EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 15, 457–466 (1990)

THE INFLUENCE OF DEBRIS FLOWS ON CHANNELS AND VALLEY FLOORS IN THE OREGON COAST RANGE, U.S.A.

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Received 24 August 1989
Revised 2 January 1990

ABSTRACT

Debris flows are one of the most important processes which influence the morphology of channels and valley floors in the Oregon Coast Range. Debris flows that initiate in bedrock hollows at heads of first-order basins erode the long-accumulated sediment and organic debris from the floors of headwater, first- and second-order channels. This material is deposited on valley floors in the form of fans, levees, and terraces. In channels, deposits of debris flows control the distribution of boulders. The stochastic nature of sediment supply to alluvial channels by debris flows promotes cycling between channel aggradation which results in a gravel-bed morphology, and channel degradation which results in a mixed bedrock- and boulder-bed morphology. Temporal and spatial variability of channel-bed morphology is expected in other landscapes where debris flows are an important process.

KEY WORDS Debris flows Mountain channels Channel aggradation

INTRODUCTION

Debris flows in the west coast of North America form as landslide debris liquifies and moves through steep, confined, headwater channels for distances up to several kilometres at speeds up to 10–15 m s^{-1}. The flows are extremely erosive and incorporate additional sediment from channels, as well as organic debris and water, and they deposit this material in lower-gradient channels and valley bottoms. The steep, dissected mountains of the west coast of North America favour the formation of debris flows (Eisbacher and Clague, 1984; Swanson *et al.*, 1987).

Debris flows are an important sediment transport link between hillslopes and alluvial channels and thus are an important factor in basin sediment budgets (Dietrich and Dunne, 1978; Swanson *et al.*, 1982; Benda and Dunne, 1987). In addition, debris flows influence the spatial and temporal distribution of sediments in alluvial channels either because they deposit sediment in alluvial channels, or because the deposits provide a source for accelerated transport of sediment further downstream. Despite the importance of debris flows in the transport of sediment from headwater channels, little is known of their role in shaping the morphology of channels and valley floors in the northwest region of North America.

In this paper I present a field study of the erosional and depositional characteristics of debris flows and their influence on alluvial channels and valley floors.

STUDY BASIN

Forty-four debris flows were examined in Knowles Creek, a 52 km^2, fifth-order basin underlain by marine sandstones of the Tyee and Flournoy formations in the central Coast Range of Oregon, U.S.A. (Baldwin,

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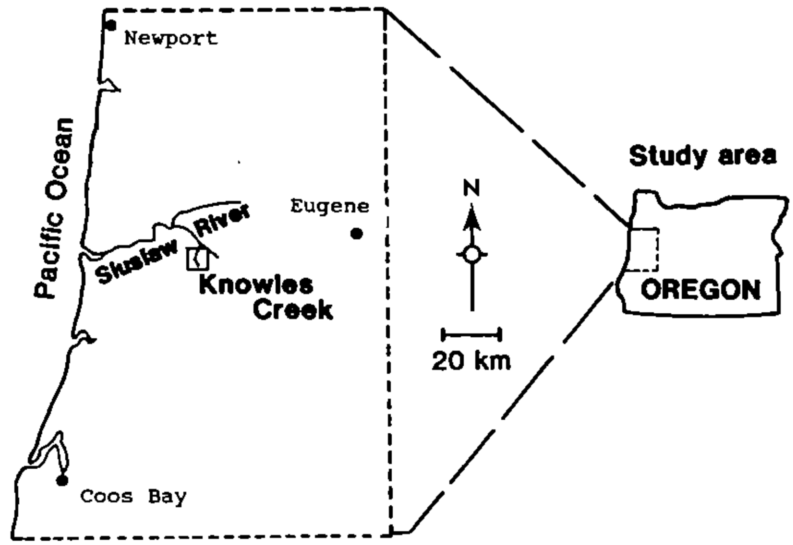

Figure 1. Study area in the Oregon Coast Range, U.S.A.

1964) (Figure 1). The Tyee and Flournoy formations are massive, rhythmically-bedded sandstones with interbeds of siltstones. Hillslopes have gradients of 35° to 45° and are sculpted into bedrock hollows (Dietrich and Dunne, 1978) also referred to as zero-order basins (Tsukamoto *et al.*, 1982). Colluvium on hillslopes ranges in depth from 0·3 m to 0·5 m, and in hollows from 0·4 m to 3·5 m. Bedrock hollows lead into steep, partially-vegetated headwater channels with bouldery and cobbly beds. Benda and Dunne (1987) examined the texture of sediment in these first- and second-order channels, and concluded that, apart from a sorted surface pavement, the deposits consisted primarily of colluvium supplied from the adjacent hillslopes. Colluvium is transported to stream channels by a variety of processes which include rheological soil creep, treethrow, animal burrowing, and small streamside landslides. Depths of colluvium which range from one to three metres in headwater channels constitute a source of sediment to augment the volume of scouring debris flows.

Annual precipitation of 1600 mm, falling almost entirely as rain during winter, supports dense stands of Douglas Fir (*Pseudostuga menziesii*) and western hemlock (*Tsuga heterophylla*). Road construction and clearcut logging began intensively during the 1950s and continues to the present. Recent large rainstorms in conjunction with land-use activities have resulted in at least 44 debris flows in the Knowles Creek drainage over the last 30 years.

CHARACTERISTICS OF DEBRIS FLOWS

Bedrock hollows: loci for initiation of debris flows

In the highly-dissected basins of Knowles Creek, debris flows were initiated by landslides which occurred in colluvium-filled bedrock hollows in 78 per cent of the 36 cases where initiation sites could be identified. The remaining 22 per cent of failures occurred along relatively planar hillslopes. Initiation of debris flows was not observed to occur in headwater channels.

The spatial density of hollows in the study basin averages 100/km^2.The number of hollows in a first-order basin averages seven. Two to five bedrock hollows (average four) located at heads of first-order channels, and entering stream channels at angles less than 45°consistently initiated debris flows; these have been referred to as trigger hollows (Benda and Dunne 1987). The other three hollows in a typical first-order basin, and those in second-order basins (7) enter channels approximately at right angles and the sediment from them deposit in first- and second-order channels.

Debris flows travel through first-, second-, and third-order channels. Ninety-three per cent (40) of all debris flows reached at least the mouths of first-order basins, an average distance of 250 m. Eighty-two per cent (36) continued to travel through second-order channels, increasing their travel distance to an average of 550 m. Forty-one per cent (18) entered and traversed at least a portion of a third-order channel, increasing their average distance to 1050 m.

Erosion of headwater channels by debris flows

A comparison of sediment sizes from several locations in the basin indicates that deposits in first- and second-order channels are dominated by colluvium (Figure 2). The sediment size distributions shown in Figure 2 are the averages of combinations of surface counts (Wolman, 1954), and bulk sieve analyses for hollows ($n = 4$), first- and second-order channels ($n = 4$) in two second-order basins, debris flow deposits ($n = 3$) at second-order tributary junctions, and surface and freeze-core sampling (Everest and Meehan, 1981) in fourth-order streams ($n = 4$). The freeze-core method samples the armour layer and 0·3 m into the underlying sediment. Similar proportions of sediment finer than coarse sand ($<1{\cdot}0$ mm) in first-order channels (12 per cent) and second-order channels (14 per cent), and bedrock hollows (9 per cent) suggest little selective transport or abrasion by fluvial processes in headwater channels. The texture, shape, sorting, and cohesion of sediments in headwater channels which indicates their colluvial origin is discussed in detail by Benda and Dunne (1987) and by Benda (1988).

In Knowles Creek basin debris flows completely scour the sediments from the floors of first- and second-order channels exposing the channel bedrock in almost all cases. To estimate the volume of sediment stored in first- and second-order channels and thus the amount eroded by debris flows, I measured the cross-sectional areas of surviving deposits of colluvium in channels, and multiplied the areas by the lengths of channels. These measurements were made in four first-order and two second-order channels. Based on these measurements, debris flows erode 5 to 10 m^3 of sediment per metre length of channel (average 8 $m^3 m^{-1}$).

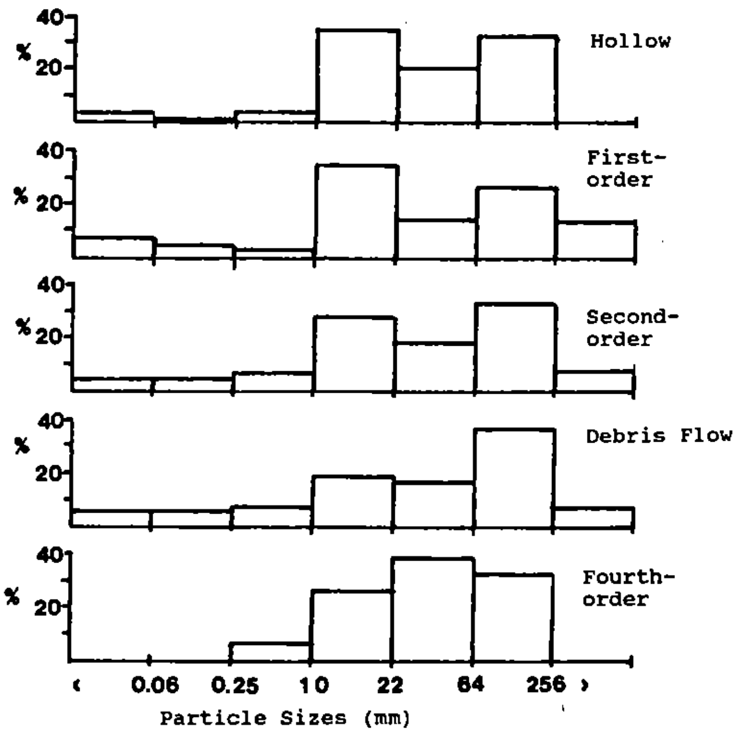

Figure 2. Sizes of sediment from various locations in Knowles Creek basin

Erosion of channel sediments increased the volume of debris flows from an average of 450 m^3 (range 35 m^3–1200 m^3) at the initial failure to 2400 m^3 (range 1700 m^3–3000 m^3) at the mouths of first-order channels. Debris flows which continued to erode throughout second-order channels increased their average to 4000 m^3 (range 3400 m^3–6000 m^3). Erosion by debris flow continued into third-order channels, but usually less than a distance of 100 m.

There are several reasons why sediment delivered to first- and second-order channels resists fluvial erosion and accumulates until eroded by a debris flow. Channels scoured by debris flows commonly refill by landslides from hollows and hillslopes. Instantaneous delivery of thick wedges of sediments to narrow channels reduces the opportunity for streamflow to erode and transport sediments. In addition, headwater channels have large boulders and both live and dead large woody material on surfaces of deposits which increases roughness and reduces gradients thereby reducing sediment transport. Fluvial sediment transport in headwater channels is minimal also because water velocities in streams are insufficient to transport the coarse armour layer that protects the underlying sediment from stream erosion.

Deposition of debris flows

Deposition of debris flows occurs in third- through fifth-order channels and valley floors typically at mouths of first- and second-order basins. Deposits consist of less than 1000 m^3 of organic debris followed by a 50 to 150 m-long accumulation of unsorted sediments ranging in width from 10–20 m and in thickness from one to two metres. The deposits, which completely fill alluvial channels, are composed of gravels, cobbles, boulders, sand, and small amounts of silts and clays (Figure 2).

Debris flows which enter third-order channels at their heads travel and deposit over a distance of 100 m to 750 m. Boulders drop out of debris flows gradually several hundred metres prior to the final deposition.

INFLUENCE OF DEBRIS FLOWS ON CHANNELS AND VALLEY FLOORS

Forms of deposits: Fans, levees, and terraces

Fans in Knowles Creek basin located at mouths of first- and second-order basins are composed of coarse, unsorted sediment. This and their lobate shape indicate that they were formed by debris flows. Fans are the dominant form of debris flow deposits in fourth- and fifth-order valleys. Debris fans have areas of 1000 to 5000 m^2, gradients of 4° to 8°, and a streamside perimeter of 20 m to 60 m. Fans are significant morphological features in valleys which have widths of between 10 m and 50 m. Fans in narrow valleys force streams to curve around them. A survey of channel sinuosity in a third- and fourth-order basin showed that sixty-five per cent of meanders (stream length/valley length) $> 1{\cdot}2$ are associated with debris flow fans.

Debris flows in third-order valleys often form levees and large terraces. The distinction between levees and terraces is based primarily on the rheological properties of debris flow materials which promote different sizes and shapes of deposits. Levees form at the margins of debris flows while they are moving and are distinctly concave downward in cross-section (Costa and Jarrett, 1981). Debris flows in the study basin form levees along third-order valley floors adjacent and parallel to channels for distances of several hundred metres prior to the final deposit. Levees are discontinuous two to five metre wide, one to two metre high deposits composed of unsorted sediments, including boulders on surfaces of deposits. Levees may be paired across the channel or unpaired. Significant amounts of large organic debris oriented subparallel to the valley floor typically accompany the deposits. Large boulders and organic debris originating from levees contribute large structure to channels.

In contrast, the massive distal portions of debris flow deposits form terraces, particularly in third-order basins in the study area. Debris flow terraces in these valleys are 50 m to 100 m in length, 5 m to 10 m in width and one to two metres in thickness. Debris flow terraces are composed of unsorted sediments smaller than boulders (<256 mm) because boulders gradually drop out prior to the final deposit.

Forms of deposits controlled by stream erosion and location in basin

Stream erosion influences the form and longevity of the various types of deposits. To determine the effects of stream erosion on deposits, I measured debris flows less than five years old in the study basin. Using drainage area as an indicator of flood discharge, I compared erosion of debris flow deposits to drainage area of the receiving channel for 14 recent (≤ 5 years old) debris flows. By surveying a portion of the channel of the receiving stream adjacent to where debris flows entered, a percentage of the remaining deposit was obtained; this was used as an indicator of erosion of the total deposit. The surviving portion of the deposits is plotted against drainage area in Figure 3. Erosion is directly related to drainage area with an $r^2$of 0·86.

The various forms of deposits and their longevity are partially explained by their position in the drainage basin (Figure 3). For example, deposits within third-order valleys had small drainage areas ($< 10\ km^2$) and had less than 20 per cent erosion within five years (Figure 3). The majority of the deposits are in the form of discontinuous levees and terraces and are protected from stream erosion due to their horizontal and vertical isolation from stream channels.

Debris flows which deposited in approximately the centre of the basin (drainage areas of 10 km^2 to 20 km^2) had 40 per cent to 65 per cent erosion and formed relatively large fans (Figure 3). To a lesser extent, small terraces would form as a downstream extension of debris flow fans. The deposits had less organic debris and less sediment in storage in channels because of the higher transporting capacity of the channel at those locations. Constriction of the channel and valley floor often resulted in the creation of ponds. Field observations indicate that ponds may survive years to decades prior to filling with sediment or draining.

At drainage areas greater than 20 km^2, the deposits were more thoroughly eroded (20 per cent surviving), and fans were truncated by the stream. Only large boulders and cobbles survived fluvial transport during the first several years after deposition. Debris flows entering large streams (drainage are $> 28\ km^2$) often became debris-laden floods; this process is discussed by Benda (1985).

Distribution of boulders in alluvial channels

Boulders in the study area accumulate along axes of bedrock hollows and in first- and second-order channels. Though boulders were not measured in hollows in the particle size analysis shown in Figure 2, a survey of boulders on hillslopes within one clearcut first-order basin showed that 51 per cent of boulders greater than one metre in diameter are located on the surface of hollows. Deposits in first- and second-order channels contained approximately 10 per cent boulders (Figure 2). Debris flows that originate in hollows and scour first- and second-order channels transport boulders to sites of deposition.

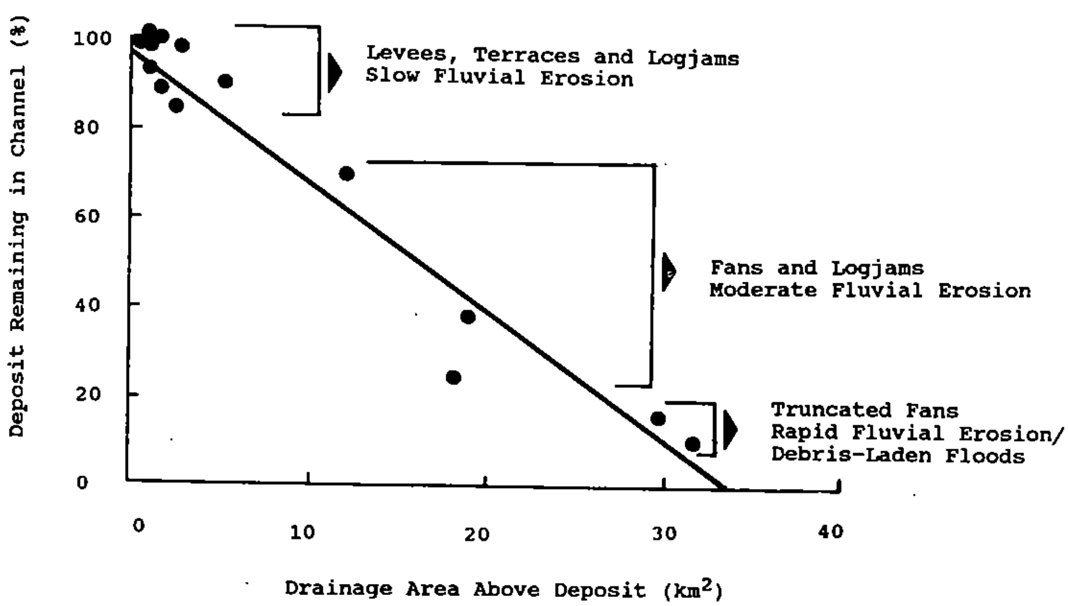

Figure 3. Erosion of debris flow deposits compared to drainage area and the resulting forms of deposits

Debris flow deposits evolve through time as finer sediments, including gravels, are transported by streamflow in third- through fifth-order streams. Boulders in these deposits resist fluvial transport and remain behind as lag deposits. Alluvial channels between mouths of first- and second-order channels have smaller numbers of boulders. Boulders were observed to weather by exfoliation and therefore they become smaller over time and easier to transport.

The distribution of boulders was surveyed throughout an entire third- and fourth-order channel. The surveyed channel had only two recent debris flows (≤30 years old), one at the head of the third-order channel, and the other in the fourth-order channel. The remaining debris flow fans are colonized by conifer trees, approximately 350 years old according to tree ring counts on nearby stumps. There are significant reaches of channel bedrock along the study reach. Figure 4 displays the distribution of boulders larger than or equal to 0·5 m in diameter (intermediate axis) throughout the 2800 m study reach. The highest densities of boulders are consistently localized adjacent to fans at mouths of headwater, first- and second-order basins throughout the lower fourth-order segment of the study channel (1400 m to 2800 m stream distance, Figure 4). The high densities of boulders often extend downstream of the mouth of headwater channels. This offset also occurs at recent deposits in the fourth-order basin, and is the result of the debris flow depositing past the mouth of the basin.

In the upper portion of the basin (900 m to 1300 m), boulders are more evenly distributed reflecting gradual deposition of boulders by debris flows as they move through third-order channels. Above 800 m the channel is scoured to bedrock and thus boulders are absent. The absence of boulders at 1400 m (Figure 4) denotes the location of the final deposit of the recent debris flow in the third-order channel which had a final deposit devoid of boulders, or boulders may have been covered by finer sediments.

Influence of debris flows on sediment supply: Cycles of aggradation and degradation

To understand the role of debris flows in supplying sediment to alluvial channels a sediment budget was constructed for the 30 km^2 upstream portion of the study basin based on recurrence intervals of landslides and debris flows. Radiocarbon dating of charcoal obtained at the bedrock–colluvium interface at seven recent landslide scars in the study basin provided an indication of the duration of colluvium accumulation between landslides. An average recurrence interval of 6000 years for landslides from bedrock hollows was obtained; the range was 1600 to 10 400 years (Benda and Dunne, 1987; Benda, 1988). Based on the number of trigger hollows which initiate debris flows (average 4), average recurrence intervals of 1500 years for debris flows in first-order channels (6000 years/4 trigger hollows), and of 750 years for debris flows in second-order channels (6000 years/8 trigger hollows) were estimated for the study basin (Benda and Dunne, 1987).

Estimating long-term fluvial transport from headwater, first- and second-order channels does not lend itself to field measurements. Fluvial export of sediment from headwater basins depends upon availability of

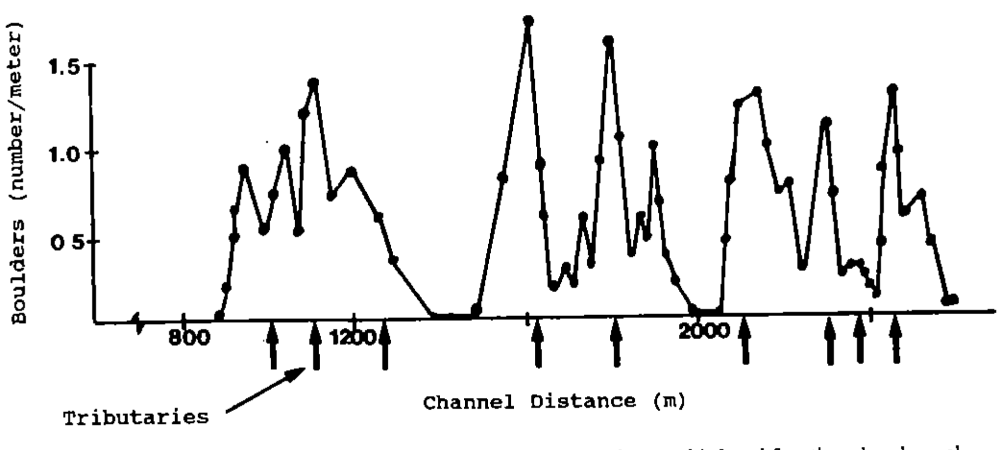

Figure 4. Density of boulders greater than 0·5 m in diameter along a third and fourth-order channel

mobile sediment which is controlled by time since last debris flow and the occurrence of landslides and floods in the basin. Nevertheless, for the purposes of constructing a basin sediment budget, a proportion of sediment transport by fluvial processes from headwater channels equal to 20 per cent of the total sediment yield was used based on results from the only other comparable study in a first-order basin (Swanson *et al.*, 1982). Textural analyses of sediments from headwater channels, which indicated little selective fluvial transport (Figure 2) (Benda and Dunne, 1987) suggest that this 20 per cent proportion is reasonable.

The processes which transport colluvium to stream channels, such as landslides, animal burrowing, and treethrow, can be collectively accounted for by a continuous soil creep rate over long time periods (Dietrich and Dunne, 1978). Soil creep was estimated for Knowles Creek basin based on measurements of the volume of sediment which had accumulated between successive failures in bedrock hollows. Dividing the sediment volume by the time interval between landslides determined by the radiocarbon analysis, and accounting for differences in bulk density, an average soil creep rate of $1{\cdot}9\ \mathrm{mm\,yr^{-1}}$ was obtained (Benda and Dunne, 1987). This value is similar to the creep rate of $1{\cdot}6\ \mathrm{mm\,yr^{-1}}$ obtained in the Olympic Mountains of Washington by Reid (1981), and compares well with the range of soil creep values of $0{\cdot}5\ \mathrm{mm\,yr^{-1}}$ to $2\ \mathrm{mm\,yr^{-1}}$ (Young and Saunders, 1986).

Total sediment production in an average $0{\cdot}7\ \mathrm{km^2}$ first-order basin was calculated by summing the sediment delivered to the channel by landslides originating from seven bedrock hollows, and the sediment transported by soil creep along 248 m of a first-order channel over a period of 6000 years.This was also done for second-order basins ($0{\cdot}26\ \mathrm{km^2}$) which has an average of 6 bedrock hollows and a third first-order contributing basin along their 302 m length. This yielded a sediment production rate of approximately $28\ \mathrm{tons\,km^{-1}\,yr^{-1}}$ for first- and second-order basins.

Sediment input to first- and second-order channels in the presence of a 20 per cent fluvial export rate was calculated over respectively a 1500 year and 750 year period, the estimated average recurrence intervals of debris flows in first- and second-order basins. The majority (80 per cent) of sediment delivered to first- and second-order channels accumulates during the time between successive scouring debris flows. Sediment stored in first- and second-order channels between debris flows predicted by the sediment budget was respectively $1000\ \mathrm{m^3}$ and $1800\ \mathrm{m^3}$. The predicted sediment volumes are similar to the volumes of $1450\ \mathrm{m^3}$ and $2400\ \mathrm{m^3}$ measured in first- and second-order channels in the study basin. A more thorough discussion of the sediment budget is given in Benda (1988).

The total length of third-, fourth-, and fifth-order channels in the $30\ \mathrm{km^2}$ basin was 26 km; in this basin there were also 195 first-order basins, and 122 second-order basins. The number of hollows adjacent to both sides of alluvial channels was estimated using a hollow frequency of 1/100 m. Combining the sediment export from first- and second-order basins with soil creep and landslides from hollows yielded a total sediment export rate to alluvial channels for the $30\ \mathrm{km^2}$ basin of $43\ \mathrm{m^3\,km^{-1}\,yr^{-1}}$ or $48\ \mathrm{tons\,km^{-1}\,yr^{-1}}$.

Figure 5 displays the relative proportions of different processes of sediment supply as a function of basin order according to the sediment budget. Sediment supply to first-order channels is divided approximately equally between landslides from hollows and streamside soil creep processes. In contrast, the majority of sediment which accumulates in second-order channels between debris flows is supplied by mass wasting, 32 per cent from landslides and 38 per cent from debris flows (Figure 5). The debris flows which contribute sediment to second-order channels emanate from a third first-order tributary which intersects the lower portion of second-order basins. The lower gradients of second-order channels near their mouths and sharp junction angle between the first- and second-order channels promote deposition of debris flows.

Assuming no change in sediment storage over long time periods in fans, terraces, and levees as a first approximation, debris flows in first- and second-order channels are responsible for 68 per cent of the total sediment supplied to alluvial channels (Figure 5). In addition, landslides from hollows adjacent to alluvial channels account for 10 per cent of the sediment supply. The contribution of sediment from soil creep to alluvial channels is minor.

The transport of a majority of sediments (78 per cent) to alluvial channels by debris flows and landslides indicates a strong stochastic character in the supply of sediments to channels. The stochastic nature of sediment supply and routing is supported by field evidence. Observations of recent debris flows indicate that portions of alluvial channels adjacent to mouths of first- and second-order channels aggrade several metres

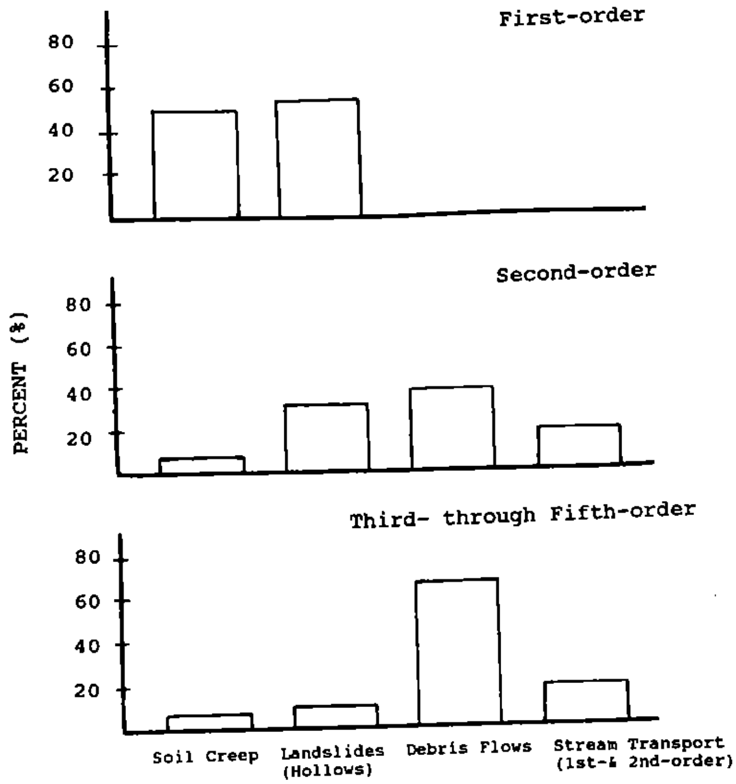

Figure 5. Proportions of sediment delivered to channels from various processes

following deposition by debris flows and, provided that no debris flows enter the channel upstream, the deposit subsequently erodes and develops a boulder lag deposit. Following depletion of the sediment from the deposit channel bedrock is exposed with some armouring by coarse sediments, such as cobbles and boulders. Boulders no longer buried undergo weathering by exfoliation and stream abrasion.

This pattern of channel aggradation due to debris flow is evident on a larger scale. In third-order basins in the study area, numerous first- and second-order basins have experienced recent road construction and timber harvest. Consequently, many debris flows in headwater basins have deposited sediment in third-order channels. Sediment from these multiple debris flows have coalesced into a relatively continuous sediment wedge between one and two metres in thickness. The sediment wedge is being routed down channel resulting in aggradation of a fifth-order channel.

Therefore, the sediment budget verified by field observations indicates that channels of third- through fifth-order in the study area alternate between conditions of channel aggradation and channel degradation. Figure 6 illustrates this cycle. Deposition of one or more debris flows in alluvial channels promotes a gravel-bed morphology (Figure 6). Subsequent fluvial erosion results in channel degradation which exhumes boulders and leads to a mixed boulder and gravel-bed morphology. Further degradation and weathering of boulders leads to a mixed bedrock- and boulder-bed morphology (Figure 6). Later debris flow(s) begin this cycle anew.

There is additional field evidence that the cycle of aggradation and degradation has occurred historically at the scale of entire fourth- and fifth-order basins. Fourth-order channels in undisturbed basins of Knowles Creek, with old growth forest cover, are characterized by boulder and discontinuous channel bedrock morphology. This suggests that during recent centuries fluvial sediment export from undisturbed first- and second-order basins and by soil creep along fourth-order channels has not delivered enough sediment to keep up with fluvial transport in these channels. In contrast, fourth- and fifth-order channels in a nearby basin entirely burned by wildfire in the late 1800s are aggraded with sediments up to three metres thick and a

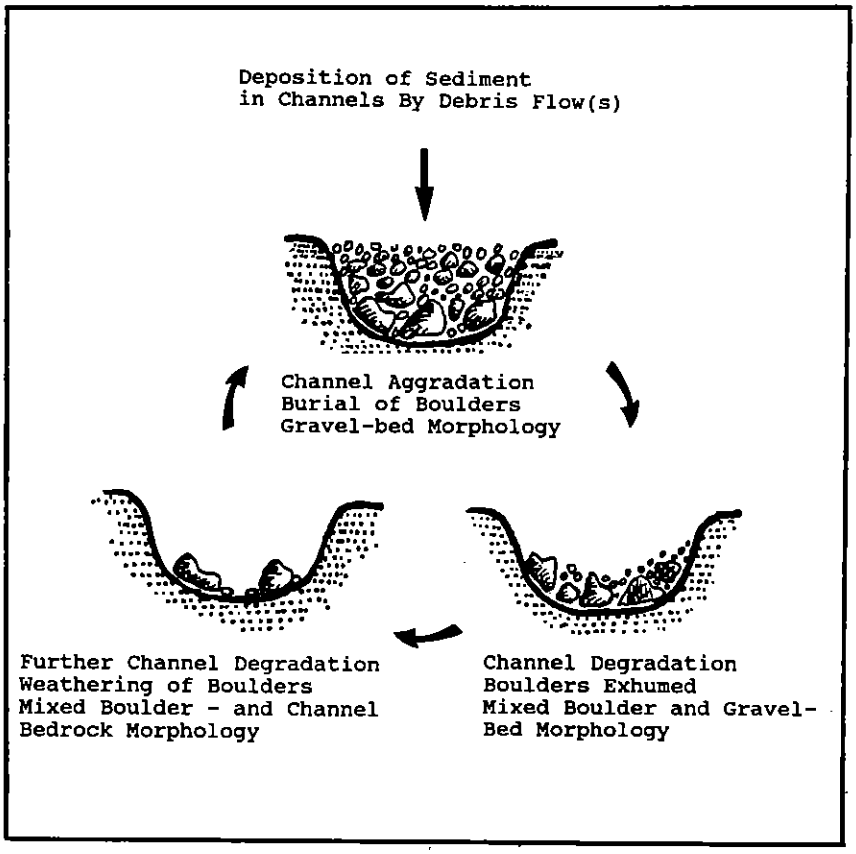

Figure 6. Cycle of alluvial channel aggradation and degradation due to the stochastic nature of debris flows

gravel-bed morphology dominates. Boulder deposits at mouths of headwater basins in these channels are buried beneath the sediment wedge. This implies that numerous debris flows may have occurred during intense rainstorms during the first few decades following wildfire when root strength was at its lowest.

The stochastic nature of sediment supply to alluvial channels which promotes temporal and spatial variations in the substrate morphology of channels is expected to apply to other landscapes where debris flows are an important process. The types of channel morphology which would result due to stochastic sediment supply will vary depending upon the nature of the lithology, morphology of the valley floor, and the frequency and magnitude of debris flows.

CONCLUSIONS

This field study has contributed to an understanding of how debris flows influence the morphology of streams in mountain environments. Of particular significance is the stochastic nature of sediment supply and routing which leads to cycles of channel aggradation and degradation and the resulting variations in channel-bed morphology. This aspect may have special relevance for studies involved with measuring sediment transport and various aspects of the morphology of channels in mountain terrains.

ACKNOWLEDGEMENTS

This study has been supported by the U.S. Department of Agriculture, U.S. Forest Service, Pacific Northwest Research Station, Anadromous Fish Habitat Work Unit, Corvallis, Oregon, and the Streamside Management Work Unit, Seattle, Washington. Suggestions by anonymous reviewers improved the manuscript.

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