Sediment transport-storage relations for degrading, gravel bed channels

Thomas E. Lisle
Pacific Southwest Research Station, Redwood Sciences Laboratory, USDA Forest Service, Arcata, California, USA

Michael Church
Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada

Received 26 November 2001; revised 24 May 2002; accepted 24 May 2002; published 1 November 2002.

[1] In a drainage network, sediment is transferred through a series of channel/valley segments (natural sediment storage reservoirs) that are distinguished from their neighbors by their particular capacity to store and transport sediment. We propose that the sediment transport capacity of each reservoir is a unique positive function of storage volume, which influences sediment mobility and availability through variations in bed surface texture, channel gradient, and availability of valley floor sediments for erosion. Examinations of the form of transport-storage relations of degrading alluvial reservoirs using published field studies, flume experiments, and simulations support a conceptual model that includes two phases. In phase I, filled channels respond to variations in supply primarily by changes in stored sediment volume, with little change in transport rate. In phase II, channel mobility is responsive to supply through armoring and form roughness. Although these phases could represent idealized transport-limited (phase 1) or supply-limited (phase II) states, we propose that every alluvial reservoir responds to changes in sediment inputs by changing both storage and transport rate, the propensity for either depending on reservoir characteristics and the sediment exchange processes in the channel. Transport-storage relations for phase II are approximately linear, but examination of numerical simulations and flume experiments indicates that armoring imparts positive curvature. Simulations of degradation of an alluvial reservoir with channel and valley floor surfaces indicate that interactions between channel lowering and lateral erosion are critical in the manifestation of a transport-storage relation. Better knowledge of transport–storage relations could lead to improved sediment-routing models for drainage basins wherein component sediment reservoirs dynamically adjust to varying sediment loads. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* sediment transport, sediment storage, alluvial reservoirs, bed load, armoring

Citation: Lisle, T. E., and M. Church, Sediment transport-storage relations for degrading, gravel bed channels, *Water Resour. Res.*, *38*(11), 1219, doi:10.1029/2001WR001086, 2002.

1. Introduction

[2] Clastic sediment moves through a drainage network in complex sequences of storage and transport, creating alluvial landforms that act as natural sediment storage reservoirs [*Dietrich et al.*, 1982; *Kelsey et al.*, 1987]. Such a sedimentary system can be regarded as a series of reservoirs consisting of channel and valley segments, each of which is distinguished from its neighbors by its particular capacity to store or transfer sediment, depending on the rate of sediment input and the volume of sediment stored. Accurate mathematical representation of transport-storage relations is critical to routing sediment through any dynamic sedimentary system. For example, many observers would expect that for a given rate of sediment input, a steep, confined reach of channel would be capable of transferring more sediment and storing less than a gently sloping reach with a wide valley bottom [*Griffiths*, 1989].

[3] An association between sediment storage and transport might be particularly important in gravel bed channels, where the balance of sediment supply and onward transfer influences the surface textures of the deposit, hence the propensity for continued entrainment and transport [*Dietrich et al.*, 1989; *Church et al.*, 1998]. A focus on sediment storage represents a departure from previous investigations which, beginning with *Gilbert* [1914] and *Mackin* [1948], focused on adjustments of dependent channel variables to accommodate variations in sediment supply but neglected associated variations in the volume of sediment stored.

[4] To develop these concepts, our usage of terms needs to be clarified. *A sediment reservoir* is a reach of valley floor, including the channel, floodplain, and modern terraces, that stores fluvial sediment that could be activated under the

0043-1397/02/2001WR001086$09.00

prevailing hydroclimatic regime. (This usage differs from that of *Kelsey et al.* [1987] who regard channels, floodplains, and terraces as separate reservoirs.) The upstream and downstream boundaries of a sediment reservoir are defined according to scales appropriate for a sediment routing investigation. Reservoirs are homogeneous reaches (no significant variation in principal conditions governing transport and storage) with no large intervening inputs of flow or sediment [*Grant and Swanson*, 1995]. In most cases, such a reach would be equivalent to a link in a drainage network or, since the emphasis is on sediment routing, a sediment link [*Rice and Church*, 1998]. Volume of sediment stored is the total contained in the channel and valley flat above some datum and is controlled by the difference in input and output at the reservoir boundaries. When investigating channel elevations, it can be useful to define sediment stage as the elevation of the bed above a datum at some section, although the relation between stored volume and sediment stage may be nonlinear and may vary between reservoirs.

[5] As the mediator between sediment supply, transport, and storage, transport capacity must be carefully defined. *Gilbert*'s [1914] original definition, which provided the conceptual framework of his flume experiments, is "the maximum load of a given kind of debris which a given stream can transport." This implies a simple relation–transport capacity is achieved when transport rate is in equilibrium with supply rate, i.e., the channel is at grade. The channel aggrades and steepens its profile if supply increases; it degrades and flattens its profile if supply decreases. However, *Gilbert* [1914] recognized that in some cases, supply rate can fall short of satisfying transport capacity without a resulting change in grade. These include channels with bedrock exposures and channels that could transport more if the sediment supplied were finer. As an example of the latter case, coarse-bedded riffles can transport more of the selectively transported fine sediment than is available to them during waning flood stages as the fine sediment becomes trapped in pools [*Gilbert*, 1914; *Lisle and Hilton*, 1999]. However, calling on a variation in the particle size of the sediment supplied appears to violate the condition in his definition that capacity be associated with a "given kind of debris."

[6] *Mackin* [1948] stipulated that where it exists, a meaningful balance of grade in natural rivers occurs over "a period of years." He thereby disregarded shorter term variations in supply, transport, and storage. This implies that within the longer time frame, transport rates could often fall below a maximum rate describing capacity, given that associated variations in stored volume would merely constitute variations around an average graded condition. Consistent with Mackin's usage, channels have been considered to be supply-limited (supply rates not meeting transport capacity) when measured transport rates are over-predicted by transport formulae based on the concept of transport capacity [*Reid and Dunne*, 1996] or fall below maximum measured values for a particular discharge [*Rice et al.*, 1979]. For our analysis, we invoke *Gilbert*'s [1914] definition of transport capacity because it allows for more specific statements on the relation between supply, transport, and storage.

[7] Many channel changes can mediate the adjustment between sediment supply and transport capacity, including gradient, channel morphology, roughness, and bed surface texture [*Gilbert*, 1914; *Mackin*, 1948; *Leopold and Bull*, 1979; *Andrews*, 1979; *Lisle*, 1982; *Dietrich et al.*, 1989; *Church et al.*, 1998; *Madej*, 2001]. However, investigators have largely ignored variations in stored volume that accompany these adjustments. Part of the reason may be that negative feedback mechanisms triggered by changes in supply can be so effective that associated changes in stored volume are considered to be minor. In step-pool channels, for example, reconstruction of particle frameworks following large floods and sediment inputs is associated with large decreases in transport rate [*Grant and Mizuyama*, 1992; *Lenzi*, 2001], and depletion of gravel in pools is associated with large downward shifts in bed load rating curves [*Sawada et al.*, 1985]. As bed material supplies most of the bed load during transport events in many channels, bed load transport rates can be expected to be correlated with volumes of sediment available to be transported. That, in turn, and mediated by surface texture, exhibits a marked correlation with the volume of sediment stored.

[8] Our purpose in this paper is to promote investigation of transport-storage relations of sediment reservoirs better to understand and model sediment routing. Our investigation is limited to degrading gravel systems, where most information is available, and where the control exerted over sediment entrainment by evolving surface texture most obviously furnishes a mechanism to mediate transport-storage relations. We do not propose that transport-storage relations for degrading gravel reservoirs would hold during full episodes of aggradation and degradation. In the following sections, we examine variations in sediment transport and stored volume in degrading gravel reservoirs using flume experiments, numerical simulations, and field examples.

2. Theory

[9] We return to *Gilbert*'s [1914] original concept of transport capacity and re-assert that any change in the rate of sediment supply results in a change in stored volume as well as transport rate, which is regulated by channel adjustments. These adjustments determine the quantity transported at a particular sediment stage–the transport capacity of the channel at that stage. Transport capacity is not a fixed quantity but signifies different equilibria between transport and supply rates at different sediment stages. Let us define transport capacity as the bed material output rate from a sediment reservoir that is summed over the range of discharges according to their probabilities (i.e., transport rate under a given hydrologic regime). Transport capacity (Θ) is, then,

$$\Theta = \int_Q p(Q) f(Q) dQ \qquad (1)$$

where $p(Q)$ = frequency of discharge (Q) of a given magnitude, and $f(Q) = Q_S$ is the rating relation between sediment transport rate (Q_s) and discharge. In our investigation, we neglect hydroclimatically driven variations in Q and instead focus on variations in the sediment rating relation that would affect Θ. Transport capacity depends on the sum of the conditions in the system that determine transport rates effected over the range of experienced flows. Some of the conditions affecting transport capacity (e.g., armoring or gradient) may respond to variations in the supply of sediment and prompt changes in the system that alter transport to match the supply. Others may respond to structural changes such as inputs or outputs of large woody debris that alter the distribution of forces responsible to transport sediment [*Buffington and Montgomery*, 1999].

[10] We propose that each sediment reservoir is governed by a unique relation between sediment transport capacity and the volume stored. What forms might such relations take? At the most elementary level, positive relations are indicated by increases in bed mobility associated with decreased roughness and reduced armoring as sediment supply and storage increase [*Andrews*, 1979; *Lisle*, 1982; *Sawada et al.*, 1985; *Lisle et al.*, 2000; *Madej*, 2001]. The simplest form of a positive transport-storage relation would be linear:

$$\Theta = KV \tag{2}$$

where K is a transport-storage coefficient in units of time^{-1}, and V is stored volume. Another form, particularly for analyzing for effects of changes in slope, might substitute sediment stage for V, although relations may not be linear for both stored volume and stage.

[11] Equation 2 resembles the first time derivative of an exponential decay function for volume of sediment stored

$$V = V_0 \exp(-Kt) \tag{3}$$

where t = time. (To be physically correct, t must be nondimensionalized by dividing by a reference time, e.g., the total time of observation. However, for simplicity and allowing an empirical approach, we will retain the form of equation 3.) Exponential decay functions have been found to accurately model change in the volume of sediment stored resulting from extensions of gully networks [*Graf*, 1977] and erosion of channels of the Toutle River, Washington, following inundation by volcanic sediments after the 1980 eruption of Mount St. Helens [*Simon*, 1992; *Simon and Thorne*, 1996].

[12] In most channels, ambient sediment supply maintains a base level above an obvious bedrock control, creating high uncertainty in finding a physical expression of local base level from which to measure stored volume. Using an equation similar to one used by *Simon* [1992, equation 6] to describe changes in cross-section elevations in the Toutle River, we assume a reference stored volume (V_{BL}) corresponding to some base level and the exponential decay function for stored volume whose domain lies above it:

$$V - V_{BL} = (V_0 - V_{BL}) \exp(-Kt) \tag{4}$$

To derive a transport-storage relation, the first derivative of equation 4 yields

$$\frac{dV}{dt} = -K(V - V_{BL}) \tag{5}$$

[13] Transport capacity can be satisfied by inputs from upstream $(Q_S)_{in}$ as well as from changes in storage in the reservoir,

$$\Theta = (Q_s)_{in} - \frac{dV}{dt} \tag{6}$$

An assumption underlying equation 6 is that the rate at which sediment leaves a reservoir during a period of time is solely a function of the physical state of the reservoir, which governs transport capacity, and is independent of the proportions of sediment that originated from within the reservoir or was transferred from the next reservoir upstream. Later, we present a limited test of this assumption using experimental data.

3. Degradation of a Mixed Size Bed Under Controlled Sediment Input: A Flume Experiment

[14] Model experiments in gravel bed channels with mixed particle size have shown bed coarsening and reduced bed mobility accompanying a reduction in sediment supply [e.g., *Harrison*, 1950; *Gessler*, 1970; *Little and Mayer*, 1972; *Proffitt*, 1980; *Dietrich et al.*, 1989; *Hassan and Church*, 2000]. However, flume experiments cannot fully model the adjustability of the bed surface of natural streambeds. Natural bed surfaces respond to variations in flow, as well as sediment supply, and it is difficult to impose simultaneously variations in sediment feed rate, sediment size, and flow in a flume to model realistically such variations in a natural channel [*Wilcock*, 2001]. Results of experiments in which only sediment feed rate is varied may over-represent the adjustment of armoring to variations in supply in natural channels.

[15] Nevertheless, coarsening of bed surfaces during degradation in gravel bed rivers has been observed [*Hirano*, 1971; *Lisle*, 1982; *Gomez*, 1983; *Nolan and Marron*, 1995; *Madej*, 2001]. *Lisle et al.* [2000] found that bed mobility is greater in natural channels with higher sediment supply, and that bed surface particle size accounts for the variation in bed mobility. The degree of armoring (measured by the ratio of average median particle size (D_{50}) of the bed surface to that of the bed load) for the maximum feed rates of the experiment of *Lisle et al.* [1993], which modeled a gravel bed channel, was 1.6. This agrees closely with values reported for aggraded channels, including two reaches of Redwood Creek, California (1.2 and 1.6 [*Lisle and Madej*, 1992]) and at many sampling locations in the Waipaoa River, New Zealand (1.4 [*Gomez et al.*, 2001]). Therefore a small degree of armoring is apparently maintained in channels with high sediment supply rates.

[16] We used a flume experiment to examine degradation of a channel under controlled rates of sediment and water input [*Lisle et al.*, 1990, 1993]. A model gravel bed channel was formed under a steady discharge in a small flume (width = 0.3 m; length = 7m; S = 0.03) containing a mixture of sand and fine gravel. The channel was sufficiently wide to allow the formation of alternate bars, and terraces were formed and laterally eroded during channel degradation. The same mixture of sediment used as bed material was fed into the flume at a high, steady rate until equilibrium between supply and transport rates was achieved, and then

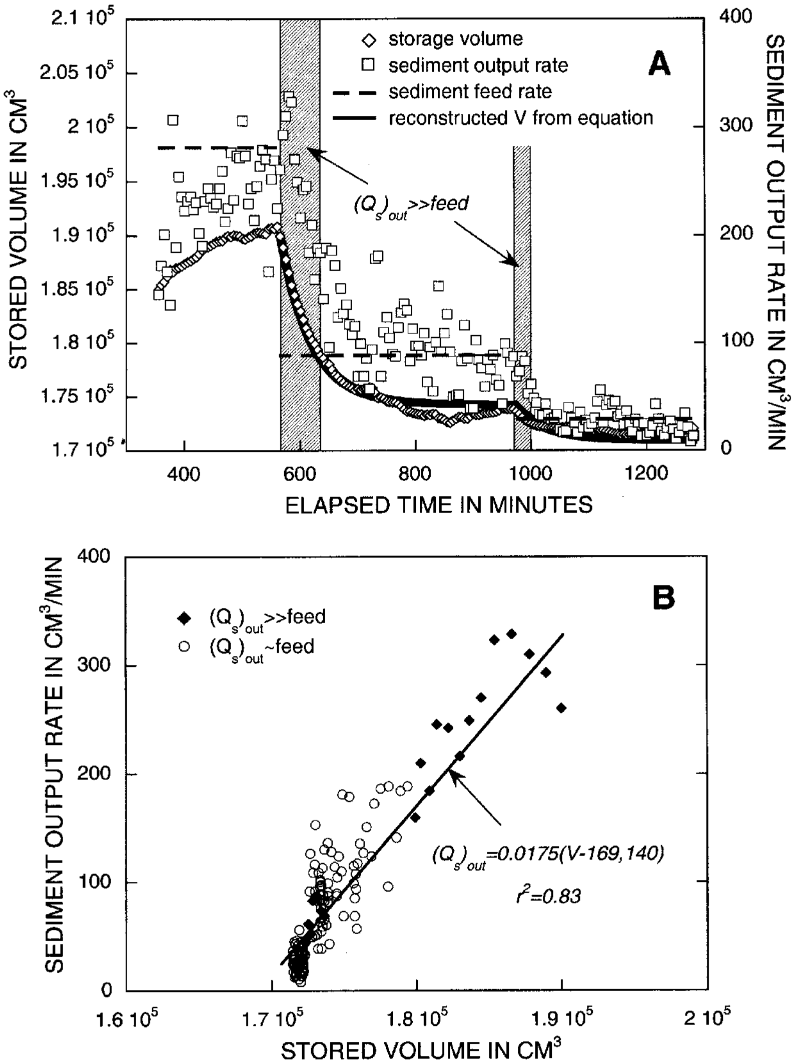

Figure 1. Variation of sediment storage volume and output rate in a flume with mixed size sediment [*Lisle et al.*, 1991, 1993]. (a) Variation of storage volume and output rate with elapsed time. Shaded areas identify when sediment output from the flume exceeded the feed rate by twofold or greater; corresponding data points are identified in Figure 1b. A line describes the back casted variation of storage volume versus time that was computed using equation 4, which was fit by finding a value of V_{BL} so that a linear relation between sediment output and storage volume passes through the origin (Figure 1b). (b) Variation of sediment output rate with storage volume. Time progresses from right to left. In the equation, the minus sign of equation 5 is dropped because $(Q_s)_{out}$ is presented as a positive quantity.

feed rate was reduced by two thirds in each of two steps, between which equilibrium sediment transport was re-established. We calculated changes in the stored volume from differences between fixed rates of sediment input and variable rates of sediment output, which was accumulated continuously and measured every 5 minutes.

[17] The stored volume decreased rapidly just after the feed rate was reduced each time, but more slowly as equilibrium between sediment output and input was approached (Figure 1a). Channel incision exposed high surfaces that were built by bar formation during maximum feed rates. A slight decrease in channel gradient (0.031 to 0.028) resulted in an increase in terrace height upstream. The terraces were eroded laterally during incision, but remnants were left at the end of the experiment [*Iseya et al.*, 1990a; *Lisle et al.*, 1993]. Armoring increased after each feed rate reduction and was primarily responsible for decreased transport rates [*Lisle et al.*, 1993].

[18] After adjustments for base level are made (equation 4), a linear function fits the relation between output rate and stored volume (Figure 1b). No systematic deviation is evident for periods when sediment output was dominated by loss of stored sediment (shaded area in Figure 1a). This indicated that in this case, the assumption underlying equation 6 is valid. Around this general trend are fluctuations in output that are attributed to lateral erosion of terraces.

[19] An exponential function, calibrated to the values of K and V_{BL} derived from the linear transport-storage function, reconstructed variations in stored volume and

Table 1. Experimental Conditions

Experiment	Sediment Size Parameters D_{50} (mm)/σ_g	Bedforms	Duration, hours	Ratio of Final to Initial Transport Rate
Harrison [1950][a]				
Run B	1.2/1.4	small dunes	24	0.005
Run C	1.0/0.8	large dunes	15	0.008
Little and Mayer [1972][b]				
Run 1.1	1.0/1.5	large dunes	330	0.005
Run 2.1	1.0/1.0	large dunes	168	0.002
Run 3.1	1.0/1.3	large dunes	247	0.009
Run 3.4	1.0/1.3	large dunes	76	0.005
Run 4.1	1.0/0.6	small dunes	95	0.25
Run 4.2	1.0/0.6	small dunes	38	0.39
Run 5.4	1.0/0.4	small dunes	1.2	~1
Run 6.1	1.0/1.6	large dunes	142	0.003
Proffitt [1980][b]				
Run 1.2	2.9/1.1	dunes	61	0.007
Run 1.3	2.9/1.1	dunes	24	0.01
Run 1.4	2.9/1.1	dunes	48	0.004
Run 1.5	2.9/1.1	dunes	48	0.007
Run 1.7	2.9/1.1	dunes	36	0.01
Run 2.1	3.2/1.7	dunes	48	0.004
Run 2.2	3.2/1.7	dunes	55	0.003
Run 2.3	3.2/1.7	dunes	36	0.003
Run 3.1	3.1/1.5	dunes	25	0.006
Run 3.2	3.1/1.5	dunes	32	0.005
Run 3.3	3.1/1.5	dunes	48	0.005
Run 3.4	3.1/1.5	dunes	30	0.006
Run 4.1	4.2/1.0	dunes	54	0.01
Run 4.2	4.2/1.0	dunes	73	0.02
Run 4.3	4.2/1.0	dunes	98	0.009
Lisle et al. [1993][a]	1.4/1.0	Stable alternate bars	12	0.003
Hassan and Church [2000][b]				
Run HM-1	1.4/1.7	none	96	0.0007
Run HM-7	1.4/1.7	small bedforms	96	0.003
Run HM-8	1.4/1.7	none	96	0.011

Initial bed condition: (a) Shear worked; (b) Screeded.

sediment output under different sediment input rates as the channel evolved through multiple stages of disequilibrium and equilibrium (Figure 1a). It does not reconstruct smaller fluctuations during quasi-equilibrium and generally underestimates stored volume as equilibrium was approached after the final feed rate reduction. Nevertheless, the exponential function appears to model the dynamics of sediment transport and storage in this experiment fairly well.

4. Influence of Particle Sorting and Tractive Force on Degradation

4.1. More Experiments

[20] Bed armoring is a primary mediator between bed load transport and bed material storage in gravel bed rivers. Empirical models by *Gessler* [1970] and *Borah* [1989] predict the depth of degradation of a bed stabilized by armoring, given particle size distribution and excess boundary shear stress, but do not predict transport rates as the bed degrades. Several investigators have starved flume channels of sediment to investigate the development of bed armoring. Their data also include sediment output rates, allowing investigation of the relation between transport and stored volume of bed material. Among several such experiments, we chose those that had minimal changes in bed gradient in order to exclude adjustments other than bed texture and the formation of particulate structures on the bed. Experimental conditions are summarized in Table 1. *Little and Mayer* [1972], *Proffitt* [1980], and *Hassan and Church* [2000] ran a constant discharge with no sediment feed over a screeded bed of mixed size material and measured sediment output and changes in sediment texture. *Harrison* [1950] recirculated sediment under a constant flow over an initially screeded bed until equilibrium was achieved, then cut sediment recirculation. The range of D_{50} of bed material in these experiments was moderate (1.0–4.2 mm), and the range in particle sorting as represented by the graphic standard deviation [$\sigma_G = (\Phi_{84} - \Phi_{16})/2$] was wide [$0.4 < \sigma_G < 1.7$]. *Hassan and Church* [2000] reported development of bed structure (cellular arrangements of large particles) during late experimental stages when transport was minimal. Similar phenomena may have occurred in other experiments but are not reported. Experiments typically ran for a period of days and ceased after final transport rates were $\leq$1% of initial rates, unless the bed was about to be scoured to the bottom of the flume.

[21] For comparing experimental results, bed load transport rate is expressed nondimensionally as

$$W^* = \frac{Rgq_s}{(\tau/\rho)^{3/2}} \qquad (7)$$

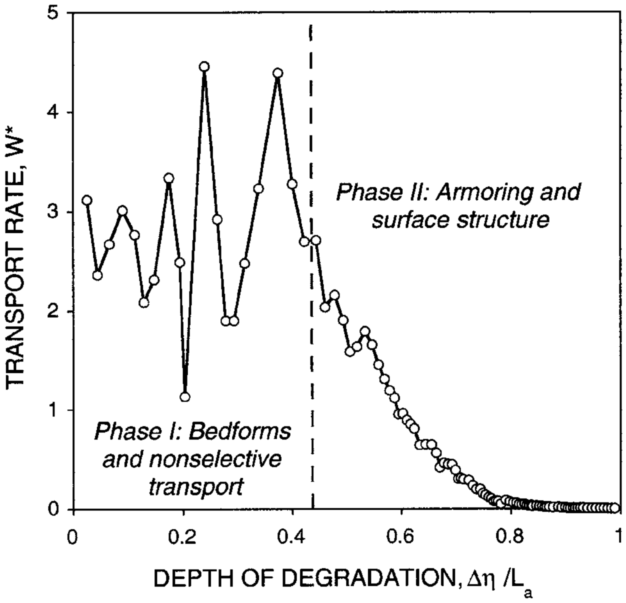

Figure 2. Variation of dimensionless transport rate (W*) and depth of degradation ($\Delta\eta/L_a$) for run 6.1 of *Little and Mayer* [1972]. Degradation is computed as the average change in bed elevation for the entire flume. Time progresses from left to right. Positions of boundaries between phases of bed surface evolution are interpreted from the authors' description of the bed form- armoring transition and freely extrapolated from observations by *Hassan and Church* [2000] of the armoring structure transition in their experiments.

where R = submerged specific gravity of sediment, g = gravitational acceleration, q_S = the volumetric transport rate per unit width, τ = mean boundary shear stress (corrected for sidewall effects), and ρ = fluid density [*Parker and Klingeman*, 1982]. Bed elevation is expressed in active layer thicknesses, η/L_a, where η is bed elevation relative to a datum of zero, and L_a is active layer thickness, which is assumed equal to D_{90} of the bed material [*Parker and Sutherland*, 1990].

[22] Run 6.1 of *Little and Mayer* [1972] illustrates two phases of a transport-storage relation in a degrading channel that exhibit strongly contrasting responses of bed surface texture and structure to diminishing sediment supply (Figure 2). (In this and succeeding figures, data are conventionally plotted in time sequence from left to right, but the plots represent positive relations between sediment transport and sediment stage.) In the first phase (phase I), sediment output was high and pulsating and showed little systematic variation with bed elevation as bed forms of unsorted bed material migrated down the channel. Armoring was absent. In this experiment total degradation did not proceed below the depth of the original active surface layer (η/L_a < 1). But in others, phase I so delayed extensive armoring that scour approached the floor of the flume or the experiment was terminated beforehand.

[23] In phase II, transport rates became less variable and rapidly declined with further degradation as finer particles were selectively removed and the bed armored. Transition from phase I to phase II occurred once bed forms were no longer produced and the last bed form exited the flume. Sediment output was measured at increasing time intervals during the experiment, which totaled 142 hours. Thus the close spacing of points projected onto the x axis indicates very low rates of degradation as armoring progressed and bed structures formed. The variation of transport rate with bed elevation was clearly nonlinear (contrary to equation 5); transport rate decreased with degradation more gradually as degradation proceeded. This would cause the variation of bed elevation with time to have greater positive curvature than an exponential equation fit to all points. In this case, stored volume varied as bed elevation (sediment stage) because the reservoir was rectilinear. In final stages of degradation, large surface particles became arranged in structures in the form of cells that further limit sediment transport and scour [*Hassan and Church*, 2000]. Such structures in natural channels indicate a low sediment supply and a stable bed elevation [*Church et al.*, 1998].

[24] Results of all experiments are plotted in Figure 3. Experiments that degraded the most started with the highest transport rates and had the best-sorted material (lowest σ_G). As shown in Figure 2, transport rates fluctuated widely but unsystematically during early stages of degradation when bed forms were present (phase I; Table 1). This may be an artifact of starting with a thoroughly mixed bed surface in most experiments, but those of *Harrison* [1950], which started with a shear-worked bed, show the same pattern. Later, the beginning of rapid decreases in transport rate was marked by smaller fluctuations as bed forms disappeared and the beds became armored and structured (phase II). In some runs, phase II degradation was limited to a single surface layer, but in others armoring progressed as the bed degraded through several surface-layer thicknesses. Only in the experiments of *Hassan and Church* [2000] did trans-

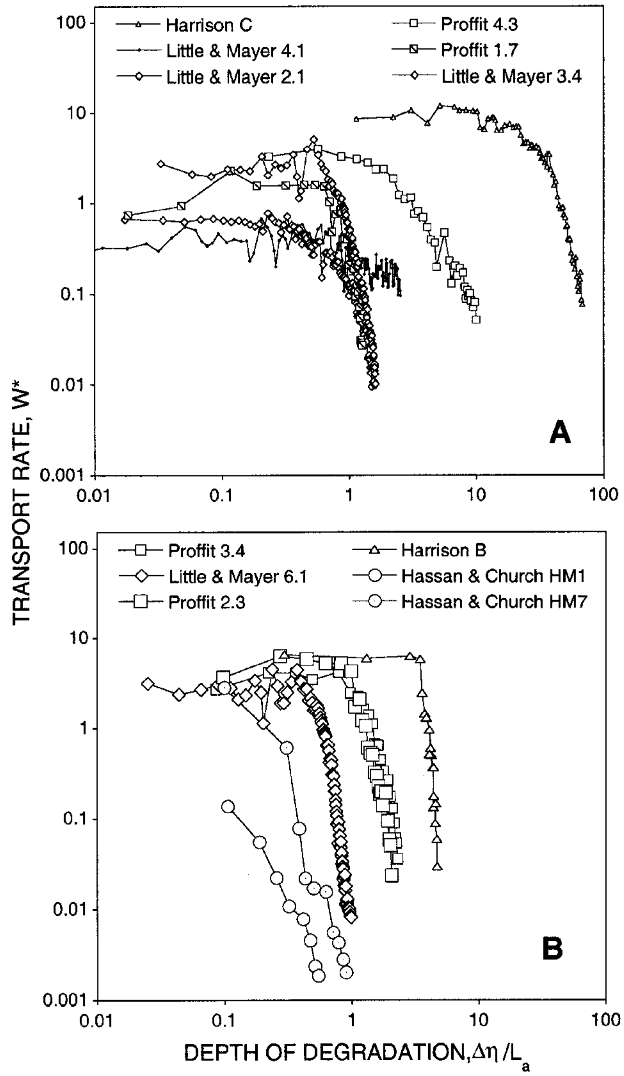

Figure 3. Variation of dimensionless transport rate (W*) and depth of degradation ($\Delta\eta/L_a$) for experimental runs using sediment with A.$\sigma_G < 1.2$; and B.$\sigma_G > 1.2$. Time progresses from left to right. The size of symbols is proportional to values of σ_G (Table 1).

port rates decrease to $W^* = 0.002$, a reference value that *Parker and Klingeman* [1982] used to define a threshold of entrainment.

4.2. Simulations of Armoring and Degradation

[25] To compare experimental results in a theoretical framework of interactions between armoring, bed elevation, and sediment transport, we adapted the approach of *Parker and Sutherland* [1990]. Consider a mixed bed that degrades a small increment of depth $\Delta\eta$ in the time interval Δt by selective transport of particles in the active layer L_a (Figure 4). During the interval, a unit volume ($\Delta\eta p_i$) of particles of size i is selectively removed from the volume in the surface layer $[(F_i)_1 L_a]$ and, to conserve layer thickness, is replaced by particles in an equal thickness of underlying bed material $\Delta\eta f_I$. (p_i, F_i, and f_i are fractions of size i in the bed load, surface, and subsurface layers.) The volume of size i in the surface layer then becomes

$$(F_i)_2 L_a = \left[(F_i)_1 L_a - \Delta\eta\, p_i\right] + \Delta\eta f_i \tag{8}$$

Rearranging terms gives the change in the volume of particle size i in the surface layer,

$$(F_i)_2 - (F_i)_1 = \left(\frac{\Delta\eta}{L_a}\right)(p_i - f_i) \tag{9}$$

or taken to the limit $\Delta t \rightarrow 0$,

$$\frac{d_{F_i}}{d(\eta/L_a)} = p_i - f_i \tag{10}$$

which is equation 38 of *Parker and Sutherland* [1990]. The increment of degradation is related to transport by

$$d(\eta/L_a) = kq_s dt \tag{11}$$

where k is inversely proportional to the length scale of the reservoir. Substituting in equation 10,

$$\frac{dF_i}{dt} = kq_s(p_i - f_i) \tag{12}$$

[26] A numerical model based on equation 12 was used to compute transport rates and changes in surface particle size distribution during the progression of degradation, given unit discharge, slope, and a subsurface particle size distribution. In the first step of computations, the surface distribution is assigned the subsurface distribution (zero armoring) and the transport rate and its size distribution are computed with the ACRONYM1 bed load program of *Parker* [1990].

[27] This transport rate produces an arbitrary depth of degradation, which is a small fraction of L_a. A new surface size distribution is computed from equation 9 and provides the input for the next equal time step. In this step, the new increment of degradation is made proportional to the ratio of transport rates of the present and preceding steps. To facilitate computation, L_a is assumed to remain constant at the value for the subsurface material. These computations are continued until transport rate decreases to a value of $W^* = 0.01$. This value was arbitrarily chosen to match the lowest rates achieved in the majority of the experiments.

[28] For a number of reasons, simulations from this model are poor predictors of results of individual experiments, and it is not our intent to make such predictions. First, the bed load equation on which the model is based

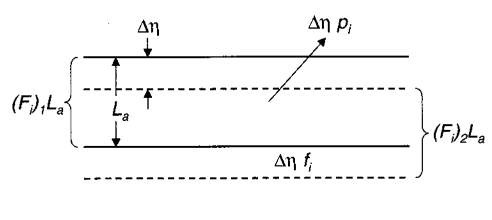

Figure 4. Model for degradation of a gravel bed [after *Parker and Sutherland*, 1990].

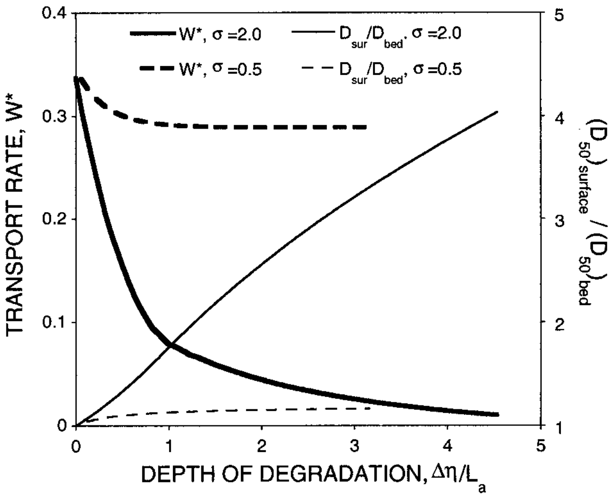

Figure 5. Variation of transport rate (*W**) and armoring (ratio of D_{50} of the bed surface to D_{50} of the sediment mixture) with depth of degradation ($\Delta\eta/L_a$) from simulations of armoring of a well sorted bed ($\sigma_G = 0.5$, initial $\tau^* = 0.05$) and a poorly sorted bed ($\sigma_G = 2$, initial $\tau^* = 0.17$).

was developed for equilibrium transport in beds with a range of armoring, and does not explicitly incorporate bed forms or bed structures other than armoring. The model does not account for longitudinal variations in transport and bed structure that are associated with disequilibrium in sediment transport. Second, the ACRONYM1 program was developed for gravel bed rivers and applies to particles transported primarily as bed load. It has been realized, however, that some of the parameters in the equation may have to be adjusted when applied to scaled-down laboratory experiments [*Cui et al.* 1996; *Cui and Parker*, 1997; Y. Cui et al., Sediment pulses in mountain rivers, 2, Comparison between experiments and numerical predictions, manuscript in preparation, 2002.]. Sediment used in the experiments was mostly sand transported primarily as bed load. We used a modified ACRONYM1 program that could be applied to scaled-down bed material, but we otherwise kept the parameters that would apply to gravel beds. While the ACRONYM1 program was scaled down to cover the full size distribution of the experimental material, it is doubtful that the modified program and the experiments would both accurately represent full-scale gravel transport processes or whether simulated and experimental results would agree, even for equilibrium conditions. In fact, there were wide discrepancies in predicting initial transport rates in the experiments using the modified ACRONYM1 program. Lastly, the simulations were unable to effectively model transitions from phase I to phase II transport, indicating either an immediate onset of armoring or runaway degradation. In appreciation of these limitations, we intend these simulations to model only the relative influences of initial flow strength and particle sorting on degradation caused by selective transport on a planar, unstructured bed.

[29] Examples of simulated degradation into a well-sorted bed ($\sigma_G = 0.5$) and poorly sorted bed ($\sigma_G = 2$) are shown in Figure 5. Initial flow strengths were adjusted to produce equal initial transport rates. Both examples show nonlinear decreases in transport rate with degradation, similar to the armoring phases (phase II) in degradation experiments. In the poorly sorted example, enough armoring develops to drive transport rates below the reference value ($W^* = 0.01$) (see runs of *Hassan and Church* [2000]). In the well-sorted example, armoring is weak and transport rates remain high (see run 4.1 of *Little and Mayer* [1972]).

[30] Simulations were run to define relations between η/L_a achieved at $W^* = 0.01$ and initial Shields stress exerted on unarmored beds of given sorting (σ_G = 1.0, 1.5, and 2.0) (Figure 6). Agreement between simulations and experimental results (also plotted) is poor, particularly for the runs of *Harrison* [1950] and *Hassan and Church* [2000], in which degradation is over-predicted. Trends are more consistent between runs of individual experiments than between different experiments. Nevertheless, the trends shown by simulations and experiments are similar. For well-sorted beds (σ_G less than about 1), degradation increases rapidly with increasing Shields stress not far above the entrainment threshold ($\tau^* \sim 0.05$). For poorly sorted beds (σ_G approaching 2), degradation increases more gradually with Shields stress, and is generally limited to several surface layers or less within a range of Shields stress ($0.06 < \tau^* < 0.15$) that is usually achieved in natural gravel bed channels during annual peak flows [*Andrews*, 1984]. The discrepancy between simulation and experiment is also consistent with the influences of structures developed on armored surfaces [*Church et al.*, 1998], the effect of which is not comprehended in the simulations.

[31] With these caveats in mind, we believe that the results of these experiments and simulations indicate general tendencies of transport-storage relations for degrading channels. Following peak sediment stages, high transport rates associated with nonselective transport and migrating bed forms can vary about a nearly constant mean as the bed degrades (phase I), although decreases in gradient accompanying degradation of the profile would be expected to

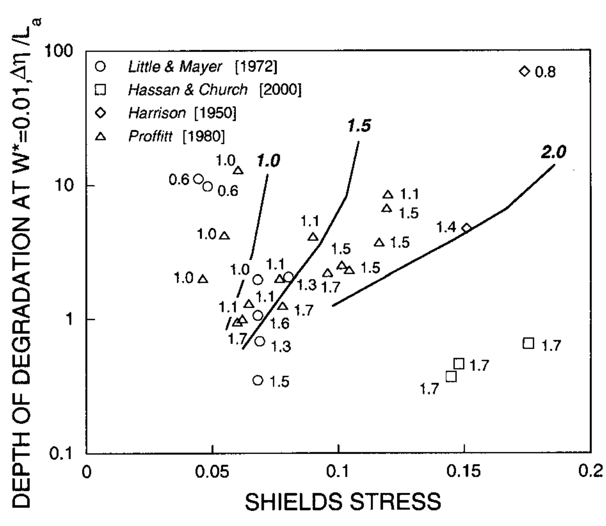

Figure 6. Depth of degradation ($\Delta\eta/L_a$) achieved at a final low transport rate ($W^* = 0.01$) versus Shields stress. Experimental results are plotted with values of particle sorting (σ_G) of the sediment mixture; simulation results are plotted as relations between $\Delta\eta/L_a$ and Shields stress for given values of σ_G.

reduce transport capacity [*Gilbert*, 1914]. Once armoring begins, transport rate decreases rapidly with decreasing sediment stage (phase II), defining a positive, nonlinear relation between transport and stored volume. Poorer sorting of bed material accelerates bed stabilization, thereby limiting degradation [*Church et al.*, 1998].

5. Lateral Erosion and Its Influence on Sediment Evacuation

[32] Lateral erosion of floodplains and terraces by channels also contributes to the evacuation of sediment from sediment reservoirs. Information on patterns of net export of sediment by lateral erosion is limited, but *Nakamura et al.* [1995] and *Nakamura and Kikuchi* [1996] analyzed variations in size and age of valley floor surfaces in Japan. Their focus was on the age structure of valley floor surfaces of sediment reservoirs in approximate equilibrium; net evacuation was documented in only one of their examples (Higashi-gouchi River) [*Nakamura et al.*, 1995]. We adapted their model to examine forms of transport-storage functions that embody both lateral erosion and degradation.

[33] From their data and similar results reported by *Everitt* [1968], *Nakamura et al.* [1995] estimate that the decrease in area of floodplain deposits with age is proportional to the total area occupied by each age class, which leads to the continuity equation (their equation 6),

$$\partial a_{(x,t)}/\partial t = -\partial a_{(x,t)}/\partial x - c a_{(x,t)} \quad (13)$$

where $a_{(x,t)}$ is the area of deposits of age x years at time t years, and c is a constant erosion rate per unit area. (Original notation has been modified to avoid confusion with other parts of our analysis.) The area initially created for each age class, $a_{(0,t-x)}$, given that the area of age x was created at time $t - x$, is (their equation 7)

$$a_{(0,t-x)} = a_{(x,t)}/\exp(-cx) \quad (14)$$

Because equation 13 is symmetrical, equation 14 can be recast in terms of variations in area with respect to time instead of age and rearranged into the exponential form of equation 3 for area of sediment stored,

$$a_{(x,t)} = a_{(0,t-x)}\exp(-ct) \quad (15)$$

This implies that if sediment eroded from valley floor surfaces were not replaced by new deposits, then stored volume would decrease exponentially and the sediment transfer-storage relation would be linear. Such a pattern observed in Higashi-Gouchi River (described later) is consistent with this implication [*Maita*, 1991; *Nakamura et al.*, 1995].

[34] In a more recent paper, *Nakamura and Kikuchi* [1996] modified equation 13 to take into account observations that deposits become less vulnerable to erosion with age, because they become more marginalized as the main channel migrates, thus decreasing the probability that any section would be attacked. Older surfaces are also less likely to be inundated by floods as the channel degrades and may become more resistant with the growth of riparian vegetation. Data from the Saru River indicate an exponential function for erosion rate that replaces the constant c in equation 15. With this modification equation 15 can be written

$$a_{(x,t)} = a_{(0,t-x)}\exp\left\{\frac{\alpha}{\beta}[\exp(-\beta t) - 1]\right\} \quad (16)$$

where α and β are determined empirically. This causes the erosion rate of a surface to decrease faster than would be predicted by a simple exponential relation such as equation 15. The variation in lateral erosion rate of the original floodplain surface is shown in Figure 7a; surfaces formed later would start with smaller areas and decrease similarly.

[35] We simulated sediment evacuation from a sediment reservoir modeled after the Saru River over a 40-year period by combining equation 16 to model rates of lateral erosion and an arbitrary relation (see below) modeling the decrease in bed elevation with time. We began with a fully filled reservoir and computed annual loss of volume of sediment stored. In each step, a portion of each existing valley floor surface was eroded laterally at the elevation of the bed at that time step. A new lowest valley floor surface was created in each step and was subsequently eroded. Remaining stored volume V_t at time t years is given by

$$V_t = V_{(t-1)} - \sum_0^x \left(a_{(x,t-1)} - a_{(x,t)}\right)(\eta_x - \eta_t) \quad (17)$$

where η_x is channel elevation corresponding to a surface of age x and η_t is channel elevation at time t.

[36] We made three simplifying assumptions: (1) Sediment inputs from upstream were negligible. (2) Only the lowest surface (the level of the channel) is eroded vertically; higher surfaces are subject to lateral erosion. (3) Processes of degradation and lateral erosion are independent of one another.

[37] The lateral erosion component of the model was constrained by values of the empirical constants in equation 16 for the Saru; total valley floor surface area ($a_{(40,0)}$) was approximated at 500,000 m^2 [*Nakamura and Kikuchi*, 1996]. We arbitrarily chose a value of η_0 = 5 m.

[38] We used alternative equations to describe erosion in the vertical plane. In case 1, which includes only a phase II component, we assumed that armoring begins immediately and channel elevation decreases with time according to an exponential equation

$$\eta = \eta_0\exp(-ht). \quad (18)$$

As stated earlier, variation of bed elevation with time in degrading, armoring beds commonly has greater positive curvature than exponential relations, but we used an exponential form here as an approximation that would not unduly bias our results toward a nonexponential variation of volume of sediment stored with time. Having little constraint on rates of degradation, we chose a value of h = 0.5 yr^{-1}. Similar to the rapid exponential degradation of the Higashi-gouchi River, case 1 simulates initially high but rapidly decreasing rates of degradation (Figure 7b), leaving only 0.4 m of excess bed elevation after 5 years.

[39] In case 2, which includes phase I and phase II components, bed elevation initially decreases at a constant rate of 0.5 m/yr until all but 1 m is evacuated. This

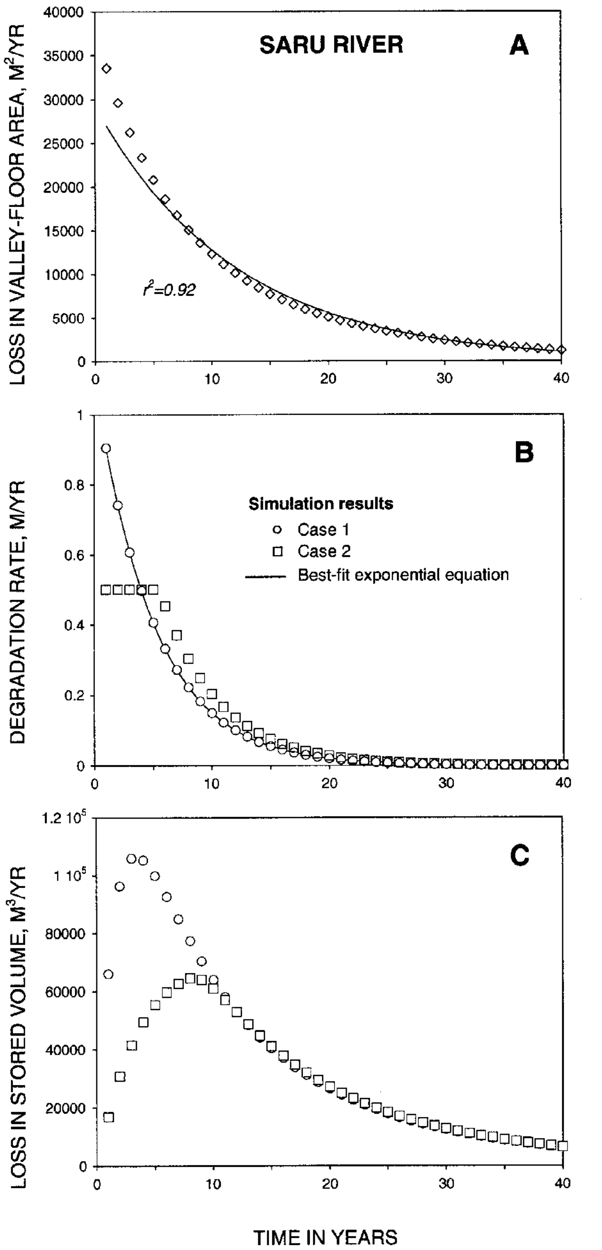

Figure 7. Results of simulations of sediment evacuation from a sediment reservoir modeled after the Saru River over a 40-year period starting from a filled sediment stage: Temporal variations in rates of decrease in (a) area of the original valley floor surface, (b) bed elevation given alternative values of h in equation 18, and (c) volume of stored sediment.

represents an initial period of unsorted bed load transport over a poorly armored bed when transport rate remains constant (phase I) and, as discussed later, may better represent interactions with lateral erosion than does case 1. During final stages of degradation, armoring commences and the bed elevation decreases with time according to equation 18.

[40] Results of the simulations show sediment export rate increasing to a peak after 3 years (case 1) and 10 years (case 2) and then decreasing at an approximate exponential rate with time (Figure 7c). The initial increase in export rate is due to increasing thicknesses of terraces being laterally eroded after the first time steps while the probability of attack is still high. Later, as rates of degradation become small, surfaces standing at a given height above the channel become older, smaller, and less likely to be attacked at any section of channel. Partial confirmation of this behavior is provided by results of the flume experiment previously described (Figure 1b), when sediment output rate initially increased as terraces were exposed and trimmed.

[41] However, simulation results challenge the validity of the assumption of independence of lateral erosion and degradation. Peak sediment export rates would be limited by the maximum transport capacity of the channel, when it has minimum armoring. If this limit were exceeded because of lateral inputs, then degradation would slow and lateral erosion would proceed, probably at an altered rate. Lateral erosion clearly complicates the relation between sediment transport and sediment stage in a degrading sediment reservoir. More information is needed before this interaction can be accurately modeled. In the meantime, results of this simulation are more likely to represent systems where interactions between incision and lateral erosion are not strong, which is most likely where rates of lateral erosion are low.

6. Field Examples

[42] Two field studies provide examples of transport-storage relations in natural, degrading, gravel bed channels that eroded vertically and laterally. Comparisons of observations with results from modeling and flume experiments are uncertain because discharge varied and sediment input rates were poorly known during degradation. To equate the rate of loss of stored volume to transport rate, we must assume that input rates from upstream were small or constant enough to be disregarded. This assumption is apparently valid in these cases, because there was little sediment stored in the channels upstream of the study reaches, and most sediment input from hillslopes occurs during large, infrequent floods [*Iseya et al.*, 1990b; *Marutani et al.*, 1999]. The contribution of lateral erosion of flood deposits to sediment evacuation was not sufficiently detailed to compare to the model presented in the previous section. However, examples of cross sections show that the highest deposits were laterally eroded during channel incision, but some remained at the end of the measurement period, as observed in the experiment of *Lisle et al.* [1993]. The channel in this experiment resembled the natural channels in having steep slopes, a wide range in particle sizes, and low relative submergence of dominant bed particles, although it was not specifically modeled after either one.

[43] *Maita* [1991] surveyed a 1-km reach of Higashi-Gouchi River in the Southern Japanese Alps before the channel filled during a typhoon in 1982 and then afterward as it progressively scoured in later floods. Higashi-Gouchi is a tributary (drainage area, A_d = 28 km^2) of the Oi River, Honshu Island, which drains into the Pacific Ocean. The channel is steep (gradient, $S \sim 0.1$) and the bed contains a wide range of grain sizes, including boulders. During the typhoon, the channel and valley floor (approximately 70 m wide) filled to a depth of 3 to 8 m with heterogeneous

sediment, including a basal unit of coarse cobbles and boulders and a thicker, stratified unit of gravel and sand [*Iseya et al.*, 1990b]. During six smaller floods in the next four years, the channel scoured to nearly its pretyphoon profile. To compensate for the effects of variable flood magnitude on scour, Maita scaled increments of scour by the magnitudes of the intervening peak discharges. We modified this scaling slightly by normalizing peak discharge by mean peak discharge in order to make the equation presented below dimensionally correct. Time is defined as the sequence of intervals between flood events occurring after the channel filled.

[44] Maita's data can be fit to an exponential decay function for stored sediment (r^2 = 0.997) after computing the apparent base level from equation 4 (Figure 8a). However, he found that increments of scour decreased exponentially with flood order, and we confirmed that variations in the rate of loss of stored sediment ($-\Delta V/\Delta t$) fit a power function (r^2 = 0.999; n = 5) better than a linear function (r^2 = 0.982) (Figure 8b). This indicates that the decrease in stored volume was more rapid than exponential. This may be due to rapid erosion of the top layers of the torrent deposits, which were fine-grained. Nevertheless, an exponential decay function and the implied linear transport-storage function describe the initial stages of sediment evacuation nearly as well as the power function, and the uncertainty in scaling time and the rate of loss of stored sediment preclude a meaningful choice between the two equations based on a slight difference in goodness of fit.

[45] *Marutani et al.* [1999] provide a contrasting example of transport-storage relations from two tributaries of the Waipaoa River, New Zealand (Matakonekone Stream, A_d = 4.3 km^2, S = 0.077; Oil Springs Stream, A_d = 3.0 km^2, S = 0.057). These channels fill with gravel and sand eroded from large gully systems during infrequent cyclonic storms, then scour in subsequent years during smaller flows, leaving flood terraces. After a filling episode in 1988, annual volumetric loss of stored volume was approximately constant over six years, although the rate of loss of stored sediment was not scaled to flow magnitudes. Assuming no significant differences in flow or sediment input in this period, the observations indicate that transport capacity remained constant as stored volume decreased.

[46] In summary, sediment transport capacity decreased sharply as stored volume decreased in the Higashi-gouchi River, and remained approximately constant in the Waipaoa tributaries [*Marutani et al.*, 1999]. The former example suggests a phase II transport-storage relation and the latter a phase I relation. This suggests that selective transport and armoring were initiated quickly in Higashi-gouchi but were delayed in the Waipaoa tributaries.

7. Discussion and Conclusions

[47] Results of field studies, experiments, and numerical simulations of gravel bed channels generally demonstrate decreases in the rate of sediment transport from sediment reservoirs as the volume of sediment in storage decreases. Root causes of this relation are the increasing resistance of the channel to entrainment afforded by armoring and form resistance and the depletion of marginal sources of sediment available to lateral erosion. Of these, armoring is best understood.

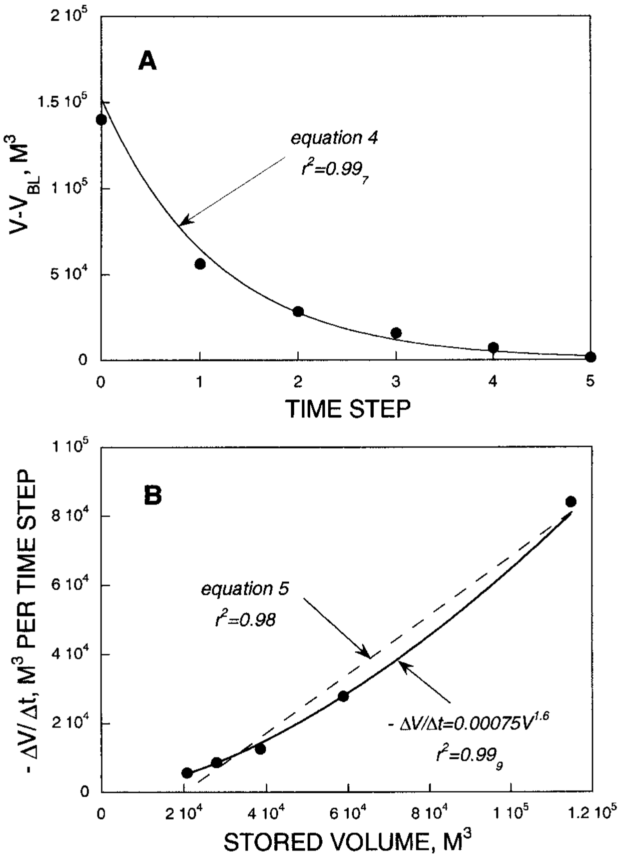

Figure 8. Variation of sediment stored in the Higashi-gouchi River, southern Japanese Alps [*Maita*, 1991]. (a) Variation of stored volume with time step. The beginning storage volume (V_0) for the original data set is the net volume deposited in the study reach during the flood of August 1982. According to equation 4, a base storage volume, V_{BL}, is subtracted from V_0 to optimize the fit of an exponential equation, resulting in V_{BL} = 19700 m^3 and K = -0.85 time units^{-1}. (b) Variation of the rate of loss of stored volume with stored volume. Time progresses from right to left.

[48] During initial phases of degradation in one field example (Waipaoa River [*Marutani et al.*, 1999]) and some experiments, however, sediment transport rate appeared not to decrease as stored sediment decreased but varied about a stable mean. The apparent lack of feedback from channel condition is attributed to nonselective transport of sediment and the near-absence of armoring. We refer to this initial phase of a transport-storage relation of a degrading sediment reservoir as phase I. Changes in gradient would be one of the primary remaining adjustments to changes in stored sediment volume during phase I, as *Gilbert* [1914] and *Mackin* [1948] proposed for degrading systems, but significant changes in gradient would require large decreases in stored volume. The commencement of an armoring phase, which we term phase II, occurred later in some of these experiments and at the beginning of others but was never apparent in the Waipaoa example. We believe that selective transport of surface material in natural gravel bed channels eventually drives the transition from phase I to phase II, but this transition is poorly understood. Once it begins, selective

transport perpetuates greater armoring and increasing resistance to tractive forces by positive feedback. Transport rate decreases as stored sediment decreases.

[49] A simple form of a transport-storage function for phase II would be a positive, linear variation with stored volume or sediment stage. This would be manifest as an exponential decay in stored volume with time under constant inputs of flow and sediment. Linear transport-storage functions appeared to be reasonable approximations for trends in sediment export from sediment reservoirs represented in a natural channel (Higashi-Gouchi River; *Maita* [1991]) and in a flume experiment where sediment supply was reduced but not entirely eliminated. However, closer examination of flume experiments and a numerical simulation of transport and armoring reveal that transport-storage relations for armoring channels may not be characteristically linear, but instead have positive curvature, that is, transport rates are greater during early stages of degradation and lesser during later stages than would be predicted by a linear relation.

[50] Uncertainty of the base datum from which variations in stored sediment volume are measured can lead to misidentification of exponential decay of stored volume and, thereby, linear transport-storage relations. Exponential equations are robust descriptors of data describing process rates in decaying systems. Without prior knowledge of the base datum, data can often be fit closely to an exponential equation by adjusting the datum upward or downward, thereby misrepresenting the true form of the variation. We made such an adjustment to data of *Lisle et al.* [1993] and *Maita* [1991], and *Simon* [1992] made a similar adjustment. Storage datums of sediment reservoirs in natural systems are usually poorly constrained but need to be known before the accuracy of linear transport-storage relations can be evaluated.

[51] Differences in the tendency for selective transport at high sediment stage may create differences in transport-storage relations between proximal and distal sediment reservoirs in a drainage system. Armoring in degrading systems commences earliest and depth of degradation is least where tractive forces are low and the spread of the particle size distribution is wide. The narrow range of sizes in well-sorted beds ($\sigma_G \leq 1$) limits the formation of a resistant armor in channels that are subjected to the common range of tractive forces during peak flow and, as a result, a diminishing sediment supply can perpetuate deep degradation unless other negative feedback mechanisms, such as a decrease in local channel gradient, are imposed. In contrast, the wide range of sizes in poorly sorted beds ($\sigma_G \geq 2$) promotes formation of resistant armor layers that tends to limit degradation to a few surface layers. Given the usual tendency for bed material sorting to be poorer in proximal channels close to sediment sources than in distal channels, the corresponding contrast in-depths of potential degradation would lead to a narrow range of sediment stage in proximal reaches with prevailing strong armoring and a rapid transfer of bed material to distal reaches. In contrast, variations in sediment stage in distal reaches would be influenced less by armoring, and variations in input would be accommodated more by changes in storage. We are unaware of data from natural systems that could be used to test this hypothesis, but it is consistent with the typical distribution of alluvial sediments in river systems. A countervailing factor would be the tendency for the range of aggradation and degradation to decrease downstream of sediment sources because of dispersion of sediment waves [*Lisle et al.*, 2001] and storage in intermediate sediment reservoirs [*Benda and Dunne*, 1997].

[52] At this juncture, interpretations about transfer-storage relations from our investigations have severe limitations. First, we have regarded sediment transfer only from sediment reservoirs that are degrading. To simplify the problem, we have avoided the issue of the effect of variations in the rate and particle size of sediment input on transport-storage relations. There was no sediment input in most of the experiments we analyzed, and we assumed that in the field examples, sediment inputs were so much smaller than sediment outputs that the inputs could be ignored. However, three sediment input rates were imposed in the experiment of *Lisle et al.* [1993]. Sediment input rates were reduced twice but maintained sufficiently long in each step to reach equilibrium with output rates. A single, linear transport-storage relation replicated sediment output during two stages of degradation and equilibrium and did not appear to be affected significantly by whether or not transport rate was in equilibrium with supply rate. This suggests some robustness in transport-storage relations as long as a reservoir is either degrading or stable. Progressive or stepwise declines in sediment inputs may prolong the period of degradation without affecting the transport-storage relation. However, we have no information on responses to increases in sediment stage and, more comprehensively, on full episodes of aggradation and degradation.

[53] Secondly, we have neglected the role of the stratigraphy of flood deposits. Torrent deposits in the Higashi-Gouchi River were initially rapidly eroded partly because of the fineness of the thick top layer; excavation of the coarse basal layer presumably inhibited further degradation [*Maita*, 1991; *Iseya et al.*, 1990b].

[54] Finally, we have much to learn about how aggradation and degradation interact with construction and lateral erosion of valley floor surfaces to govern sediment transfer through sediment reservoirs. Our simulation of a degrading reservoir with laterally eroding surfaces suggests that sediment transfers from valley floor surfaces to the channel and the creation of surfaces by channel migration can have profound influences on sediment transport-storage relations. In this regard, we have also neglected the role of riparian vegetation. Establishment of riparian vegetation on valley floor deposits increases erosional resistance [*Smith*, 1976; *Baker*, 1977; *Hickin*, 1984; *Stott*, 1997] and may thereby decrease rates of sediment transfer from valley floor surfaces to channels over time. All of these issues need to be investigated in order to accurately formulate sediment transport-storage relations.

[55] In light of our results and these uncertainties, we reexamine our account of *Gilbert*'s [1914] concept of transport capacity, by which sediment transport and storage both respond to changes in the rate of sediment supply according to a transport-storage relation regulated by channel adjustments. The lack of systematic change in transport rate with decreasing stored volume in channels exhibiting phase I relations supports a more conventional interpretation that transport capacity is the maximum transport rate achievable

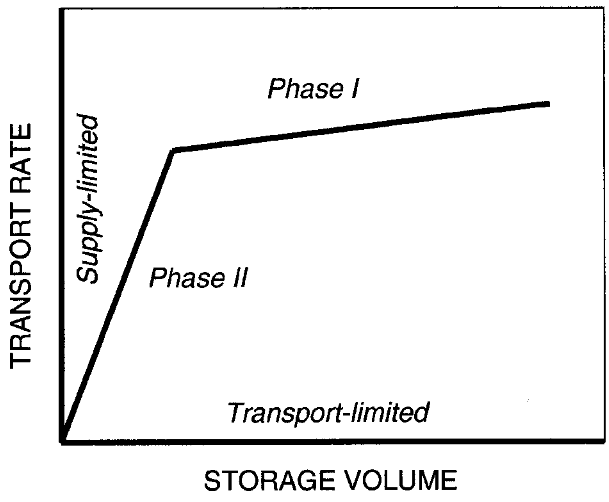

Figure 9. Conceptual model of a comprehensive transport-storage relation.

given sediment size and discharge, regardless of sediment stage. However, this cannot be strictly true for, with deep aggradation and subsequent degradation of a channel profile, gradient must vary and affect transport capacity, especially in short sediment reservoirs with local base levels. We maintain that our interpretation of *Gilbert*'s [1914] concept of transport capacity is more generally applicable to a variety of relations between transport capacity and stored volume, including those for aggrading channels and other cases that we have not investigateed. We conclude that when viewed over wide ranges of variation of sediment stage, gravel bed channels have some form of a positive transport-storage relation.

[56] If so, this would challenge strict designations of "transport-limited" and "supply-limited" sediment regimes, as well as the assumption of a constant or characteristic value of transport capacity for a channel. Conventionally, a transport-limited channel is one that responds to sediment inputs by increased storage (describing a horizontal line if it were plotted in Figure 9), since it is already transporting sediment "at capacity;" a supply-limited channel is one that responds by increased transport with no change in storage (describing a vertical line in Figure 9), since its capacity was not met beforehand. Alternatively, we propose that such transport- and supply-limited designations represent end-members of a continuum of transport-storage tendencies of natural sediment reservoirs. If transport capacity is a dynamic function of sediment stored then, at any time, every alluvial channel is transporting sediment according to the water discharge imposed and channel adjustments related to the volume available in the channel and other storage elements in the reservoir. Any additional input of sediment beyond the transient transport capacity will result in increased storage and transport; any deficit will result in decreased storage and transport, whether or not changes in transport and stored volume are detectable with available methods. Relative tendencies for transport or storage would be reflected in the steepness of transport-storage relations, the forms of which would be determined by hydraulic, sedimentologic, and geomorphic adjustments to sediment supply. Including the magnitude of variations in stored sediment volume in investigations of the dynamics of fluvial systems would improve our understanding of the routing of sediment and the formation of alluvial landforms.

[57] **Acknowledgments.** We gratefully acknowledge Yantao Cui for providing the program to run the numerical simulations of degradation and armoring and Jack Lewis for help with mathematical derivations. Comments from two anonymous reviewers led to important improvements in the paper.

References

Andrews, E. D., Hydraulic adjustment of the East Fork River, Wyoming to the supply of sediment, in *Adjustments of the Fluvial System, Tenth Annual Geomorphology Symposia Series*, edited by D. D. Rhodes and G. P. Williams, pp. 69–94, Kendall-Hunt, Binghamton, N.Y., 1979.

Andrews, E. D., Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado, *Geol. Soc. Am. Bull.*, *95*, 371–378, 1984.

Baker, V. R., Stream-channel response to floods, with examples from central Texas, *Geol. Soc. Am. Bull.*, *88*, 1057–1071, 1977.

Benda, L., and T. Dunne, Stochastic forcing of sediment routing and storage in channel networks, *Water Resour. Res.*, *33*(12), 2865–2880, 1997.

Borah, D. K., Scour depth predictions under armoring conditions, *J. Hydraul. Eng.*, *115*(10), 1421–1425, 1989.

Buffington, J. M., and D. R. Montgomery, Effects of hydraulic roughness on surface textures of gravel-bed rivers, *Water Resour. Res.*, *35*(11), 3507–3521, 1999.

Church, M., M. A. Hassan, and J. F. Wolcott, Stabilizing self-organized structures in gravel-bed stream channels: Field and experimental observations, *Water Resour. Res.*, *34*(11), 3169–3179, 1998.

Cui, Y., and G. Parker, A quasi-normal simulation of aggradation and downstream fining with shock fitting, *Int. J. Sediment Res.*, *12*, 68–82, 1997.

Cui, Y., G. Parker, and C. Paola, Numerical simulation of aggradation and downstream fining, *J. Hydraul. Res.*, *34*(2), 185–204, 1996.

Dietrich, W. E., T. Dunne, N. F. Humphrey, and L. M. Reid, Construction of sediment budgets for drainage basins, in *Sediment Budgets and Routing in Forested Drainage Basins*, edited by F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston, pp. 5–23, For. Serv., Pac. Northwest For. and Range Exp. Stat., U. S. Dep. of Agric., Arcata, Calif., 1982.

Dietrich, W. E., J. W. Kirchner, H. Ikeda, and F. Iseya, Sediment supply and the development of the coarse surface layer in gravel-bedded rivers, *Nature*, *340*, 215–217, 1989.

Everitt, B. L., Use of the cottonwood in an investigation of the recent history of a flood plain, *Am. J. Sci.*, *266*, 417–439, 1968.

Gessler, J., Self-stabilizing tendencies of alluvial channels, *J. Waterw. Harbors Div. Am. Soc. Civ. Eng.*, *96*(WW2), 235–249, 1970.

Gilbert, G. K., The transportation of debris by running water, *U.S. Geol. Surv. Prof. Pap.*, *86*, 221 pp., 1914.

Gomez, B., Temporal variations in the particle size distribution of surficial bed material: The effect of progressive bed armouring, *Geogr. Ann.*, *65A*, 183–192, 1983.

Gomez, B., B. J. Rosser, D. H. Peacock, D. M. Hicks, and J. A. Palmer, Downstream fining in a rapidly aggrading gravel bed river, *Water Resour. Res.*, *37*(6), 1813–1823, 2001.

Graf, W. L., The rate law in fluvial geomorphology, *Am. J. Sci.*, *277*, 178–191, 1977.

Grant, G. E., and T. Mizuyama, Origin of step-pool sequences in high-gradient streams: A flume experiment, in *Proceedings of the Japan-U.S. Symposium on Snow Avalanche, Landslide, and Debris Flow Prediction and Control*, edited by M. Tominaga, pp. 523–532, Sci. and Technol. Agency of Jpn., Tsukuba, Japan, 1992.

Grant, G. E., and F. J. Swanson, Morphology and processes of valley floors in mountain streams, western Cascades, Oregon, in *Natural and Anthropogenic Influences in Fluvial Geomorphology: The Wolman Volume*, *Geophys. Monogr. Ser.*, vol. 89, edited by J. E. Costa et al., pp. 83–101, AGU, Washington, D. C., 1995.

Griffiths, G. A., Conversion of braided gravel-bed rivers to single-thread channels of equivalent transport capacity, *J. Hydrol. N. Z.*, *28*(1), 63–75, 1989.

Harrison, H. S., Report on special investigations of bed sediment segregation in a degrading bed, *33*(1), Inst. of Eng. Res., Univ. of Calif., Berkeley, 1950.

Hassan, M. A., and M. Church, Experiments on surface structure and partial sediment transport on a gravel bed, *Water Resour. Res.*, *36*(7), 1885–1896, 2000.

Hickin, E. J., Vegetation and river channel dynamics, *Can. Geogr.*, *28*, 111–126, 1984.

Hirano, M., On bed lowering accompanying armoring, *Trans. Jpn. Soc. Civ. Eng.*, 195, 1971.

Iseya, F., H. Ikeda, and T. E. Lisle, Fill-top and fill-strath terraces in a flume with decreasing sediment supply of sand-gravel mixtures, *Trans. Jpn. Geomorphol. Union*, *10*(4), 323–342, 1990a.

Iseya, F., H. Ikeda, H. Maita, and Y. Kodama, Fluvial deposits in a torrential gravel-bed stream by extreme sediment supply: sedimentary structure and depositional mechanism, paper presented at the Third International Workshop on Gravel-bed Rivers, Gruppo Naz. Defesa Catastrofi Idrogeol., Florence, Italy, 1990b.

Kelsey, H. M., R. L. Lamberson, and M. A. Madej, Stochastic model for the long-term transport of stored sediment in a river channel, *Water Resour. Res.*, *23*(9), 1738–1750, 1987.

Lenzi, M. A., Step-pool evolution in the Rio Cordon, northeastern Italy, *Earth Surf. Processes Landforms*, *26*(9), 991–1008, 2001.

Leopold, L. B., and W. B. Bull, Base level, aggradation and grade, *Proc. Am. Philos. Soc.*, *123*(3), 168–202, 1979.

Lisle, T. E., Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northern California, *Water Resour. Res.*, *18*(6), 1643–1651, 1982.

Lisle, T. E., and S. Hilton, Fine bed material in pools of natural gravel-bed channels, *Water Resour. Res.*, *35*, 1291–1304, 1999.

Lisle, T. E., and M. A. Madej, Spatial variation in armouring in a channel with high sediment supply, in *Dynamics of Gravel-Bed Rivers*, edited by P. Billi et al., pp. 277–291, John Wiley, New York, 1992.

Lisle, T. E., H. Ikeda, and F. Iseya, Formation of stationary alternate bars in a steep channel with mixed-size bedload: A flume experiment, *Earth Surf. Processes Landforms*, *16*(5), 463–469, 1990.

Lisle, T. E., F. Iseya, and H. Ikeda, Response of a channel with alternate bars to a decrease in supply of mixed-size bedload: A flume experiment, *Water Resour. Res.*, *29*(11), 3623–3629, 1993.

Lisle, T. E., J. M. Nelson, J. Pitlick, M. A. Madej, and B. L. Barkett, Variability of bed mobility in natural gravel-bed channels and adjustments to sediment load at the local and reach scales, *Water Resour. Res.*, *36*(12), 3743–3756, 2000.

Lisle, T. E., Y. Cui, G. Parker, J. E. Pizzuto, and A. M. Dodd, The dominance of dispersion in the evolution of bed material waves in gravel bed rivers, *Earth Surf. Processes Landforms*, *26*(13), 1409–1420, 2001.

Little, W. C., and P. G. Mayer, The role of sediment gradation of channel armoring, *Publ. ERC-0672*, 104 pp., Ga. Inst. of Technol., Atlanta, 1972.

Mackin, J. H., Concept of the graded river, *Geol. Soc. Am. Bull.*, *59*, 463–512, 1948.

Madej, M. A., Development of channel organization and roughness following sediment pulses in single-thread, gravel bed rivers, *Water Resour. Res.*, *37*(8), 2259–2272, 2001.

Maita, H., Sediment dynamics of a high gradient stream in the Oi River Basin of Japan, *USDA For. Serv. General Tech. Rep., PSW-GTR-130*, 56–64, 1991.

Marutani, T., M. Kasai, L. M. Reid, and N. A. Trustrum, Influence of storm-related sediment storage on the sediment delivery from tributary catchments in the upper Waipaoa River, New Zealand, *Earth Surf. Processes Landforms*, *24*(10), 881–896, 1999.

Nakamura, F., and S. Kikuchi, Some methodological developments in the analysis of sediment transport processes using age distribution of floodplain deposits, *Geomorphology*, *16*, 139–145, 1996.

Nakamura, F., H. Maita, and T. Araya, Sediment routing analysis based on chronological changes in hillslope and riverbed morphologies, *Earth Surf. Processes Landforms*, *20*, 333–346, 1995.

Nolan, K. M., and D. C. Marron, History, causes, and significance of changes in the channel geometry of Redwood Creek, northwestern California, 1936 to 1982, in *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California*, edited by K. M. Nolan, H. M. Kelsey, and D. C. Marron, *U.S. Geol. Surv. Prof. Pap.*, *1454*, N1–N22, 1995.

Parker, G., The ACRONYM series of PASCAL programs for computing bedload transport in gravel rivers, *External Memo. M-220*, 124 pp., St. Anthony Falls Lab., Univ. of Minn., Minneapolis, 1990.

Parker, G., and P. C. Klingeman, On why gravel bed streams are paved, *Water Resour. Res.*, *18*(5), 1409–1423, 1982.

Parker, G., and A. J. Sutherland, Fluvial armor, *J. Hydraul. Res.*, *28*, 529–544, 1990.

Proffitt, G. T., Selective transport and armouring of non-uniform alluvial sediments, *Res. Rep. 80/22*, 203 pp., Dep. of Civ. Eng., Univ. of Canterbury, Christchurch, New Zealand, 1980.

Reid, L. M., and T. Dunne, *Rapid Evaluation of Sediment Budgets*, 164 pp., Catena Verlag GMBH, Reiskirchen, Germany, 1996.

Rice, R. M., F. B. Tilley, and P. A. Datzman, A watershed's response to logging and roads: South Fork Caspar Creek, California, 1967–1976, *Res. Pap. PSW-146*, USDA For. Serv. Pac. Southwest Res. Statn., Albany, Calif., 1979.

Rice, S., and M. Church, Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links, *Earth Surf. Processes Landforms*, *23*, 345–363, 1998.

Sawada, T., K. Ashida, T. Takahashi, Sediment transport in mountain basins, paper presented at International Symposium on Erosion, Debris Flow and Disaster Prevention, Tsukuba, Japan, 1985.

Simon, A., Energy, time, and channel evolution in catastrophically disturbed fluvial systems, *Geomorphology*, *5*, 345–372, 1992.

Simon, A., and C. R. Thorne, Channel adjustment of an unstable coarse-grained stream: Opposing trends of boundary and critical shear stress, and the applicability of extremal hypotheses, *Earth Surf. Processes Landforms*, *2*, 155–180, 1996.

Smith, D. G., Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river, *Geol. Soc. Am. Bull.*, *87*, 857–860, 1976.

Stott, T., A comparison of stream bank erosion processes in forested, and moorland streams in the Balquhidder catchments, central Scotland, *Earth Surf. Processes Landforms*, *22*, 383–399, 1997.

Wilcock, P. R., The flow, the bed, and the transport: Interaction in flume and field, in *Gravel-Bed Rivers V*, edited by M. P. Mosley, pp. 183–209, New Zealand Hydrol. Soc., Wellington, 2001.

M. Church, Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z2. (mchurch@geog.ubc.ca)

T. E. Lisle, Pacific Southwest Research Station, Redwood Sciences Laboratory, USDA Forest Service, 1700 Bayview Drive, Arcata, CA 95521, USA. (tel7001@humboldt.edu)