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Bed load transport in an obstruction-formed pool in a forest, gravelbed stream

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Abstract

This paper examines channel dynamics and bed load transport relations through an obstruction-forced pool in a forest, gravel-bed stream by comparing flow conditions, sediment mobility, and bed morphology among transects at the pool head, centre, and tail. Variable sediment supply from within and outside of the channel led to a complex pattern of scour and fill hysteresis. Despite the large flood magnitude, large portions of the bed did not scour. Scour was observed at three distinct locations: two of these were adjacent to large woody debris (LWD), and the third was along the flow path deflected by a major LWD obstruction. Bed material texture showed little change in size distribution of either surface or subsurface material, suggesting lack of disruption of the pre-flood bed. Fractions larger than the median size of the bed surface material were rarely mobile. Sediment rating relations were similar, although temporal variation within and among stations was relatively high. Relations between bed load size distribution and discharge were complex, showing coarsening with increasing discharge followed by fining as more sand was mobilized at high flow. Lack of local scour in the pool combined with bed load fining and net fill by relatively fine material implied that the dominant sources of mobile sediment were upstream storage sites and local bank collapse. Patterns of flow, channel dynamics, and sediment mobility were strongly affected by a LWD flow obstruction in the pool centre that created turbulent effects, thereby enhancing entrainment and transport in a manner similar to scour at bridge piers.

Keywords: Bed load; Pool; Scour and fill; Bankfull discharge; Large woody debris

1. Introduction

Interest in sediment transport in forest streams stems largely from concerns for water quality and salmonid habitat (e.g., Beschta, 1981; Sidle, 1988; Smith et al., 1993a; Hassan and Church, 2001). Sediment transport at any point along the channel depends on local flow conditions, bed material composition, and composition and amount of sediment supplied from local and upstream sources. Changes in the balance between these two sources causes changes in both the bed surface composition and transport rates (cf. Wilcock, 2001). Furthermore, bed load sediment is supplied from sources both outside and inside the channel. Rapid mass wasting and bank erosion are the primary external sources (e.g., Roberts

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and Church, 1987; Lisle and Madej, 1992; Buffington and Montgomery, 1999). Roberts and Church (1987) reported that in the Pacific Northwest rapid mass wasting is the most significant input to channels, while surface erosion and creep processes are of relatively minor importance.

In forest streams, channel obstructions complicate the interaction between local bed and flow conditions and sediment supply. Sediment storage sites in pools and behind logs and boulders are primary in-channel sources of sediment supply (e.g., Whittaker, 1987; Lisle and Hilton, 1992; Smith et al., 1993b). Temporal and spatial variation in the amount of sediment stored within the channel depends largely on sediment input from external sources and density of obstructions along the channel (e.g., Benda, 1990). Sediment storage within these sites can delay the routing of sediment from external sources; however, displacement of obstructions may release large amounts of sediment, making it suddenly available for transport (Beschta, 1979; Heede, 1985; Sidle, 1988; Smith et al., 1993a). The volume of sediment stored behind obstructions can be an order of magnitude larger than the mean annual export of total particulate sediment (Megahan and Nowlin, 1976; Swanson et al., 1982a,b).

An important structural and ecological element in most forest streams is large woody debris (LWD). Effects of within channel accumulations and channel margin trees (including the influence on channel morphology, channel dynamics, and ecosystem diversity) have long been studied, especially in low-gradient channels (e.g., Keller and Swanson, 1979; Harmon et al., 1986; Gurnell et al., 1995; Woodsmith and Swanson, 1997). Bed load transport and channel morphology and habitat are affected by the volume and stability of LWD, which can control channel longitudinal profile and hydraulic geometry (Bilby and Ward, 1989; Hogan and Church, 1989; Robison and Beschta, 1990; Van Sickle and Gregory, 1990; Smith et al., 1993b; Montgomery et al., 1996; Bilby and Bisson, 1998; Hogan et al., 1998).

In many streams in forested environments, certain aspects of channel morphology are considered "forced" because of the influence of large in-channel obstructions such as LWD. This is in contrast to "free" morphology in streams with minor LWD inputs or in large rivers (Lisle, 1986; Montgomery et al., 1995; Montgomery and Buffington, 1997). The majority of pools in forest streams in the Pacific Northwest are formed at flow obstructions, and pool morphology largely depends on LWD characteristics (Lisle, 1986; Smith, 1990; Hogan et al., 1998; Buffington et al., 2002). Hydraulic roughness provided by LWD affects bed load transport, bed topography, and surface sediment texture (Heede, 1985; Buffington and Montgomery, 1999).

The objective of this study was to examine bed load transport relations through a stream reach dominated by an obstruction-forced pool by comparing flow conditions, sediment mobility, and bed morphology among the pool head (immediately upstream of pool scour), pool centre (maximum depth), and pool tail (crest of the downstream riffle). Of special interest is the impact of sediment supply on the relative mobility of particles of given sizes over a range of flows along the pool.

2. Study area

The study reach is in the lower section of Tom McDonald Creek, a tributary to Redwood Creek in north coastal California. The creek drains an area of 18 km^2 underlain by schist. The dominant soil in the basin is brown acidic loam exhibiting good drainage and high erodibility. A wet season occurs from October to April and a drier period characterizes May through September. Based on a Redwood National Park rain gauge located 3.5 km from the study site, the estimated mean annual precipitation is about 2000 mm; more than 80% occurs in the wet season, leading to strongly seasonal flood occurrence. Bankfull discharge (Q_{BF}) at the study site is 3.6 m^3/s. Flow measurements were not made prior to 1984; therefore the gauging records for the creek are insufficient to perform frequency-magnitude analysis. The largest peak flow is estimated at 25 m^3/s based on post-flood trimlines at the site and comparisons with nearby gauged streams (Smith, 1990). These nearby gauging records indicate that the return period for this flood is about 5 years.

At the study site, the channel gradient is 0.006 and the mean channel width is 10 m. The study reach consists of a distinct pool head, pool centre, and pool tail, where thalweg depth at bankfull discharge is

0.71, 1.46 and 0.59 m, respectively (Fig. 1). Pieces of LWD are located near the upper, middle, and lower parts of the reach. We focus on the largest LWD piece, which controls pool morphology and lies on the channel bed, allowing very little flow and sediment to pass underneath. At low flow, the effective width of this obstruction with respect to effects on flow is about 3.6 m, roughly one-third of the active channel width. At flows of about 8.2 m^3/s, this LWD is totally submerged.

Pebbles and cobbles dominate the pool head, sand covers most of the pool centre, and pebbles dominate the pool tail. The median size of the surface material ranges between 31 mm at the pool head and 3.8 mm at

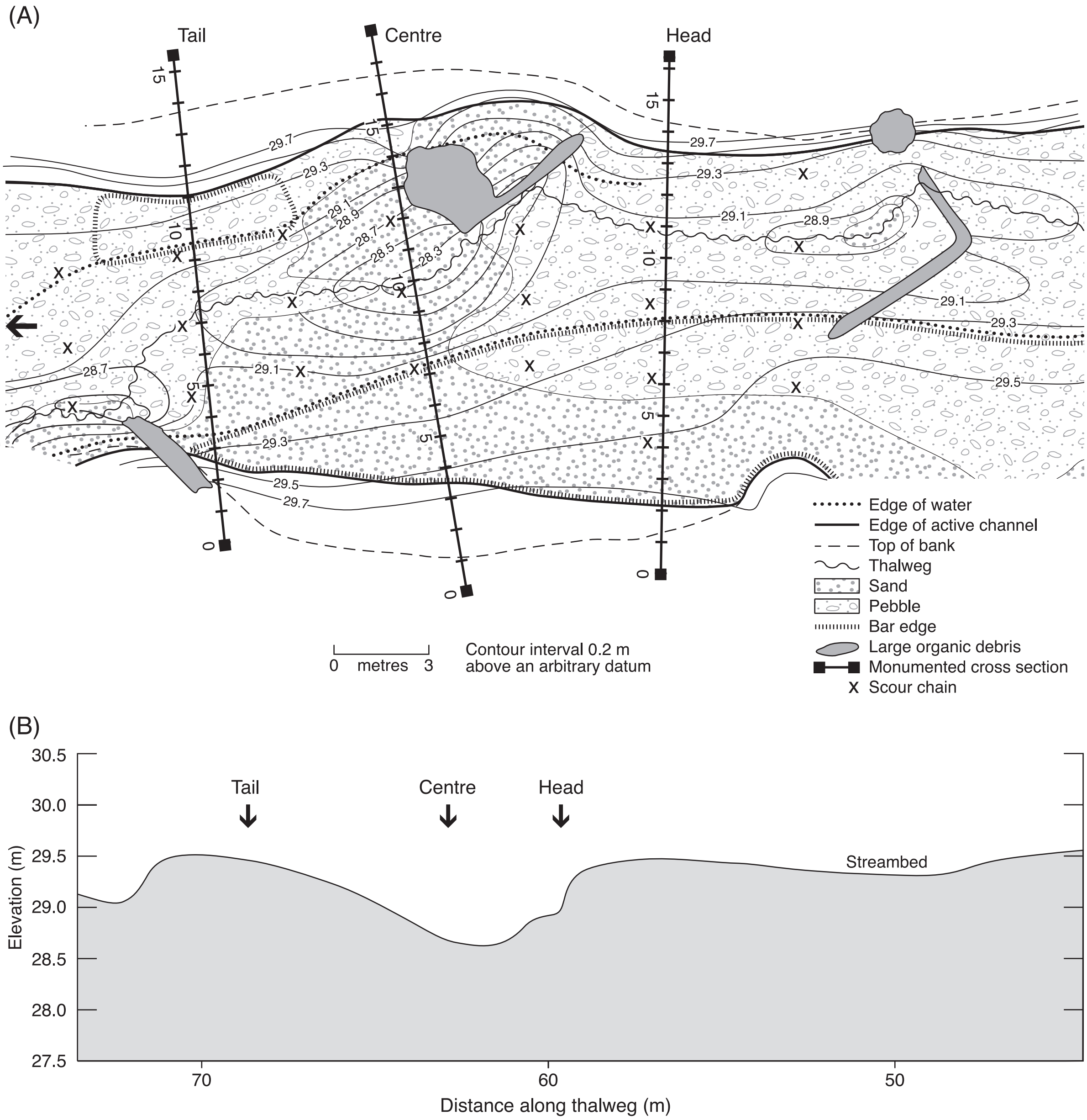


Fig. 1. Tom McDonald Creek study site. Topographic map (A) and longitudinal profile (B) of the study reach.

the pool centre (Fig. 2A). Composite freeze core samples (~ 100 kg each) of surface and subsurface material provide data to assess textural changes over the study period. Samples were taken from a riffle crest immediately downstream of the study pool. Prior to a large flood on 13 February 1986, subsurface (10–40 cm below the bed surface) samples showed little change over time with a median size of 16 mm. For the same period of time, surface (0–10 cm below the bed surface) samples were somewhat coarser than the subsurface, but these differences are statistically insignificant (Fig. 2B). Because of net filling by fine-grained material during the 13 February 1986 flood (see scour and fill section), the median size of subsurface material drops to 7.9 mm. The median size of the freeze core-sampled surface material after the 13 February 1986 event was 15.8 mm, very similar to the subsurface material measured prior to the event (Fig. 2B). Absence of major scour indicates that most

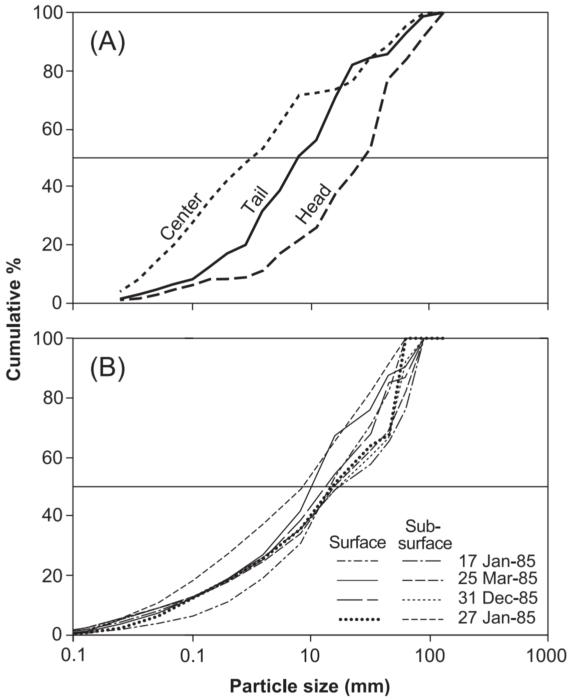


Fig. 2. Size distribution of surface and subsurface bed material from the study pool. (A) Wolman grid by number pebble count data and (B) surface and subsurface freeze core samples taken from a riffle crest immediately downstream of the study site. Each sample is a composite of nine subsamples taken between January 1985 and March 1986.

changes in both surface and subsurface sediment texture are associated with filling, even during the large flood, suggesting little vertical mixing between the surface and subsurface sediment layers.

3. Data collection methods

Bed load samples were collected using a Helley–Smith sampler with an enlarged bag (Helley and Smith, 1971; Beschta, 1981) during the 1986 flood season. Measurements covered a wide range of flows from the beginning of significant sediment transport to flows exceeding bankfull stage. Bed load samples were collected along three transects located at the pool head, pool centre, and pool tail (Fig. 1). At each transect, eight samples were collected at equal intervals to represent transport across the channel. The bed load samples were dried and sieved for particle size analysis.

The Helley–Smith is the most commonly used sampler; however, it is designed for use in coarse sand and granule-gravel beds (Helley and Smith, 1971) and is known to produce biased results in coarse materials (Sterling and Church, 2002). Emmett (1980) reported nearly perfect trapping efficiency for particle sizes between 0.50 and 16 mm; for particles >16 mm, the sampler had a low efficiency. However, most of the study site bed material at the pool centre and pool tail fall within the range of high sampler efficiency; for these two transects we assume that the Helley–Smith yields reasonable results. Due to coarser bed material at the pool head, sampler efficiency is likely to be somewhat lower. We assume that neither the finest nor the coarsest mobile fractions are well represented by the sampler, imposing some limitation on the analysis of bed load data. Furthermore, few samples contain material >32 mm; therefore, to limit error in sampling coarse fractions, we truncate our samples at 32 mm. Finally, we assume that bias in our results is systematic, and therefore comparison among the three cross-sections is reasonable. There is no consensus regarding the best sampler for obtaining true sediment transport rates in gravel-bed rivers (Ryan and Troendle, 1996; Hassan and Church, 2001).

To supplement bed load measurements, scour and fill were measured using scour chains and repeat soundings. Because the movement of bed load is nonuniform, such data can provide valuable information on local scour and sediment mobility. Thirty-eight repeat soundings were performed along the three transects (Fig. 1). Twenty-three scour chains were installed throughout the pool in July 1985 (Fig. 1). Twenty-two chains were recovered in September 1986 and used to estimate channel bed changes during the flood season. Scour chains provided data on maximum scour and net deposition during the study season.

A water level recorder was installed about 25 m downstream of the study pool and calibrated against discharge (Q) computed from cross-sectional measurements of stream velocity, width, and depth over a range of flow at each cross section. An array of staff gauges was installed along the study reach, and stage height-discharge relations developed for them. In order to characterize flow pattern and calculate shear stress across and along the reach, velocity profiles were measured at 30-cm or larger intervals across the three transects. Using a Price type current meter, velocity profile measurements started as close to the bed as possible (5 cm); vertical measurement intervals were 2.5 cm at the pool head and tail and 15 cm at the pool centre. Magnitude and direction of cross-stream flow was measured by attaching the current meter to a free-moving insert in a hand-held pole. A high-quality bearing at the insert-pole contact allowed the current meter to adjust freely to flow direction and azimuth to be measured along with velocity, even at low discharge. Cross-stream flow magnitude gives an indication of the degree of flow modification by features such as the LWD obstruction. Direct measurements of turbulence were not made, rather turbulence was inferred from velocity profile measurements and observations. These data provided a qualitative measure of flow modification by the primary LWD obstruction. Following Whiting and Dietrich (1990), boundary shear stress was calculated using near-bed velocity measurements taken along the three transects. The shear stress calculations were averaged over the active channel width, spanning the zone of maximum shear stress.

4. Flow hydrograph and flow pattern

Flow measurements began in 1984. Two small events (peak flow <2 m^3/s) were recorded in 1985. During 1986, three small events (peak flow <3 m^3/s) occurred in January and early February, followed by a major flood. Storm rainfall began on 12 February, flows began increasing 13 February, and the flood peaked on 17 February with an estimated flow of about 25 m^3/s (Fig. 3). During this event, flow reached the sampling bridges and measurements could no longer be made safely. Therefore, sediment transport and survey data were available for parts of the rising and falling limbs of the flood hydrograph (<13 m^3/s), whereas scour chain data represented the entire hydrograph. The 13 February 1986 flood was the major event during the study period and, hence, the focus of this paper.

Patterns of flow determined boundary shear stress magnitude and distribution across the channel, which in turn controlled sediment entrainment and transport. The major LWD obstruction had a strong influence on flow pattern and therefore on magnitude and distribution of boundary shear stress, sediment entrainment and transport, and, in turn, channel morphology. At the pool head at low discharges, velocity profiles were approximately logarithmic, the maximum shear stress was on the left side of the channel, and no effect of the LWD on the flow pattern was evident (Fig. 4A). As discharge reached 0.5 Q_{BF}, a portion of the flow approaching the pool head was deflected toward the right by a left-bank lateral bar (Fig. 1). Accordingly, locations of the shear stress maximum and thalweg

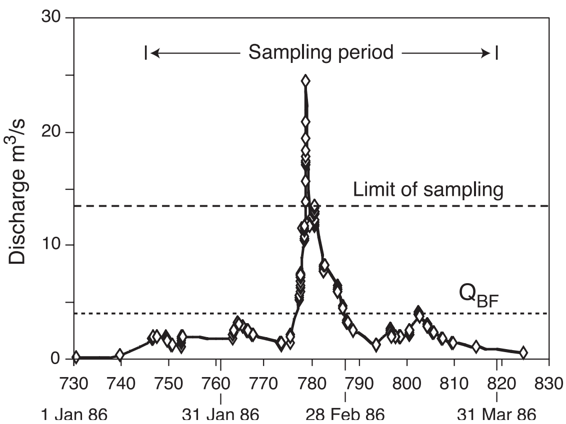


Fig. 3. Flow hydrograph at the study site for the 1986 season. The period of bed load sampling and scour and fill measurements is indicated. Days are indicated numerically: 1 January 1986 is day 731.

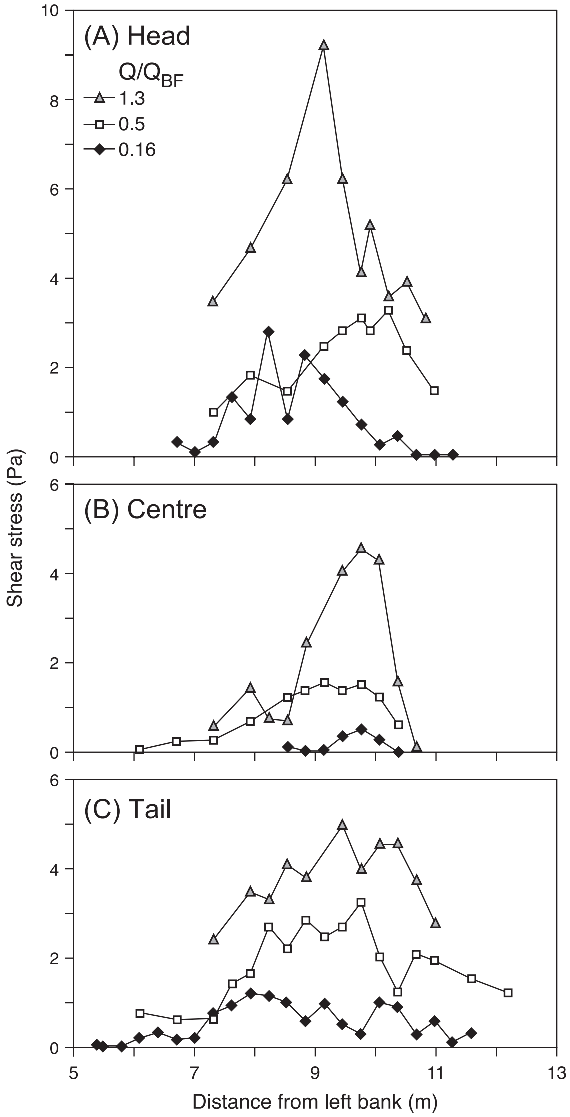


Fig. 4. Cross-channel variation in bed shear stress: (A) pool head, (B) pool centre and (C) pool tail. Symbols indicate discharge (Q) relative to bankfull discharge (Q_{BF}).

shifted roughly 2 m to the right. At discharges above 0.5 Q_{BF}, back water effects of the LWD obstruction caused super elevation of the water surface on the right side of the channel. This was particularly evident at flows greater than bankfull, becoming less pronounced at very high discharges when the LWD was submerged. Super elevation at the pool head caused the previously right-directed cross stream flow to shift back toward the primary flow direction, and the shear stress maximum returned about 1 m toward the left side of the channel (Fig. 4A).

At the pool centre, effects of the primary LWD obstruction on streamflow patterns were most pronounced, including the generation of turbulent eddies and vortices, which entrained sediment at the obstruction base. At discharges above 0.5 Q_{BF}, flow was strongly deflected toward the left bank by the obstruction, increasing water surface elevation and expanding the zone of high shear stress toward the left side of the channel, thereby terminating the upstream left-bank lateral bar (Fig 4B). Deflection of flow by the LWD obstruction anchored the location of high velocity flow and shear stress maximum to the vicinity of the obstruction and the thalweg. Although flow and velocity profiles became increasingly complex above bankfull discharge, location of the shear stress maximum remained within 1 m of the thalweg at the base of the obstruction, and the streamflow pattern was altered only slightly when flow overtopped the LWD at discharges >2 Q_{BF} (Fig. 4B).

At the pool tail, streamflow was modified by strong leftward deflection of flow by the large obstruction and by deflection in opposing directions by the upstream left bank lateral bar and the right bank lateral bar in the lee of the obstruction (Fig. 1). High bed shear stress was distributed over several meters of channel width, becoming more constricted as discharge increased (Fig. 4C). Shear stress magnitude was generally greater than at the pool centre, but less that at the pool head (Fig. 4C). At all three transects, the shear stress maximum was not commonly located at the thalweg, rather it coincided with the maximum combined depth and velocity, which was strongly affected by the LWD obstruction (Fig. 4).

5. Scour and fill

5.1. Scour chains

Scour and fill data provided information on sediment sources and storage along the channel and were used to evaluate channel changes. We assumed that scour was primarily related to peak flood flow, while fill occurred on the waning part of the flood. Scour chains were excavated only once, after the 13 February 1986 event; therefore, data characterized only maximum scour and net fill for the 1985–86 high flow period.

Only 18% of the study reach scoured during the large flood. Scour was highly localized and strongly influenced by LWD (Fig. 5A). Scour depth ranged from zero to a maximum of about 25 cm at three distinct locations; two of these were adjacent to LWD, and the third was along the path of flow deflected by the primary LWD piece (Fig. 5A). The mean gross scour depth for the study reach was 6.5 cm, a relatively low value given the magnitude of the 13 February 1986 event. This is about the D_{84} of the combined pool head and pool tail, and 1.5 times the D_{84} of the pool centre.

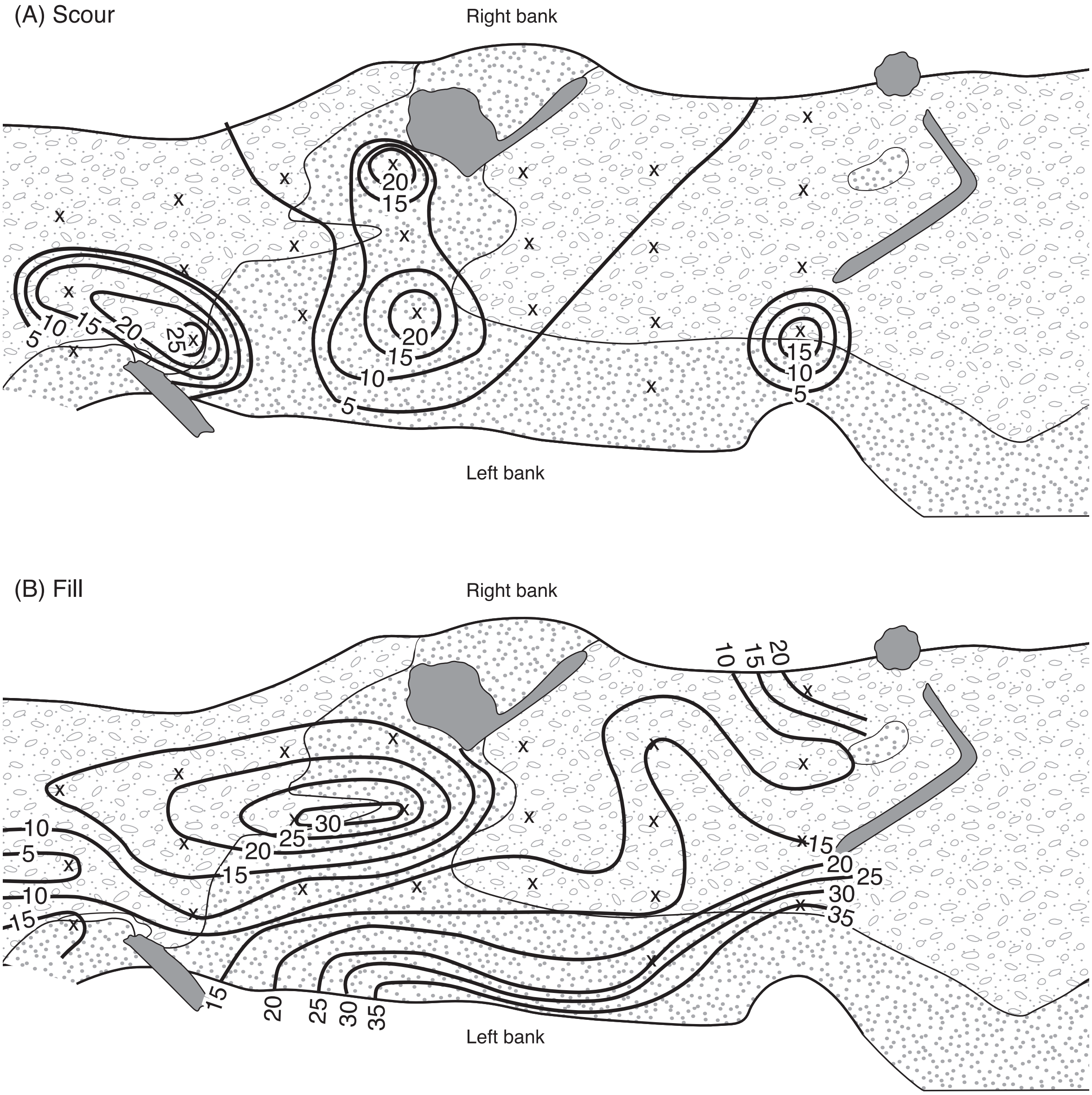


Fig. 5. (A) Scour and (B) fill, primarily during the 13 February 1986 flow event. Scour chain locations are marked with an X.

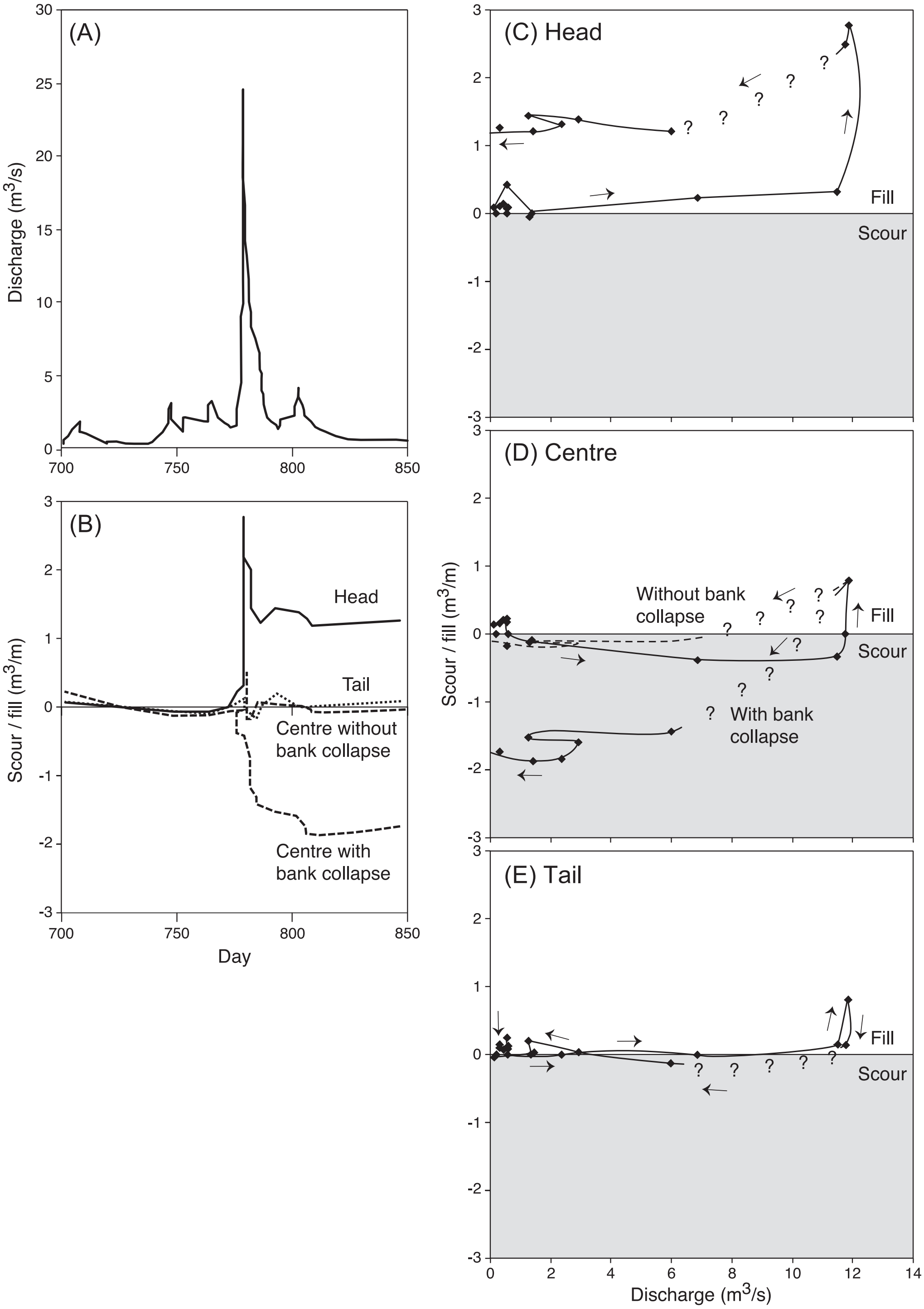


Fig. 6. (A) Flow hydrograph, (B) scour and fill of the cross-sectional area of stream bed during of the 13 February 1986 (day 774) flood, and (C–E) time line plots for scour and fill at the pool head, pool centre, and pool tail, respectively.

All scour chains recorded some filling during the study period (Fig. 5B). A maximum of 37 cm was recorded on the left side of the channel, just upstream of the pool head. This bar aggradation continued farther downstream on the left side and at another bar on the right side in the lee of the primary LWD obstruction (Fig. 5B). All chains except four experienced net filling. Three of these were located along the thalweg; the fourth was adjacent to the primary LWD obstruction. The mean gross fill for the study reach was 15.7 cm, almost three times the mean gross scour. Mean net change over the study period was 10.8 cm of fill (Fig. 5A,B).

5.2. Soundings

Cross-sectional soundings provided detailed information on changes in the channel bed elevation during and between flow events. At the pool head, prior to the 13 February (day 774) flood, most changes in bed elevation were minor (< 2 cm) and were concentrated near the left bank (Fig. 6A,B). Flood-related deposition was recorded beginning February 16 (day 777) and increased dramatically following the flood peak on 17 February; a maximum local fill depth of 60 cm was recorded, reflecting downstream enlargement of the left bank lateral bar (Fig. 1). Deposition peaked on 18 February (day 779). Reworking of this fill began one day later and ceased by 4 March (day 793) as flows continued to recede, leaving significant deposition at the base of the left bank and the thalweg displaced about 1 m to the right (Fig. 6A,B). In order to compare between scour chain and sounding data, we calculated the net change in bed surface elevation using scour chain data close to the sounding transects. The scour chain data yielded a mean gross filling of 1.56 m^3/m, which is very close to that obtained from the soundings (Fig. 6B).

Prior to the 13 February event, the pool centre showed minor (< 2 cm) change in the bed elevation, involving mainly fine sand and organic material (Fig. 6A,B). Maximum scour of 17% of the pool volume occurred during the rising limb and peak of the major flood hydrograph. As at the pool head, the waning part of the flood resulted in significant sedimentation on the left side of the pool, owing to enlargement of the upstream left bank lateral bar. Lateral bar aggradation on the right side, downstream of the primary LWD piece, was also evident. For the pool centre, scour chain data indicated zero net change in the bed surface elevation. However, soundings included the banks and indicated major lateral erosion of the right bank, resulting from flow deflection by the LWD obstruction. Disregarding this bank erosion, scour chains and soundings indicated very minor net changes to the average bed elevation at the pool centre for the study period (Fig. 6B).

The pool tail showed very similar patterns of scour and fill to that of the pool head, although with negligible net change in average bed elevation (Fig. 6B). Most of the short-term changes in bed elevation occurred during the falling limb of the 13 February flood. These consisted of aggradation and subsequent reworking of the right-bank lateral bar in the low shear stress zone in the lee of the LWD obstruction (Fig. 6B). Here, both scour chains and soundings indicated a few centimetres of net fill following the large flood (Fig. 6B).

In general, a complex pattern of hysteresis in scour and fill occurred during the rising and falling limbs of the 13 February event (Fig. 6C–E). At all three transects, marked aggradation of pre-existing lateral bars occurred early during the falling limb, followed by reworking of this fill. A significant volume of this aggradation persisted at the pool head, while the stream bed at the pool centre and tail returned to the pre-flood state, disregarding bank erosion at the pool centre (Fig. 6C–E). The most striking aspect of this pattern was the lack of major scour despite flows that well exceeded bankfull stage.

6. Sediment transport

6.1. Observations

During the study period, 29 composite bed load samples were taken at the pool head, 31 from the pool centre, and 29 from the pool tail. These samples covered a wide range of flows from 0.3 Q_{BF} (1.26 m^3/s) to 3.5 Q_{BF} (15 m^3/s). Only a few grams of sample were collected at the lowest discharge (1.26 m^3/s). This flow was selected as the minimum for bed load sampling.

Examples of the size distribution of bed load collected along the three transects were selected to represent the range of observed flow and sediment transport conditions (Fig. 7). For comparison purposes, the particle size distributions of the bed surface material at each transect are also plotted. At low flows (<2 m^3/s), fine material was transported, usually from riffles to the downstream adjacent pool, and very fine sediment and organic matter were scoured from the pools. During higher flows at the pool head, the relation between size distribution and discharge was complex (Fig. 7A). A progressive coarsening was evident in the transported material texture for flows between 5.3 and 7.4 m^3/s (1–2 Q_{BF}). The median size shifted from 0.9 at 1.8–5.5 mm at 7.4 m^3/s (Fig. 7A). For flows larger than 2 Q_{BF}, a fining trend in the transported sediment was observed. For example, the sediment texture at 12.8 m^3/s was very similar to that of 5.3 m^3/s; the median size dropped from 5.5 mm at 7.4 m^3/s to 2.8 mm at 12.8 m^3/s (Fig. 7A). For all samples, the size distribution of the transported material remained significantly finer than that of the bed surface.

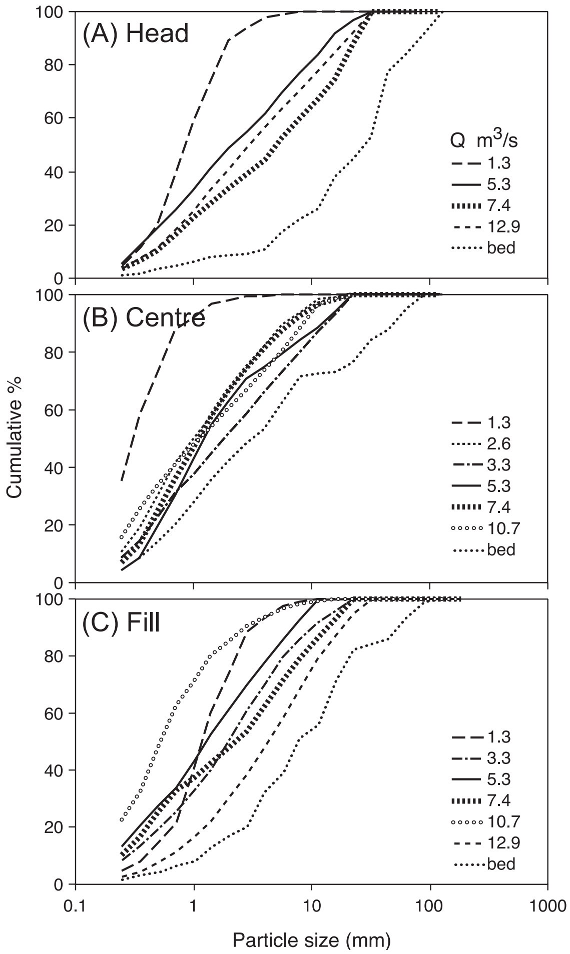


Fig. 7. Changes in the bed load texture from samples collected at (A) pool head, (B) pool centre, and (C) pool tail. Discharge is given for each sample. For comparison, the size distribution of the bed surface material is plotted.

The discharge-bed load grain size relation at the pool centre was also complex (Fig. 7B). For the lowest sampled flow (1.3 m^3/s), the sediment texture was fine (<2.83 mm) with a median size of 0.31 mm. At larger discharge, the median size coarsened to 1.9 mm at 3.3 m^3/s. Flows> 3.3 m^3/s showed a decrease in the sediment size. During the highest flows (~ 10 m^3/s), about 70% of the mobile sediment was in the range of sand. For all samples, the transported sediment was finer than that of the bed, however only slightly so for flows of about 1 Q_{BF} (3.3 m^3/s).

Samples collected at the pool tail yielded very similar results to those of the pool centre (Fig. 7C). However, high flows (12.9 m^3/s) during the falling limb of the major flood hydrograph transported coarser material than those close to the peak or somewhat lower flows (10.6 m^3/s) (Fig. 7C). Here again, the size-discharge relation was complex; and the texture of the transported material was finer than that of the bed even during high flow conditions.

To better understand sediment transport dynamics at the study site, we explored the relation between flow conditions and sediment transport rate (Table 1). Transport rates increased as the discharge increased at all transects (Fig. 8A). The data are very scattered, which is probably due to hysteresis in the transport load between the rising and falling limbs of the storm hydrographs (e.g., Smith, 1990; Whiting et al., 1999; Hassan and Church, 2001). For each regression slope and constant, confidence intervals were calculated at the 0.1 significance level using Student's *t*-test with appropriate degrees of freedom (Neter et al., 1983). Statistically, the three rating curves were similar, based on these confidence intervals. However, sensitivity (slope) of the rating relation changed at a critical discharge of about Q_{BF}. Below Q_{BF}, the sediment transport rate increased rapidly as the discharge increased, but increased more slowly at flows above Q_{BF}. Piecewise regression, using Q_{BF} as a critical

Table 1
Bed load rating relations at each transect in Tom McDonald Creek

Transect	r^2	N	a	b	m
Model 1[a]					
Head	0.81	33	0.123	3.51	
Centre	0.77	27	0.131	3.88	
Tail	0.76	29	0.085	3.54	
Model 2[b]					
Head	0.90	33	0.029	5.71	−3.85
Centre	0.89	27	0.032	5.91	−4.65
Tail	0.85	29	0.023	5.31	−2.94

[a] Model 1: We applied the usual scale relation $g = aQ^b$, in the linearized form log $g = a + b$ log Q where g is the mean transport rate (g/ms), Q is the mean discharge for the measuring period, and a and b are regression coefficients.

[b] Model 2: We used a rating curve of the form log $g = a + b$ log $Q + m$ $(\log Q - Q_{BF})|Q > Q_{BF}$, where Q_{BF} is the bankfull discharge above which the rating sensitivity changed and m is an additional regression coefficients. The change in the sensitivity was selected using breakpoint analysis, and then the two-part regression line was fitted.

value, improved the fit of the rating relation markedly (Fig. 8B, Table 1). Statistically, the three piecewise rating curves presented in Fig. 8B were similar.

6.2. Fractional mobility of sediment

Sediment transport rates and textures at each transect reflected the interactions among channel morphology, bed surface texture, flow conditions, and sediment inputs from upstream sources. To examine variability in sediment mobility along the pool, we analyzed the fractional transport rate at each transect following Wilcock and McArdell (1993, 1997). Our observations indicated that most of the mobile sediment came from upstream sources or bank collapse and little from the local bed surface. The fractional transport rate was scaled using the particle size distribution of subsurface material, which is likely to represent the mobile sediment (see Church and Hassan, 2002). In scaling the transported material, we truncated the subsurface material at 32 mm because of the limitation of the Helley–Smith sampler in trapping coarse material and because of the lack of information on the amount and texture of material >32 mm.

For most flows at the pool head, the scaled fractional transport rate ranged over about two orders of magnitude and increased as flow increased (Fig. 9A). All curves show a break in the slope where transport rate begins to decline with increasing grain size, i.e., a shift from full to partial mobility. The breaks in slope shifted from 1.4 mm at 2.7 Pa to 8 mm at 5.1 Pa. For larger flows, the break point in the slope shifted to 16 mm at around 10.1 Pa and remained about the same for higher shear stresses. This implies that for high flows the full mobility limit was about that of the median size of the subsurface material but finer than that of the median size of the surface material. In general, the break point in the fractional mobility was at the sand fractions for flows smaller than bankfull (Fig. 9A).

At the pool centre, for a given flow, the scaled fractional transport rate ranged over one to three orders of magnitude (Fig. 9B). The size limit between full and partial mobility shifted from 1 mm at about 1 Pa to 11.2 mm at 3.5 Pa. The maximum mobile size at

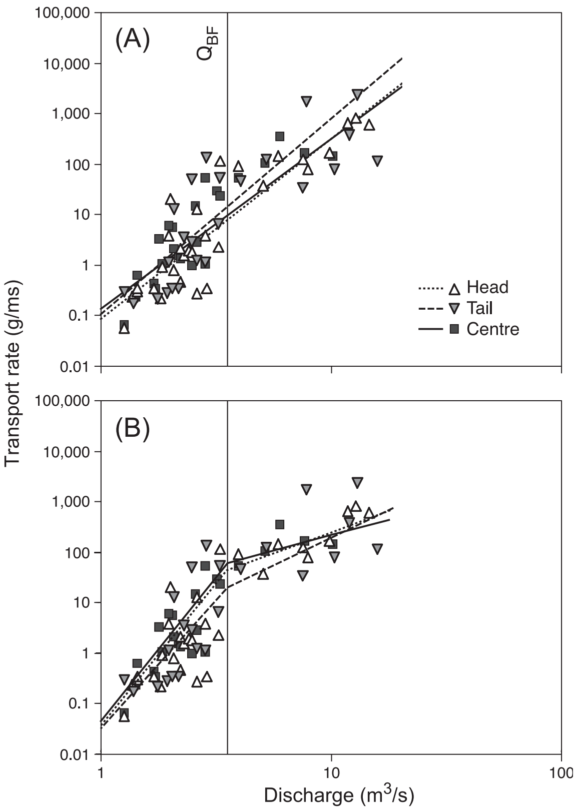


Fig. 8. Total bed load rating curves for the pool head, pool centre, and pool tail. (A) Model 1 and (B) model 2 (see Table 1).

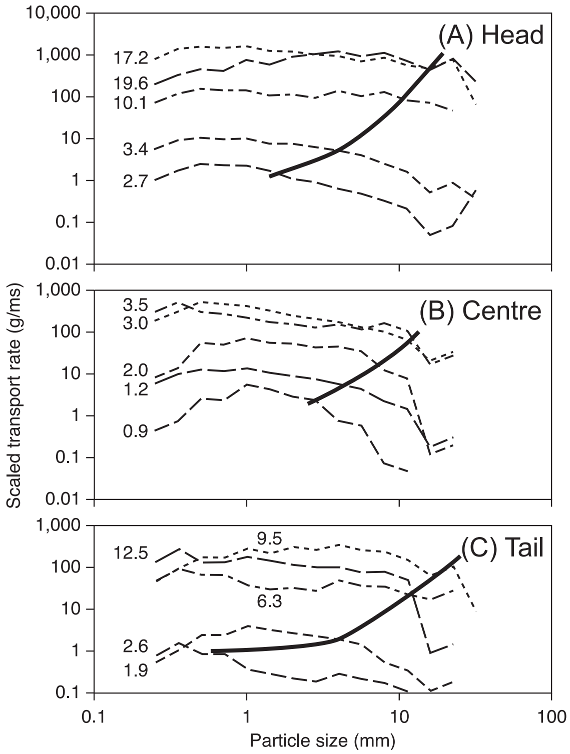


Fig. 9. Scaled fractional sediment transport rate versus particle sizes for selected flows, shown as the associated bed shear stress (Pa): (A) pool head; (B) pool centre; (C) pool tail. The dark line indicates the approximate transition from full to partial mobility.

this transect seldom exceeded 22 mm. However, during high flows, most of the sampled sizes were fully mobile (Fig. 9B). This could be due to the fact that entrainment was enhanced by turbulent lift forces associated with the obstruction (e.g., Lisle, 1986; Smith, 1990; Buffington et al., 2002).

The pattern of fractional sediment mobility was complex in the pool tail (Fig. 9C). The shift from full to partial mobility occurred at the 1.4-mm particle size during low flows (1.9 Pa), compared to 4 mm at 2.6 Pa and 16 mm at about 9.0 Pa. However, the texture of the mobile sediment at the highest observed flow was mainly fine to medium sand indicating higher rates of sand transport (not plotted in Fig. 9C).

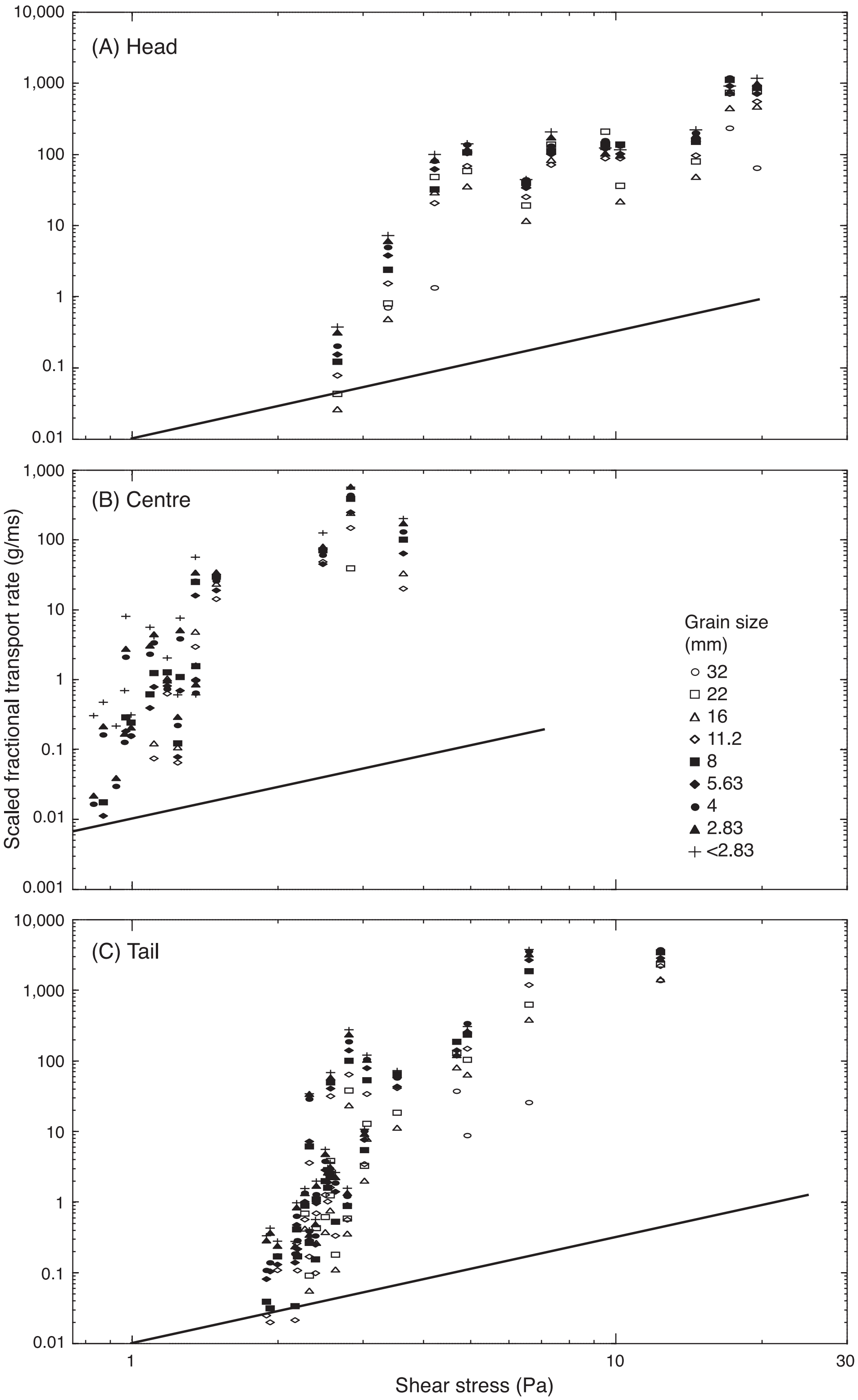
6.3. Sediment entrainment and mobility domains in the field study

Entrainment and scour of gravel particles occur when shear stress is sufficient to overcome particle resistance forces. Thresholds for sediment entrainment for individual sizes were estimated using the Wilcock and McArdell (1993) technique. The entrainment condition was determined using the Parker et al. (1982) reference transport relation as detailed by Wilcock and McArdell (1993). For most of the flows, the Parker et al. relation plotted near the measured minimum-scaled sediment transport rates and, therefore was used to estimate entrainment conditions (Fig. 10).

At the pool head, the scaled fractional transport rates covered about five orders of magnitude; nearly all plotted above the reference transport relation of Parker et al. (1982) (Fig. 10A). Furthermore, a systematic increase in the fractional transport rate was evident as bed shear stress increased. At the pool centre, maximum transport rate and especially measured bed shear stress were smaller than at the two other transects. For all flows, the scaled fractional transport rate plotted above the reference line (Fig. 10B). Patterns at the pool tail were similar to those of the pool head (Fig. 10C).

The critical shear stress needed to initiate transport for a given size fraction was determined using the reference transport rates (see Wilcock and McArdell, 1993; Church and Hassan, 2002). Sand sizes were found to be mobile during most of the flow observations, and hence the reference transport rate could not be used for the sand fractions. In order to estimate initial flow conditions of entrainment and mobilization for the fine fractions, we used size-specific rating relations for the sizes 1, 1.41 and 2 mm. We had no confidence in using this method for material finer than 1 mm because these sizes may move in suspension during high flows. For sizes between 1 and 2 mm, the estimated shear stresses for particle entrainments at the pool head, pool centre, and pool tail were 1.2, 0.70 and 1.6 Pa,

Fig. 10. Size-specific fractional sediment transport rate as a function of bed shear stress. The reference transport relation of Parker et al. (1982) is shown: (A) pool head; (B) pool centre; (C) pool tail. Plotting all samples for each transect would obscure the transport rate and bed shear stress relations. Therefore, we plotted only the number of samples required to represent the range of flow conditions observed. In determining the entrainment conditions, however, we used all samples. Likewise, we used only one symbol for sizes finer than 2.83 mm.


(A) Head
(B) Centre
(C) Tail
10,000
1,000
100
10
1
0.1
0.01
0.001
Scaled fractional transport rate (g/ms)
Shear stress (Pa)
1
10
30
Grain size (mm)
32
22
16
11.2
8
5.63
4
2.83
<2.83

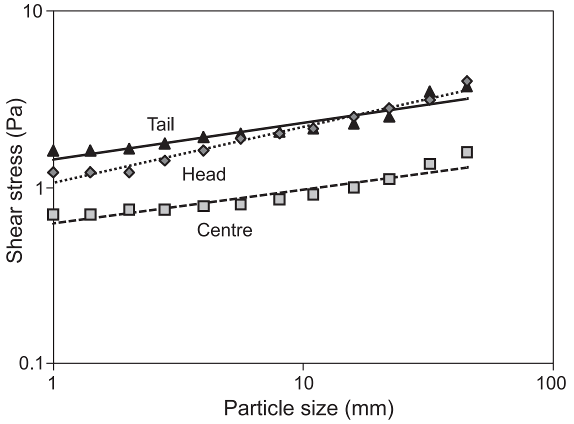


Fig. 11. The relation between particle size and bed shear stress needed to initiate the movement of individual particles as determined in Fig. 10.

respectively. In the case of coarse material (>32 mm) we used the maximum trapped size to estimate entrainment condition. Because of the sampler limitation, however, we limited the analysis to 45 mm or less.

The following threshold relations as a function of grain size were obtained (Fig. 11):

$$\tau_{ri} = 1.05D_i^{0.32\pm0.016} \text{ for the pool head}$$

$$\tau_{ri} = 0.62D_i^{0.19\pm0.022} \text{ for the pool centre}$$

$$\tau_{ri} = 1.43D_i^{0.21\pm0.024} \text{ for the pool tail}$$

Where D_{i} is the particle size in mm, and τ_{ri} is the shear stress in Pascals. Exponent confidence intervals indicated that the exponents of the pool centre and pool tail relations were statistically similar, while both were statistically different from that obtained for the pool head. The difference occurred chiefly for the finest sizes, which required greater bed shear stress to move in the head and tail. Furthermore, coarse bed surface material at the pool head probably provided significant sheltering for the fine material. There was

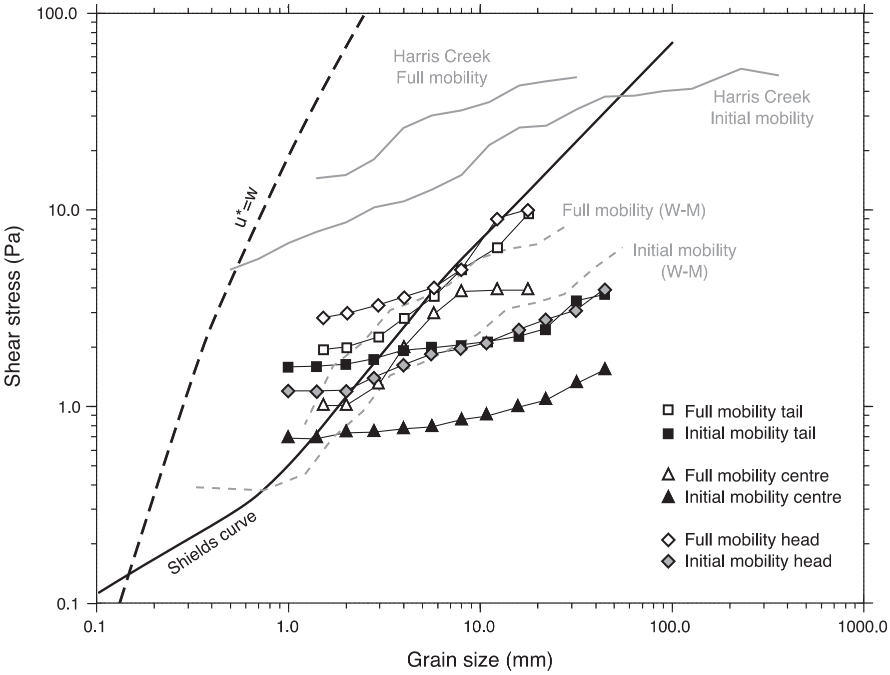


Fig. 12. Bed shear stresses needed to initiate and to fully mobilize sediment in Tom McDonald Creek are plotted against grain size. The initial conditions were estimated based on the analysis presented in Fig. 10, while the full mobility analysis was based on Fig. 9. The flume experiment results (Wilcock and McArdell, 1993), Harris Creek field results (Church and Hassan, 2002), and a modified form of Shields' curve (Shields, 1936; Miller et al., 1977) are plotted for comparison. The line $u^*=w$ is shown (where w is the grain settling velocity and u^* is the shear velocity).

also marked lateral segregation of sediment along the study area, which was likely to contribute to the differences among transects. In comparison with published results, the above exponents are statistically different from reported flume (Wilcock and McArdell, 1993) and field relations (Church and Hassan, 2002).

We calculated the domains of sediment mobility (i.e., thresholds for initiation of movement and full mobility) using the analyses presented in Figs. 9 and 10, and compared these to the modified Shields curve (after Miller et al., 1977), the full and partial transport domains from flume experiments (Wilcock and McArdell, 1993), and those from Harris Creek (Church and Hassan, 2002) (Fig. 12). For both partial and full transport domains, the pool centre data plotted much lower than those of the pool head and pool tail. Initial motion curves for the pool head and pool tail plotted very close to those of Wilcock and McArdell. In the case of the full mobility curves, all three field curves plotted near the Wilcock and McArdell curve. However, for grain sizes less than about 4 mm, the initial and full mobility curves obtained for the flume experiments were steeper than those of the study pool in Tom McDonald Creek. Similar results for the pool head, pool tail, and flume experiments were not surprising because both contained large amounts of mobile sand. In comparison, Harris Creek domains plotted much above the Tom McDonald Creek and flume data, which could be attributed to the relatively stable bed in Harris Creek (Church and Hassan, 2002). Both the Wilcock and McArdell (1993) and Church and Hassan (2002) relations were obtained for bimodal sediment. This may explain some of the differences between our data and those reported in the literature.

7. Discussion

We examined channel bed dynamics and sediment mobility along an obstruction-formed pool in a forest, gravel-bed stream using scour chains, cross-sectional surveys, and bed load material caught in a Helley–Smith sampler. A number of studies have reported seasonal and annual patterns of hysteresis in scour and fill (e.g., Andrews, 1979) or sediment transport (e.g., Nanson, 1974; Andrews, 1979; Reid et al., 1985; Kuhnle, 1992; Moog and Whiting, 1998; Hassan and Church, 2001). None of these studies reported both types of hysteresis. These patterns were related to variable sediment supply from external sources and internal storage within the channel. Similarly, changes in sediment availability led to a complex pattern of scour and fill hysteresis in the study creek. Channel assessment during the study period showed no major input of sediment from the flood plain and hillslopes, indicating that most mobile sediment came either from bank collapse or sediment stored in the channel, commonly behind LWD. Following a major flood, significant bed material storage remained at the pool head in an aggraded lateral bar, while scour of flood deposits during the receding limb resulted in little net bed material storage change at the pool center and tail.

In comparison to other studies, (e.g., Emmett, 1976, Klingeman and Emmett, 1982, Andrews, 1994; Hassan and Church, 2001), bed load transport in Tom McDonald Creek was relatively high because of the large amount of sand and fine gravel that moved during even relatively low flows. Tom McDonald Creek transport rates were comparable to those reported for flashy ephemeral streams (e.g., Laronne and Reid, 1993; Reid and Laronne, 1995; Hassan and Egozi, 2001).

Temporal variation in bed load transport at a station and between stations was relatively high. However, despite the differences in local flow conditions, local morphology, and sediment texture, rating relations between transport rate and discharge were strikingly similar among the three transects; differences were within the error around the best fit line. For all three transects, the sensitivity of rating relations changed around bankfull discharge. Similarity in the rating relation between the three transects may have been related to their close proximity, which masked spatial variations. Sensitive rating relations for gravel-bed rivers have also been reported in a number of other studies (Nanson, 1974; Emmett and Wolman, 2001; Hassan and Church, 2001). Hassan and Church (2001) showed that site-specific rating relations were very sensitive and unstable between sites and between seasons for the same site. However, few studies reported stable rating curves for gravel-bed streams (e.g., Whiting et al., 1999; Emmett and Wolman, 2001). The reported bed load rating relations in this study were a little higher than the commonly reported range between 1.5 and 3 (Leopold, 1994;

Whiting et al., 1999) but much lower than site-specific relations reported for Harris Creek (see Hassan and Church, 2001). Hassan and Church (2001) asserted that low values reflect the sensitivity of the transport phenomenon to changes in flow under conditions of generally established motion, which appeared to be the case in our study site.

Observations and interpretations of sediment entrainment in both natural rivers and laboratory models have been reported for fully and partially mobilized beds (e.g., Parker et al., 1982; Ashworth and Ferguson, 1989; Wilcock and McArdell, 1993, 1997; Church et al., 1998; Hassan and Church, 2000). In Tom McDonald Creek, the large pebble-cobble size fractions were not mobile during our observation; this despite the relatively large event of 13 February 1986. On the other hand, sand fractions were mobile for more than 90% of the flood duration. The scaled fractional transport rates for grain sizes up to 32 mm plotted up to three orders of magnitude above the suggested reference transport rate (Parker et al., 1982; Wilcock and McArdell, 1993). This supported the outcome of the rating relations, which indicated that this sediment was fully mobile. In comparison, data for Harris Creek (a well-structured, stable channel) plotted three orders of magnitude below the reference transport rate (see Church and Hassan, 2002). We attributed the relatively high transport rates in our field study to high sediment supply from bank collapse and other upstream sources.

The full/partial bed load mobility data from our study creek plotted near those obtained in flume experiments by Wilcock and McArdell (1993). This may be due to the large amount of sand on the surface of both the flume experiments and the study stream. Furthermore, Wilcock and McArdell (1993) data were obtained from flume experiments under conditions of generally established motion. Tom McDonald values plotted much lower than those obtained for Harris Creek (Church and Hassan, 2002). We ascribed the differences between Tom McDonald and Harris Creek to bed surface compositions; Harris Creek has a well-armoured surface with little scour and fill during even relatively high flows.

Incipient motion analyses suggested a strong size effect on the entrainment of individual grains. The pool head relation was close to that obtained for Harris Creek. The pool head and pool tail yielded very similar relations between shear stress and particle sizes. This was probably influenced by limited modification of the texture of mobile sediment between the two closely spaced transects. On the other hand, the pool centre yielded a different relation than those of the pool head and tail, owing to lower measured bed shear stress.

The above incipient motion estimates indicated the availability of shear stress to entrain much larger material than we observed in the field. For conditions at our field site, critical shear stress calculations using a Shields' number of 0.045, which seems to be reasonable for gravel-bed rivers (cf. Wilcock and Southard, 1988; Church et al., 1998), for flows greater than bankfull showed that material as large as 90 mm should have been entrained. The absence of large size fractions from sampled bed load could be partially explained by the limitation of the Helley–Smith sampler. However, scour chain and sounding data suggested little disruption of the pre-flood bed by the 13 February 1986 event. Indeed, flood-related filling followed by reworking of deposits was the general pattern (see Figs. 5 and 6). Scour depth calculations using empirical relations (see Leopold et al., 1966, Hassan, 1990) predicted an average scour at peak flow (25 m^3/s) on the order of 17 cm for the entire reach, yet field measurements yielded an average value of only 6 cm with large areas of no scouring.

8. Conclusions

Two site specific factors appeared to strongly influence channel dynamics and bedload transport in the study pool. These were the abundant supply of fine sediment and the dominant LWD obstruction in the pool centre. Large amounts of sand and fine gravel were mobile even during low flows, and size fractions larger than the bed surface median size were rarely mobile even during high flows. As discharge increased, bedload texture initially coarsened then became finer, and sand predominated during the highest flows. These observations suggested that large sediment supply from bank collapse and other upstream sources, rather than the channel bed, dominated the sediment transport regime in the creek and contributed to the relatively high bed load transport rates.

The primary LWD obstruction affected sediment entrainment, transport, and deposition. The obstruction created backwater effects and deflected flow, thereby anchoring the location of shear stress maxima that controlled entrainment and scour and limited the downstream migration of an upstream lateral bar. Flow deflection and energy expenditure created a low energy environment in the lee of the obstruction, permitting development and controlling the location of a downstream lateral bar. Most scour and fill measured in this study were associated with aggradation and subsequent reworking of these two bars.

Turbulent vortices generated at the primary LWD obstruction appear to have enhanced entrainment and transport in a manner similar to scour at bridge piers (e.g., Lisle, 1986; Smith, 1990; Buffington et al., 2002). This effect was evidenced in measured fractional transport rates at the pool centre (Fig. 10) and full mobility extending over a wide range of grain sizes despite lower mean bed shear stress at the pool centre (Fig. 9). Entrainment thresholds for the range of grain sizes measured are estimated to be lower (entrainment at lower mean bed shear stress) at the pool centre than at the pool head or tail (Fig. 11). Enhanced entrainment and bed load transport through turbulent effects associated with the LWD obstruction explain maintenance of the pool despite lower average bed shear stress than at the upstream riffle (pool head) and the large volume of bed load transported through the reach.

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References

Andrews, E.D., 1979. Scour and Fill in a Stream Channel, East Fork River, Western Wyoming. U.S. Geol. Survey Prof. Paper 1117, Washington, DC. 49 pp.

Andrews, E.D., 1994. Marginal bed load transport in gravel bed stream, Sagehen Creek, California. Water Resources Research 30, 2241–2250.

Ashworth, P.J., Ferguson, R.I., 1989. Size-selective entrainment of bed load in gravel bed streams. Water Resources Research 25, 627–634.

Benda, L., 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surface Processes and Landforms 15, 457–466.

Beschta, R.L., 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range Stream. Northwest Science 53, 71–77.

Beschta, R.L., 1981. Patterns of sediment and organic-matter transport in Oregon Coast Range stream. In: Davies, T.H.R., Pearce, A.J. (Eds.), Erosion and Sediment Transport in Pacific Rim Steeplands, Wallingford, UK. IAHS Publ., vol. 132, pp. 236–251.

Bilby, R.E., Bisson, P.A., 1998. Function and distribution of large woody debris. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management: Lesson from the Pacific Coastal Ecoregion. Springer-Verlag, New York, pp. 324–346.

Bilby, R.E., Ward, J.W., 1989. Changes in characteristics and function of woody debris with increasing size of stream in western Washington. Transactions of the American Fisheries Society 118, 368–378.

Buffington, J.M., Montgomery, D.R., 1999. Effects of supply on surface textures of gravel-bed rivers. Water Resources Research 35, 3523–3530.

Buffington, J.M., Lisle, T.E., Woodsmith, R.D., Hilton, S., 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18, 507–531.

Church, M., Hassan, M.A., 2002. Mobility of bed material in Harris Creek. Water Resources Research 38 (11), 1237 (doi:10.1029/2001WR000753).

Church, M., Hassan, M.A., Wolcott, J.F., 1998. Stabilizing self-organized structures in gravel-bed stream channels: field and experimental observations. Water Resources Research 34, 3169–3179.

Emmett, W.W., 1976. Bedload transport in two large, gravel-bed rivers, Idaho and Washington. Third Inter-Agency Sedimentation Conference, March 22–25, Denver, Colorado, pp. 4-101–4-114.

Emmett, W.W., 1980. A field calibration of the sediment trapping characteristics of the Helley–Smith Bedload Sampler. U.S. Geol. Survey, Prof. Paper 1139. Washington, DC. 44 pp.

Emmett, W.W., Wolman, M.G., 2001. Effective discharge and gravel-bed rivers. Earth Surface Processes and Landforms 26, 1369–1380.

Gurnell, A.M., Gregory, K.J., Petts, G.E., 1995. The role of coarse woody debris in forest aquatic habitats: implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems 5, 143–166.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack Jr., K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15, 133–302.

Hassan, M.A., 1990. Scour, fill, and burial depth of coarse material in gravel bed streams. Earth Surface Processes and Landforms 15, 341–356.

Hassan, M.A., Church, M., 2000. Experiments on surface structure and partial sediment transport on a gravel bed. Water Resources Research 36, 1885–1895.

Hassan, M.A., Church, M., 2001. Rating bed load transport in Harris Creek: seasonal and spatial variation over a cobble-gravel bed. Water Resources Research 37, 813–825.

Hassan, M.A., Egozi, R., 2001. Impact of wastewater discharge on the channel morphology of ephemeral streams. Earth Surface Processes and Landforms 26, 1285–1302.

Heede, B.H., 1985. Interactions between streamside vegetation and stream dynamics. Proceedings of the Symposium, Riparian Ecosystems and Their Management: Reconciling Conflicting Uses, U.S.D.A., Forest Service, Region 3, Albuquerque, NM, U.S.A., pp. 54–58.

Helley, E.J., Smith, W., 1971. The development and calibration of a pressure difference bed load sampler. U.S. Geol. Survey Open File Report, Washington, DC. 18 pp.

Hogan, D.L., Church, M., 1989. Hydraulic geometry in small, coastal streams: progress toward quantification of salmonid habitat. Canadian Journal of Fisheries and Aquatic Sciences 46, 844–852.

Hogan, D.L., Bird, S.A., Hassan, M.A., 1998. Spatial and temporal evolution of small coastal gravel-bed streams: the influence of forest management on channel morphology and fish habitat. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B. (Eds.), Gravel-Bed Rivers in the Environment. Water Resources Publications, LLC, Highland Ranch, CO, USA, pp. 365–392.

Keller, E.A., Swanson, F.J., 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4, 361–380.

Klingeman, P.C., Emmett, W.W., 1982. Gravel bed load transport processes. In: Hey, R.D., Bathurst, J.C., Thornes, C.R. (Eds.), Gravel-bed Rivers: Fluvial Processes, Engineering and Management. Wiley, New York, pp. 141–169.

Kuhnle, R.A., 1992. Bed load transport during rising and falling stages on two small streams. Earth Surface Processes and Landforms 17, 191–197.

Laronne, J.B., Reid, I., 1993. Very high rates of bed load sediment transport by ephemeral desert rivers. Nature 366, 148–150.

Leopold, L.B., 1994. A View of the River. Harvard University Press, Cambride, MA, USA. 298 pp.

Leopold, L.B., Emmett, W.W., Myrick, R.M., 1996. Channel and Hillslope Processes in a Semiarid Area, New Mexico. U. S. Geol. Survey Prof. Paper, 352-G. Washington, DC, pp. 193–253.

Lisle, T.E., 1986. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. Geological Society of America, Bulletin 97, 999–1011.

Lisle, T.E., Hilton, S., 1992. The volume of fine sediment in pools: an index of sediment supply in gravel bed streams. Water Resources Bulletin 28, 371–383.

Lisle, T.E., Madej, M.A., 1992. Spatial variation in armouring in a channel with high sediment supply. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), Dynamics of Gravel-Bed Rivers. Wiley, Chichester, UK, pp. 277–293.

Megahan, W.F., Nowlin, R.A., 1976. Sediment storage in channels draining small forested watersheds. Proceedings, Third Federal Interagency Sedimentation Conference, Water Resour. Council, Washington, DC, U.S.A., pp. 4.115–4.126.

Miller, M.C., McCave, I.N., Komar, P.D., 1977. Threshold of sediment motion under unidirectional currents. Sedimentology 24, 507–527.

Montgomery, D.R., Buffington, J.M., 1997. Channel reach morphology in mountain drainage basins. Geological Society of American, Bulletin 109, 596–611.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., Pess, G., 1995. Pool spacing in forest channels. Water Resources Research 31, 1097–1105.

Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M., Stock, J.D., 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381, 587–589.

Moog, D.B., Whiting, P.J., 1998. Annual hysteresis in bed load rating curves. Water Resources Research 34, 2393–2399.

Nanson, G.C., 1974. Bed load and suspended load transport in a small, steep, mountain stream. American Journal of Science 274, 471–486.

Neter, J., Wasserman, W., Kutner, M.H., 1983. Applied Linear Regression Models. Richard D. Irwin, Homewood, IL. 547 pp.

Parker, G., Klingeman, P.C., McLean, D.L., 1982. Bed load and size distribution in paved gravel-bed streams. Journal of Hydraulic Division, ASCE 108 (HY4), 544–571.

Reid, I., Laronne, J.B., 1995. Bed load sediment transport in an ephemeral stream and a comparison with seasonal and perennial counterparts. Water Resources Research 31, 773–781.

Reid, I., Frostick, L.E., Layman, J.T., 1985. The incidence and nature of bed load transport during flood flows in coarse-grained alluvial channels. Earth Surface Processes and Landforms 10, 33–44.

Roberts, R.G., Church, M., 1987. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Canadian Journal of Earth Sciences 16, 1092–1106.

Robison, E.G., Beschta, R.L., 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, U.S.A. Earth Surface Processes and Landforms 15, 149–156.

Ryan, S.E., Troendle, C.A., 1996. Bed load transport patterns in coarse-grained channels under varying conditions of flows. Sedimentation Technologies for Management of Natural Resources in the 21st Century. Proceeding of the Sixth Federal Interagency Sedimentation Conference, March 10–14, 1996, Las Vegas, vol. 2, pp. VI-22–VI-27.

Shields, A., 1936. Andwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung (Application of the Theory of Similarity and Turbulence Research to the Bed load Movement: translated by Q.M. Saleh), Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, 26, Berlin.

Sidle, R.C., 1988. Bed load transport regime of a small forested stream. Water Resources Research 24, 207–218.

Smith, R.D., 1990. Streamflow and Bedload Transport in an Obstruction-affected, Gravel-bed Stream. PhD Thesis, Oregon State University, Corvallis. 181 pp.

Smith, R.D., Sidle, R.C., Porter, P.E., 1993a. Effects on bed load transport of experimental removal of woody debris from a forest gravel-bed stream. Earth Surface Processes and Landforms 18, 455–468.

Smith, R.D., Sidle, R.C., Porter, P.E., Noel, J.R., 1993b. Effects of experimental removal of woody debris on the channel morphology of a forest, gravel bed stream. Journal of Hydrology 152, 153–178.

Sterling, S., Church, M., 2002. Sediment trapping characteristics of a pit trap and a Helley–Smith sampler in a cobble-gravel bed river. Water Resources Research 38 (8), 10 (1029/2000WR00 0052).

Swanson, F.J., Janda, R.J., Dunne, T., Swanston, D.N., (Eds.) 1982a. Sediment Budgets and Routing in Forested Drainage Basins. United States Department of Agriculture, General Technical Report Number PNW-141. 165 pp.

Swanson, F.J., Janda, R.J., Dunne, T., 1982b. Summary: Sediment Budgets and Routing in Forested Drainage Basins. In: Swanson, F.J., Janda, R.J., Dunne, T., Swanston, D.N. (Eds.), Sediment Budgets and Routing in Forested Drainage Basins, United States Department of Agriculture, General Technical Report Number PNW-141, pp. 157–165.

Van Sickle, J., Gregory, S.V., 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research 20, 1593–1601.

Whittaker, J.G., 1987. Sediment transport in step-pool streams. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel-Bed Rivers. Wiley, Chichester, UK, pp. 545–579.

Whiting, P.J., Dietrich, W.E., 1990. Boundary shear stress and roughness over mobile alluvial beds. Journal of Hydraulic Engineering 116, 1495–1511.

Whiting, P.J., Stamm, J.F., Moog, D.B., Orndorff, R.L., 1999. Sediment transporting flows in headwater streams. Geological Society of America Bulletin 111, 450–466.

Wilcock, P.J., 2001. The flow, the bed, and the transport: interaction in flume and field. In: Mosley, M.P. (Ed.), Gravel-Bed Rivers V. New Zealand Hydrological Society, Wellington, New Zealand, pp. 183–220.

Wilcock, P.R., McArdell, B.W., 1993. Surface-based fractional transport rates: mobilization thresholds and partial transport of a sand-gravel sediment. Water Resources Research 29, 1297–1312.

Wilcock, P.R., McArdell, B.W., 1997. Partial transport of a sand/gravel sediment. Water Resources Research 33, 235–245.

Wilcock, P.R., Southard, J.B., 1988. Experimental study of incipient motion in mixed size sediment. Water Resources Research 24, 1137–1151.

Woodsmith, R.D., Swanson, F.J., 1997. The influence of large woody debris on forest stream geomorphology. In: Wang, S.S.Y., Langedoen, E.J., Douglas Shields Jr., F. (Eds.), Proceedings of Management of Landscape Disturbed by Channel Incision, Oxford Campus in the University of Mississippi, May 1997, pp. 133–138.