Effects of sediment pulses on channel morphology in a gravel-bed river

Daniel F. Hoffman[†]
Emmanuel J. Gabet[‡]
Department of Geosciences, University of Montana, Missoula, Montana 59802, USA

ABSTRACT

Sediment delivery to stream channels in mountainous basins is strongly episodic, with large pulses of sediment typically delivered by infrequent landslides and debris flows. Identifying the role of large but rare sediment delivery events in the evolution of channel morphology and fluvial sediment transport is crucial to an understanding of the development of mountain basins. In July 2001, intense rainfall triggered numerous debris flows in a severely burnt watershed in the Sapphire Mountains of Montana. Ten large debris flow fans were deposited on the valley floor, and investigations focused on the channel response to these sediment pulses. The channel has aggraded immediately upstream of each fan, and braided in reaches immediately downstream. Channel incision through the fans has created sets of coarse-grained terraces. The deposition upstream of the pulses consists almost exclusively of fine material, resulting in a median bed material size (D_{50}) 1–2 orders of magnitude lower than the ambient channel material. The volume of sand being transported is so great that these aggrading reaches can extend hundreds of meters upstream of the fans, with 1–2 m of sand deposited across the entire valley floor. Along a 10 km study reach, cross section surveys, longitudinal profiles, and pebble counts chronicle channel response to a punctuated increase in sediment supply and provide insight on the processes of sediment wave dispersal.

Keywords: fluvial geomorphology, sediment, debris flows, bed load, fire.

INTRODUCTION

The morphology of a stream channel is an expression of the supply of water and sediment available to it. The delivery of sediment to rivers and streams in mountain drainage basins often comes in large, infrequent pulses from landslides and debris flows (Benda and Dunne, 1997; Gabet and Dunne, 2003). This sediment supply regime differs from that of channels in lowland environments with a more regular sediment supply and is reflected in the form and textural composition of the channel and floodplain. Processing large pulses of sediment can be slow and leave a lasting legacy on the valley floor. Identifying how channels process these sediment pulses is critical to an understanding of the morphological development of mountainous landscapes.

This investigation examines the response of a stream channel to a large, sudden increase in sediment supply and presents a conceptual model of sediment pulse effects on channel morphology and sediment transport processes. Intense rainfall in July 2001 triggered 10 debris flows that deposited fans of mixed coarse and fine sediment in the channel of Sleeping Child Creek. This provided an opportunity to chronicle channel response to large sediment pulses soon after the initial disturbance and to observe how the channel has begun to process the sediment.

One of the most obvious effects of a large sediment pulse is a change in channel form. Griffiths (1979) noted channel aggradation, followed by incision and entrenchment on the Waimakariri River in New Zealand following increased sediment pulses from bank erosion. Beschta (1984) documented channel widening, followed by subsequent narrowing as a consequence of increased soil erosion from logging activities. Roberts and Church (1986) documented channel incision and fining of the bed material in an aggraded channel, following increased sediment pulses from timber harvest. Madej and Ozaki (1996) analyzed changes in channel cross-sectional geometry, and documented channel aggradation, subsequent degradation, and channel widening, following increased sediment supply from poor land use practices. Following several debris-flow sediment pulses, Miller and Benda (2000) observed channel widening, braiding, and fining of bed material, followed by coarsening, construction of coarse grained terraces, and formation of new side channels. After the sediment wave had passed, they observed channel incision down to an immobile bed and bedrock. Cui et al. (2003) conducted flume experiments to investigate sediment pulses and found that in a channel with alternate bars, the bed relief decreased with the arrival of the downstream edge of the sediment wave, and increased as the upstream edge of the wave passed. Bartley and Rutherford (2005) investigated channel recovery after sediment slugs on three Australian rivers and observed a decrease in pool depths for all three, as well as channel widening and bed material fining in the Ringarooma River, and bed material coarsening in Creighton Creek and the Wannon River.

Most of the sediment transported through the fluvial system is generated through hillslope erosion in the headwater reaches (Schumm, 1977). The rates at which these headwater channels deliver sediment to downstream reaches affect the building and modification of alluvial landforms far downstream of the episodic events that deliver sediment to the channel. Channel depositional processes, such as the construction of bars, floodplains, and deltas, depend strongly on sediment supply. A large increase in sediment supply to channels with established floodplains can lead to floodplain aggradation and terrace construction (Miller and Benda, 2000). Understanding how headwater channels process sediment pulses will help in understanding how sediment is routed through a channel network, helping to predict any possible damage to infrastructure downstream and may assist in predicting the results of sediment released from dam removal projects (Sutherland et al., 2002).

Large sediment contributions to stream channels also affect associated riparian and aquatic ecosystems. Some riparian floodplain plant species are dependent on the overbank deposition of fine sediments for propagation, whereas deposition of fine sediments in salmonid spawning areas can significantly reduce spawning success (Carnefix, 2002). Benda et al. (2003)

[†]E-mail: dfhoffman@pbsj.com.
[‡]E-mail: manny.gabet@mso.umt.edu.

GSA Bulletin; January/February 2007; v. 119; no. 1/2; p. 116–125; doi: 10.1130/B25982.1; 12 figures.

found that debris flow fans deposited in channels increase the physical heterogeneity of the channel. This increase in channel heterogeneity has implications for riverine ecology, because physical heterogeneity is a vital part of maintaining aquatic and riparian biodiversity and productivity (Benda et al., 2003).

In addition, debris flows and landslides can deliver large amounts of large woody debris (LWD), and Miller and Benda (2000) documented channel logjams associated with debris flow deposits. Benda et. al. (2003) found that up to 80% of the wood in low-order channels in Washington's Olympic Mountains was delivered with debris flows. Previous studies have documented pool formation associated with in-channel LWD (Montgomery et al., 1995; Beechie and Sibley, 1997). Benda et al. (2003) found a correlation between LWD and pools in channels with debris-flow sediment pulses, where the number of pools was proportional to the amount of LWD. The presence of pools formed by LWD has implications for fish habitat. Carnefix (2002) found that bull trout *(Salvelinus confluentus)* preferentially use pools with LWD cover and documented increased spawning recruitment to channels with these types of habitats.

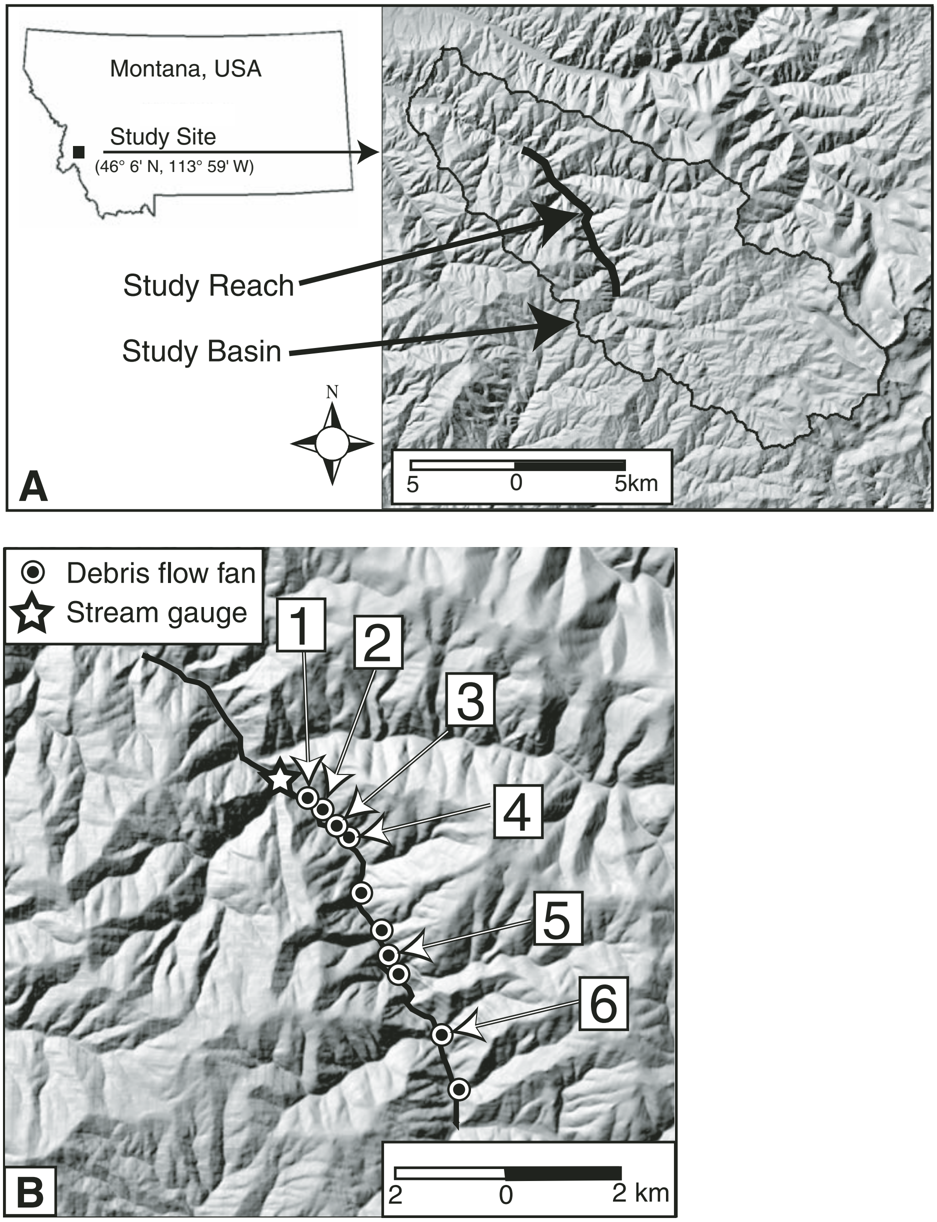

Figure 1. (A) Map of study site. (B) Locations of 10 debris flow fans, including the 6 described here (numbered).

Furthermore, the delivery of a large pulse of sediment can affect the sediment transport rate of a channel. Cui et al. (2003) found through flume experiments that the introduction of a sediment pulse significantly reduced the sediment transport rate upstream of the pulse. This result is in agreement with the observations of Sutherland et al. (2002), who documented a similar response upstream of a sediment pulse on the Navarro River in California. Downstream of a pulse, however, punctuated sediment pulses have been linked to two mechanisms that can increase sediment transport rates. First, a local increase in slope at the downstream edge of a sediment pulse increases the tractive force acting on the bed and increases sediment transport capacity (Cui et al., 2003; Lisle et al., 1997). Second, Cui et al. (2003) documented that the addition of a pulse of fine sediment to a coarse armored channel increased the sediment transport rate and greatly increased the mobility of the coarse material, often destroying the armored surface layer. Wilcock (1998) described a similar increase in sediment transport rate with the addition of fine material to a coarse bed.

Finally, punctuated sediment delivery often produces *pulses* or *waves,* defined as transient areas of sediment aggradation in channels, created by large sediment pulses (Lisle et al., 2001). Theoretical, experimental, and field studies have investigated the behavior of sediment waves and the processes responsible for wave translation or dispersion. Wavelike behavior of sediment pulses was first described in Gilbert's (1917) seminal paper on sediment waves of placer mining debris in tributaries of California's Sacramento and American Rivers. He documented translation of a discrete sediment wave with the apex of the wave moving "like a great body of storm water" in the downstream direction. Numerous studies have documented a similar translational behavior in sediment waves (Griffiths, 1979; Pickup et al., 1983; Meade, 1985; Turner, 1995; Madej and Ozaki, 1996; Miller and Benda, 2000; Kasai et al., 2004a; Bartley and Rutherford, 2005). However, other studies of sediment waves in natural rivers and experimental flumes show a dispersion-dominated behavior (Roberts and Church, 1986; Knighton, 1989; Lisle et al., 1997; Dodd, 1998; Lisle et al., 2001).

STUDY SITE

Sleeping Child Creek is a tributary of the Bitterroot River in the Sapphire Mountains of west-central Montana (Fig. 1). The upper part of the basin is steep (~25°; Hyde 2003), forested terrain typical of the Northern Rockies. Mixed coniferous forests of Douglas fir *(Pseudotsuga menzeiesii),* ponderosa pine *(Pinus* *ponderosa),* lodgepole pine *(Pinus contorta),* and subalpine fir *(Abies lasiocarpa)* dominate. Understory species consist of ninebark *(Physocarpus malveceus),* snowberry *(Symphoricarpos albus),* Oregon grape *(Berberis repens),* and native bunchgrasses. The lower part of Sleeping Child Creek winds through relatively low-gradient (~0–10°; Hyde 2003) agricultural lands and the Bitterroot River floodplain.

The climate is semiarid montane, with warm, dry summers and mild winters (Hyde, 2003). The average annual precipitation is 79 cm/yr, characterized by snowfall from November to March, with May and June being the wettest months. Sleeping Child Creek (Fig. 1) drains 169 km^2, with a mean basin elevation of 1900 m. Streamflow is snowmelt-dominated with an annual peak during spring runoff, and occasional winter peaks from rain-on-snow events. Bankfull discharge in the study reach is estimated to be 12.8 m^3/s. Gneiss and granite compose the dominant lithology of the study area (Hyde, 2003). Soils are generally thin, poorly developed sandy to silty loams with a significant fraction of coarse material.

Approximately 80% of the Sleeping Child basin underwent a severe forest fire in August 2000 (Hyde, 2003). High-intensity (4.1–16.8 mm/h) convective storms triggered numerous progressively bulked debris flows in the burned areas in July 2001 (Fig. 2), and 10 debris flows from steep, unchanneled swales adjacent to the channel deposited fans on the valley floor along the study reach. All of the debris flows were in high severity burn areas. Five of the debris flow gullies were surveyed (Bookter, 2006), and debris flow fan volumes ranged from 500 m^3 to 3400 m^3. The debris flow fans are composed of a mix of coarse sand, gravel, and large cobbles and boulders. Numerous broken trees are on top of and in debris flow fans. The source of these trees was the debris flow gullies as well as trees on the valley floor that were destroyed by the debris flow. Hyde (2003) reported an additional six debris flow fans in the channel upstream of the study reach.

The 10 km study reach of Sleeping Child Creek is in the middle part of the watershed (Fig. 1). The third-order channel is confined by steep valley walls with numerous bedrock outcrops, and the active floodplain width varies between 20 and 130 m. In reaches not affected by the sediment pulses, channel width is 10–30 m, with channel gradients between 2% and 7%. Unaffected study reaches have armored beds of coarse cobble and boulders inset with large lag deposits (150 mm < D_{50} < 300 mm), and channel morphology is best described by Montgomery and Buffington's (1997) classification as boulder-cascade and step-pool. Stream banks are stable and consist of boulders, cobbles, and fine alluvium that is well vegetated with a mix of riparian species. Stream-bank erosion does not appear to be a large source of sediment to the channel, with the only unstable banks located near debris flows (Fig. 2).

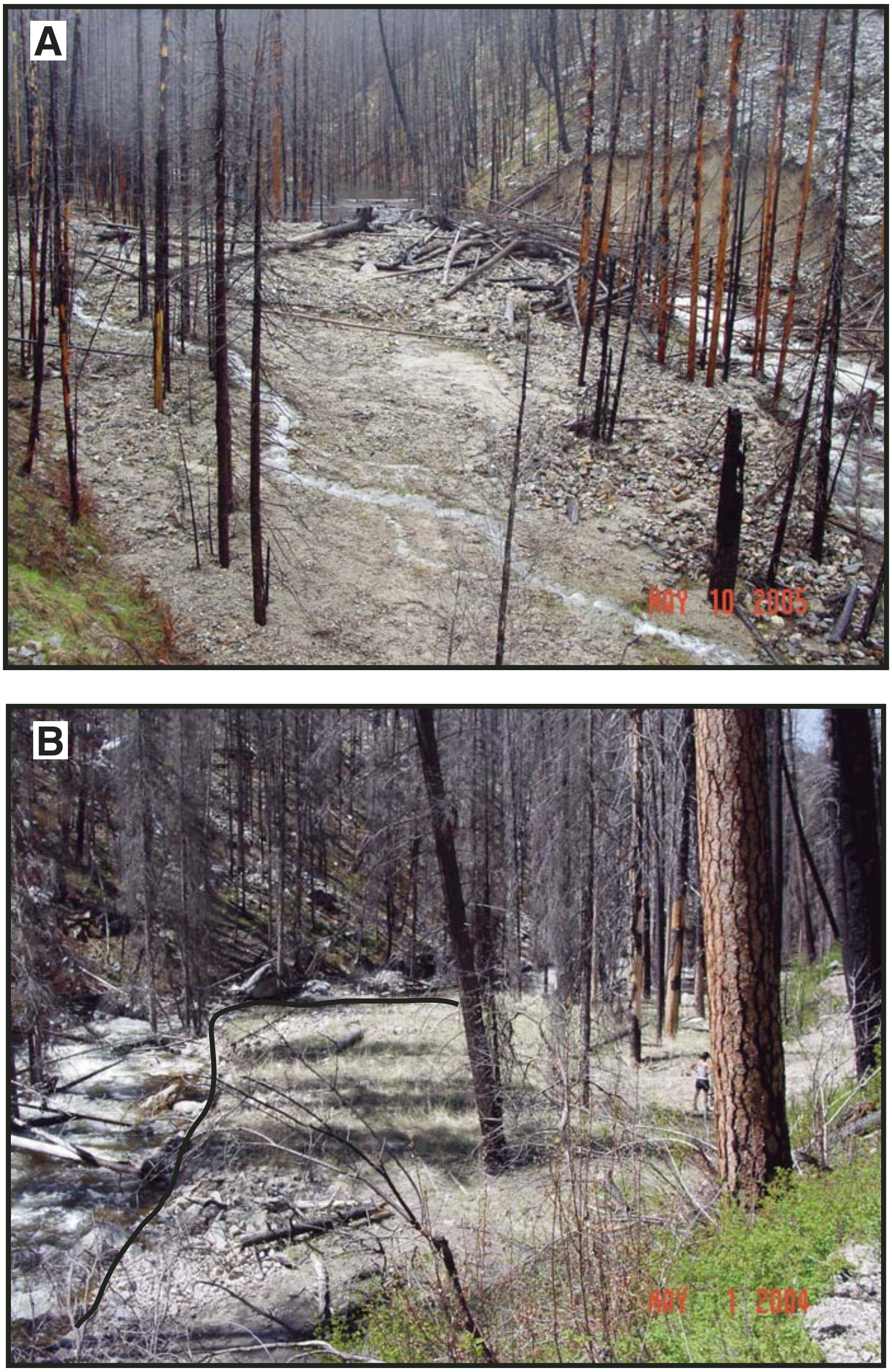

Figure 2. (A) Debris flow fan 6. Debris flow came from the left and has pinned the river against the opposite valley wall. Small channel in the center of the picture is flow coming from the valley scoured by the debris flow. (B) Debris flow fan 4 outlined in color photo. Debris flow came from the right.

METHODS

Eighteen channel cross sections, along with 23 water surface and bed slopes, were surveyed with a surveyor's level or hand level on a 10 km reach of Sleeping Child Creek in the summer of 2004 and 2005, 3–4 yr after the debris flows occurred. Channel cross section locations were organized with respect to 6 of the 10 debris flow fans in the study area. Four debris flow fans were excluded because local topography and dense vegetation prohibited surveying. The longitudinal profile (Fig. 3) identifies all 10 debris flow fans in the study reach, and the 6 fans associated with the cross section surveys.

For each fan, a cross section was surveyed 10–30 m upstream of the fan, in the middle of the reach cutting through the fan, and 10–30 m downstream of the fan. These are referred to as up-fan reaches, fan reaches, and down-fan reaches, respectively. The upstream and downstream boundaries of fan channels were determined by visual observation of fan deposits on the valley floor. Cross sections were surveyed at locations typical of the reach. Water surface slopes were measured over the entire length of fan reaches and a minimum of five channel widths on up-fan and down-fan reaches. Grain size distributions were estimated at each cross section with pebble counts (Wolman, 1954). Clasts <2 mm were grouped together, as were those >520 mm.

Residual pool depths, pool lengths, bank stability, and pool spacing were surveyed with a hip chain and stadia rod along the entire study reach. To be classified as a pool, a channel unit had to display obvious scour and a downstream crest. Residual pool depths were calculated as the depth of water below the elevation of the downstream riffle crest (Lisle, 1987). Pool spacing was defined as the distance between the downstream crest of one pool and the head, or beginning of scour, of the closest downstream pool. The occurrence and number of LWD were also recorded in the channel survey following the methodology of Degerman et al. (2004). LWD was defined as logs with a minimum diameter of 25 cm and a length greater than the channel width.

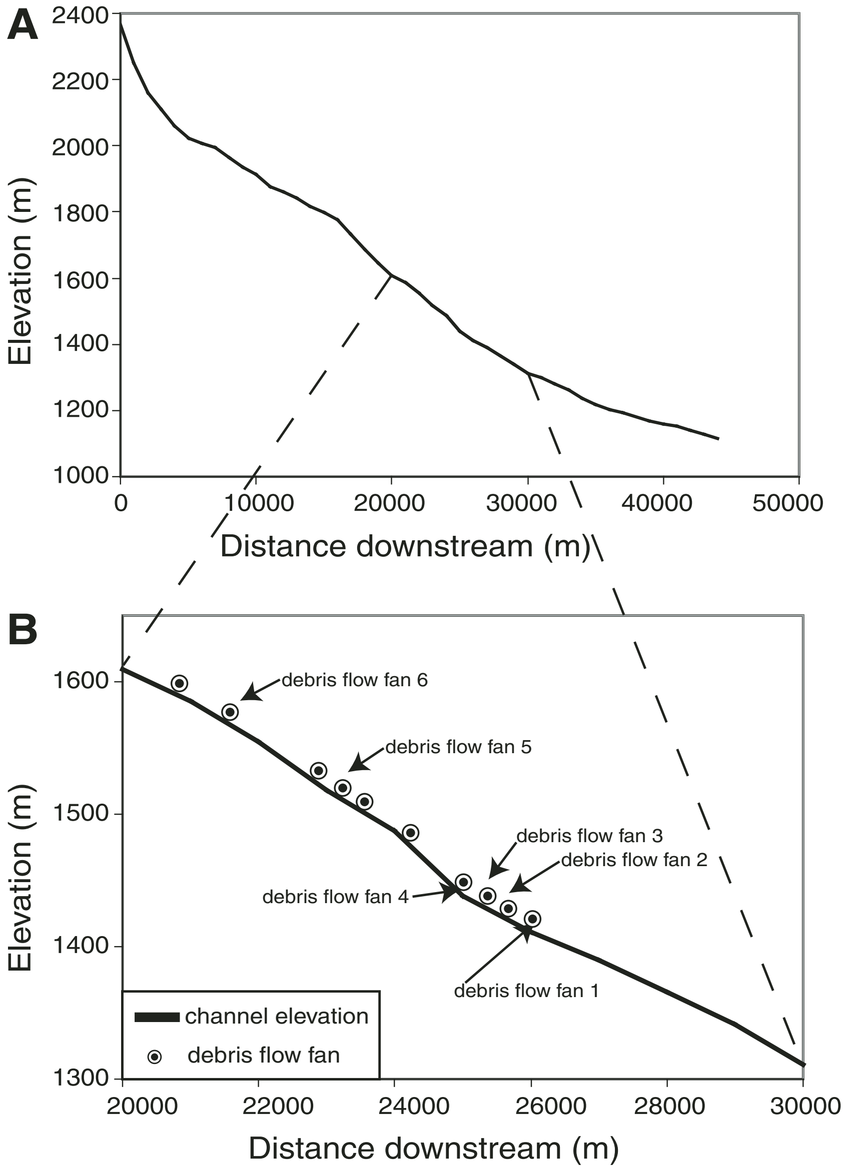

Figure 3. (A) Longitudinal profile of Sleeping Child Creek. (B) Locations of debris flow fans in the study reach.

Rating curves were developed for each cross section by calculating the discharge for every 1 cm increase in flow depth. For each flow depth measured from the thalweg, flow area and hydraulic radius were calculated from the cross section survey. Flow velocity was estimated with the Law of the Wall,

$$u = \frac{1}{\kappa}\sqrt{gRS}\,\ln 3.14\frac{h}{D_{84}}, \qquad (1)$$

where u (m/s) is the flow velocity, κ is von Kármán's constant (0.4), g is gravitational acceleration (m/s^2), R is the hydraulic radius, S is the water surface slope, h is the flow depth, and D_{84} is the bed material size that 84% of the bed material is finer than (h and D_{84} have the same units of length). Discharge was then calculated with the continuity equation

$$Q = whu, \qquad (2)$$

where w (m) is the flow width. Width/depth ratios at bankfull discharge were calculated from the survey points for every cross section. Bankfull discharge was estimated as the flood with an annual exceedance probability of 50% from a flood frequency plot, calculated at U.S. Geological Survey station 12345850, located within the study reach, from the 20 yr period of record (1972–1992). Although the 1–2 yr flood may not be the bankfull discharge for this type of channel, we were unable to estimate bankfull discharge from morphologic bankfull indicators owing to the coarse nature of the bed and bank material.

RESULTS

Visual observation indicates that the channels were initially pinned against the opposite valley wall and dammed by the debris flow fans. The flow then overtopped the fans and started to incise through them: these fan reaches have coarse bed material and are entrenched. Large-scale aggradation of coarse sand and fine gravel was observed in the up-fan reaches and, in some reaches, this deposition is valley-wide and

1–2 m deep. Channel braiding and the construction of numerous gravel bars were observed in channels immediately downstream of the debris flow fans. Recent channel displacement has been observed in up-fan, fan, and down-fan reaches and is obvious from the presence of trees in the middle of the channel.

Channel Geometry and Width/Depth Ratios

High width/depth ratios can be indicative of aggraded reaches, and low width/depth ratios suggest an incised or entrenched channel (Miller and Benda, 2000). Several previous studies have documented aggradation followed by incision in channels with a sediment pulse or wave (Gilbert, 1917; Griffiths, 1979; Roberts and Church, 1986). Width/depth ratios in up-fan channels 1, 2, 3, and 6 ranged from 72 to 170 (Fig. 4). Figure 4 shows the high width/depth ratios in up-fan channels, suggesting that these reaches are aggrading. This agrees with observations of trapping of bed load material behind some of the debris flow fans. The process responsible for this channel widening is not bank erosion; the channel has aggraded to a point at which the old channel and banks are completely buried by 1–2 m of sand. This is evident when excavating sand from around the trunks of standing trees in the floodplain: branches can be found at a depth >1 m below the surface, demonstrating recent deposition. Figure 5 shows typical cross sections for each reach type. The width/depth ratios in fan channels 1, 2, 3, 5, and 6 range from 12 to 37; these low values suggest that these reaches are incising and are moderately entrenched (Fig. 4). The reaches associated with debris flow 4 and the up-fan channel of debris flow 5 have a channel geometry that is bedrock controlled and do not reflect the processes described. Although Sleeping Child Creek is not a bedrock channel, and the bed is alluvial, the debris flow fans have pushed the channel against bedrock outcrops.

The width/depth ratios in down-fan channels 1, 2, 3, 5, and 6 range from 22 to 147. In these downstream reaches, deposition of coarse fan material has aggraded the channel up to the adjacent floodplain elevation, resulting in braiding and the formation of side channels in what was previously riparian forest. The presence of gravel and cobble bars suggests a depositional environment in which the channel is overwhelmed by a coarse bed load. Braiding is typical in channels transporting large amounts of bed load and with a high coarse sediment supply (Bridge, 2003). Other workers have documented channel braiding in aggrading reaches following a sediment pulse, including Miller and Benda (2000) on Gate Creek in Oregon, Madej and Ozaki (1996) on California's Redwood Creek, and Roberts and Church (1986) in British Columbia.

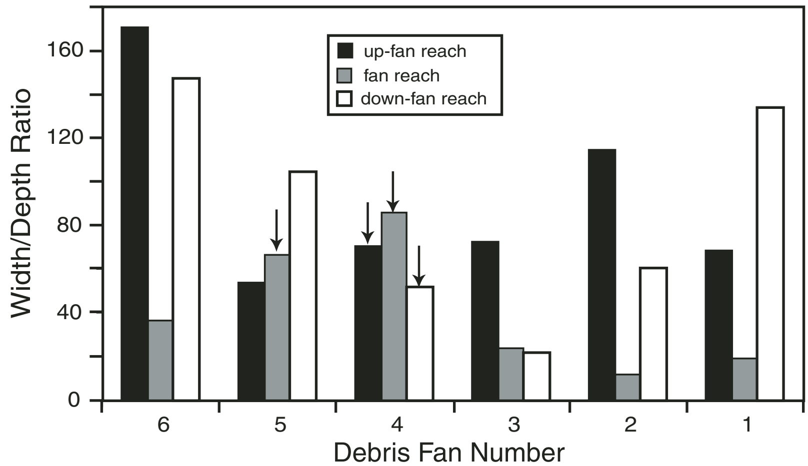

Figure 4. Channel width/depth ratios show a pattern of deposition in up-fan channels, incision in fan channels, and braiding in down-fan channels. Channels marked with an arrow are bedrock controlled, explaining, perhaps, why they do not exhibit a pattern similar to the others. The down-fan channel of debris flow 3 did not braid, possibly because debris flow 3 deposited the least amount of sediment on the valley floor.

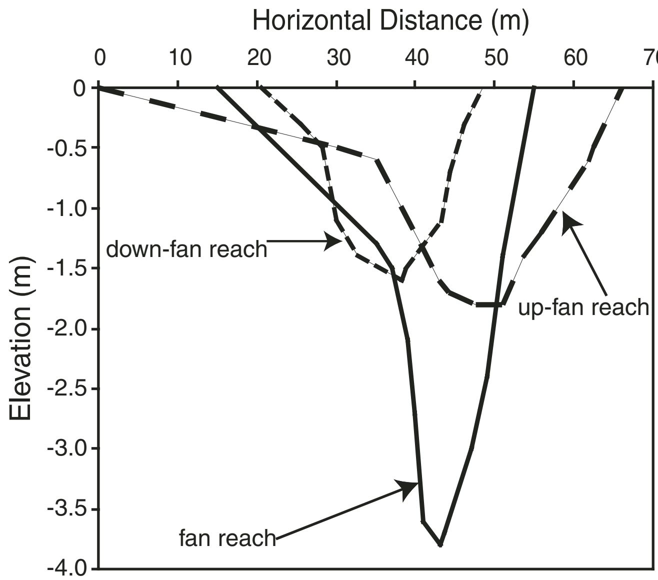

Figure 5. Typical up-fan, fan, and down-fan reach channel cross sections.

Channel Gradient

Changes in channel geometry and morphology are often associated with adjustments in channel gradient (Montgomery and Buffington, 1997). A repeating pattern of gradient changes over a short distance owing to debris flow fans has been observed on Sleeping Child Creek (Fig. 6). Up-fan water surface slopes range from 0.007 to 0.038, fan channel gradients range from 0.021 to 0.072, and down-fan channel gradients range from 0.027 to 0.047. The increase in channel gradient at the transition from up-fan reaches to fan reaches is often great. For example, the slope of the reach associated with debris flow fan 6 increases by a factor of 7 (from 0.009 to 0.067) over a distance of 10 m. It is important to differentiate between the processes responsible for these gradient changes. The decrease in channel gradient upstream of the debris flow fans is due to the sudden change in valley slope that accompanied

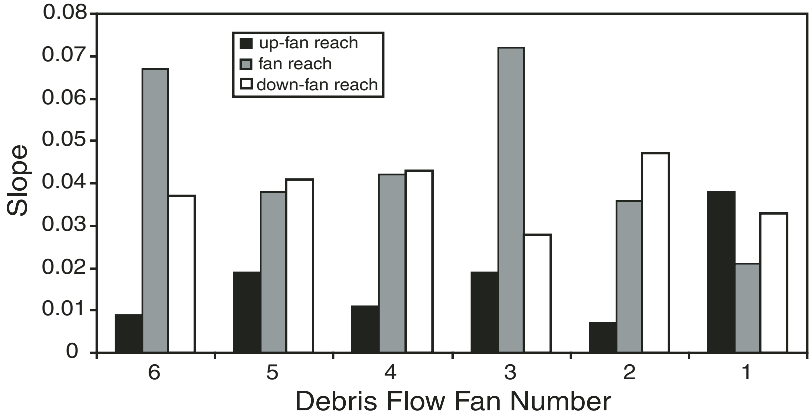

Figure 6. Channel slopes generally show a pattern of low slopes upstream of debris flow fans and steeper slopes in fan reaches and downstream reaches. The up-fan reach of debris flow fan 1 does not exhibit a similar pattern to the others, possibly because the fan was deposited at the downstream edge of a locally steep reach.

the deposition of a debris flow fan. In reaches cutting through debris flow fans, and the reaches below the fans, the gradient is adjusted to the supply and size of the sediment that was delivered to the channel by the debris flow. The down-fan braided reach may be as steep or steeper than the fan reach because of the sediment supply and character: the greater the sediment size and supply, the steeper the reach (Hack, 1957).

Size of Bed Material

Earlier studies of sediment pulses have documented a fining of bed material, subsequently followed by a coarsening (Meade, 1985; Roberts and Church, 1986; Miller and Benda, 2000). The bed material in the aggrading reaches upstream of debris flow fans was finer than in the incising reaches through the fans and the braided reaches downstream of the fans (Fig. 7). Median bed material size (D_{50}) in up-fan reaches ranges from 2 to 104 mm, fan reaches range from 105 to 192 mm, and down-fan reaches range from 93 to 222 mm. Sampling fan reaches was often difficult owing to the high flow depths and the degree of imbrication of the bed material in these reaches. The change in grain size between reach types is often large: the up-fan reach of debris flow 6 has a D_{50} <2 mm, whereas the fan reach just downstream has a D_{50} of 146 mm, an increase of two orders of magnitude in just 7 m. This supports the assertion that some of the debris fans are functioning as bed-load traps with large-scale deposition of well-sorted bed-load material. The bed material in fan and down-fan reaches is a mobile pavement of coarse gravel and cobbles with a fraction of immobile boulders. As the channel cuts through the fan, the fine fraction of the fan material is winnowed out, leaving the coarse pavement; during high flows this coarse material may be entrained and transported as bed load. Fresh, unvegetated bar deposits composed of coarse gravel and cobbles provide evidence of recent bed material mobility.

Spatial Distribution of Large Woody Debris

Large amounts of LWD have been delivered to the channel of Sleeping Child Creek by the debris flows, and aggregates of LWD have accumulated in the fan reaches and down-fan reaches. Figure 8 illustrates the large amount of LWD in close proximity to debris flow fans.

Pool Depths and Frequency

Residual pool depths were used by Madej and Ozaki (1996) to signal the arrival of a sediment wave, for calculation of sediment wave transit rates, and as an indicator of channel recovery. Bartley and Rutherford (2005) used pool depths as an indicator of geomorphic variability and for identification of channel response pathways following a sediment slug. Residual pool depths were measured for every pool in the 10 km study reach. Residual pool depths were spatially averaged by calculating the mean residual depth of every pool in 50 m increments downstream of debris flow fans. The results show that pool depths decrease with downstream proximity to a debris flow fan (Fig. 9), supporting the idea that pools aggrade with sediment after the introduction of a sediment pulse.

Pool spacing was averaged over nine reaches, with each reach beginning at a debris flow fan. The mean distance between pools is plotted against the number of the pool downstream from the point of sediment entry, with pool 1 being the closest downstream pool to the debris flow fan (Fig. 10). Pool spacing increases with proximity to a debris flow fan, suggesting that pools are aggrading to a point at which they are no longer recognizable.

DISCUSSION

Channel Morphology

In July 2001, post-fire debris flows triggered by thunderstorms deposited fans of mixed fine and coarse sediment across the channel of

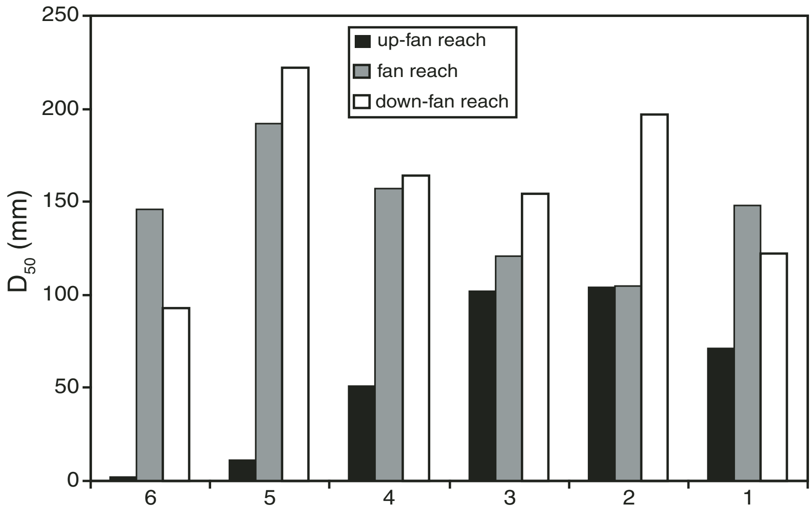

Figure 7. Median bed material size (D_{50}) follows a pattern in which up-fan reaches are finer than down-fan and fan channel reaches.

Sleeping Child Creek. The flow overtopped each fan and dropped off its downslope edge, forming a headcut in the easily erodible fan material. The headcut eventually rotated upstream, and the channel was downcut, leaving an incised, entrenched channel with a low width/depth ratio and an inset between 1- and 2-m-high terraces of fan material. As the finer material has been winnowed away, the channel bed and banks are presently armored with large cobbles and boulder lag, preventing lateral migration and further downcutting. Several of the debris flow fans function as channel sediment traps, with little to no bed-load throughput. This has led to large-scale aggradation of gravels and coarse sand upstream of the fans, completely burying the old channel and raising the channel bed elevation to, or above, the adjacent floodplain. The obvious source of the sediment is the closest upstream debris flow fan. As the channel aggraded, and flow began to spill onto the floodplain during high discharges, overbank deposition of sediment on the floodplain led to the construction of a new floodplain at a higher elevation, composed almost completely of coarse sand. In many cases, the riparian forest that occupies the floodplain immediately upstream of the fan is dying, probably as a result of being buried by 1–2 m of sediment and from a rise in the water table caused by the channel aggradation. As the channel downcuts through the fan, the easily transported fine sediment (sand and small gravel) is flushed downstream to the closest downstream fan, where it becomes trapped. The coarse fraction of the fan is transported as bed load for much shorter distances and deposited in reaches directly downstream of debris flow fans. As the channel transitions from fan reaches to down-fan reaches, the channel width/depth ratio increases and it loses sediment transport capacity. The channel drops some of its bed load and braids into multiple channels separated by coarse gravel and cobble bars. In addition, bars form from sediment wedges building upstream of LWD delivered with the debris flows.

Model of Channel Response

From the data, a repeating pattern of changes in channel morphology, bed material, and bed elevation has been identified, and the following is a model of channel response to a large sediment delivery event (Figs. 11, 12). Up-fan channels are typically single-thread, with lower slopes and finer bed material than the other channel reaches. These channels are aggrading and exhibit high width/depth ratios. Fan reaches are incised and entrenched single-thread channels with steep slopes and coarse bed material. They are commonly in a state of active downcutting and progressive armoring. Down-fan

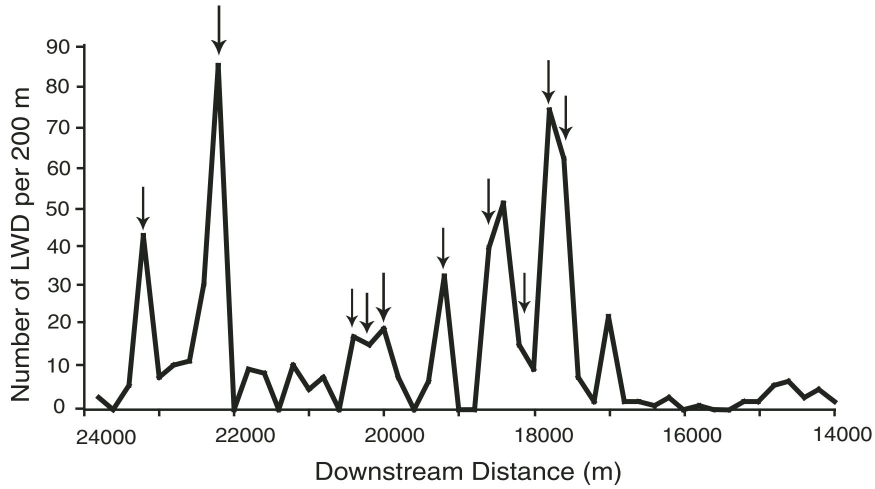

Figure 8. Spatial distribution of large woody debris (LWD). Arrows identify locations of debris flow fans. The pattern of high amounts of LWD in close proximity to debris flow fans suggests the importance of debris flows in supplying LWD to the channel. Note the relative absence of LWD in the 3 km reach below the fans.

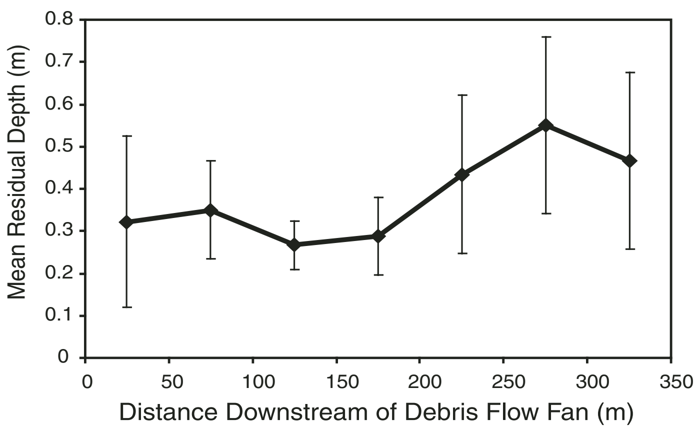

Figure 9. Spatial distribution of spatially averaged pool residual depths demonstrates that pool depths decrease with downstream proximity to debris flow fans. Error bars represent ±1 standard deviation.

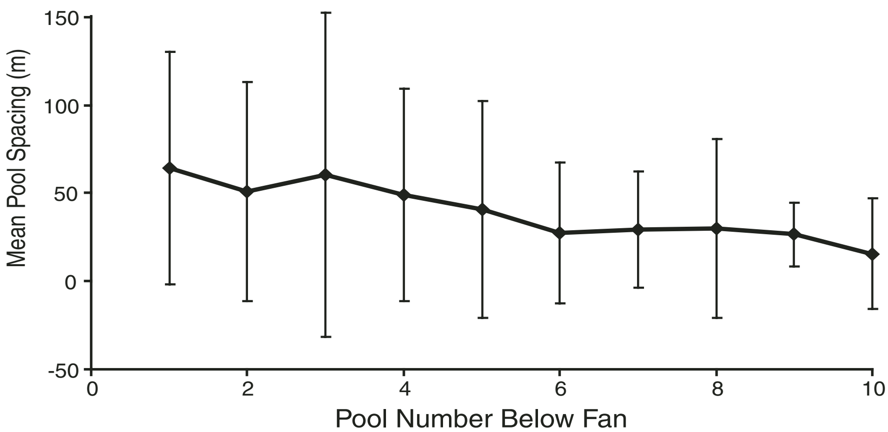

Figure 10. Mean pool spacing increases with proximity to the debris flow fans. Error bars represent one standard deviation.

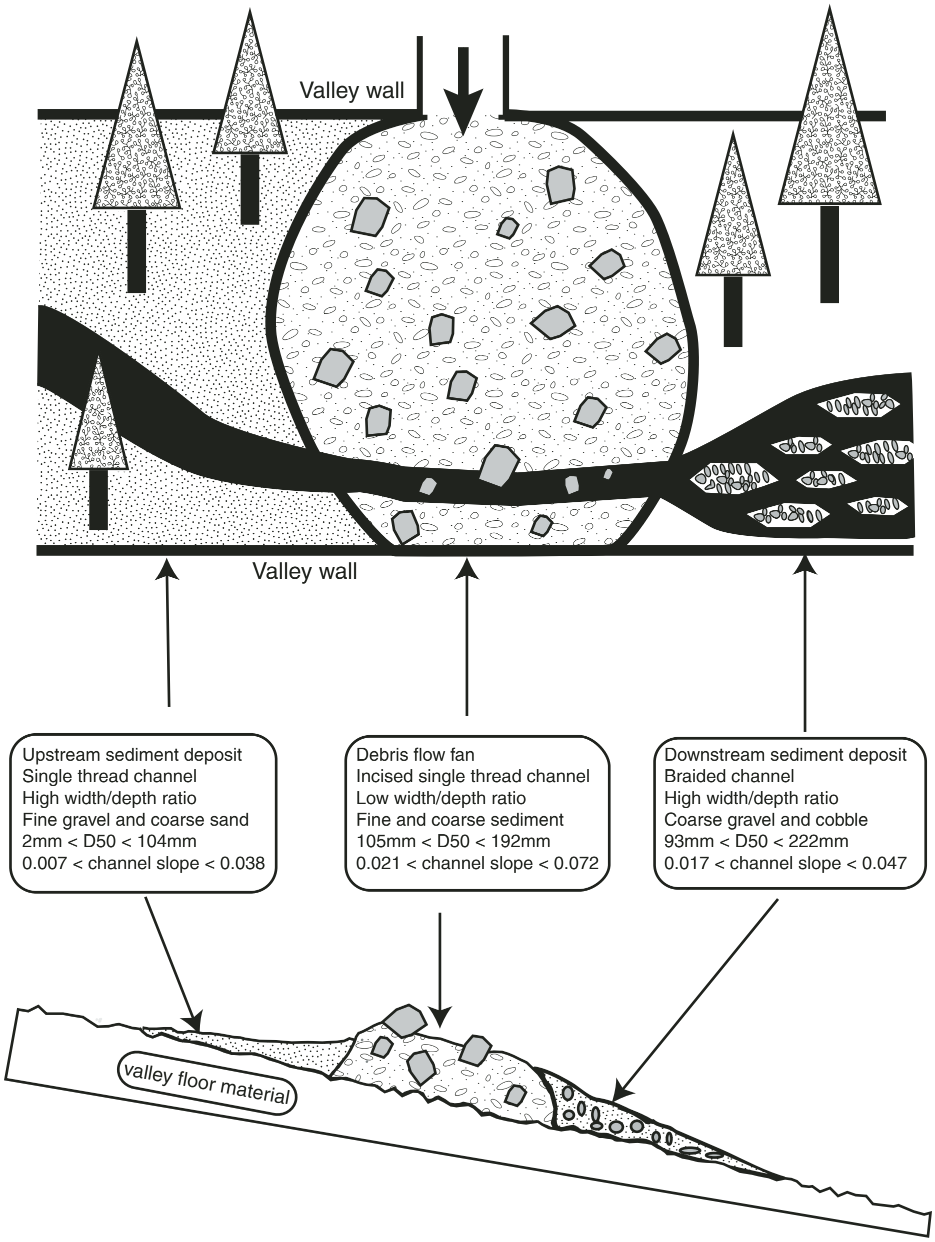

Figure 11. Planform view (upper) and longitudinal view (lower) of the typical pattern of channel response to the deposition of debris flow fans in Sleeping Child Creek.

reaches are typically braided, with high width/depth ratios, steep slopes, and coarse bed material. These reaches are aggrading, with numerous cobble and gravel bars.

The debris flows have deposited large amounts of LWD on the valley floor and in the channel. LWD jams are common in the braided reaches of Sleeping Child Creek and are the loci of aggradation; this observation is in agreement with the work of Keller and Swanson (1979). LWD can play a significant role in pool formation, fish habitat, and bank erosion (Keller and Tally, 1979; Carnefix, 2002), and debris flows appear to be a significant mechanism for LWD recruitment on Sleeping Child Creek. Bartley and Rutherford (2005) observed that LWD on the Ringarooma River acted to increase geomorphic variability following a sediment pulse, and, in doing so, significantly impacted channel recovery.

Sediment Transport

Sleeping Child Creek is transporting debris flow fan material under conditions of size-selective transport. Coarse sand is winnowed out of the fan and transported as suspended load. Sand has been deposited on channel margins; behind obstructions such as LWD, boulders, or other velocity shelters; on the active floodplain during overbank flows; and upstream of debris flow fans. The volume of sand stored upstream of debris flow fans is great, in some instances filling a 100-m-wide valley floor with 1–2 m of sediment for several hundred meters upstream. The degree to which the accommodation space upstream of debris fans is presently filled is unknown, but the absence of coarse bed material in these depositional reaches suggests that coarse material is still being trapped upstream. The volume of sand stored in the active channel is also great; channel obstructions have created areas of sand deposition that, while small, are numerous; and channel margins display thin (1–100 mm) sand lenses that continue uninterrupted through most of the study reach.

The influence of sand on the mobility of a coarse bed has been investigated experimentally (Wiberg and Smith, 1987; Wilcock, 1998; Cui et al., 2003). The presence of a fine fraction increases the mobility of the coarse fraction by reducing the pocket angle or grain pivot angle and by reducing the form drag associated with individual clasts (Wiberg and Smith, 1987; Wilcock, 1998). We have not attempted to quantify the effect of the addition of large amounts of sand on the mobility of the coarse bed material in Sleeping Child Creek, but visual observations of reaches where sand has filled all the interstitial space in a predominantly coarse bed suggests that the addition of sand from debris flow fans has led to increased bed-load transport of coarse bed material.

Visual observation of recent bar formation and fresh depositional surfaces suggests that gravels and cobbles are transported as bed load much shorter distances than the sand and deposited in downstream tapering wedges from debris flow fans. This coarser sediment is filling in pools and reducing bed relief (Figs. 9, 10). The reduction in bed relief should result in a decrease in the form drag or bed form resistance. As the form drag of a channel decreases, the portion of the total boundary shear stress acting on the grains in the boundary increases, thereby increasing the channel's capacity to transport sediment (Meyer-Peter and Muller, 1948). Other workers have observed reductions in bed relief associated with sediment pulses similar to those measured at Sleeping Child Creek. Meade (1985) described the migration of bed-load waves and documented that with the arrival of a wave, the pools filled in with sediment. In severely disturbed watersheds in British Columbia, Roberts and Church (1986) describe a decrease in channel complexity in aggraded reaches following a sediment wave. Madej and Ozaki (1996) investigated the effects of a sediment wave on Redwood Creek, California, and documented a decrease in pool depths and an increase in pool spacing. Madej (1999) reported that the variation in bed elevation is low immediately following a sediment pulse and increases with time. Madej (2001) further documented that as channels recovered from the passage of a sediment wave, bed topography complexity increased, pool spacing decreased, and flow depths increased. Smith et al. (2002) observed from field and laboratory flume investigations that sediment waves produced plane beds with little bed complexity. Kasai et al. (2004b) documented channel aggradation following sediment pulses on Oyabu Creek, Japan. This aggradation led to bed "smoothing" owing to the loss of pool-riffle structures.

There is no evidence of the sediment pulses observed on Sleeping Child Creek behaving as a "wave" and translating downstream. Although the time period since deposition of the debris flow fans is still short (4 yr), the dominant behavior has been dispersive. We speculate that the gradation in sediment sizes that make up the pulse may lead to this dispersive behavior; the wide range of sediment mobility disrupts the coherence of the pulse and prevents translation.

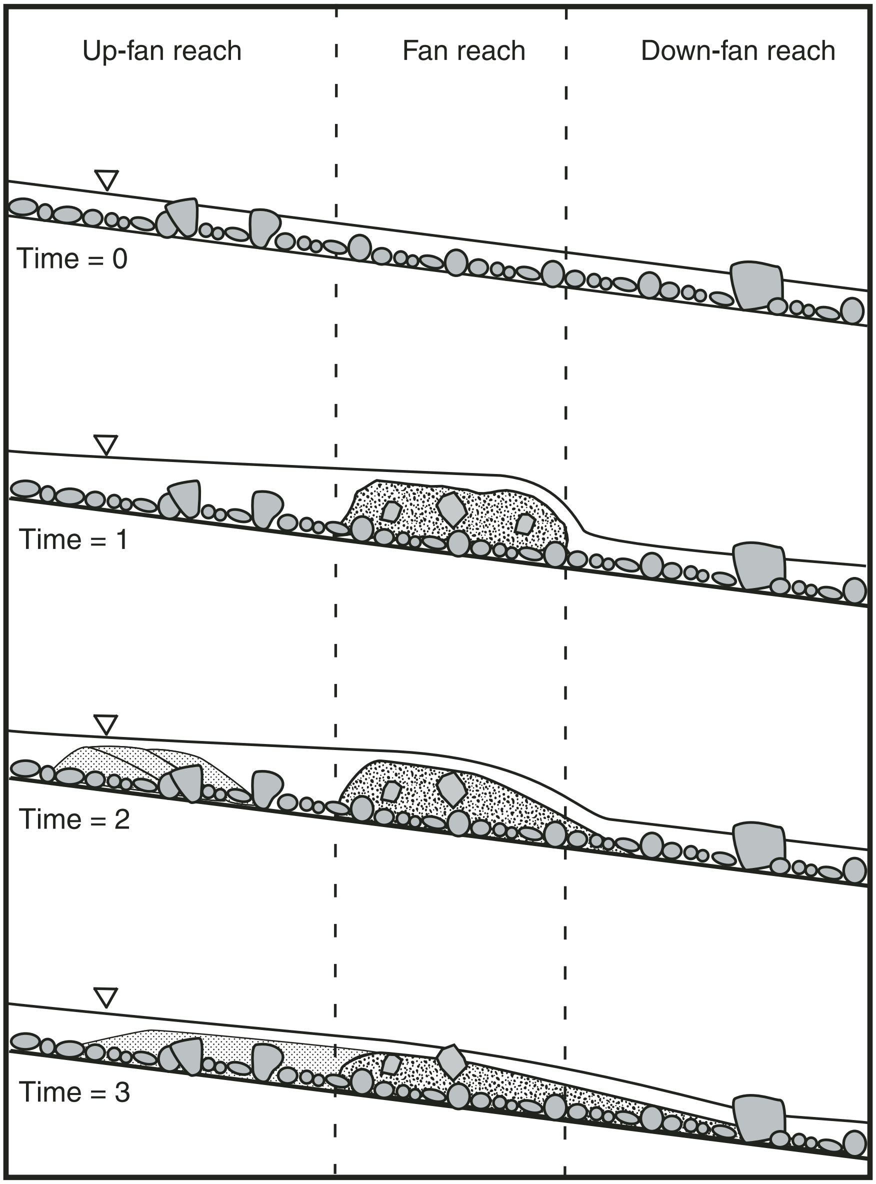

Figure 12. Evolution of channel profile following sediment input from debris flow (time units are arbitrary).

Scenarios of Continued Response

The amount of time needed for Sleeping Child Creek to recover to some equilibrium state, defined here as the point at which a continuity of bed-load transport is established, is partially controlled by the channel reaches that cut through the debris flow fans. These coarse, armored channels act as a local base-level control. As these reaches continue to downcut through the debris flow fan, their bed becomes armored as new boulder lag is exposed in the bed or deposited in the channel from its unstable banks. The channel will stop downcutting if the bed material becomes too coarse, or the channel reaches an elevation where a balance is reached between sediment deposited in and transported out of the reach. If the former occurs, the reach upstream of the fan will continue to aggrade until the accommodation space is filled and it no longer traps bed load, and bed-load throughput becomes possible. If the latter condition is reached, the up-fan reach may downcut through the fine material deposited there and form a set of fine grained terraces.

Previous workers (Kasai et al., 2004b) identified sediment pulse recurrence intervals in landscapes where landslide and debris flow are common. We were unable to identify any landforms associated with previous debris flows in the study area and cannot speculate on event frequency. Better predictions of continued response would be possible if evidence of previous sediment delivery events was available in the Sleeping Child basin. The lack of evidence in the form of old debris flow gullies, fans, terraces, or other valley floor landforms suggests that (1) these events are rare, (2) the signature left on the landscape has a limited persistence, or (3) the landscape is entering a new erosional regime provoked by global warming. In the case of the latter, Meyer et al. (1992) chronicled episodes of aggradation in mountainous terrain during periods of increased fire frequency. If Sleeping Child Creek is unable to transport sediment delivered by debris flows, the valley will begin to aggrade, both from the debris flow deposits themselves and also from fluvial sediment that becomes trapped behind the fans.

CONCLUSION

The supply of sediment to the fluvial network in mountain drainage basins is episodic, with large infrequent landslides and debris flows contributing large sediment influxes. Identifying the processes of sediment pulse dispersal provides insight into the development of mountain landscapes. A series of post-fire debris flows deposited fans of mixed fine and coarse sediment into Sleeping Child Creek and pinned it against the valley wall. The channel incised through the fans, creating a set of coarse grained terraces. The upstream edge of the fans acts as bed-load traps, creating longitudinal discontinuities in sediment transport and causing large-scale aggradation of fine sediment. This aggradation has raised the bed elevation and created new floodplains. Reaches downstream of the fans widened and braided. Overall, channel bed material became finer with great spatial variation in median bed-material size. These results are consistent with our conceptual model of channel response on the basis of present sediment transport and channel formation in mountain drainage basins.

ACKNOWLEDGMENTS

R. Perez and K. Burns contributed substantially to the field work. Financial support for this research was provided by the U.S. National Science Foundation EPSCoR program. L. Benda and an anonymous reviewer are thanked for their careful reviews. We thank J. Moore, S. Woods, and P. Callahan for their insightful criticisms of earlier drafts of this work, and W. Dietrich for his valuable field observations and comments.

REFERENCES CITED

Bartley, R., and Rutherford, I., 2005, Re-evaluation of the wave model as a tool for quantifying the geomorphic recovery potential of streams disturbed by sediment slugs: Geomorphology, v. 64, p. 221–242, doi: 10.1016/j.geomorph.2004.07.005.

Beechie, T.J., and Sibley, T.H., 1997, Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams: Transactions of the American Fisheries Society, v. 126, p. 217–229, doi: 10.1577/1548-8659(1997)126<0217:RBCCWD>2.3.CO;2.

Benda, L., and Dunne, T., 1997, Stochastic forcing of sediment supply to channel networks from landsliding and debris flow: Water Resources Research, v. 33, p. 2865–2880, doi: 10.1029/97WR02387.

Benda, L., Veldhuisen, C., and Black, J., 2003, Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington: Geological Society of America Bulletin, v. 115, p. 1110–1121, doi: 10.1130/B25265.1.

Beschta, R.L., 1984, River channel response to accelerated mass soil erosion, *in* O'Loughlin, C.L., et al., eds., Proceedings, Symposium on Effects of Forest Land Use on Erosion and Slope Stability: Honolulu, East-West Center, p. 155–164.

Bookter, A., 2006, Post wildfire debris flow morphology [M.S. thesis]: Missoula, University of Montana, 120 p.

Bridge, J.S., 2003, Rivers and floodplains: Oxford, UK, Blackwell Publishing, 512 p.

Carnefix, G., 2002, Movement patterns of fluvial bull trout in relation to habitat parameters in the Rock Creek drainage, Missoula and Granite Counties, Montana [M.S. thesis]: Missoula, University of Montana, 185 p.

Cui, Y., Parker, G., Lisle, T.E., Gott, J., Hansler-Ball, M.A., Pizzuto, J.E., Allmendinger, N.E., and Reed, J.M., 2003, Sediment pulses in mountain rivers: 1: Experiments: Water Resources Research, v. 39, no. 9, 1239, doi: 10.1029/2002WR001803.

Dodd, A.M., 1998, Modeling the movement of sediment waves in a channel [M.S. thesis]: Arcata, California, Humboldt State University, 53 p.

Gabet, E.J., and Dunne, T., 2003, A stochastic sediment delivery model for a steep Mediterranean landscape: Water Resources Research, v. 39, no. 9, 1237, doi: 10.1029/2003WR002341.

Gilbert, G.K., 1917, Hydraulic-mining debris in the Sierra Nevada: U.S. Geological Survey Professional Paper 105, 154 p.

Griffiths, G.A., 1979, Recent sedimentation history of the Waimakariri River, New Zealand: Journal of Hydrology (New Zealand), v. 18, p. 6–28.

Hack, J.T., 1957, Studies of longitudinal stream profiles in Virginia and Maryland: U.S. Geological Survey Professional Paper 504B, 40 p.

Hyde, K., 2003, The use of burn severity mapping to indicate potential locations for gully rejuvenation [M.S. thesis]: Missoula, University of Montana, 116 p.

Kasai, M., Marutani, T., and Brierley, G.J., 2004a, Patterns of sediment slug translation and dispersion following typhoon-induced disturbance, Oyabu Creek, Kyushu, Japan: Earth Surface Processes and Landforms, v. 29, p. 59–76, doi: 10.1002/esp.1013.

Kasai, M., Marutani, T., and Brierley, G.J., 2004b, Channel bed adjustments following major aggradation in a steep headwater setting: Findings from Oyabu Creek, Kyushu, Japan: Geomorphology, v. 62, p. 199–215, doi: 10.1016/j.geomorph.2004.03.001.

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

Keller, E.A., and Tally, T., 1979, Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment, *in* Rhodes, D.D., et al., eds., Adjustments of the fluvial system: Dubuque, Iowa, Kendall Hunt, p. 169–197.

Knighton, A.D., 1989, River adjustments to changes in sediment load: The effects of tin mining on the Ringarooma River, Tasmania, 1875–1984: Earth Surface Processes and Landforms, v. 14, p. 333–359.

Lisle, T.E., 1987, Using "Residual Depths" to monitor pool depths independently of discharge: Berkeley, California, U.S. Department of Agriculture, 4 p.

Lisle, T.E., Pizzuto, J.E., Ikeda, H., Iseya, F., and Kodama, Y., 1997, Evolution of a sediment wave in an experimental channel: Water Resources Research, v. 33, p. 1971–1981, doi: 10.1029/97WR01180.

Lisle, T.E., Cui, Y., Parker, G., Pizzuto, J.E., and Dodd, A.M., 2001, The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers: Earth Surface Processes and Landforms, v. 26, p. 1409–1420, doi: 10.1002/esp.300.

Madej, M.A., 1999, Temporal and spatial variability in thalweg profiles of a gravel-bed river: Earth Surface Processes and Landforms, v. 24, p. 1153–1169, doi: 10.1002/(SICI)1096-9837(199911)24:12<1153::AID-ESP41>3.0.CO;2-8.

Madej, M.A., 2001, Development of channel organization and roughness following sediment pulses in single-thread gravel bed rivers: Water Resources Research, v. 37, p. 2259–2272, doi: 10.1029/2001WR000229.

Madej, M.A., and Ozaki, V., 1996, Channel response to sediment wave propagation and movement, Redwood Creek, California, USA: Earth Surface Processes and Landforms, v. 21, p. 911–927, doi: 10.1002/(SICI)1096-9837(199610)21:10<911::AID-ESP621>3.0.CO;2-1.

Meade, R.H., 1985, Wavelike movement of bedload sediment, East Fork River, Wyoming: Environmental Geology and Water Science, v. 7, p. 215–225.

Meyer, G., Wells, S.G., Balling, R.C., and Jull, A.J.T., 1992, Response of alluvial systems to fire and climate change in Yellowstone National Park: Nature, v. 357, p. 147–150, doi: 10.1038/357147a0.

Meyer-Peter, E., and Muller, R., 1948, Formulas for bedload transport, *in* Proceedings of 2nd Meeting of International Association of Hydraulic Research: Stockholm, International Association for Hydraulic Structures Research, p. 39–64.

Miller, D.J., and Benda, L.E., 2000, Effects of punctuated sediment supply on valley-floor landforms and sediment transport: Geological Society of America Bulletin, v. 112, p. 1814–1824, doi: 10.1130/0016-7606(2000)112<1814:EOPSSO>2.0.CO;2.

Montgomery, D.R., and Buffington, J.M., 1997, Channel-reach morphology in mountain drainage basins: Geological Society of America Bulletin, v. 109, p. 596–611, doi: 10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., and Pess, G., 1995, Pool spacing in forest channels: Water Resources Research, v. 31, p. 1097–1105, doi: 10.1029/94WR03285.

Pickup, G., Higgins, R.J., and Grant, I., 1983, Modeling sediment transport as a moving wave—The transfer and deposition of mining waste: Journal of Hydrology, v. 60, p. 281–301, doi: 10.1016/0022-1694(83)90027-6.

Roberts, R.G., and Church, M., 1986, The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia: Canadian Journal of Forest Research, v. 16, p. 1092–1106.

Schumm, S.A., 1977, The fluvial system: New York, Wiley-Interscience, 338 p.

Smith, B.J., Lisle, T.E., Sutherland, D.G., Kelsey, H.M., and Cashman, E.M., 2002, Interactions between sediment storage and bed material transport: A field and flume study: Eos (Transactions, American Geophysical Union), Fall Meeting Supplement., v. 83, abs. H11C-0850.

Sutherland, D.G., Ball, M.H., Hilton, S.J., and Lisle, T.E., 2002, Evolution of a landslide-induced sediment wave in the Navarro River, California: Geological Society of America Bulletin, v. 114, p. 1036–1048, doi: 10.1130/0016-7606(2002)114<1036:EOALIS>2.0.CO;2.

Turner, T.R., 1995, Geomorphic response of the Madison River to point sediment loading at the Madison Slide, southwest Montana [M.S. thesis]: Bozeman, Montana State University, 99 p.

Wiberg, P.L., and Smith, J.D., 1987, Calculations of the critical shear stress for motion of uniform and heterogeneous sediments: Water Resources Research, v. 23, p. 1471–1480.

Wilcock, P.R., 1998, Two-fraction model of initial sediment motion in gravel-bed rivers: Science, v. 280, p. 410–412, doi: 10.1126/science.280.5362.410.

Wolman, M.G., 1954, A method of sampling coarse bed material: Eos (Transactions, American Geophysical Union), v. 35, p. 951–956.

Manuscript Received 6 February 2006
Revised Manuscript Received 6 June 2006
Manuscript Accepted 3 August 2006

Printed in the USA