Sediment routing by debris flow

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ABSTRACT Forty-six debris flows in a fifth-order basin
in the Oregon Coast Range, U.S.A.,were studied to
determine the role and significance of debris flows in
sediment routing. Dating of charcoal from basal
colluvium in three bedrock hollows and in one first-order
channel yielded an average landslide recurrence interval
of approximately 6000 years. This resulted in recurrence
intervals of debris flows in first- and second-order
channels of respectively 1500 and 750 years. These time
intervals were used to construct sediment budgets for
first- and second-order basins, which, in conjunction
with textural analyses of colluvium in hollows and
sediments in channels, indicated that first- and second-
order basins store the majority of sediments supplied to
them by mass wasting and release it periodically by debris
flows. The transport of a majority of sediments to third-
and higher-order channels by debris flows implies a
strong stochastic character in the routing of sediments
through basins that may include alluvial channels alter-
nating between conditions of aggradation and degradation
and armoring over time scales of 10^2 to 10^3 years.

INTRODUCTION

Though debris flows have received considerable study because they
are a significant form of erosion, their role in sediment routing
needs to be better defined. This is important for at least two
reasons. First, debris flows act as a sediment transport link
between hillslopes and alluvial channels and thus are important
factors in sediment budgets (Dietrich & Dunne, 1978), yet their
role in sediment routing has not been adequately quantified. Second,
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 sediment transport further downstream. Therefore,
knowledge of the role of debris flows in sediment routing will aid
in the construction of sediment budgets, and in interpreting the
morphology of channels and the measurements of sediment transport in
mountainous basins.
    To explore the role and significance of debris flows in sediment
routing we studied characteristics of 46 debris flows in a fifth-
order basin in the Oregon Coast Range, U.S.A. A sediment budget
for first- and second-order basins and textural analyses of sediments
in bedrock hollows and in channels were used in this endeavor.

STUDY CATCHMENT

The study was conducted in Knowles Creek basin, a fifth-order, 52 km^2 catchment in the central Oregon Coast Range. Knowles Creek basin is formed in massive, rhythmically bedded sandstones of the Tyee and Flournoy Formations (Baldwin, 1964). Soils and saprolite that range in depth from 0.25 to 0.5 meter mantle the 30 to 45° slopes. Hillslopes are sculpted into numerous bedrock hollows (Dietrich & Dunne, 1978, p.195) or zero-order basins (Tsukamoto et al., 1982) where colluvium accumulates to depths exceeding one meter. Drainage density of first- through fifth-order channels identified on aerial photos taken into the field was 4.6 km/km^2, but increased to 20 km/km^2 when the length of zero-order basins was added. The spatial frequency of the hollows was on the average 100/km^2.

   Annual precipitation of 160 cm, falling mostly as rain in the winter, supports dense stands of Douglas-Fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla). Clearcutting and road construction began in 1950 in the basin and continues to the present. Forestry practices and large storms have resulted in a spate of debris-flow activity during the last 30 years; 46 of these flows were studied during the course of this research.

DEBRIS FLOWS IN FIRST- AND SECOND-ORDER CHANNELS

Debris flows were initiated by landslides in bedrock hollows and on planar hillslopes. Of 36 debris flows for which initiation sites could be identified, 78% originated in bedrock hollows. Two to five bedrock hollows located at heads of first-order channels, and entering the channel at an acute angle, approximately less than 45°, were consistently responsible for triggering debris flows which scoured sediment from the floors of first-order channels. Landslides entering the channel from the other three hollows in a typical first-order basin came to rest in the channel at the mouth of the hollow and did not initiate debris flows.

   Between scouring debris flows, colluvium ravels and slides into channels,but streamflow is not competent to transport the coarse debris, which then forms an armor. Woody debris also falls into channels and protects the sediment from transport. Hence, channels tend to accumulate sediments that can only be eroded by debris flows.

   Debris-flow transport in Knowles Creek was confined to first-, second- and third-order channels. Twenty-two percent of debris flows were confined to first-order channels,and 78% of debris flows traversed both first- and second-order channel reaches.

   One of the most distinctive characteristics of debris flows in the study basin was that they scoured all sediments from first- and second-order channels. Erosion occurred in channels steeper than 10°, and the debris flows usually transported all sediments to low-gradient alluvial channels of third- and higher-order. Scouring of first-order channels increased the average volume of the mobilized sediment from 900 m^3 at the initial failure in the hollow to 2400 m^3 at the deposit. The amount of finer sediment washed

further downstream immediately after the debris flow is not known
but is thought to be relatively small because the texture of the
deposits is very similar to that of the mixture to be expected from
the landslide and the scoured bed material (see later). Debris
flows which continued to erode throughout second-order channels
increased the average volume at the deposit to 3800 m^3. These
volumes do not include organic material, such as trees, which added
approximately 500 to 1000 m^3 to deposits of debris flows.

Debris flows deposited sediments in channels and on floodplains,
terraces, debris fans, and footslopes along alluvial valleys of
third through fifth order, typically at tributary junctions.
Eighty-five percent of the deposits came to rest at tributary
junctions of first- and second-order channels with third- through
fifth-order channels. Deposits typically consisted of leading
edges of woody debris downstream of a 50 to 150 m long accumulation
of unsorted sediments dominated by gravels, cobbles and boulders.

Deposits of debris flows in channels were eroded by floodwaters,
but the boulders and cobbles resisted transport and remained as lag
deposits. Deposits outside of channels formed fans that often
induced channel bends at the mouths of second-order basins, and also
formed terraces and levees in third- through fifth-order valleys.

TEXTURE OF SEDIMENT IN BEDROCK HOLLOWS AND IN CHANNELS

Particle-size distributions of sediments stored in hollows, first-
and second-order valley bottoms, and fourth-order channels are
shown in figure 1. These distributions are the averages of a
combination of surface counts (Wolman, 1954) and bulk sieve analyses
for two sets of hollows, first- and second-order channels in two
different second-order basins, and surface and freeze-core sampling
(Everest et al., 1980) in four fourth-order streams. Boulders were
observed along the axes of hollows but were not sampled. Despite
the fact that no boulders were measured in hollows, the texture of
colluvium was very similar to that of the deposits in the first-
and second-order channels, suggesting that little selective
transport of fines occurred, either during the debris flow or in
later streamflow. Alluvium in the fourth-order channels contained
3% sand; boulders could not be sampled by the freeze-core method,
but our field observations indicated that boulders were found only
adjacent to fans at mouths of second-order basins in these reaches.
There is some selective removal of fines as sediment passes from
second- to fourth-order channels.

The shapes of 85% of the coarse particles in hollows and first-
and second-order channels were angular and subangular (Powers, 1953),
while 80% of alluvium in fourth-order channels were round and sub-
round. The sorting coefficients (Folk, 1974) of sediments from
hollows and first- and second-order channels were respectively
3.2, 3.6, and 3.5, all very poorly sorted, while the coefficient
averaged 1.9 for combined surface and subsurface sediments in
fourth-order channels. Deposits in first- and second-order channels
were highly consolidated due to relatively large amounts of fine
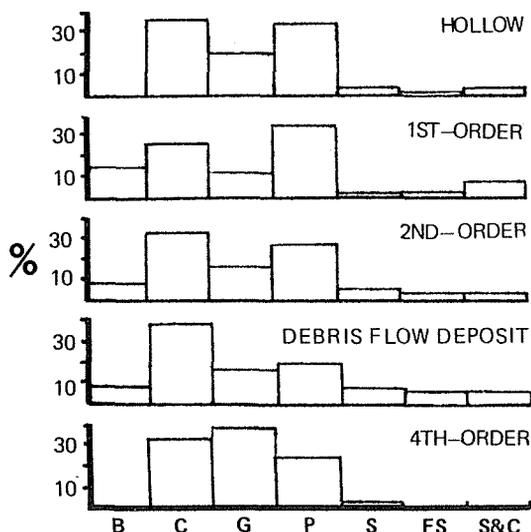sediments. Deposits in these channels displayed in-situ cohesion

Figure 1. Histograms of particle sizes. B=boulders
(> 512mm), C=cobbles (512-64mm), G=gravels (64-22mm),
P=pebbles (22-1mm), S=sands (1-0.25mm), FS=fine
sands (0.25-0.06mm), S&C=silt and clay (< 0.06mm).

of 20 to 40 kPa measured by shear graph (Bowles, 1984), whereas
those in alluvial channels were distinctly unconsolidated, with a
cohesion of zero.
    Cross sections of first- and second-order valley bottoms were
remarkably semi-circular, whereas those of higher-order, alluvial
channels were rectangular and had a width to depth ratio of 4 to 6.

SEDIMENT STORAGE IN FIRST- AND SECOND-ORDER CHANNELS

There was evidence that much of the sediment entering first- and
second-order channels from hillslope mass-wasting was stored as
colluvium rather than transported by fluvial processes. First, the
texture, shape, sorting and cohesion of sediments in first- and
second-order channels indicated that little fluvial sorting or
abrasion occurred and characterized these sediments as colluvium,
similar to sediments in bedrock hollows (fig.1). In contrast,
fourth-order channels were filled with coarser, better sorted,
rounded, and non-cohesive alluvial sediments. Second, sediment
budgets constructed for first- and second-order basins indicated
that first- and second-order channels stored rather than released
to streamflow the majority of sediments delivered to them from
hillslopes, including sediment input from hollows other than those
entering the heads of the channels at acute angles.
    Debris flows were initiated by landslides originating from two
to five bedrock hollows, referred to as trigger hollows, that were
located at heads of first-order channels (see figure 2). The debris
flows emanating from these trigger hollows scoured sediments from
first- and second-order channels.   Therefore, the ages

of colluvium stored in bedrock hollows that entered the heads of first-order channels at angles less than 45° can be used as indicators of the recurrence interval of debris flows in this terrain.
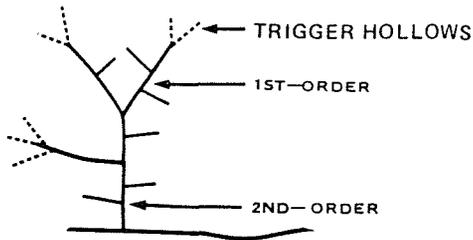

Figure 2.   An idealized channel network of a 2nd-order basin that displays the location of trigger hollows.

Dates from radiocarbon analyses of charcoal collected from the colluvium-bedrock contact at landslide scars in three widely spaced hollows indicate the duration of colluvium accumulation between successive failures. The dates were 1600, 6375, and 9400 years B.P. beneath colluvium 0.8, 1.25, and 1.8 m thick. A fourth charcoal sample was collected from the base of a partially eroded debris flow deposit in a first-order channel immediately downstream of a hollow which entered the valley orthogonally and presumably did not trigger scouring in a first-order channel. It yielded a date of 6300 B.P., indicating that accumulation began in the hollow at or before that time.

It is not possible to define well a mean value or a probability distribution of ages for the colluvial wedges in the hollows of the region from these four samples. However, it is possible to conclude from them that the inter-failure accumulation periods of colluvium in hollows lie in the range of thousands of years. These values are minimal because the recent failures were triggered by clearcutting, which therefore curtailed the natural accumulation period. The only conclusion which we draw from the dates is that the order of magnitude of the average accumulation period is thousands of years, and for the purpose of the following illustrative computation we use 6000 years, which is the mean of the four measured values.

We emphasize the need to define the entire probability distribution of ages and possible clustering of dates due to climatic fluctuations, as Reneau et al. (1986) have suggested for hollows in California. These issues will be addressed in our continued sampling and dating program, but it seems unlikely that future measurements can alter the order of magnitude of the mean. The important conclusion for the present purpose is that colluvium accumulates in hollows for thousands of years between failures, and we here use a mean of 6000 years based on four samples to illustrate schematically the consequences of this situation for sediment routing and channel conditions within fourth-order basins. We believe the principle is transferable to other humid mountainous

regions where debris flows affect the sediment budget and the
morphology and sedimentology of channels.

Colluvium is transported from hillslopes to bedrock hollows, to
landslide sites along stream margins, and to channels by a variety
of processes that include creep, treethrow, and animal burrowing.
These processes can be generalized by a continuous transport rate
over long time periods (Dietrich and Dunne, 1978). The long-term
transport rate can be used to estimate average rates of sediment
input to channels. By dividing the measured volumes of colluvium
within dated hollows by the ages of the colluvium in Knowles Creek
basin, and taking into account variations of colluvial bulk
densities between hillslopes and hollows and of soil depths
between sites, we computed downslope transport rates of 4.1, 5.8,
and 6.7 cm^3/cm/yr, which were equivalent to transport of the entire
soil column at speeds of 1.4, 1.9, and 2.4 mm/yr, respectively
(Benda, 1987). These values are similar to the creep rate of
2.5 mm/yr (based on two field measurements in other countries) which
Dietrich and Dunne (1978) employed in their construction of a
sediment budget for Rock Creek, Oregon. Reid (1981) obtained a
field measured rate of 1.6 mm/yr for transport by treethrow on an
average slope of 21° in the Olympic Mountains. In general, measure-
ments of soil creep in temperate maritime climates range between
0.5 to 2.0 mm/yr (Young and Saunders, 1986).

There has been much recent interest in the computation of
equilibrium and transient hillslope profiles subject to soil creep
(Carson and Kirkby, 1972). Such computations require the use of a
sediment transport equation of the form q_s = as, where q_s equals
the volume transport rate, a equals the transport coefficient, and
s equals the tangent of the slope angle. Our field data give values
of 12 to 21 cm^3/cm/yr for the a value in this equation.

An average of four trigger hollows (fig.2) lie at the head of
each first-order channel; the range is two to five. If the
colluvial wedges in hollows fail independently of one another
with an average recurrence interval of 6000 years, then (ignoring
the small probability of various combinations of simultaneous
failures because of the uncertainty in the original value) a
scouring debris flow travels down a first-order channel within an
average frequency of 1500 years.

We recognize that several trigger hollows in a first-order basin
may experience landslides simultaneously which will alter our
computed frequency of debris flows in first-order channels. In
first-order basins in Knowles Creek we have observed both a failure
in a single trigger hollow and failures in more than one trigger
hollow. However, it was not possible to accurately define the
probability of occurrence of simultaneous landslides in trigger
hollows because the majority of landslides occurred in clearcuts
and many of them were associated with roads. Our continuing
research program will address this issue, but in the absence of
being able to presently define the probability of simultaneous
failures, we will proceed with our computation assuming that
failures in trigger hollows are independent events.

Calculating the residence time of sediments in reservoirs, such
as those in first-order channels, can also provide an estimate for

the recurrence interval of debris flows. Average residence time can
be determined by dividing the total mass of sediment in the reser-
voir by the flux rate of sediment coming into the reservoir, assum-
ing steady state conditions over long periods of time (Dietrich et
al., 1982). In addition to the four trigger hollows which initiate
debris flows, an average first-order basin contains three other
hollows the failure of which, with a recurrence interval of 6000
years each, releases colluvium into the first-order channel but does
not generate debris flows. The long-term average flux of colluvium
from these hollows and the soil creep from hillsides which supply
sediment directly to the channel was 1.0 m^3/yr (Benda, 1987). The
average volume of sediment stored in a first-order channel was
estimated from field surveys of six channels to be 1850 m^3 (hillslope
bulk density). The calculated residence time for sediments in first-
order channels is therefore somewhat greater than 1800 years. This
value is approximately the same as the 1500 year recurrence interval
obtained for scouring debris flows.

   Some debris flows in first-order channels flowed entirely
through second-order channel reaches. On average, the bifurcation
ratio of second-order channels was three; only two of the first-order
channels (the ones at the heads of second-order channels, which
formed angles less than 45° with it) produced debris flows that
continued through second-order channels (figure 2). The probability
of a second-order channel experiencing a debris flow is thus twice
the probability of a debris flow in a first-order channel, that is
1/750 years, assuming that the occurrences of debris flows in two
first-order channels are independent of each other.

SEDIMENT BUDGET

A soil creep rate of 1.9 mm/yr, the average of the three calculated
creep rates, and recurrence intervals of landslides in bedrock
hollows of 1/6000 years, and debris flows in first-order channels
of 1/1500 years and in second-order channels of 1/750 years were
used to construct a sediment budget for first- and second-order
basins.

First-order basins

Total sediment production in an average first-order basin was cal-
culated by summing the sediment delivered to the channel by seven
bedrock hollows and the sediment transported by soil creep along
248 meters of first-order channel over a period of 6000 years. The
average of 900 m^3 of sediment per hollow equaled a sediment pro-
duction rate of 1.24 m^3/yr, and creep entering from hillslopes along
the channel equaled 0.47 m^3/yr, for a total of 1.70 m^3/yr
(Benda, 1987). This equals a sediment production rate for the
average area of 0.07 km^2 for first-order basins of 28 t/km^2/yr.

   This long-term rate of sediment production is approximately
one-third the value reported in the only other comparable study in
a small headwater basin. Swanson et al. (1982) calculated a total

sediment production rate of 77 t/km^2/yr, including 60 t/km^2/yr from
debris avalanches, for a 0.1 km^2 basin in volcaniclastic rocks in
the Cascade Range of Oregon. This difference in sediment yields
may arise for several reasons. First, volcaniclastic rocks are
weaker and may have faster weathering rates, and volumes of land-
slides are larger than those of the Oregon Coast Range. Second,
determination of sediment yields for debris avalanches and debris
flows by Swanson et al. (1982) as well as by other investigators
(Dietrich and Dunne, 1978; Reid, 1981; and Lehre, 1982) have
largely relied on summing occurrences of failures divided by the
sampled area and the time period of their occurrence. This
procedure has inherent difficulties that may lead to anomalously
high or low values that could significantly affect calculated
sediment yields. Influences on landslide occurrence of such
factors as major storms (such as the 1964 event) or forest manage-
ment activities could result in high values. Likewise, sampling
basins during a period of low storm frequency could result in low
values.

   Sediment input to first-order channels in the absence of fluvial
export was calculated over a 1500-year period, the estimated
average recurrence interval of debris flows in first-order basins.
Sediment input to channels by a creep rate of 1.9mm/yr from two
sides of a 0.5-meter thick hillslope along a 248-meter length of
first-order channel equaled a channel volume of 600 m^3. Our
observations indicate that hollows located adjacent to lower first-
order and second-order channels had junction angles close to 90°,
and the sediments released from them by landslides did not evolve
into debris flows but would come to rest and remain in storage in
channels. Therefore, sediment input from hollows was determined
by assuming that three of the seven hollows (minus four trigger
hollows) released landslides in an average 6000-year period and
stored this unsorted sediment in channels. Accordingly, during
1500 years, taking into account variations in bulk densities of
sediment between hillslopes (1160 kg/m^3) and hollows (1370 kg/m^3),
a sediment volume of 1275 m^3, or 14 t/km^2/yr, will accumulate in
first-order channels in the absence of export by fluvial processes
(Benda, 1987).

   The volume of sediment accumulating in first-order channels must
vary randomly from zero, immediately after a scouring debris flow,
to some large value at the end of a long period without scouring.
However, the most probable value of storage in any randomly chosen
year (such as the year of our measurements) would be the long-term
mean volume. The average of sediment volume measurements in six
first-order channels was 1570 m^3. The closeness of this measured
value to the expected long-term average may be fortuitous, but the
measurements confirm the sediment yield of approximately 1500 years
that would be generated between debris flows. These calculations
and the textural analyses indicate that first-order basins retain
the majority of the sediments delivered to them.

Second-order basins

A sediment budget was calculated for typical second-order basins
using the soil creep from hillslopes, the sediment from landslides
in hollows, and from a debris flow in the third first-order basin
(which typically intersects a second-order channel; see figure 2).
Such a debris flow entering orthogonally comes to rest at the
junction, contributing sediment from the intitial failure and that
scoured from the first-order channel to the sediment stored in the
second-order channel. In addition, for the purpose of these
calculations we assume that the two first-order basins at heads of
second-order channels retain all sediments (i.e. there is little or
no export by fluvial transport).

The estimated recurrence interval of a scouring debris flow in
a second-order channel is 750 years. During such a period land-
slides from the average of six hollows adjacent to second-order
channels should yield 800 m^3 and the third first-order basin should
yield 1.7 m^3/yr * 750 years = 1275 m^3. Soil creep along 302 m of
second-order channels should equal 430 m^3. This equals a combined
sediment volume (with channel bulk density) in second-order
channels during the 750 years between debris flows of 2125 m^3, or
12 t/km^2/yr.

The predicted sediment volume of 2125 m^3 was very similar to the
average measured volume (2400 m^3) of sediment in six second-order
channels. This measured quantity of sediment in second-order
channels, together with the similarity of its texture to that of
colluvium, support the idea that no debris flow has scoured this
channel for approximately 750 years, and also that there has been
little selective transport during that time.

It is not possible to accurately determine the amounts of
sediment exported by fluvial processes from first- and second-
order channels during their respective 1500 and 750 year periods
(during which times debris flows did not occur). Examining the
sediment histograms in figure 1, however, indicates that little
sediment transport by streamflow occurred in first- and second-
order channels in the fine and pebble sediment size classes,
those most likely to display the effects of fluvial sorting.
The similar amounts of fines in hollows and in first- and second-
order channels suggest a high sediment trapping efficiency in
these channels. There is a decrease in the amount of pebbles from
first- to second-order channels, and from second-order channels to
debris flow deposits (fig. 1). We interpret this reduction in
pebbles to abrasion and disintegration during transport, partic-
ularly by landslide and debris flow, based on our field observations
that pebbles have the greatest weathered volume to total particle
volume of any of the coarsest particles, and that they are easily
broken apart by hand to their constituent sand grains. This is
best displayed in debris flow deposits, where a significant
reduction in pebbles is accompanied by an increase in the amount
of fines.

There are several reasons why sediments delivered to first- and
second-order channels might resist fluvial erosion. First, our
observations of channels scoured by recent debris flows revealed

that channels commonly refill by landslides from hollows and hill-slopes.   Instantaneous delivery of thick deposits of coarse sediments to narrow channels greatly diminishes the opportunity for subsequent fluvial transport of a majority of the sediments at depth.   Second, these channels have large amounts of boulders and woody debris (including live trees) on surfaces of deposits, that greatly reduce the local channel gradient.   These obstacles, in combination with increased roughness, can reduce sediment trans-port.   Third, these channels drain small areas that produce small peak discharges that may be insufficient to transport the largest sediments.   This results in the formation of lag deposits on the surface of channels that would protect the underlying sediment from stream erosion.

There is additional evidence to indicate that episodic debris flows are the dominant sediment-transporting agent in first- and second-order basins.   Third- and fourth-order channels in un-disturbed subbasins of Knowles Creek, with old-growth forest cover, are dominated by bedrock substrate with the exception of boulder accumulations at fans, at least 3.5 centuries old, formed by pre-historic debris flows at the mouths of second-order basins.   In contrast, recent debris flows in the logged portion of the basin have filled similarly-sized channels with extensive deposits of sediments.   This suggests that during recent centuries sediment export by streamflow from unlogged first- and second-order basins and soil creep along third- and fourth-order channels has not delivered enough sediment to keep up with fluvial transport in these channels, resulting in a net removal of sediment from the higher-order channels.   If failures in hollows at the heads of first-order channels evolve into debris flows, they will scour the long-accumulated sediments from first- and second-order channels, and deposit them in third- and fourth-order channels, temporarily overtaxing the sediment-transport capacity and causing sediment aggradation in alluvial channels.

CONCLUSIONS

The transport of sediments from first- and second-order basins by debris flows dominates the input of sediment to alluvial channels. This implies that the routing of sediments to alluvial channels is strongly episodic, resulting in alluvial channels alternating   · between aggradation and degradation and armoring over time scales of 10^2 to 10^3 years.

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