SEDIMENT TRANSPORT REGIMES AFTER A WILDFIRE IN STEEP MOUNTAINOUS TERRAIN

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Abstract: Intense rains after a wildfire created catastrophic erosion and deposition in a mountainous watershed. The result was a slug of sediment filling the main channel and parts of many tributaries up to 4 m thick. This changed a supply-limited system to a transport-limited system. During the four years after the wildfire, three different transport regimes were identified. These regimes were not persistent enough to transport sediment as a wave but changed frequently, thus altering the morphology of the sediment slug.

INTRODUCTION

Wildfires are a natural disturbance that lowers the intrinsic threshold of erosion in a watershed; when followed by rain in steep mountainous-terrain, a dramatic erosional response can occur. Steep mountainous channels, in general, are supply-limited systems, but the erosion-response after a wildfire can provide so much sediment that these channels become transport-limited (Martin and Moody, unpublished data). Conditions for sediment transport in these mountainous channels and in similar ephemeral channels differ from the widely studied low-gradient, transport-limited sand channels (Leopold and Emmett, 1977; Brownlie, 1981) and from the steeper and rougher, supply-limited gravel channels (Milhous, 1973; Parker et al., 1982). Channel slopes often exceed 2%, the relative roughness (particle diameter/water depth) is nearly 1, and the beds are sometimes composed of an unsorted coarse mixture of sand and gravel rather than well-sorted sand. Other natural disturbances such as hurricanes and volcanic eruptions can also create transport-limited systems as do some anthropogenic activities such as mining and clear cutting. The eruption of Mount St. Helens in 1980 created a debris avalanche and debris flows that deposited slugs of sediment in the Toutle, Cowlitz, and Columbia River channels (Voight et al., 1981; Simon, 1999). Mining activities often deposit slugs of sediment into channel networks (Gilbert, 1917; Knighton, 1989). These inputs of sediment resulting from disequilibrium of the fluvial system have been defined by Nicholas et al. (1995) to be sediment slugs if they persist over time scales greater than the time of a flood event. They are classified by the spatial scale and the impacts they impart on the fluvial system. Macroslugs are controlled by in-channel processes, scale as the channel width, and result in minor channel changes . Larger megaslugs are controlled by local sediment supply and valley-floor configuration, and cause major channel changes whereas still larger superslugs are controlled by watershed-scale sediment supply and cause major changes in valley-floor morphology.

The movement of sediment slugs in flumes and perennial streams and rivers has been modeled as translational and dispersive sediment waves (Gilbert, 1917; Pickup et al., 1983; Knighton, 1989), as stationary and dispersive sediment waves (Lisle et al., 1997), as sediment bores (Needham and Hey, 1992), or as a stochastic process characterized by random particle movement (Pickup and Higgins, 1979; Griffiths, 1994). Wave-like transport of natural bedload has been described by Meade (1985) for the East Fork River in Wyoming over a spatial scale equal to about 100 channel widths. He related transport and storage to the changes in slope over pools and riffles caused by the increase and decrease in water level in response to the unsteady flow from snowmelt. Wave-like pulses of sediment have also been observed at fixed points during the duration of a flood event (Lekach and Schick, 1983) in ephemeral channels.

This paper describes the transient sediment-transport regimes of a superslug that was created by initial basin-scale erosion after a wildfire. The time scale (about 4 years) was greater than the flood-event time scale but shorter than the time scale for complete recovery of the channel to pre-fire conditions. This system, unlike many described and modeled in the literature, is characterized by unsteady and intermittent flow with a non-uniform channel; it represents typical systems found in steep mountainous terrain burned by wildfires.

BACKGROUND

The wildfire burned 4690 hectares in two watersheds (Buffalo and Spring Creeks) located in the Colorado Front Range southwest of Denver, Colorado in May 1996. This area of the Colorado Front Range is characterized by short duration, intense rainfall events in the summer (Henz, 1974) that produce flashfloods and longer duration runoff from snowmelt in the winter and early spring. The main channels are steep (the slope of Buffalo Creek is about 1% and the slope of Spring Creek is about 4%) and baseflow in these channels may be elevated because the tree canopy and ground vegetation was destroyed which decreased evapotranspiration (Figure 1). The primary erosional event was a thunderstorm on 12 July 1996 that was much greater than the estimated 100-yr, 1-hr rainstorm (Miller et al., 1973; based on empirical equations developed from 6 and 24-hr precipitation data). The initial erosion in Buffalo Creek was relatively minimal, and subsequent sediment deposition was in the form of alluvial fans from each tributary with sediment thickness decreasing in the main channel downstream from the fan. Although the Buffalo Creek flood plain was buried near the mouth of each tributary, it was, in general, preserved throughout the length of the valley. Erosion and deposition in the main, east-west channel of Spring Creek was much different. Initial erosion (probably during the rising limb of the hydrograph) occurred across the entire valley and removed any pre-existing flood plain; alluvial fans were deposited at the mouths of tributaries (probably on the falling limb of the hydrograph) and were connected with in-channel sediment deposits up to 4 m thick, producing a sediment superslug in Spring Creek occupying about 5000 m along the main channel and filling the entire valley.

METHODS

Morphology The morphological changes of this superslug were monitored for four years (June 1996 to June 2000) by a series of closely spaced channel cross-sections in a study reach near the mouth of Spring Creek. This reach, which was 1490 m long and extended from the mouth upstream to a stream gage, was selected to encompass more than one wavelength of degradation and aggradation of a possible sediment wave. The width of the valley in Spring Creek was about 30 m; cross sections were spaced 10 m apart to provide detailed measurements of changes in morphology and in the total volume of stored sediment. Changes in volume at several neighboring cross sections were very similar during 1997, so in 1998, 1999, and 2000 the interval between cross sections was increased to approximately 30 m. Initially, the absolute location and elevations of each cross section were measured by using a Nikon 720 DTM, but after the absolute location had been established, a surveying level, metric tape, and surveying rod were used to remeasure the elevations at each cross section. Initial post-fire but pre-flood bed morphology was determined from 1:12,000 stereo photographs taken in June 1996, and the morphology of the superslug was determined as the difference between the pre-flood and additional post-flood 1:12,000 stereo photographs taken in August 1996.

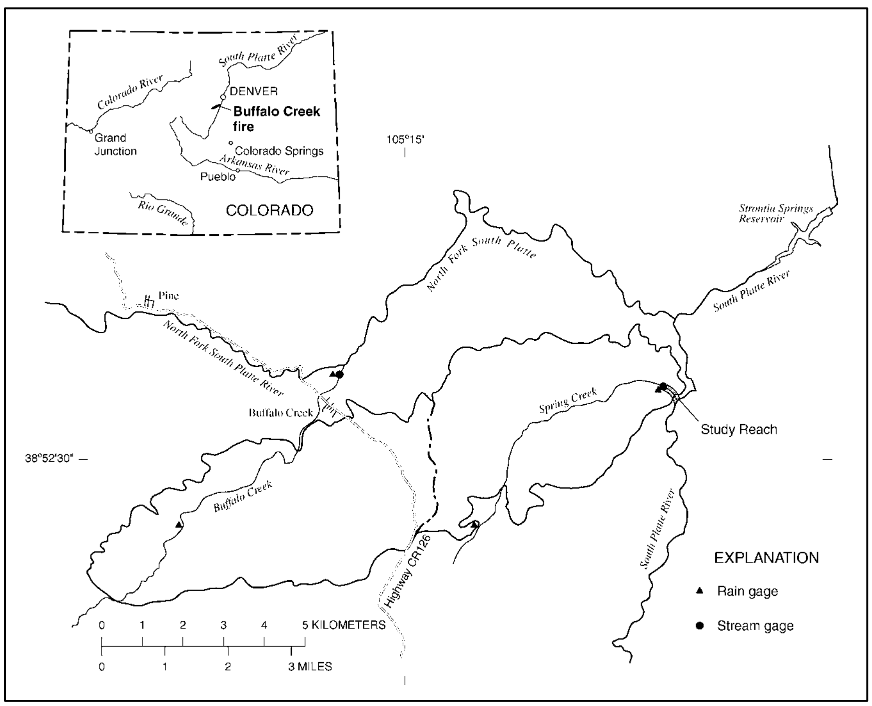

Figure 1. Location of the areas burned in two watersheds (shown by different crosshatching patterns) at elevations between 1880 and 2360 meters above sea level. Transport regimes were monitored in the study reach near the mouth of Spring Creek.

Particle-size Distributions Particle-size characteristics of the superslug were determined by collecting: 1) sediment cores from unburned hillslopes to characterize the source of sediment, 2) surficial-sediment samples to assess longitudinal variations , 3) vertical stratigraphic samples to differentiate between bedload and flash-flood deposits, and 4) a large-volume sediment sample coupled with surface mapping of boulder deposits to characterize all the bed material available for transport. The particle-size distribution for each sample was measured by using standard sieves at 1-phi intervals after 15-20 minutes on a RoTap machine. The distributions were computed as the slope of a third-order polynomial spline fit to the cumulative data (R.F. Stallard, per. comm., 1997), and are characterized by the median diameter and the dispersion or phi deviation (Inman, 1952) which equals 1.0 in a very well sorted sample with only one phi size class.

RESULTS AND DISCUSSION

Initial Morphology Cross-valley and longitudinal surface topography of the superslug in the main channel of Spring Creek appeared relatively smooth and was confined by steep and sometimes nearly vertical hillslopes with colluvial material as well as bedrock outcrops of the easily eroded Pikes Peak granite (Moore, 1992). The longitudinal surface topography was broken by several steep bedrock outcrops which had been eroded and had essentially no sediment deposits. Within the 1490-m study reach, the valley width was narrowest at the upstream end (10 m), widest at the mouth (45 m), and the mean valley width was 27 m (Figure 2A). Pre-flood bed slopes were slightly more variable (standard deviation = 38%) than the widths (standard deviation = 20%) and the mean bed slope was 0.040. After the flood, the superslug had a mean bed slope of 0.041 and was less variable (standard deviation =27%) than the pre-flood channel (Figure 2A). At each channel cross-section, the sediment deposition was measured as the change in area or change in sediment volume per unit channel length by using photogrammetry methods. This area was converted to an equivalent thickness for a uniform channel with a width of 27 m. The mean sediment deposition was 0.6 m thick (Figure 2B). It was thickest at the mouth (2.6 m), which represents a truncated deposit that had dammed the South Platte River, and thinnest at narrow cross sections (0.20-0.23 m) where bedrock outcrops were exposed in the channel.

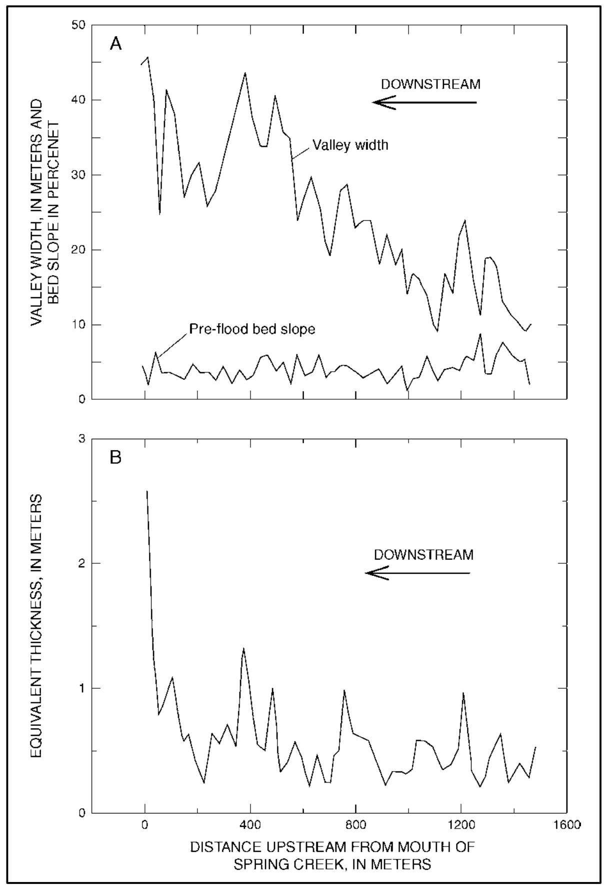

Figure 2. Initial morphology of the superslug created by severe erosion after a wildfire. A. Valley widths were measured in 1997 and the bed slopes (before the flash flood on 12 July 1996) were measured approximately every 30 m from 1:12000 aerial photographs. B. Equivalent thickness of sediment is the thickness in a uniform channel 27 m wide. Sediment deposited after the flood was measured as the difference in elevations between pre- and post-flood aerial photographs.

Particle-Size Bed material composing the superslug had a bimodal distribution with components from the hillslopes and from the pre-flood channel banks. Particle-size distribution of the hillslope sources had a median diameter of 2.8 mm, a dispersion of 4.6, and was similar to the particle-size distribution of the surficial sediment of the superslug (Figure 3). Characteristics of surficial sediment varied from upstream to downstream and indicated that some sorting had occurred. At about 5000 m upstream from the mouth of Spring Creek, the median diameter of the surficial sediment was about 2.5 mm and was consequently better sorted (dispersion = 3.4) than the hillslope sources. The median diameter increased downstream and was about 4.4 mm (dispersion = 2.9) at the mouth.

The second component of the bimodal distribution came from channel banks and had a median diameter of 110 mm and a dispersion of 3.2. This material was eroded from the outcrops of Pikes Peak granite which is often decomposed at the soil interface and easily broken into gravel-sized material (grus) or plucked as boulder-sized material by the flow. Boulders often formed bars on the surface after the major floods, and field observations suggest they may have been deposited along the edge of an eddy in expanding reaches during the flood.

Horizontal layers of sediment were observed in the eroded banks of the superslug. However, detailed sampling indicated that apparent layers of coarse sand and gravel interbedded with fine sand were not continuous over distances much greater than 1-2 m. Rather than layers, these flash-flood deposits were actually lenses of coarse sand and gravel similar to bedload deposits in reaches of braided channel. Here, bedload was observed to be deposited by very shallow flow (0.01-0.05 m deep) as coarse sand and gravel mid-channel bars or islands (about 0.2-0.5 m wide and 0.5-1 m long) that randomly diverted the flow in these braided reaches. These small bars or islands were later covered by finer bedload material transported by a diverted channel from upstream and formed lenses of coarse sand and gravel. The median diameter of the coarse lenses in the flash-flood deposits (4.7 mm) was larger than those of the bedload deposits (3.6 mm) but neither was well sorted (dispersion >3.5).

Sediment Transport Regimes Three sediment transport regimes were identified. These are combinations of flow conditions and bed conditions and are referred to in this paper as uniform, discontinuous, and unsteady regimes.

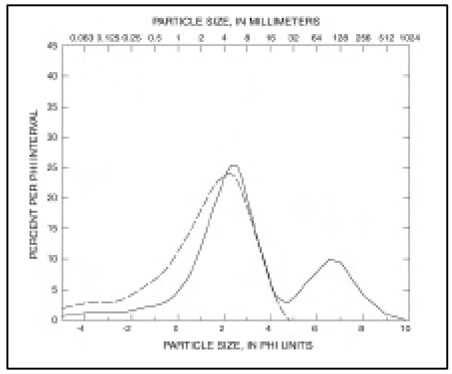

Figure 3. Particle-size distribution of the hillslope source of sediment (dashed line) and the channel bed material (solid line) composing the superslug. The median diameters of the hillslope source, the surficial sediment in the bed material, and the bank material in the bed material are 2.8 ±0.4, 4.6 ±2.7, and 110 ±3.2 mm respectively.

The uniform regime had steady and spatially continuous flow and non-cohesive and cohesive bed conditions depending upon the time of year. Relatively uniform water discharge (0.074- 0.21 m^3s^{-1}) occurred in the early spring from snowmelt and during the summer as prolonged and possibly elevated baseflow from summer rains percolating into the highly fractured granite. This flow eroded the non-cohesive surficial sediment of the superslug in some reaches creating an incised channel about 1-2 m wide with characteristically 0.5 high banks and a bed armored by the coarse bed material (median diameter of 110 mm) derived from the banks (Figure 3). Sediment was transported downstream (0.32-1.2 kg $s^{-1}m^{-1}$) and deposited in other reaches creating braided channels about 20-40 m wide which filled the entire valley. This alternating pattern of incised and braided reaches was observed along the entire 5000 m length of the superslug and was measured in detail in the study reach. For example, between October 1997 and May 1998 (Figure 4) when there were about 60 days of active transport during snowmelt runoff in the spring, the volume of sediment (4700 m^3) eroded in the reach between 1390 and 745 m was a little greater than the volume of sediment (3500 m^3) deposited downstream in the reach between 745 and 110 m. The difference in volume represents an average transport rate of 0.4 kg s^{-1} (using a bulk density of 1700 kg m^{-3}) out of the study reach. During the winter, relatively uniform discharge (about 0.02 m^3s^{-1}) also occurred from snowmelt on south-facing hillslopes; however, the surficial bed material was now frozen (and therefore cohesive). As a result, the incised reaches were narrower and had higher banks (~1 m). The sediment transport downstream from these narrow incised reaches often exceeded the carrying capacity of the narrow channels, resulting in overbank flows that created levees and irregular mounds of sediment as the sediment refroze during the night. Repeatedly during the winter seasons, sediment accumulated as an in-channel fan in the reach between 700 and 600 m, which was also a storage reach during the other seasons.

The discontinuous regime had very low discharge (<0.01 m^3s^{-1}) flowing over the non-cohesive surficial sediment. This regime frequently occurred during the summer. Surface water was discontinuous, disappearing into the bed material, depositing the bedload, and creating an in-channel fan. The fan moved very slowly upstream by deposition on the upstream edge and erosion on the downstream edge as the subsurface water emerged, creating a slip face on the fan and a narrow (~0.5 m) incised channel.

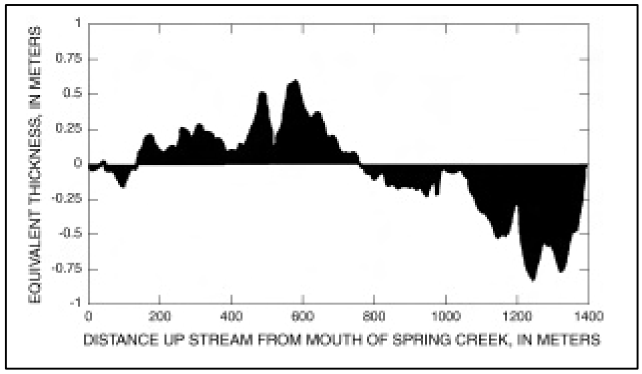

Figure 4. Equivalent thickness of eroded (negative) and deposited (positive) sediment in the main channel of Spring Creek between October 1997 and May 1998 (see figure 6, time interval 6).

The unsteady regime represents relatively short times when the discharge changed from 0.02-0.20 m^3s^{-1} to 20-180 m^3s^{-1} during flash floods caused by heavy rainfall from summer thunderstorms. Rainfall in excess of about 10 mm h^{-1} seemed to produce general overland flow and flash floods. Time to peak discharge on the rising limb was typically 0.1-0.5 hours, and the falling limb usually lasted longer than 3 hours. The number and magnitude of flash floods was greatest in 1997 (1 year after the fire) and has since decreased. The initial flash flood on 12 July 1996 was the largest, producing a watershed average unit discharge of 24 $m^3s^{-1}km^{-2}$. The next largest event was on 31 August 1997 (unit discharge of 8.6 $m^3s^{-1}km^{-2}$), and third largest event occurred on 31 July 1998 (2.8 $m^3s^{-1}km^{-2}$). Much of the sediment which had moved as bedload (1-32 mm) during other regimes was probably transported as suspended load during some of these flash floods. During the 31 August 1997 event, the estimated minimal total transport was 4000 kg s^{-1} (based on volume of sediment deposited in the study reach which acted like a bedload trap because of its expanding width); about 80% was suspended load, and 20% was bedload.

These flash floods were, in general, net depositional processes resulting in aggradation. The average equivalent thickness of deposited sediment after the12 July 1996 flood was 0.6 m, after the 31 August 1997 flood it was 1.0 m, after 31 July 1998 flood it was 1.03 m, and by May 2000 the sediment in the study reach was 1.1 m thicker than in June 1996. The deposition, however, within the study reach is spatially variable (Figure 2) and seems to reflect the spatial variability in bed slope and valley width.

Deposition Model: Deposition from major flash floods that filled the entire valley were predicted by a simple analytical model involving bed slope and valley width. This was an extension of the observations by Meade (1985) that deposition depended upon variations in slope to include deposition that depended upon variations in width. The analytical model predicts net deposition or net erosion for a single event but does not predict the changes during an event. Deposition from smaller flash floods could not be predicted with this analytical model because the water surface width was less than the valley width, confined within very erodible banks, and therefore the width was unknown. The sediment transport, G, was assumed proportional to the total shear stress to 3/2 power, the shear stress was estimated as the depth-slope product, and the velocity approximated by Manning's equation. For constant water discharge the sediment transport is then:

$$G = C\frac{S^{21/20}}{w^{9/10}}$$

where C is a proportionality constant, S is the bed slope, and w is the valley width. Deposition and erosion within a reach are then proportional to the difference between the transport at the upstream and downstream boundaries. These boundaries were the channel cross sections which were approximately 30 m apart for the initial flood on 12 July 1996 (when the deposition was determined photogrammetrically) and were approximately 10 m apart for the flood on 31 August 1997 (when the deposition was determined by ground surveys before and after the flood). The spatial variability predicted by this simple model is very similar to the actual deposition (Figure 5A) after the 12 July 1996 flood. When differences between sediment transport were computed over 3 reaches (~90 m), the difference between predicted deposition and measured deposition was less. The difference between the predicted and measured deposition was relatively greater between 1000 and 1400 m where the valley is narrow than between 20 and 1000 m where the valley is much wider. A possible explanation is that the bed roughness may have been greater in the wider reaches where willows and cottonwood trees were more numerous than in the narrower reaches. This analytical model assumes a constant roughness, and if the roughness in the narrow reach between 1000 and 1400 m was reduced there would be a decrease in the predicted thickness and an improvement in the prediction by the model. Differences between the measured and predicted deposition is also large near the mouth of Spring Creek at the junction with the South Platte River where the channel conditions change abruptly. Actual deposition was probably controlled by the water level in the South Platte River which created an effective slope that was possibly much smaller than the slope in the Spring Creek channel upstream from the mouth used in the model. This simple model was also applied to the deposition from the 31 August 1997 flash flood (Figure 5B) and once again reproduced the general spatial pattern of deposition which for this flood was measured at about 10 m intervals. The best predictions of deposition, however, were achieved when the bed slope was spatially averaged over 3 reaches (about 30 m) producing "regional" slopes similar to those used for the initial flood in 1996. In addition, the differences in the measured and predicted thickness were less when differences between sediment transport were computed over 3 reaches (~30 m) or approximately the valley width. Deposition seems to be controlled by a "regional" slope averaged over the distance of several reaches upstream. This distance was larger (~ 90 m) for the 12 July 1996 flash flood (estimated peak discharge of 510 m^3s^{-1}) than the distance (~30 m) for the 31 August 1997 flood (estimated peak discharge of 180 m^3s^{-1}).

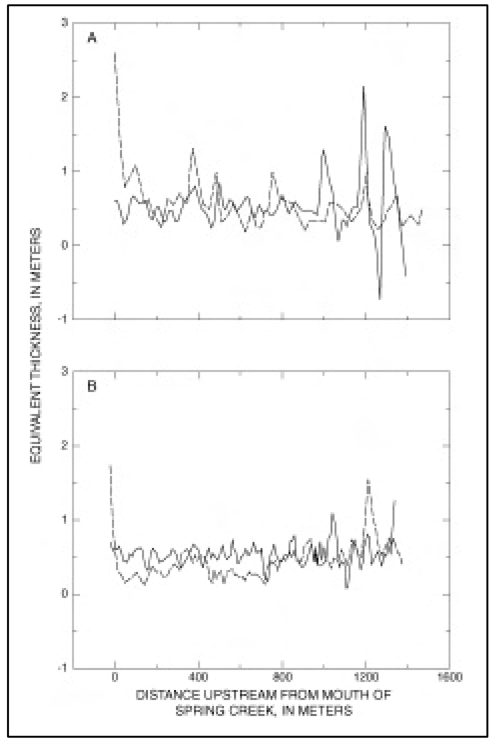

Figure 5. Analytical model for net erosion and deposition as a result of a flash flood. A. The measured equivalent thickness (dashed line) for the 12 July 1996 flash flood (see figure 2 and figure 6, time interval 1) is compared to the predicted thickness (solid line). The proportionality constant C was set arbitrarily to 10 to produce similar amplitudes and an offset of 0.5 m was applied. B. The measured equivalent thickness (dashed line) for the 31 August 1997 flash flood (see also Figure 6, time interval 4) is compared to the predicted thickness (solid line) where the proportionality constant C was set arbitrarily to 10 to produce similar amplitudes and an offset of 0.5 m was applied.

CONCLUSIONS

The transport of sediment for this superslug can not be described by a sediment wave during the transient period consisting of the first four years after its creation. Three different transport regimes existed at different times and for varying lengths of time and no single transport regime existed long enough in space or time to consistently move sediment. The unsteady regime is represented by time intervals 1, 4, 9, 10, and part of interval 14 (Figure 6), the discontinuous regime is represented by intervals 2, 3, 8, and 11, the uniform regime with non-cohesive bed conditions by intervals 5, 13, and part of 14, and 15, and finally the uniform regime with cohesive bed conditions by intervals 6, 7, 12, and 16. No translational sediment wave was observed to propagate downstream, which in Figure 6, would appear as a slug moving from right to left (along the spatial axis) and from top to bottom (along the time axis), and no diffusing stationary wave is evident.

Deposition during flash floods probably occurs on the falling limb of the hydrograph when the sediment is moving as bed load. Flash-flood deposits were coarser than bedload deposits that had formed at lower discharge. Neither deposits had vertical stratification that would indicate they were formed by the settling of suspended sediment. The spatial variability of the deposits depends mostly on the spatial variations of bed slope and valley width but also on the bed roughness which is difficult to determine during a flash flood.

The hillslopes sediment fluxes have decreased to pre-fire in 3-5 years (Moody and Martin, unpublished data), and thus the runoff response to rainfall has decreased and the unsteady nature, characteristic of the transient phase of this transport-limited system, is decreasing. The implication is that with steadier flow a stable and armored channel will probably form within the entire length of the superslug. The bulk of sediment in the superslug will go into long-term storage and will probably move only when the next disturbance such as wildfire changes the erosion threshold of the watershed.

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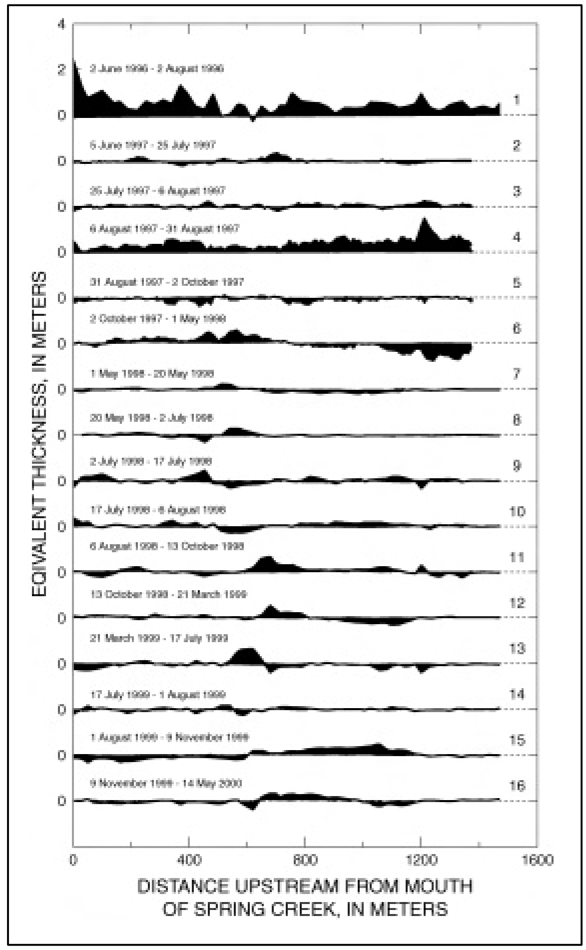

Figure 6. Changes in the morphology of the superslug within the study reach. The changes in equivalent thickness between successive surveys of the study reach are shown with time increasing downward. The time intervals are not equal but represent 16 measurements of change over the four years following the wildfire and initial erosional and depositional event.

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