
| 7D2 | 3.4                                             | 4.2                 | yes                     | 1987–1997       |

Note: 'A' runs are aggradational; 'D' runs are degradational; NA, not available.

maintained until output rate equaled feed rate. To simulate the 1964 aggradation event, sediment feed rate was increased again (Run 7A) and maintained until all areas that were aggraded during the simulated 1955 event were again aggraded, in accordance with observations of Cuneo Creek. Sediment feed was reduced in two steps (Runs 7D1 and 7D2) to model degradation from 1964 to 1997 as sediment supply decreased.

#### Measurements

Changes in storage in the entire flume were computed by varying the volumes of sediment input and output. Bed topography over 9.8 m of flume was mapped at a resolution of 1 mm using a linear laser scanner approximately every 80 minutes of run time. Wetted channel area was also measured at these times. Spatial patterns of erosion and deposition were measured by differencing sequential digital elevation models (DEMs). Areas of sediment erosion and deposition, medial and alternate bar evolution, and channel planform were also sketched on planview maps between topographic scans at 20-minute intervals throughout the experiments. Minimum and average bed elevation in 0.01-m-long sections over the entire length of the flume were extracted from the DEMs to track the relative contributions of channel incision and lateral erosion to storage removal. Differences in average bed elevation are related to scour and fill anywhere in the flume and may result from channel expansion or contraction, while changes in minimum bed elevation are due to scour or fill of the thalweg.

Transport rate was measured at the flume outlet at 20-minute intervals or more frequently if accumulated sediment exceeded 15 kg, which was the capacity of the basket used to catch sediment. Each sample was analyzed for GSD. Transport rates were computed at 1-m increments approximately every 80 minutes along the length of the flume by differencing input rates and the local change in sediment storage computed from differences in DEMs.

GSD of the bed surface was measured approximately every 80 minutes when the flow was stopped and the flume drained for topographic mapping. Patches of visually similar grain size were mapped and the bed surface of each patch that was wetted during the previous run was sampled by removing 3-cm-wide strips of the surface material. Average GSD for the active channel was computed using an area-weighted average. The degree of armoring ( $D_{50\text{sur}}/D_{50\text{sub}}$ ) is equal to  $D_{50\text{sur}}$  because  $D_{50\text{sub}}$  equals 1 mm.

## Results

We first examine variations in channel behavior during aggradation and degradation separately under different feed rates and equilibrium conditions (Runs 1–5). We then examine full cycles of aggradation and degradation in a series of runs that model events in Cuneo Creek (Runs 6 and 7).

#### Channel aggradation

The channel aggraded at various rates under a range of feed rates (Table II), but progressive changes in surface texture, output GSD, depositional pattern, and output rate were similar. The initial condition for each aggradation run was a stable, single-thread armored channel with a low sediment supply with the exception of Run 7A, which began in equilibrium but was weakly armored due to moderate feed rate that was maintained during the preceding degradation run (Run 6D). Output rates followed the same general pattern for all aggradation runs with high sediment feed rate ( $> 10 \text{ cm}^3 \text{ s}^{-1}$ ). Output rates began to increase approximately 40–90 minutes after sediment feed was increased, but remained below  $7 \text{ cm}^3 \text{ s}^{-1}$ . As a result, aggradation was more rapid in runs with higher feed rates. Larger fluctuations and higher instantaneous output rates occurred once equilibrium was reached at moderate feed rates (Figure 8).

During aggradation, the average GSD of the output material was equal to or slightly coarser than the feed material (Figure 8). The imbalance in particle sizes indicates a fining of the bed, which appears in texture maps of Runs 5A, 6A, and 7A (Figure 9). For example, the bed fined rapidly during the first mapping interval of run 6A (88 minutes) as the trough of the initial channel filled with predominantly fine material. Fining peaked by 207 minutes as the channel became multi-thread. Areas of mixed patches ( $1 \text{ mm} < D_{50\text{sur}} < 2 \text{ mm}$ ) and fine patches ( $D_{50\text{sur}} < 1 \text{ mm}$ ) grew at the expense of coarse patches ( $D_{50\text{sur}} > 2 \text{ mm}$ ) (Table III).

Changes in particle size of the bed surface and transported material were coincidental with the appearance and growth of bedload sheets. Bedload sheets are migrating accumulations of bedload one to two grain-diameters thick that alternate between fine and coarse particles (Iseya and Ikeda, 1987; Whiting *et al.*, 1988). Bedload sheets had convex fronts of intermediate size grains (1–2 mm) and tails of fine material (0.25–0.5 mm) that expanded to the full channel width. Coarse particles ( $> 2 \text{ mm}$ ) moved rapidly over the fine, smooth areas to the congested front. Downstream progression of the sheets produced a fining of the bed surface. Subsequent waves traveled over the fine surface and elongated and diffused after reaching the coarse front. The continued mobility of the intermediate grain sizes and the loss of fine material to the bed enhanced the coarseness of the sediment collected at the flume outlet.

Wetted width increased during aggradation and decreased during degradation (Figure 10). Channels in advanced stages of continuing aggradation typically contained multiple threads carrying comparable loads of sediment, large and elongated mid-channel bars, and shallow, dissected alternate bars (312 minutes in Run 6A; 841 minutes in Run 7A; Figure 9). In contrast, aggradation that culminated in approximate equilibrium (Run 5A) produced a dominant transport channel that: (1) was occasionally split by smaller mid-channel bars and alternated between widening/shallowing and narrowing/deepening phases and (2) contained well-developed alternate bars whose upper surfaces continued to be reworked by smaller channels, but overall size and shape remained roughly constant. (1483 minutes in Run 5A; Figure 9). This contrast had strong influences on channel conditions after the feed rate was cut and the channel degraded, as described later.

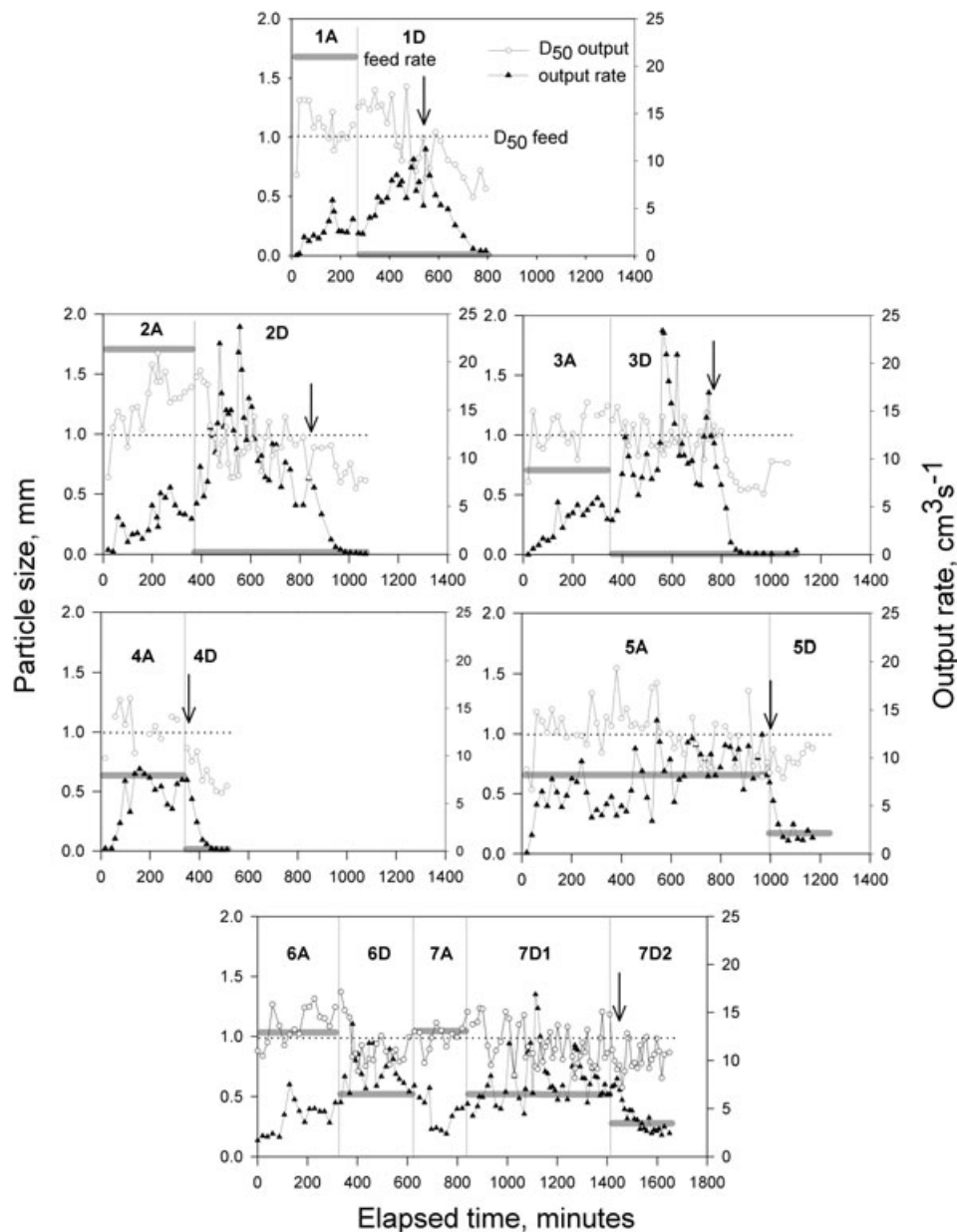


**Figure 8.** Temporal variations of feed rate, output rate, output particle size ( $D_{50}$ ), and mean surface particle size ( $D_{50sur}$ ) for experimental runs. Arrows mark transition from Phase I to Phase II conditions. Gray bars indicate feed rates given in Table II.

#### Channel degradation

Channel conditions left by the previous aggradation period strongly influenced channel response to reduced feed rates in the degradation runs. Channels in equilibrium prior to the reduction in feed rate had a dominant channel of transport which captured all flow after sediment feed was reduced (Figure 9). Under such preconditions, output rate during subsequent degradation runs (4D, 5D) appears to decrease exponentially (Figure 8). The apparent exponential decrease in output rates (and thus storage volume) and armoring of the channel indicate that Phase II conditions existed throughout these runs. Similar results were observed in flume experiments by Lisle *et al.* (1993).

In degradation runs (1D, 2D, 3D, 6D, 7D), that were preceded by disequilibrium at the end of aggradation runs, output rates were initially lower than those in degradation runs that were preceded by approximate equilibrium (Runs 4D and 5D), then increased to exceptionally high values and fluctuated widely (Figure 8). After peak transport was reached, output rates began to decline and fluctuations decreased in amplitude.

In the final stages, output rates continued to fluctuate in runs with a moderate sediment feed (Runs 6D and 7D) but decreased exponentially in runs with zero feed (Runs 1D, 2D, and 3D), similar to the pattern observed in Runs 4D and 5D.

During the period of exponential decay of output rate in all runs, output particle size ( $D_{50out}$ ) was finer than feed material, indicating selective transport and coarsening of the bed surface (Figure 8). Selective transport was strongest in degradation runs with zero sediment feed (Runs 1D, 2D, 3D, and 4D) and moderate in runs with a low sediment feed (Runs 5D, 6D, and 7D). When a continuous source of sediment was not fed to the channel, the output became progressively finer as the stable armored bed was winnowed. The low sediment feed enabled a continuous exchange of sediment, and GSD of the output remained approximately constant.

In earlier stages of degradation when output rate fluctuated widely (Runs 1D, 2D, 3D, 6D, and 7D1), output particle size ( $D_{50out}$ ) fluctuated around the feed particle size. The lack of selective transport and highly variable output rates that were associated with migrating bedforms (sheets) indicate unarmored

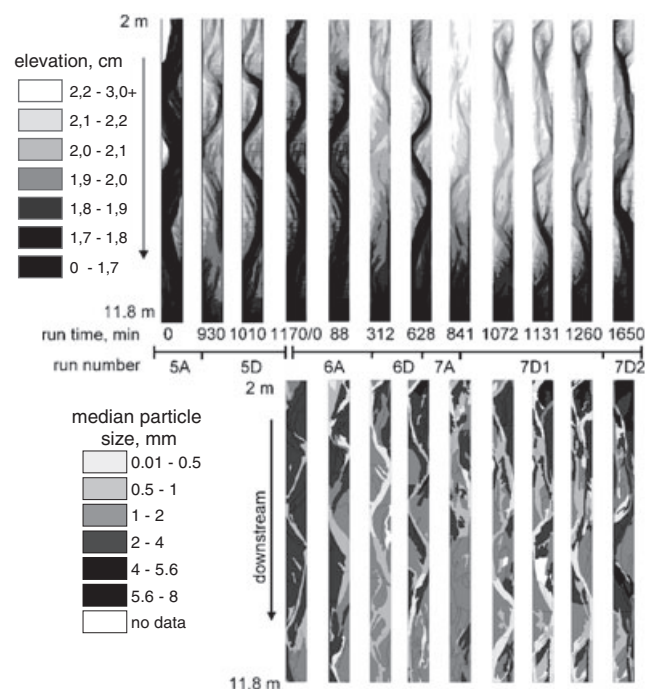


Figure 9. Channel topography and surface texture of Runs 5, 6, and 7.

Phase I conditions. Output particle size decreased in later phases of degradation runs that had zero or low feed rates. Selective transport and the exponential decline in output rates indicate developing armor (Phase II). If the channel was in equilibrium prior to the reduction in feed rate and sediment feed was low or zero, degradation immediately transitioned to Phase II (Runs 4D and 5D), otherwise Phase I and Phase II were present (Runs 1D, 2D, 3D, and 7D2). More variable output rates and less selective transport occurred when a moderate feed rate was maintained during degradation (Runs 6D and 7D1).

Transport–storage relations for aggradation–degradation cycles. The Phase II period of each of the degradation experiments shows a positive linear transport–storage function with similar values for the transport–storage coefficient, which ranges from 0.00035 to 0.00047 s<sup>-1</sup> (Figure 11). This consistency could arise from armor developing with similar particle size compositions. A decrease in output rates of one to two orders of magnitude was accompanied by depths of degradation averaging ~1 cm over the wetted width – a thickness no greater than the largest grain diameter. The increase in final storage volumes in later runs was caused by selective transport of finer particles and residual storage of coarser particles on the bed surface.

However, the same transport–storage relations were not followed during aggradation and degradation runs of the same experiment. Instead, negative hysteresis is evident in increased output rates during degradation. In runs that nearly reached equilibrium before the aggradation feed rate was cut, output rate peaked at the highest storage volume and decreased

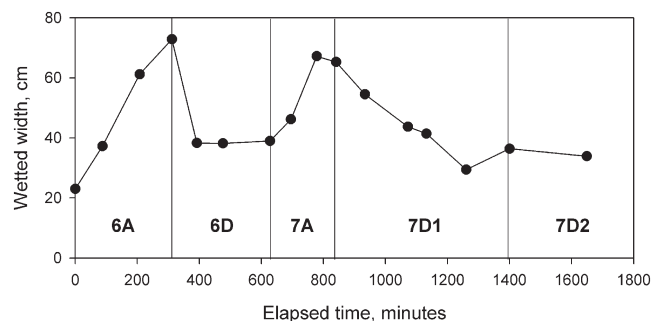


Figure 10. Variations in wetted width during Runs 6 and 7.

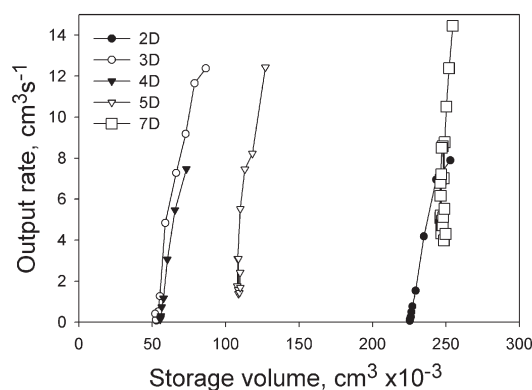


Figure 11. Relations of output rate and storage volume for degradation runs. Time proceeds from right to left.

thereafter during degradation (e.g. Run 5; Figure 12A). The transport–storage function displays a tight looping pattern at the end of the aggradation period, reflecting slight increases and decreases in output rate and compensatory changes in storage. Hysteresis is more pronounced in runs in which equilibrium was not reached before the aggradation feed rate was cut (e.g. Runs 6 and 7; Figure 12B).

Channel changes in Runs 6 and 7 can aid in the interpretation of the response of Cuneo Creek to aggradation–degradation cycles triggered in 1955 and 1964, which these experiments were designed to model. Stored volume increased steadily during both aggradation runs (6A and 7A) and decreased after sediment feed was reduced (Figure 12B). The volume of sediment stored during Run 7A was less than that during Run 6A, but total stored volume increased due to the residual storage from the former experiment.

The primary difference between the two degradation runs (6D and 7D) was the state of organization of the bed surface at the onset of degradation. At the transition to Run 6D (628 minutes), a lane of fine sediment ran down the length of the inner channel and thalweg (Figure 9). This smooth zone enabled rapid transport rates, and the channel responded with rapid incision and an immediate increase in output rates (Figure 8). In contrast, the channel at the transition to Run 7D (841 minutes) was poorly defined, and patches of surface material were

Table III. Variations in areas of surface-texture patches and bed surface  $D_{50}$  during Run 6A.

| Time (min) | Percent coarse area<br>( $D_{50} > 2$ mm) | Percent mixed area<br>( $2$ mm $< D_{50} < 1$ mm) | Percent fine area ( $D_{50} < 1$ mm) | Bed surface $D_{50}$ (mm) |
|------------|-------------------------------------------|---------------------------------------------------|--------------------------------------|---------------------------|
| 0          | 63                                        | 37                                                | 0                                    | 2.0                       |
| 88         | 38                                        | 48                                                | 14                                   | 1.5                       |
| 208        | 6                                         | 71                                                | 23                                   | 1.1                       |
| 312        | 10                                        | 74                                                | 16                                   | 1.2                       |

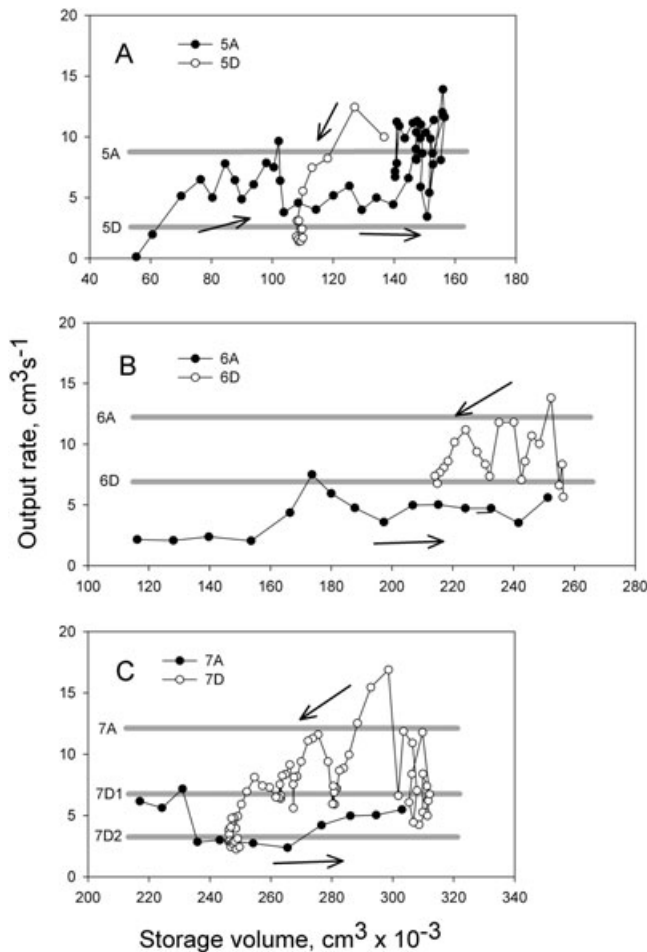


**Figure 12.** Relations between output rate and storage volume for (A) Run 5, (B) Run 6, and (C) Run 7. Arrows show time direction. Feed rates are indicated by shaded lines.

discontinuous (Figure 9). Channel degradation progressed through three stages: bar building and surface sorting, channel incision, and lateral erosion. At the onset of the bar building stage (841–1073 minutes), poorly defined channels occupied most of the flume, but channel incision and deposition at flow divergences promoted flow capture by a dominant channel, which narrowed from 65 cm to 45 cm in width and maintained its planform for the remainder of the run (Figure 9). The thalweg incised gradually as storage was in approximate equilibrium (Figure 13). Fine patches coalesced and elongated until at the start of the ensuing channel incision stage (1073–1132 minutes), a smooth zone in the inner channel and thalweg extended down

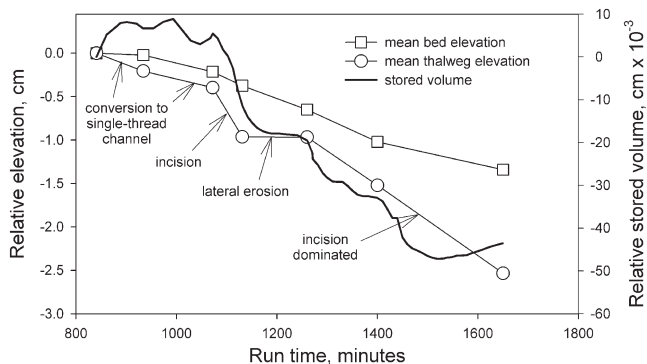


**Figure 13.** Time trends in mean-bed and mean thalweg elevation and storage volume in Run 7D. Elevations and stored volumes are deviations from values at the start of the run.

the length of the flume (Figure 9). This stage was reached near the start of Run 6D. As the channel rapidly incised (Figure 13), output rates peaked and continued to fluctuate widely, indicating Phase I transport (Figure 8), and storage was rapidly depleted. This is the period that produced the high amplitude in hysteresis in Run 7. Afterward (1132–1260 minutes), the channel eroded laterally as storage decreased but thalweg elevation remained constant. Later, thalweg incision resumed (Figure 13). Output rate decreased as the smooth zone shrank and became discontinuous (Figure 9). Discontinuities in the smooth zone proliferated and grew after the second reduction in feed rate at 1400 minutes. At the final measurement period (1650 minutes), smooth zones were relict patches of fines, and the channel was strongly armored.

Variations in average channel gradient in Runs 6 and 7 were minor. The control section at the outlet limited variations in bed elevation near the outlet as the bed upstream aggraded and degraded (Figure 14). Nevertheless, the gradient of mean channel elevation from the outlet to 10 m upstream (disregarding emergent bars) varied at most 4.4% of the gradient at the start of Run 6A. Besides elevation, the greatest contrast between aggraded and degraded profiles is the pronounced bar topography in degraded profiles. Slight changes in gradient indicate that the adjustment to sediment supply can be mostly attributed to bed texture and channel morphology, as observed by Lisle *et al.* (1993) and Nelson *et al.* (2009).

#### Longitudinal variation in transport rate

Our previous analyses of sediment transport are based on output rates at the downstream end of the flume, which do not accurately represent local transport in upstream sections due to disequilibrium. During channel aggradation under a constant sediment supply, transport rates generally declined downstream of the flume inlet due to a loss in load by deposition; during degradation, transport rates generally increased downstream due to a gain in load from eroded storage. Runs 6 and 7 were analyzed to examine longitudinal variations in transport rate during aggradation and degradation and infer variations in mobility. A mass balance was performed for the periods between topographic surveys for each 0.1-m section from 1.3 m to 11.5 m. The change in storage in a given section was computed by differencing the 1-mm resolution DEMs. Transport rates into any section were computed by adding the feed rate to the sum of changes in storage in upstream sections and dividing by the time period between surveys. Local transport rates follow similar patterns for both Runs 6 and 7.

Transport rates varied strongly longitudinally, but local rates when viewed over the length of the flume were nevertheless consistent with time trends in sediment output rates, especially during degradation (Figure 15). Longitudinal variations were greatest during aggradation and in the upstream end of the flume. Soon after sediment feed was reduced, transport rates decreased at the upstream end of the flume and increased in the downstream end. This corresponds to the bar-building stage of degradation. Transport rates increased throughout the flume and increased longitudinally during the channel incision stage (312–476 minutes in Run 6, 1072–1131 minutes in Run 7). For the remainder of the run, transport rates fell and longitudinal variations decreased as the channel stabilized. In general, transport rates peaked in both aggradation and degradation runs when there was a well-defined channel with a fine bed. During aggradation, rates increased with fining of the bed but then decreased with shallowing and braiding; during degradation, rates increased during channel incision, then decreased with armoring.

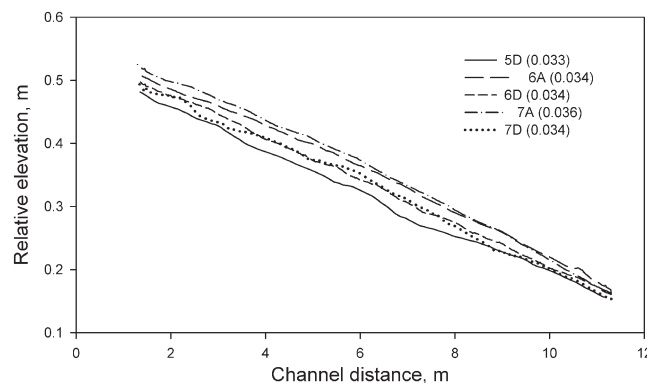


**Figure 14.** Longitudinal profiles of active channel elevation at the end of Runs 5D, 6A, 6D, 7A and 7D. Values in parentheses are average channel gradients.

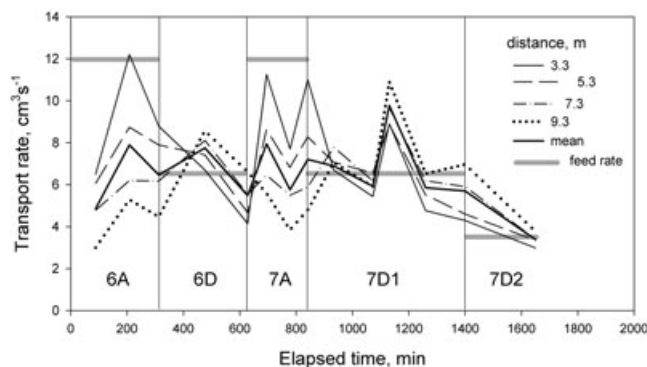


**Figure 15.** Longitudinal variations in transport rates at time intervals in Runs 6 and 7.

## Discussion

### Disequilibrium, hysteresis and lags in transport–storage relations

One objective of the experiments was to see if transport–storage relations during aggradation and degradation follow similar patterns. Although positive relations were observed in both states, there were important differences expressed in hysteresis in sediment output versus storage, such that output rates peaked in advanced stages of degradation in some experiments. Hysteresis in output could be due partly to lag behind changes in feed rate at the top of the flume. These experiments were run in conditions of disequilibrium in which changes in output rate lagged changes in sediment input rate due to the transit time of particles down the flume and to erosion and deposition in response to local adjustments between channel morphology, hydraulic conditions, and bed texture.

One component of lag is the transit time of bed particles in the active layer of the bed. A virtual particle transit time can be scaled from the ratio of the volume of the active layer of bed material to the output rate. For a high output rate (e.g.  $10 \text{ cm}^3 \text{ s}^{-1}$ ) characteristic dimensions of the active layer are  $1200 \text{ cm long} \times 60 \text{ cm wide} \times 0.4 \text{ cm deep}$  (a surface layer equal to  $D_{90}$ ). This yields a virtual transit time of about 50 minutes. This time scale is roughly equal to the lag observed in the increase in output rate and particle size of output material (e.g. Runs 1A, 2A, and 3A; Figure 8) and the decrease in surface particle size (Figure 9) at the start of aggradation runs, indicating response in particle movement on the surface of the bed. Similarly, output particle size decreased at the start of some degradation runs (e.g. 2D, 4D, 6D) over periods of  $10^1$  minutes (Figure 8). In degradation runs when there was little change in morphology

as the bed surface was winnowed of fine material (e.g. Runs 4D, 5D, and 7D2), output rate decayed over a period of approximately 100 minutes. The volume of sediment removed during Phase II for Runs 2D, 3D, 4D, and 5D ranged from  $19.4$  to  $29.3 \text{ cm}^3$ , which is equivalent to an average depth of  $8.4$  to  $12.7 \text{ mm}$  or the coarsest size class in the flume ( $8\text{--}11.2 \text{ mm}$ ). Volume removed in Run 7D during Phase II was significantly less ( $9 \text{ cm}^3$  or  $3.2 \text{ mm}$ ), which is consistent with the higher feed rate during that run. The depth of sediment removed during Phase II conditions indicates that one to two surface layers were winnowed of fine material during armoring.

Longer lag times stem from erosion and deposition at depths that exceed the thickness of the transport layer, starting at the upstream end of the flume where changes in feed rate are most strongly felt. In degradation runs, this was expressed by the lag from the cut in feed rate when the upstream end began to erode and the bed downstream continued to aggrade, to the time when transport rates in the entire flume were decreasing as the bed degraded. From Runs 6 and 7 (Figure 15), this lag appears to be approximately 100 minutes.

However, the lag between changes in input and output rates was longer than this when major changes in channel morphology accompanied changes in feed rate and affected transport rates (e.g. Runs 1D, 2D, 3D, and 7D1; Figure 8). Periodic maps of channel morphology and bed texture all show similar patterns down the entire length of the flume rather than longitudinal variations indicating lags in morphological adjustment. Transport during aggradation was suppressed by widening and shallowing; transport during degradation was enhanced by incision and deepening. In both cases, fine sediment dominated the bed surface. The result was a spike in output rates during incision, which lagged cuts in feed rate by approximately 200–300 minutes. Similar relations between the rate and GSD of sediment supply, the extent of smooth zones, and sediment transport have been observed in previous experiments (Iseya and Ikeda, 1987; Dietrich *et al.*, 1989; Lisle *et al.*, 1993; Gran *et al.*, 2006; Eaton and Church, 2009; Madej *et al.*, 2009; Nelson *et al.*, 2009) and field studies (Lisle *et al.*, 2000; Madej, 2001; Pitlick *et al.*, 2008).

This analysis indicates that lags in output rates were primarily influenced by changes in channel morphology, particularly in runs involving large changes in storage, rather than the transit time of particles in the active layer.

Hysteresis was most pronounced in experiments where equilibrium was not nearly met at the end of the aggradation run. Disequilibrium channels were wide, shallow and braided. After feed rates were cut, channel morphology underwent a major transformation to a narrower, deeper, and single-thread form that resulted in greater transport rates. In contrast, a single-thread form had already been established in runs where equilibrium was more closely approached before feed rates were

cut, and persisted as the channel degraded. Consequently, there was less of an effect on transport rates. Thus, an aggradational episode can leave a legacy of channel conditions that affect subsequent transport–storage relations. The closest commonality in transport–storage relations was observed during armoring phases (Phase II) of degradation runs and among two degradational episodes in Cuneo Creek, when slopes of the relations were similar but reference storage volumes had apparently shifted. This suggests that once decreased supply forces selective transport and increased armoring, rates of transport and channel incision are constrained in a similar manner regardless of initial sediment stage.

An artifact of the experimental method is an increase in the sediment storage volume with each aggradation–degradation cycle. Because of a constant discharge and net selective transport of finer material, bed material coarsened and the residual storage increased with each experiment after equilibrium was reached. Thus transport–storage relations shifted toward greater storage. This would not be expected to occur in most field examples, where high peak flows could continue to remove sediment from storage during degradational intervals.

A similar experiment using a distorted Froude model was performed to examine aggradation–degradation cycles in Redwood Creek, a coastal river approximately 100 km north of Cuneo Creek (Madej *et al.*, 2009). Redwood Creek is a larger channel (drainage area = 720 km<sup>2</sup>) with a lower gradient (0.0024) and finer bed material ( $D_{50}$  = 22 mm). A detailed comparison of results is beyond the scope of this paper, but some similarities and differences are noted here. Similar to the Cuneo model, the channel bed became finer during aggradation and armor was restored during degradation. A sinuous, single-thread planform was stable during a moderate increase in feed rate, but a large increase caused the channel to become smoother and mid-channel bars to form. Transport–storage relations were generally positive, but hysteresis was not as evident as in the experiment modeling Cuneo Creek.

## Application of flume results to Cuneo Creek

Similarities in responses to sediment pulses in Cuneo Creek and the flume provide confidence in using detailed observations in the flume to interpret changes in Cuneo Creek, which are evident only in a limited set of aerial photographs and cross-sectional surveys. In both cases, aggradation occurred over a short period of time, converting a single-thread channel to a shallow braided channel; over a longer period, degradation created an incised, single-thread channel that widened and left terraces recording stages of degradation.

Flume experiments provide insights into changes and processes in Cuneo Creek that could not be observed in as much detail in the field. In the flume, transport capacity under high sediment supply initially increased because of fining of the bed, but later widening and shallowing apparently limited increases in transport capacity and contributed to rapid aggradation. When sediment supply decreased, transport capacity increased as a dominant channel incised and flow became deeper over a bed with abundant fine material. Increased braiding during aggradation and decreased braiding during degradation have been observed in other flume experiments (Ashmore, 1991; Hoey and Sutherland, 1991; Germanoski and Schumm, 1993) and field studies (Maizels, 1979; Germanoski and Harvey, 1993), and increased sediment transport has been associated with simplification of braided channels (Ashmore, 1991; Hoey and Sutherland, 1991).

More specifically, the flume experiments can be used to reconstruct channel changes in Cuneo Creek from 1955 to 1997. After the floods of 1955, 1964, and 1997, the channel was wide,

braided, and fine-grained, indicating the prevalence of Phase I (unarmored) transport. Sometime after the 1964 flood, the transition to Phase II transport (developing armor) occurred after a dominant or single-thread channel began to incise, but until 1982, Phase I likely dominated as large volumes of sediment were removed from storage. Rates of loss of storage were lower from 1982 to 1986 than they were from 1976 to 1982, and surface particle size measurements in 1986 (Short, 1993) indicate strong armoring as do those in 2001 after the last period of degradation. This evidence indicates Phase II transport prior to 1986, and by extension, to 1997.

The flume experiments can help to resolve uncertainties in transport–storage relations for Cuneo Creek (Figure 7B), for which data are sparse. A first-order interpretation is that the relation during post-1964 degradation was basically linear through a scatter of points, indicating a steady reduction in transport capacity as stored sediment was evacuated. This is consistent with the 26% decrease in channel gradient between 1964 and 1998. A second-order interpretation is that transport capacity remained high during early stages of degradation (1964–1982) when armoring was weak (Phase I), and then decreased more rapidly as armoring intensified (Phase II), thereby creating an inflection in the transport–storage relation. Results of the flume runs modeling this period support the second-order interpretation.

More detail is known about channel changes following the 1997 flood. Surface particle size measurements show fining of the bed surface in 1998, followed by three years of surface coarsening and minor changes in a dominant channel, suggesting Phase II transport was restored by 1998. Similarly, small aggradation events in the flume (e.g. Run 4, Figure 8) transitioned immediately into Phase II transport. Therefore, we infer that the channel was in Phase I transport for a short period from 1997 to 1998 and in Phase II transport from 1998 to 2004.

Channel changes promoting rapid aggradation and degradation may be responsible for high fill terraces seen along Cuneo Creek, Bull Creek, and other steep-land channels subject to large, episodic inputs of sediment (Madej and Ozaki, 1996, 2009). This interpretation contrasts with interpretations of terraces as recording valley filling resulting from long-term changes in flow regimes or sediment regimes.

A comparison of results from experiments modeling aggradation–degradation episodes in Cuneo Creek and Redwood Creek offers an interpretation of responses to sediment inputs in proximal and distal reaches of a sedimentary system. More pronounced inputs of poorly sorted material in a proximal reach (represented by Cuneo Creek) would lead to radical changes in channel morphology that influence a large range in bed elevation. In a distal reach (represented by Redwood Creek), sediment inputs would be more dispersed and better sorted, and variations in load would be more gradual, thereby limiting departures from equilibrium. This would tend to result in less morphological influences on transport rates, and perhaps, less variation in transport capacity expressed in transport–storage relations (Madej *et al.*, 2009). Decreasing flood terrace height along Redwood Creek supports this interpretation, although channel confinement has limited morphological response to aggradation associated with the 1964 flood (Madej and Ozaki, 1996, 2009).

## Conclusions

Alluvial channels respond to variations in sediment load with changes in transport rate and storage, which are mediated by transport capacity. Transport capacity is constrained by flow magnitude, valley gradient, and sediment properties, but

variability in channel gradient, armoring, and channel morphology can allow a dynamic response in transport capacity to sediment load. Although variations in transport capacity in natural gravel-bed channels are poorly understood, the relation between transport capacity and stored sediment appears to be generally positive.

Three cycles of aggradation and degradation in Cuneo Creek, California, manifest wide variations in sediment load and channel response. During large floods in 1955 and 1964, the channel and floodplain were filled with sediment; afterward channels and remnant flood terraces were eroded over a period of years. We assembled and collected data on changes in stored sediment volume, channel morphology, and sediment texture, but this information is insufficient to detail changes in transport capacity. Moreover, without data on rates of sediment input from upstream, we resorted to using rates of change in storage to represent relative bed material transport rates. A relation developed from three data points for storage volume and rate of degradation following the 1964 flood is roughly positive, but it can be interpreted as non-linear. For example, sediment transfer rates remained high from 1964 to 1982 and then decreased. Indications that the channel was unarmored from 1964 to 1982 are consistent with Phase I conditions when there is no adjustment of armoring to sediment load; observations of armoring after 1982 (with the exception of the year after a flood in 1997) indicate Phase II conditions when increased armoring reduces transport capacity. Comparable periods of Phase I conditions (nearly constant transport capacity) and Phase II conditions (decreasing transport capacity) would create an overall non-linear relation between transport rate and storage.

A flume experiment modeling Cuneo Creek was performed to explore processes governing the response of Cuneo Creek and similar channels to large sediment inputs. To the best of our knowledge, this is the first such experiment to investigate channel response to aggradation as well as degradation, and in this context to examine variations in channel morphology, armoring, and channel gradient. As expected, an increase in sediment load (feed rate) and aggradation generally decreased armoring and increased channel gradient; a decrease in sediment load and degradation increased armoring and decreased gradient. However, some cycles of aggradation and degradation exhibited non-linear relations between transport rate and storage, including hysteresis whereby transport rates for a given storage volume were less during aggradation than those at the same storage volume during some phases of degradation. The distinction between cycles that did and did not show hysteretic behavior can be attributed to channel morphology. In runs in which equilibrium in sediment transport was not reached before the feed rate was cut and degradation began, a shallow, braided channel evolved into an incised, single-thread channel with enhanced transport capacity and prolonged Phase I conditions. In runs when equilibrium was reached before feed rate was cut, a pre-existing single-thread channel evolved to a lesser degree, primarily by rapidly armoring and transitioning to Phase II conditions.

Changes in channel morphology, and shallowing and braiding in particular, can thereby counteract the effects of bed-surface fining and increased gradients, which increase transport capacity during aggradation. If so, large sediment inputs at the headwaters of sedimentary systems could produce wide ranges in storage resulting from dynamic transport capacity that is mediated by channel morphology in proximal sediment reservoirs. This would tend to enhance their buffering effect for more distal reservoirs, prolong the dispersion of sediment, and reduce variations in storage and transport in distal reservoirs where departures in equilibrium in sediment transport would be limited.

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