Gravel-Bed Rivers VI: From Process Understanding to River Restoration
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Sediment storage and transport in coarse bed streams: scale considerations

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Abstract

Bedforms in gravel-bed rivers range in size from 10^{-2} to 10^{3} m and have a wide range of affects on sediment transport and channel stability. To study the affect of these bedforms on sediment transport a classification scheme is proposed that breaks the bedforms into micro, meso, macro and megaforms. Then using two creeks in British Columbia and one in California, the trend of sediment transport rates is related to the bed state, sediment and wood storage and the associated bedforms are discussed.

At small spatial and temporal scales (micro/mesoform scales), variability in sediment transport rate can be ascribed to the changing state of the bed, which largely depends on the sediment supply regime. Stabilizing bedforms develop when sediment supply is low, and reduces the depth of the bed active layer and the mobility of the grains, thereby decreasing the sediment transport rate. Sediment rating relations in a low sediment supply channel are steep and are believed to be extremely sensitive to small changes in sediment supply and flow regime when compared to higher sediment supply systems. High sediment supply suppresses the development of stabilizing bedforms and increases the mobility of grains and the depth of the active layer. At the reach scale (macroform scale), high sediment mobility is shown to produce complex cycles of aggradation and degradation that can persist for decades. In-channel woody debris can strongly influence the timing and magnitude of these aggradation–degradation cycles and also has an important effect on the development of megaforms.

1. Introduction

In the extensive literature on sediment transport in rivers, the predominant viewpoint is that the rate of sediment transport at any time is a function of hydraulic and sedimentological variables. In this framework, mass transport over a period of time is

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calculated by integration over the period when flows are competent to move the bed. The various functional relations presented for the calculation of sediment transport rates are based on dimensional analysis, stochastic or deterministic methods, and calibrated to some extent by laboratory and/or field data. Predictions of sediment transport rate via hydraulically based functional relations are often more than an order of magnitude different than measured rates. These discrepancies have been explained by bed surface armouring and low sediment availability and the assumptions that underlie the models: uniform sediment, unconstrained movement of sediment and little consideration of the role of sediment supply, storage within the channel and sediment mobility. The effect of these interactions are presumably large, since transport rates are reported to vary by more than two orders of magnitude at constant flow (e.g., Hayward, 1980; Jackson and Beschta, 1982).

Coarse sediment, which comprises the bed material load, enters the stream channels episodically from adjacent slopes or upstream tributaries and often results in a step change in channel morphology and sediment transport patterns. Sediment is either initially deposited within the channel (Goff and Ashmore, 1994; Lane et al., 1995; Reid and Dunne, 2003) to be remobilized and moved onward by fluvial processes at a later stage (e.g., Beschta, 1983; Sutherland et al., 2002), or it is immediately transported by fluvial processes some distance downstream, where it is deposited, often behind obstacles to form sediment wedges and other sedimentation features. In all cases, the sediment inputs modify the channel morphology and bed surface composition (texture and structure), which affects the local sediment transport rate by altering sediment mobility and/or the distribution of shear stress acting on the bed.

Evacuation of sediment stored in the channel following one of these episodic input events depends on flood history (i.e., magnitude, duration and sequence), sediment characteristics and the sediment supply history. The result is that the temporal and spatial variation in the amount of within-channel sediment storage depends on the supply from external sources (e.g., Swanson et al., 1982b; Benda, 1990). Consequently, flow events of the same magnitude and duration may produce different channel morphologies, bed surface texture and structure and sediment mobility (e.g., Buffington and Montgomery, 1999; Lisle et al., 2001). Streams with a relatively large sediment supply, and associated volume of in-channel sediment, typically have texturally finer surfaces, poorly developed surface structures and higher sediment transport rates for a given discharge than channels with the same slope and lower sediment supplies (e.g., Lisle and Madej, 1992). When the sediment supply is low the development of a well-structured, coarse-textured bed significantly reduces the sediment transport rates (Parker et al., 1982; Dietrich et al., 1989; Church et al., 1998; Hassan and Church, 2000; Ryan, 2001; Church and Hassan, 2002, Hassan and Woodsmith, 2004).

Depending on the scale of the storage element and position within the stream network, sediment may be stored for periods ranging from less than a year to decades or even centuries (Dietrich et al., 1982; Swanson et al., 1982a; Kelsey et al., 1987; Madej, 1987, Madej and Ozaki, 1996). The transport capacity of a channel may appear constant at both short ($<10^0$ years) and very long timescales ($>10^3$ years), but it is clearly dynamic at intermediate timescales that correspond with the passage of sediment waves that cause fluctuations in channel storage (Lisle and Church, 2002;

Lisle and Smith, 2003). At these intermediate timescales, Lisle and Church (2002) asserted that sediment transport capacity responds to changes in sediment supply and storage. For a given rate of sediment supply, the capacity regulates changes in sediment storage within a reach and the amount of sediment transferred to the next downstream segment. Lisle and Church (2002) showed an exponential decrease in the stored sediment with time implying that a linear relation may exist between transport capacity and storage. Further research has shown that a linear transport–storage function is only one possible curve and that more complex relations exist following severe aggradation that alters the channel pattern and that fundamentally different curves exist for relations between transport and storage during aggradation and degradation (Lisle and Smith, 2003; Smith, 2004). In the preceding discussion it has been emphasized that bed state and sediment storage play an important role in regulating sediment transport. What has not, however, been emphasized is the scale at which these factors are most evident. For instance, the concept of storage as a regulator of sediment supply applies at longer time scales and over larger spatial areas than have been investigated in many sediment transport studies. There is a need to illustrate with field-based studies the time and spatial scales that are most appropriate when utilizing sediment storage functions. Furthermore, much of the research on sediment storage functions to date has been based on flume studies and long-term, large-scale field investigations are needed. Finally while bed structuring has been shown to influence sediment transport rates, its prevalence in different regimes (e.g., arid versus humid) and temporal stability have not been discriminately described. The primary objective of this paper is to examine temporal and spatial scales of within-channel sediment supply (availability), storage and mobility. We focus on intermediate sized streams (as defined by Church, 1992), wherein inputs of woody debris and the development of grain-scale bedforms can both significantly affect sediment transport patterns and channel morphology. In particular, we introduce a bedform classification scheme that covers elements ranging in scale from 10^{-2} to 10^{3} m. Three field studies are then introduced and data from these studies are used to illustrate the effect of bed surface structuring on sediment transport rates as well as long-term sediment storage functions and the importance of large woody debris (LWD) as a regulator of sediment storage.

2. Bedform classification

While a number of authors have developed bedform classification schematics, a classification scheme that extends across the full range of scales over which bedforms are found in gravel-bed rivers does not exist. Such a scheme would help practitioners evaluate the space and time scales at which different bedforms are best studied and provide a template for discussion. Furthermore, the classification scheme can improve our understanding of sediment exchange dynamics between different storage elements and thereby improve sediment routing models. The classification schematic developed here is partly based on Lewin (1978), Church and Jones (1982) and Hassan (2005) and considers the channel bed of gravel-bed streams to be composed of storage and resistant elements that can be classified as microforms, mesoforms, macroforms or megaforms (Fig. 18.1).

At the channel unit scale (usually one to a few channel widths in length) microforms can occur depending on the bed state. Church (1978) defines bed state as either "overloose", "normally loose" or "underloose": overloose boundary includes open packed material and dilatant sediments (no/few microforms); a normally loose boundary consists of material resting in a nondispersed state without imbrication and with random packing (some microforms); and an underloose boundary is composed of close packed or a structured surface, including armoured surfaces and many microforms. The underloose state is typical of low sediment supply systems and overloose state is typical of high sediment supply regimes. A low sediment transport regime is often characterized by a coarse-grained and poorly sorted channel bed with imbricated structures. Large grains tend to be relatively over exposed while the smaller grains are hidden, as such, bed mobility is highly influenced by the relative exposure of particles within the bed.

In addition to microforms, in low transport regimes, mesoforms composed of clusters, ribs and stone cells are also frequently well developed, thereby reducing the sediment mobility by increasing the threshold of entrainment by dissipating energy due to flow resistance. Mesoforms are composed of two groups, at smaller scales ribs and stone cells scale with the grain size and at larger scales cascades, step-pool and riffle-pool sequences scale with the channel width. Small-scale mesoforms (e.g., ribs, stone cells) evolve in response to changes in the flow regime and sediment supply, and their existence indicates a quasi-stable bed with limited local in-channel sediment availability. For example, the size distribution of stone cells in Harris Creek, a cobble-bed stream, clearly varies from year to year (Fig. 18.2a), as does the proportion of the total bed area influenced by them (Fig. 18.2b). When the bed is well armoured, the surface is covered by a dense network of smaller cells (data from 1989 in Fig. 18.2a). Based on flume experiments modelling Harris Creek, when the sediment supply is increased the surface exhibits stone cells that are larger but which stabilize a lower proportion of the total stream bed (Hassan and Church, 2000). Spatial variations in the proportion of area covered by surface structure are also characteristic of mesoforms (Fig. 18.2b).

Within the same hydrological regime, streams with large sediment supply are likely to have a finer surface and less-developed surface structures. When present, they are usually solitary features sparsely distributed over the bed surface, or are developed in association with some larger-scale bedform that alters the local sediment transport conditions. Similarly, due to their relatively large sediment supply and flashy storm hydrographs, arid streams are likely to have less-developed armoured surface than their nival counterparts (Schick et al., 1987; Laronne et al., 1994; Reid and Laronne, 1995; Parker et al., 2003; Hassan et al., 2006; Fig. 18.3). This bed surface response is related to the local sediment transport rates and is expected to respond over short timescale (~flood timescale).

Where wood is present, the channel may become starved downstream of the wood, promoting microform development, while at the same time becoming inundated with sediment upstream reducing or eliminating microforms. While microform features may persist for several years, the individual structures are thought to be transient.

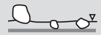
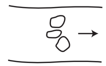
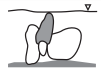
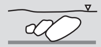
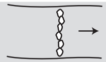
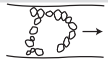
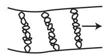
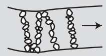
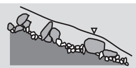
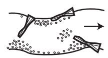
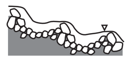
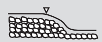
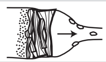
Class			Definition	Function	Sketch plan form	Sketch profile	System scale	Time scale	Entrainment
Grain parameters		size	grain diameter	flow resistance			D	na	reduce the likelihood of large particles
		shape	principle axis ratio of Zingg	flow resistance			D	na	increase the likelihood of prolate particles
Microform	Bed structure	exposure/ hiding	relative exposure of individual particles	flow resistance			D	<te	increase the likelihood of exposed particles; reduce the likelihood of hidden particles
		imbrication	arrangement of grains	flow resistance			D	<te	reduce the likelihood of constrain particles
		stone cluster	arrangement of grains	flow resistance			D	<te	reduce the likelihood of all particles
Mesoform		transverse rib	arrangement of grains	flow resistance			D (W)	<te	″
		stone cell	arrangement of grains	flow resistance			D	<te	″
		LWD pieces	arrangement of pieces (orientation)	flow resistance - storage			W, d	<te	″
	Bedforms	step-pool	arrangement of boulders/LWD	flow resistance - storage			D (W)	>te	reduce/increase the likelihood of all particles according to position
		cascade	arrangement of cobbles and fine grains	flow resistance - storage			W	>te	″
		riffle-pool	arrangement of cobbles and fine grains	flow resistance - storage			W	>te	″
Macroform		bars	arrangement of cobbles and fine grains	storage - flow resistance			W	>te	″
		LWD jams	arrangement of LWD pieces and jams	storage - flow resistance			W	>te	″
Megaform		Sedimentation zones		storage				regime	″
		Floodplain/terraces		storage				regime	″

Figure 18.1. Hierarchical bedform classification. D is the average clast size of bedform, W the channel width, d the mean depth, t_e the event time. This classification is partly based on Lewin (1978), Church and Jones (1982), and Hassan (2005). (Modified by permission of American Geophysical Union.)

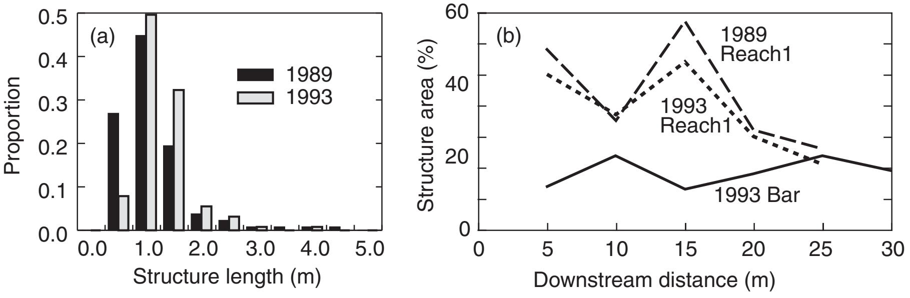


Figure 18.2. (a) Histograms of Harris Creek structure dimensions measured parallel to flow direction. (b) Percentage of the area cover by structures in Harris Creek.

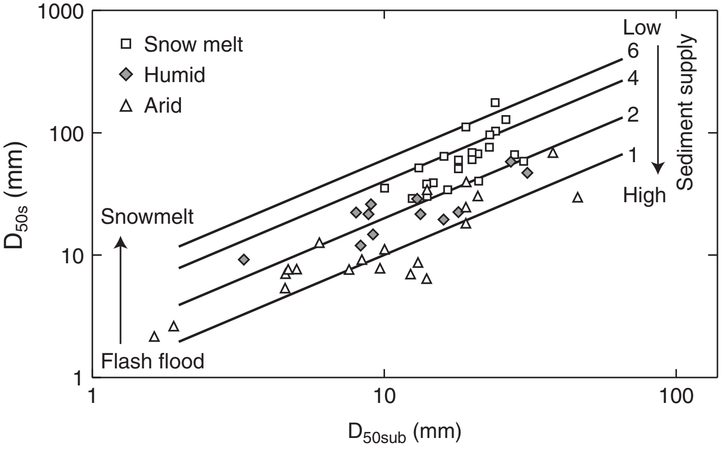


Figure 18.3. Median size of surface and subsurface of ephemeral, snowmelt, humid and arid streams. (Data complied by Hassan et. al., 2006, Reproduced by permission of American Geophysical Union.)

At the spatial scale of channel reaches (usually >10 channel widths), large-scale mesoforms develop that span the stream channel. Large-scale mesoforms include step-pool units, cascades and riffle-pool sequences and commonly persist for decades. The primary sediment storage mesoforms in intermediate streams (for definition, see Church, 1992) are bars and sediment wedges. Bars develop in association with riffle-pool sequences or LWD pieces and sediment wedges deposited upstream of a downstream rise in base level due to factors such as a channel spanning log jams or a landslide entering the stream.

The largest elements in Fig. 18.1 (macroforms and megaforms) function primarily as mid to long-term (decades-centuries) sediment stores. While, these features tend to last longer and cover a larger spatial extent in large streams, they are also present in small to intermediate streams, particularly those with a relatively large supply of sediment.

Local inputs of LWD pieces affect the local sediment flux. LWD that spans a significant part of the channel often results in local aggradation upstream, leading to

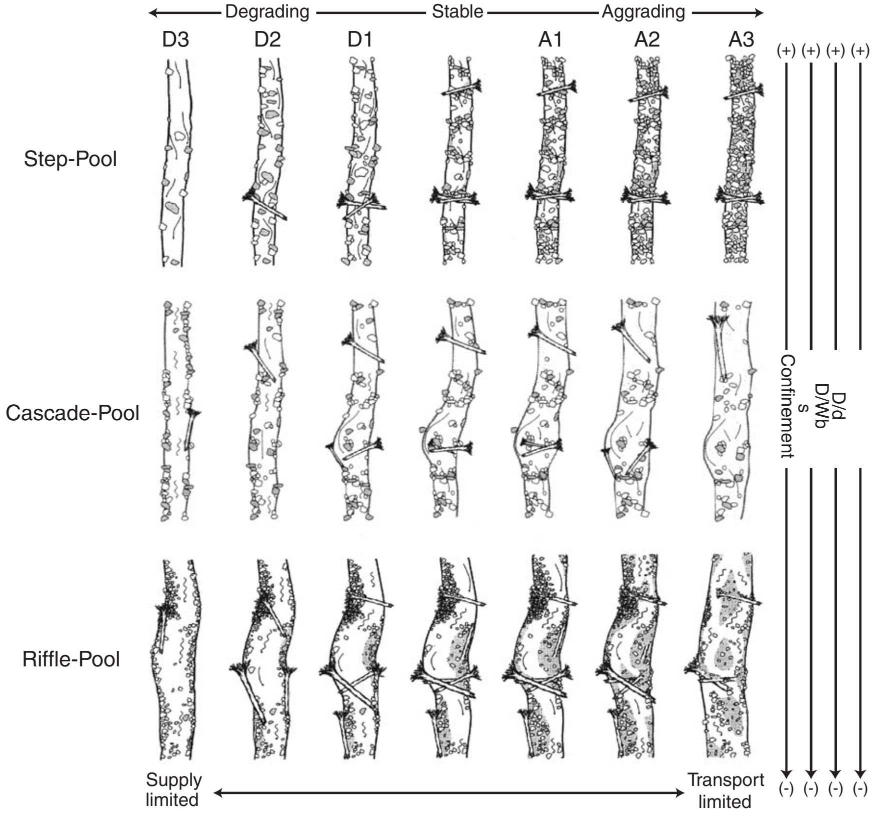


Figure 18.4. Channel morphology matrix showing levels of disturbance. (Modified from Anonymous, 1996, with permission of American Geophysical Union.)

fining and sediment starvation downstream, producing armouring (e.g., Hogan et al., 1998; Buffington and Montgomery, 1999).

The influence LWD has on the within-channel sediment depends in large part on how high the sediment flux is, and whether the channel reach is degrading, stable or aggrading (see Fig. 18.4). When the sediment supply rate is high, the channel aggrades, resulting in a morphology characterized by a series of sediment accumulation zones associated with channel-spanning LWD that has been partially buried (and thereby stabilized) by sediment. As the sediment supply is reduced or the LWD trap changes, sediment no longer accumulates behind LWD pieces. Instead, scour occurs beneath and around the ends of the LWD, exposing the LWD to greater hydraulic thrust and causing much of the wood to swing downstream, parallel to the flow where it does not interact with the sediment transport field (e.g., Hogan and Ward, 1997). Since sediment supply is highly episodic, channel morphology often cycles within or between the various morphologic states shown in Fig. 18.4. Aggradation–degradation cycles may persist and influence fish habitat for over half a century (Hogan and Ward, 1997; Hogan et al., 1998), and may comprise various changes to the bed, banks and/or function of LWD.

In general, all the elements described in Fig. 18.1 are present and functioning to varying degrees within a stream channel at any given time. Their spatial and temporal distribution within a channel changes significantly as a function of local sediment storage and/or supply. Changes in sediment and LWD supply produces changes in the average bed surface texture and bar and wedge magnitude and frequency. Fig. 18.1 provides a classification scheme that can be used to study sediment dynamics in fluvial systems at different temporal and spatial scales. The data used to examine these concepts are derived from intermediate size, gravel-bed streams with a riffle-pool morphology. Intermediate size streams were chosen because they contain all scales of sedimentation elements and required measurements have been collected over appropriate time and spatial scales.

3. Field site description

Data used in this paper come from various studies reporting sediment transport measurements, detailed topographic surveys, geomorphic mapping and LWD inventories for streams having a wide range of bed texture, structure, channel morphology and flow regime. Table 18.1 presents general characteristics of the three primary case studies Carnation Creek, Harris Creek and Tom McDonald.

Carnation Creek drains a 11 km^2 watershed on the west coast of Vancouver Island, British Columbia. The watershed is subjected to frequent rainstorms during the autumn and winter (Hartman and Scrivener, 1990). The bed material is mobile

Table 18.1. Summary characteristics of Carnation Creek, Harris Creek, and Tom McDonald.

	Carnation Creek	Harris Creek	Tom McDonald
Drainage area (km^2)	11	187	18
Bedrock	Volcanic	Volcanic	Metamorphic
Land use	Logged (since 1976)	Logged (1950s)	Logged (1930–1950)
Annual precipitation (mm)	3000	420	2000
Mean Annual flood (m^3/s)	31	21	3.6*
Unit mean annual flood (m^3/s/km^2)	2.82	0.11	0.20
Stream gradient (m/m)	0.009	0.010	0.006
Channel width (m)	5–15	15–20	10
Length of channel studied (m)	3100	500	10
Reach length relative to Bankfull width	310	33	1
Armour ratio**	1.5	3.6	1.3
D_{50} subsurface (mm)	25[a]	19[a]	16[b]
Study period	1971–present	1988–1995	1985–1986

*Bankfull discharge for Tom McDonald

**Defined as the ratio between D_{50} of the bed surface and D_{50} of the bed subsurface.

[a]Based on bulk samples.

[b]Based on freeze core samples.

during flows that occur several times a year. The surface has a low armour ratio and exhibits only solitary surface structures and irregular surface packing. Sediment and wood enters the channel through episodic debris flows and bank erosion. Sediment is stored in bars and behind LWD jams. Low rates of bed load transport occur at discharge of about $3\,m^3/s$ and significant transport rates, defined as 1 kg/m/min, occur at discharges greater than or equal to $10\,m^3/s$ in the stream (Tassone, 1987).

Harris Creek drains $187\,km^2$ watershed in the southern interior of British Columbia. Although the drainage area is 17 times larger than Carnation Creek, its average bankfull width is similar due to the much drier interior climate. The stream flow regime is dominated by snowmelt in May and June, and as a result, large flood events outside the snowmelt period are not common; the mean annual flood is about $19\,m^3/s$. The bed is well armoured and large particles on the bed form reticulate networks (stone cells on Fig. 18.1) that increase hydraulic resistance to flow and increase channel stability (Church et al., 1998). Most of the mobile sediment is delivered from upstream, where material is being released from eroding alluvial banks in laterally unstable reaches around broken LWD jams, and from sites where chronic debris raveling occurs from high banks in Pleistocene sediments (Ryder and Fletcher, 1991; Church and Hassan, 2005). Storage areas include bars, tributary alluvial fans and LWD jams.

Tom McDonald Creek drains a $18\,km^2$ watershed in north coastal California. The watershed is subjected to frequent rainstorms during the autumn and winter. Bankfull discharge at the study site is $3.6\,m^3/s$. The largest peak flow for which we have data is estimated at $25\,m^3/s$, which is approximately twice the estimated regional mean annual flood for drainage basins of similar size (Smith, 1990). The study reach consists of a single pool, including its head, centre and tail set within a riffle-pool morphology. Gravel and cobbles dominate the pool head, sand covers most of the pool centre and pebbles dominate the pool tail. The length of the pool is approximately equal to the bankfull width of the channel ($\sim$10 m).

Sediment transport estimates at these sites are derived from observations using tracers, bedload sampling (Helley–Smith and Arnhem) or pit traps. Short- and long-term changes in sediment storage have been estimated from repeated channel surveys taken during floods, between floods and annually. Since the methods used for estimating sediment transport and storage have differing inherent biases, there is a degree of uncertainty in our analyses. However, we believe that the general trends in the data are realistic, even if the data itself may contain some biases.

4. Bed state and sediment mobility

At small spatial and temporal scales, variability in sediment transport rate can be ascribed to the changing state of the bed and, in turn, the bed state largely depends on the local sediment supply regime (cf. Fig. 18.1). To demonstrate the influence of the bed state on sediment mobility, we compare two streams: Carnation Creek, where the dominant bed state is normally loose, and Harris Creek where the bed is dominantly underloose. One might suppose that since Harris Creek has a snowmelt dominated regime and Carnation Creek has a rain dominated regime that the hydrology would significantly influence the bed state. This must be true, to some extent, but since the contrast in sediment supply dynamics in the two systems appears to be greater than the hydrologic differences (they both transport sediment, on average, for the same duration per year) we attribute the observed differences in bed state to differences in sediment supply.

Two examples (for more rating relations see Tassone, 1987 and Hassan and Church, 2001) of total load rating relations for Carnation Creek and Harris Creek (Fig. 18.5a) are used here to demonstrate the influence of the bed state on sediment transport. Hassan and Church (2001) demonstrate that the observed transport rates in Harris Creek are extremely low. The rating relations they present are very steep (the typical relation exponent (*b* in Fig. 18.5a) ranged between 4 and 14) and extremely sensitive to small changes in sediment supply and flow regime. Gravel starts moving at about 4.5 m^3/s but fractions larger than D_{80} are rarely mobile. Hassan and Church (2001) describe two phases of transport based on the data; sand transport over static bed (stage I) and partial transport of gravels at higher flows (stage II). Full mobility of most sizes found on Harris Creek bed surface (called stage III) was not observed during 5 years of observations. Measured unit sediment transport rates in Carnation Creek are two to three orders of magnitude higher than those of Harris Creek at comparable discharge values and the rating relation is less sensitive and less steep, the relation exponent typically being less than 4 (Fig. 18.5a). Gravel in Carnation Creek starts moving at about 3 m^3/s and the largest fractions in the bed are mobile annually. Bedload measurements show that both stage II and stage III were observed in Carnation Creek (Fig. 18.5a).

To more systematically compare the difference in sediment mobility between the two creeks, we analyzed the fractional transport rate following Wilcock and McArdell (1993) and the proportion of tracers that moved relative to the total population of tracers in each size fraction (see Church and Hassan, 2002; Haschenburger and Wilcock, 2003). Fractional transport rates in Harris Creek are calculated from samples collected in pit traps and therefore a complete analysis of mobility of all grain sizes is possible. Transport rates in Carnation Creek were measured with an Arnhem bedload sampler which physically limits the size of the grains that can be sampled (<64 mm) and reduced sampling efficiency for grains larger than 32 mm.

Transport rates in Harris Creek are up to three orders of magnitude below the reference transport rate suggested in the literature ($W^* = 0.002$) (e.g., Parker et al., 1982; Wilcock and McArdell, 1993) (Fig. 18.5b). All fractional transport curves, scaled by the subsurface grain size distribution, show a break in the slope where transport rate begins to decline with increasing grain size, which corresponds to a shift from full to partial mobility (Fig. 18.5c). At low flows no size fraction in Harris Creek is fully mobile while at the intermediate flows ($>7\,m^3/s$) sand is fully mobile and larger material remains partially mobile. At high flows ($>12\,m^3/s$) the division between full and partially mobile size fractions occurs around 16 mm, which is finer than the median size of the subsurface material (D_{50} of the subsurface is 19 mm). Even at flows as high as the mean annual flood, scour is sporadic and limited in depth: as a result, the framework cobble and gravel remains in place and the largest material scarcely moves. These findings are supported by results of the tracer study during flood events in 1989, 1990 and 1991 (Fig. 18.5e). On an average, 60% of the

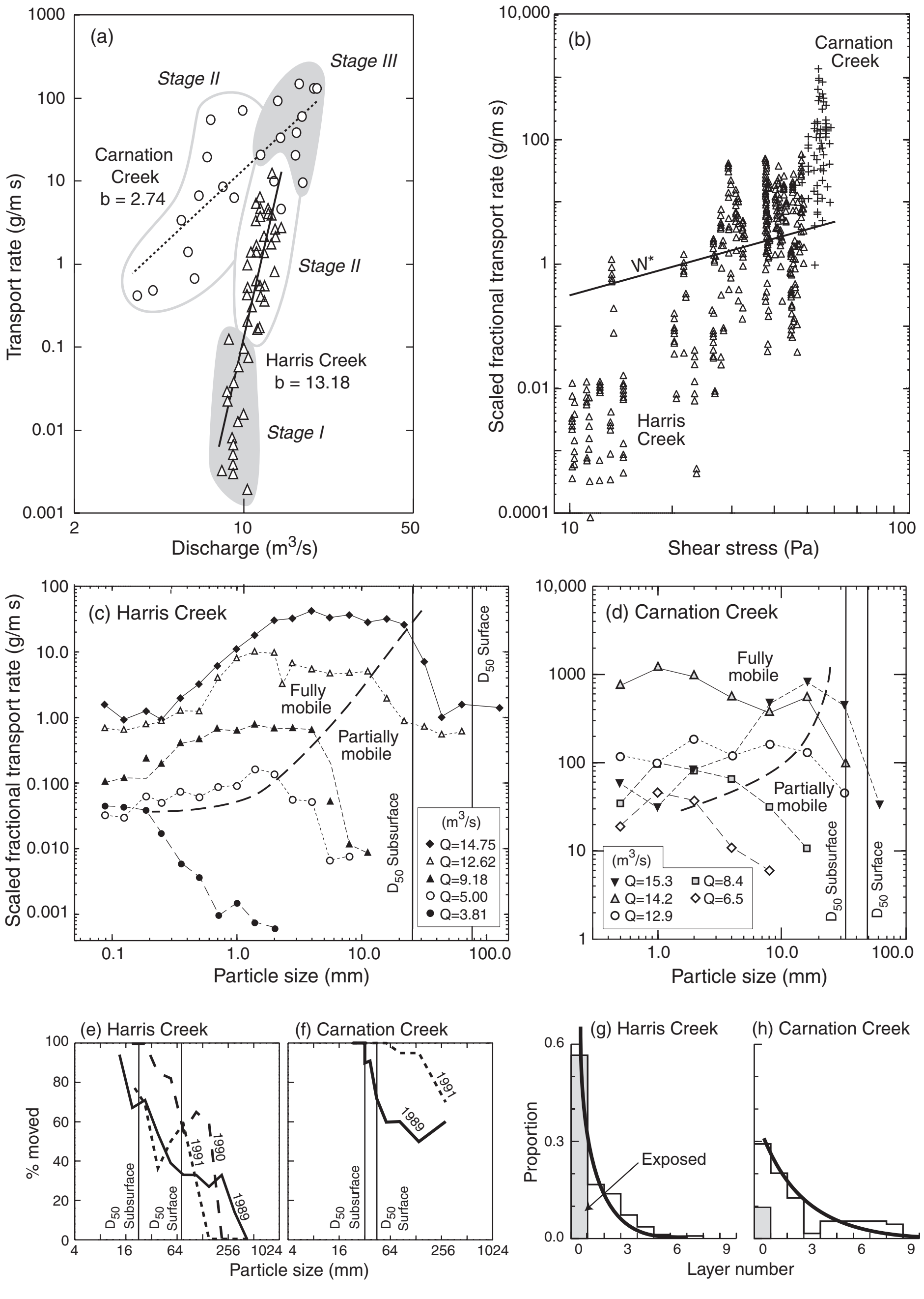


Figure 18.5. (a) Bedload rating curves derived from trap observation in Harris Creek and Arnhem sampler in Carnation Creek. (b) Scaled fractional transport rate versus shear stress for Harris Creek (after Church and Hassan, 2002) and Carnation Creek. Scaled by the subsurface grain size distribution (c and d) Scaled fraction transport rate in Harris Creek versus particle size (after Church and Hassan, 2002) and Carnation Creek, respectively. (e and f) Percent of moved tracers as a function of grain size in Harris Creek (after Church and Hassan, 2002) and in Carnation Creek, respectively. (g and h) Burial depth (layer number) distribution after individual flow events in Harris Creek and Carnation Creek, respectively (after Hassan and Church, 1994). Cross-hatching denotes exposed particles. (Reproduced by permission of American Geophysical Union.)

entire tracer population moved during the 1989 freshet, 88% during 1990 and only 36% in 1991. A plot of fractional mobility shows a sharp decline in mobility with increasing particle size for all three seasons. About 70% of sizes finer than the median size of the bed material moved during both 1989 and 1991 flood seasons. In general, measurements from both the pit trap and tracer studies show full mobility was approached only for sizes of less than about 16 mm, while the vast majority of the bed surface grain sizes were only partially mobile.

Fractional transport rates in Carnation Creek tend to be one to three orders of magnitude higher than the reference transport rate (Fig. 18.5b). The break in the slope for each curve in Fig. 18.5d represents the upper limit of full mobility for the corresponding discharge. At low flows, full mobility is limited to grain sizes less than about 2 mm, while grains up to 8 mm are fully mobile at intermediate discharges. For high flows, the largest grain size class (16–32 mm) that can be efficiently sampled with the Arnhem sampler is fully mobile. Results from the tracer study in Carnation Creek for flood events in 1989 and 1991 show that almost all particles finer than the median size of the bed material moved during 1989 and 1991 (Fig. 18.5f). Additionally, all the tracers finer than the median size of the surface material moved during 1991. For material coarser than the median size of the bed surface material, the two seasons show a decline in the mobility rates with the increasing particle size but at much lower rate than that obtained for Harris Creek. In 1989, the full mobility for Carnation Creek approached the median size of the bed material while in 1991 sizes larger than the median size of the surface material were fully mobile. Furthermore, a significant proportion (>50%) of the largest bed material was mobile during both seasons.

To better understand sediment transport dynamics in relation to bed state, we explore burial depth as an indicator of relative bed material mobility between Harris Creek and Carnation Creek. In Fig. 18.5g it is seen that a large proportion (>50%) of the tracers in Harris Creek remained on the surface during the largest flood event in the 3-year record (i.e., 1990); only small proportions were deeply buried. The rapid decline in proportion of tracers with increasing depth indicates that the scour during the flood event was shallow and localized, and that the surface framework of particles remained in place during the flood event. In contrast, less than 10% of the tracers in Carnation Creek remained on the bed surface while some were deeply buried (Fig. 18.5h). The relatively gentle decay of burial depth indicates that the bed surface was substantially disrupted during the flood event.

The difference in burial depth, transport rates and the extent of full/partial mobility cannot be explained simply by differences in the shear stress in the two streams. The dimensionless shear stress (based on the subsurface material) in Harris Creek was 0.071, and in Carnation Creek it was 0.070. However, when we substitute the surface median grain size, the dimensionless shear stress in Harris Creek falls to 0.044 and in Carnation Creek to only 0.059. Furthermore the surface structures that are pervasive on the bed of Harris Creek probably further delayed the entrainment of the surface material. The differences in particle mobility and, as a direct consequence, in sediment transport rate were, we believe, strongly conditioned by the assemblage of microforms and mesoforms that are present in Harris Creek and not in Carnation Creek. We believe that these surface structures developed in response to a relatively low sediment supply rate as supported by the experiments of Hassan and Church (2000), while the high sediment supply rate inhibited the development of similar structures in Carnation Creek. Ultimately a difference in sediment supply from hillslopes must be responsible, as over time, if supply conditions were identical Carnation Creek would be expected to structure to a state similar to that of Harris Creek (as predicted by Fig. 18.4).

5. Storage and mobility at the channel unit scale

At the macroform scale, investigations of sediment transport can be completed at the channel unit or reach scale, and examples of both are given. At the channel unit scale temporal patterns of sediment storage-transport during a flood event are demonstrated using data collected from Tom McDonald Creek (Hassan and Woodsmith, 2004). During the study period, four small events (< bankfull discharge) and one major event (~7 times bankfull discharge, 25 m^3/s) were recorded (Fig. 18.6a). Topographic surveys and bed load sampling (using a Helley–Smith sampler) were conducted along three transects (pool head, pool centre and pool tail) repeatedly during each flood event.

Net changes in sediment storage volume at each transect are typically plotted against time (Fig. 18.6b). Information from Fig. 18.6b can be used to produce a transport–storage relation (Lisle and Church, 2002) where time is implied (Fig. 18.6c). The advantage of presenting the data in the latter format is that magnitudes and cycles of aggradation and degradation can be easily identified. Data in the plot represents a measurement of initial storage volume and subsequent transport within a 1-day interval. Arrows (Fig. 18.6c) indicate the direction of increasing time.

Each transect illustrates spatial variability of storage and net accumulation of bed material (Fig. 18.6b). Prior to the largest flood event (day 775), all transects within the pool show minimal changes (Fig. 18.6c). During the rising limb of the large flood, net fill was measured at all transects with relatively small amounts of fill at the pool centre and tail and significant fill at the pool head. During the falling limb and subsequent flows, the behaviour of the transects diverge. Net change at the pool tail was minimal while the pool head filled and the pool centre degraded at constant rates.

The bed material transport–storage relation based on data from all three transects (Fig. 18.6c) shows a small net increase in storage volume through the peak of the large flood. Storage volumes then increased rapidly over a 2-day period during the falling limb of the large flood when the flow was well above bankfull discharge. Minor degradation was observed during the fourth small event. Transport–storage relations show small fluctuations, on the order of the resolution of the survey, without a clear cyclic pattern prior to the large flood. The large flood initiated a large scale aggradation–degradation cycle that was not completed during the study period (1 year).

Rating curves based on Helley–Smith measurements do not show distinct trends between the head, centre and tail (Figs.18.6d, e, f) and they do not reflect changes in local storage measured at each transects or the pool average. The sediment yield

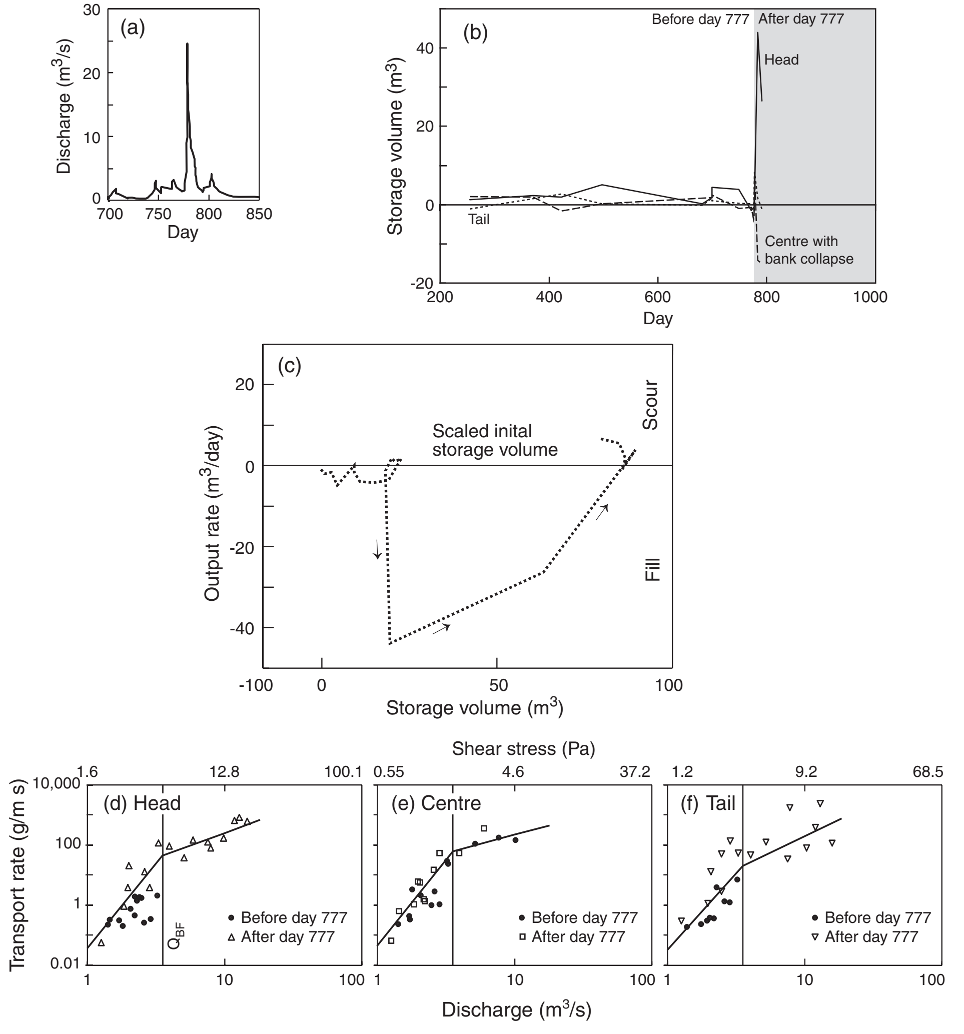


Figure 18.6. Tom McDonald Creek – (a) Flow hydrograph at the study site for the 1986 season. (After Hassan and Woodsmith, 2004.) (b) Temporal variation in the volume of sediment storage during 1985–1986 seasons. (c) Temporal variation in stored sediment versus output rate. (d, e, and f) Bedload rating curves derived from Helley–Smith sampler. The 777 day indicates major change in bed elevation. (Reproduced with permission from Elsevier, 2004.)

estimated from Helley–Smith measurements is an order of magnitude larger (head = 5686 m^3; centre = 7368 m^3; tail = 4248 m^3) relative to the change in storage measured during the same period (79 m^3). This result is likely due to the sediment transport step length being much longer than the study area, thus much of the sediment being captured in the Helly–Smith samplers did not originate from within the study area. This study clearly illustrates the disconnect that may occur if the scale of investigation, is smaller than the scale of the phenomenon being investigated.

6. Sediment storage at the reach scale

A larger spatial and temporal scale is more appropriate for studying macroform bed elements. Data from Carnation Creek illustrates the temporal variability and trends of sediment transport over a 34-year period. Since 1971 the British Columbia Ministry of Forests has maintained eight study areas (a total of approximately 500 m) along the main channel of Carnation Creek, each of which has between 18 and 36 cross-sections. Using the cross-sections, spaced on average 3 m apart, annual measurements of stream bed topography were completed to track changes in the channel morphology. These repeat cross sections are used to estimate long-term sediment flux occurring through each study area. Volumes were computed by constructing Triangular Irregular Networks (TIN) from channel cross-section survey data from each year. The TIN was converted to a 5 cm DEM and the DEM from the year of interest was subtracted from the 1971 DEM (the first year of record). The calculated change in storage since 1971 was then compared to the change in storage calculated for the previous year to determine how much sediment was lost or gained during the winter. Errors in the annual survey are generally less than about 5 cm or 50 m^3 per study site. Reach scale fluxes appear to be cyclic, involving a consistent trend of channel aggradation (or degradation) followed by a degradational (or aggradational) trend. These trends are assumed to be reflective of the role of sediment supply and LWD in modulating the storage and release of sediment. Aggradation and degradation was not found across all study sites during the same years, nor were there any observable fluxes of sediment from reach to reach. This suggests that aggradation–degradation cycles at each reach have local controls in additions to upstream sediment supply. Storage cycles have a range of characteristic magnitudes, which we classify as small (100–400 m^3) and large ($>400\,m^3$).

Data from two of the study reaches are used to illustrate the spatial and temporal changes in sediment flux and storage over several decades. These cycles are hypothesized to be controlled by a combination of sediment supply, channel morphology and LWD. Large–scale aggradation–degradation cycles are only found in reaches with channel spanning LWD jams which trap sediment and create reach scale sediment wedges. Small-scale aggradation–degradation cycles are present within the record in all reaches and are hypothesized to correspond to the growth and lateral shifting of bars driven by changes in sediment supply and sedimentation associated with smaller wood accumulations.

Study area VIII (Fig. 18.7) is the upstream-most zone considered here. It is situated downstream of a steep canyon (Fig. 18.7), and demonstrates the role of LWD in affecting spatiotemporal patterns of sediment storage. Study area VI is approximately 475 m downstream of study area VIII. While LWD is found in the channel as isolated wood pieces at study area VI, no channel spanning LWD jams have been documented within the reach in the last 32 years (Fig. 18.8). Both scales of aggradation–degradation cycles are evident in the data from reach VIII (Fig. 18.7a). The first aggradation–degradation cycle (1971–1981) is small in size ($\sim$270 m^3) and roughly corresponds with the pre-jam phase and the early stages of jam development (jam adolescence, Luzi, 2000), as shown in Fig. 18.7b. In 1982, the LWD jam in Fig. 18.7b trapped a significant amount of additional debris

(Fig. 18.7c): this additional accumulation deflected flows against the right bank and caused substantial erosion of the bank and a net decline in sediment storage in the reach.

Degradation stopped abruptly in 1984 when material that originated from a debris flow in the canyon, displaced the existing LWD jam downstream (Powell, 1987), forming a channel wide barrier to downstream sediment transport (Fig. 18.7d) which initiated a large-scale aggradation–degradation cycle (1982–1991) (Fig. 18.7a). Sediment accumulated behind the LWD jam from 1983 to 1989 in the form of a large sediment wedge (Luzi, 2000). In 1990, the channel cut partially around the LWD jam and began to incise into the sediment wedge deposit. The majority of sediment removal occurred in 3 years (1989–1991), marking the end of the large–scale aggradation–degradation cycle. The volume of stored sediment in 1991 was 290 m^3 greater than the pre-disturbance storage volume measured in 1971.

A third small-scale aggradation–degradation cycle ($\sim$100 m^3), equivalent in size to the 1971–1982 cycles, occurred between 1991 and 1995. By 1995, the channel had incised vertically such that the jam only interacted with the channel during high flows (Luzi, 2000). The channel degraded from 1995 to 2000 an additional 370 m^3 and had a final storage volume 36 m^3 less than that measured in 1971.

Four small-scale cycles of aggradation and degradation are identified in study area VI (Fig. 18.8a). The first two cycles are similar in magnitude to those observed in study area VIII, spanning 5 and 12 years respectively (1971–1976 and 1976–1988). Cycle 3 is slightly larger than the earlier cycles and spans 15 years, and cycle 4 is nested within cycle 3 (Fig. 18.8a). Aggradation–degradation cycles 2 and 4 are separated by rapid aggradation from 1989–1991, and may correspond to the release of sediment from the LWD jam in study area VIII. However, there is not a similar signal at study area VII, located between study area VIII and VI. In 2003, there was about 50 m^3 of sediment left in storage compared to 1971, which is within the errors associated with the surveys.

These two study areas illustrate that the trajectory of change in transport and storage persist through multiple years at the reach scale. The small-scale cycles are the most common, are present in both study areas and are associated with sediment accumulation and release. Large-scale aggradation–degradation cycles are clearly controlled by the formation of LWD jams which trap sediment and create reach scale sediment wedges. LWD jams may also affect downstream reaches by interrupting small cycles by changing the sediment supply regime.

Carnation Creek reaches have a level of disturbance between D1 and A3 on the conceptual matrix shown in Fig. 18.4 based on channel morphology that include mid-channel bars, LWD jams and poorly developed structures. If sediment supply is reduced in Carnation Creek, such as downstream of an intact recently formed LWD jam, the channel will degrade and develop surface armouring and structures (as shown by Haschenburger and Rice, 2004). This change in bed state will reduce sediment mobility and create small-scale cycles of aggradation–degradation. Under reduced sediment supply, Carnation Creek will likely shift to a level of disturbance between D2 and D3 (Fig. 18.4), similar to Harris Creek. A significant increase in the sediment supply into Harris Creek will result in aggradation, development of more substantial bars, increased bank erosion and destruction of bed surface structure and

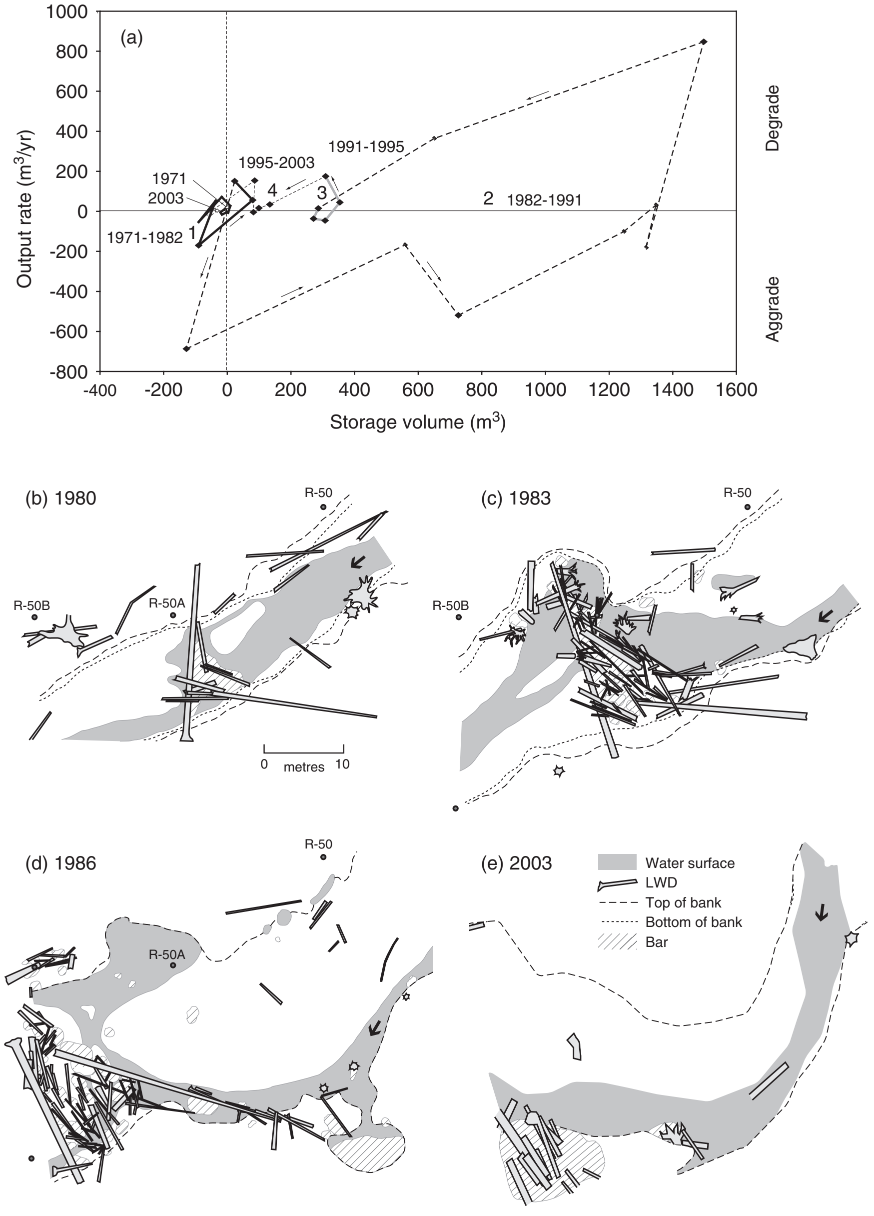


Figure 18.7. Carnation Creek – (a) Temporal variations in stored sediment versus output rate in study area VIII. (b, c, d, and e) Examples of temporal changes in LWD jam formation and channel morphology of study area VIII. Top and bottom of banks are indicated.

armouring. Likewise an increase in wood supply will lead to more log jams and intern more bars and sediment wedges. Under the increased sediment supply scenario, the sediment mobility will increase the magnitude of the aggradation–degradation cycles.

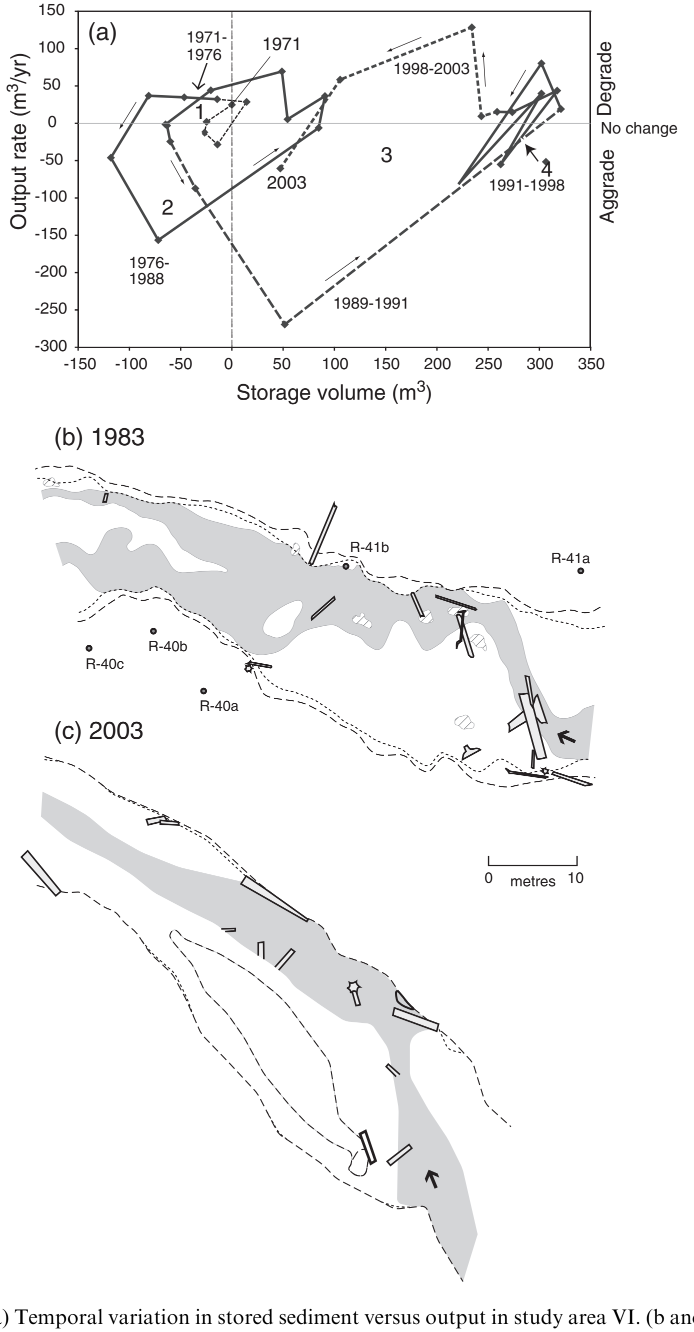


Figure 18.8. (a) Temporal variation in stored sediment versus output in study area VI. (b and c) Examples of temporal changes in channel morphology of study area VI. Top and bottom of banks are indicated.

7. Sediment storage at the channel scale: the role of LWD

In the previous sections we considered temporal and spatial patterns of sediment storage and transport at the channel unit and reach scales. The impact of LWD on channel characteristics has been demonstrated in study areas VI and VIII in Carnation Creek (Figs. 18.7 and 18.8). However, LWD jams are not isolated occurrences along the longitudinal profile of the stream. The spatial and temporal pattern of sediment storage in association with both bars and LWD jams was documented along the entire mainstem of Carnation Creek. Longitudinal thalweg profiles, LWD jam age, volume, span, height and channel location, log steps, and individual LWD piece, length and mean diameter were inventoried in 1991 and 1999. The 3.2 km survey included 55 jams in 1991, and 48 jams in 1999.

The impact of a LWD jam on channel morphology depends on its size relative to the bankfull channel dimensions as well as the level of jam development. Detailed longitudinal profiles from a selected section of channel are shown from the 1991 and 1999 surveys (Figs. 18.9a, b). Areas where bar and bank top elevation merge indicate an exhausted local channel storage capacity due to severe aggradation and are probable sites for overbank flow during flood events and potential channel migration/avulsion areas (Luzi, 2000). Large convexities exhibited by the longitudinal profile are the result of sediment accumulation upstream and scour downstream of a LWD jam, these features are more pronounced around newly formed channels spanning LWD jams. The difference in thalweg elevation upstream and downstream of LWD jams becomes less pronounced with time as the trapping efficiency of jams decline (Fig. 18.9a). The total average LWD volume per bankfull interval was 19.7 m^3 in 1991 and 22.5 m^3 in 1999, with large volumes (about 70 m^3) associated with jams (Figs. 18.9c, d). The percentage of LWD volume associated with jams was 90% during both 1991 and 1999. Although the LWD volume remains relatively constant, jam function (trapping sediment) changes over time.

Jams directly influence the amount of sediment stored in the channel (Figs. 18.9e, f). Sediment volume was greatest at sites upstream of channel spanning jams. However, the temporal and spatial extent of the sediment accumulation is strongly dependent on jam age. Variation in the volume of sediment storage per bankfull interval in the 1991 survey is closely linked to its spatial proximity to jams (Fig. 18.9e).

Twenty-one jams with associated upstream sediment wedges were identified in 1991. In total, these wedges accounted for 10,100 m^3 of sediment, approximately 47% of the total sediment stored in bars (21,400 m^3) based on bar depth estimates in conjunction with channel width measurements from the long profile surveys. In 1999, 20 jams with upstream sediment wedges were identified, and total sediment storage was estimated at 7000 m^3, accounting for 38% of total bar-stored sediment (18,400 m^3). Nineteen of the jams associated with sediment wedges were the same for both survey years. At the channel scale in Carnation Creek, bars store more sediment than LWD jams. However, LWD jams store large volumes of sediment at a few, infrequent, locations. Conversely, bars store sediment in many small structures distributed somewhat evenly along the channel length (approximately 70 bars as opposed to far fewer than 20 intact jam locations).

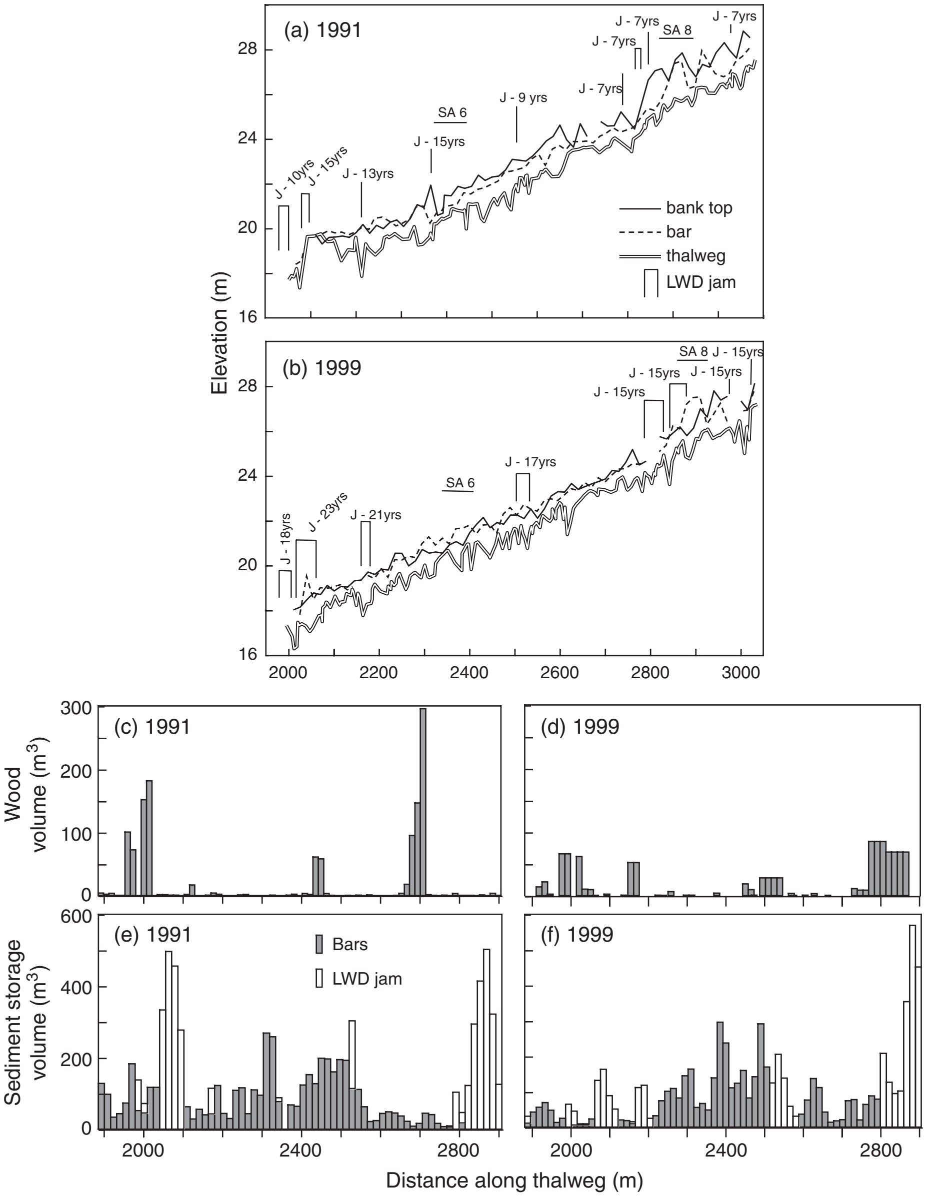


Figure 18.9. Carnation Creek – (a and b) Detailed longitudinal profile of selected section of the 1991 and 1999 survey, respectively. (c and d) Within-channel LWD volume in 1991 and 1999. (e and f) Volume stored sediment behind LWD and bars (after Luzi, 2000). Bars show total storage, shading shows proportion associated with wood (grey) and bars (white). (Reproduced by permission of American Geophysical Union.)

Recently formed, intact jams can be very large. Hogan and Bird (1998) classify jams according to 11 attributes (e.g., height, width, sediment trapping efficiency, among others) and four size classes (micro, meso, macro and mega). They documented mega jams that influence channel morphology for over 100 bankfull width in length. This includes aggraded zones upstream of the barrier (upstream extent is a function of pre-jam formation channel gradient) but the most extensive changes occur downstream as a result of scour with no recruitment of sediment from upstream (unable to pass the intact jam). In Carnation Creek, the net loss of sediment supply from behind jams was approximately 5800 m^3 between 1991 and 1999. Of this, an additional 3100 m^3 was deposited at sites either immediately downstream of the jam or within jam complexes further downstream. It appears that smaller secondary jams are developed downstream as the mega jams begin to deteriorate; mega jams release debris that form jams (range in size from macro to micro) that then influences sediment storage at the reach and unit channel scales.

8. Conclusions

To study the affect of bedforms on sediment transport in gravel-bed rivers a classification scheme was proposed that breaks the bedforms into micro, meso, macro and megaforms. It was shown that at small spatial and temporal scales (micro/mesoform scales), bed structures regulate within channel sediment supply and are strongly influenced by upstream sediment supply. Stabilizing bedforms develop when sediment supply is low, this reduces the depth of the bed active layer and the mobility of the grains, thereby decreasing the sediment transport rate. Sediment rating relations in a low sediment supply channel are shown to be steep and are believed to be extremely sensitive to small changes in sediment supply and flow regime when compared to higher sediment supply systems. High sediment supply suppresses the development of stabilizing bedforms and increases the mobility of grains and the depth of the active layer.

At the reach scale (macroform scale), using Carnation Creek data, it was shown that the supply of sediment and wood from upstream can influence the development of sediment stores, such as channel bars and sediment wedges, which in turn have a pronounced effect on downstream sediment transport rates. The accumulation and release of sediment from bars and sediment wedges created characteristic aggradation–degradation cycles that persist for multiple years and are believed to depend more on external sediment supply rate, bedform dynamics and the supply of LWD than on the hydraulic forcing.

These results have obvious implications on the stability of rating curves which are based solely on stream flow and neglect changes in sediment or wood supply. Rating curves may be stable for a constant sediment supply that produces small scale aggradation–degradation cycles, but may have significant shifts for large-scale aggradation–degradation cycles. It is possible that the cyclic nature of aggradation–degradation may appear as actual shifts in the rating, or as scatter within the rating curve.

More careful attention to the full range of bedforms occurring across all scales will enable us to better predict sediment transport rates, particularly for intermediate to long time scales when storage and bed state conditions are unlikely to be stable. Incorporating such instabilities into multi-year sediment transport models remains an important challenge today.

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Discussion by Ian Reid

Hassan et al. draw attention to the effects of sediment supply on the degree of armour development in gravel-bed channels, using this as an explanation for the differences between the armoured beds of Harris Creek (sediment starved) and