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GEOMORPHOLOGY OF STEEPLAND HEADWATERS: THE TRANSITION FROM HILLSLOPES TO CHANNELS[1]

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ABSTRACT: Headwater streams comprise 60 to 80 percent of the cumulative length of river networks. In hilly to mountainous terrain, they reflect a mix of hillslope and channel processes because of their close proximity to sediment source areas. Their morphology is an assemblage of residual soils, landslide deposits, wood, boulders, thin patches of poorly sorted alluvium, and stretches of bedrock. Longitudinal profiles of these channels are strongly influenced by steps created by sediment deposits, large wood, and boulders. Due to the combination of small drainage area, stepped shallow gradient, large roughness elements, and cohesive sediments, headwater streams typically transport little sediment or coarse wood debris by fluvial processes. Consequently, headwaters act as sediment reservoirs for periods spanning decades to centuries. The accumulated sediment and wood may be episodically evacuated by debris flows, debris floods, or gully erosion and transported to larger channels. In mountain environments, these processes deliver significant amounts of materials that form riverine habitats in larger channels. In managed steepland forests, accelerated rates of landslides and debris flows resulting from the harvest of headwater forests have the potential to seriously impact the morphology of headwater streams and downstream resources.
(KEY TERMS: debris flow; debris flood; forest management; gullying; headwater streams; zero-order basin.)

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INTRODUCTION

This paper reviews the geomorphology of forested mountain headwater streams, drawing primarily upon research conducted in the Pacific Northwest region of North America. The paper is limited to channels classified as first-order and second-order (Strahler, 1952), at the upper limit of the drainage network. Where they are incised into the hillslope, such headwater channels are referred to as "gullies" (Bovis *et al.,* 1998). For a review of the fluvial geomorphology of larger forest streams, see Hassan *et al.* (2005).

Headwaters comprise 60 to 80 percent of the cumulative length of the drainage network (Schumm, 1956; Shreve, 1969) (Figure 1A). Consequently, for the forest industry and its regulators, headwater streams present a management dilemma because of their sheer number and extent. For example, a 30 m wide buffer strip on each side of all channels throughout a humid mountain drainage network with a drainage density of 5 km/km^2 would encompass approximately 30 percent of all the land area.

Headwater streams have received less study than larger rivers primarily because the latter are associated with well recognized resources, while headwater streams generally lack obvious resources, in particular fish, and are difficult to access and work in. In part because of an absence of knowledge, headwater streams have received little protection from land management activities. In many areas, riparian reserves are not mandatory for headwater streams without fish. In contrast to fishless headwater streams, for example, fish bearing streams may have a buffer zone of width generally between 5 and 50 m, varying with jurisdiction and stream conditions.

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Because of the increasing interest in forest ecosystems, studies of headwater streams are on the rise. Research into headwater hydrology and geomorphology is increasing the understanding about how small streams differ from larger ones. The hydrology of small catchments has received considerable study to elucidate the linkages between subsurface hillslope runoff and channelized flow (e.g., Tsukamoto, 1973; Dieterich and Anderson, 1998; Sidle *et al.,* 2000). The susceptibility of headwater streams to scouring by debris flows and gullying has placed these small channels in a spotlight, especially following major storms and fires (Figure 1B, 1C) (Hack and Goodlett, 1960; Kelsey, 1980; Schwab, 1998; Benda *et al.,* 2003b). Recently, the geomorphological and ecological relations between headwater streams and the remainder of the network have received considerable attention (Benda and Dunne, 1997b; Nakamura *et al.,* 2000; Gomi *et al.,* 2002). This understanding is leading to new forest management perspectives (Reeves *et al.,* 1995; Muchow and Richardson, 2000). For example, the Oregon Department of Forestry mandates forest buffers along certain headwater streams in state forests in the Oregon Coast Range to ensure that debris flows, when they occur, deliver large wood to fish-bearing streams, as does the U.S. Northwest Forest Plan on federal lands.

The paper begins by reviewing a range of criteria that have been used to define headwater channels. Next, the inputs of sediment and wood and their transport and storage mechanisms are covered. Special attention is given to material transport by debris flows and floods. Using material transport and storage as context, the morphology and classification

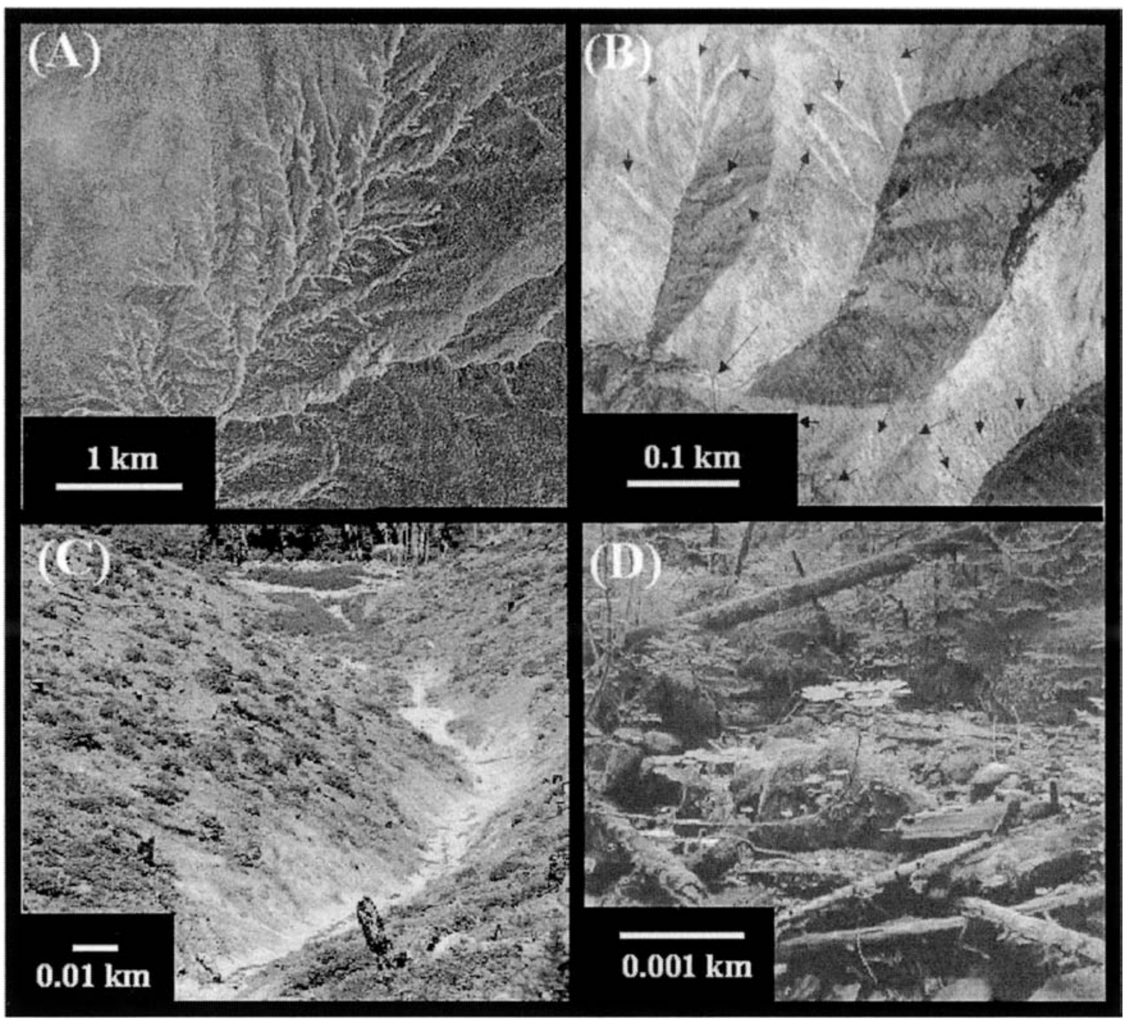

Figure 1. Photographs of Headwater Streams in Mountain Drainage Basins at Four Different Spatial Scales. (A) Headwater drainage network, showing massive landsliding and debris flows in the Central Cordillera National Park, Dominican Republic, following Hurricane Georges; (B) Channels scoured by post-fire landslides and debris flows in the Oregon Coast Range; (C) Debris flow in a clear-cut, Oregon Coast Range; and (D) Typical channel morphology in a headwater stream, Oregon Cascade Range.

of headwater streams are reviewed. Finally, the influence of headwater streams on the morphology of larger, fish bearing channels and the implications of headwater streams for forest management are discussed.

MOUNTAIN HEADWATER STREAMS: DEFINITION

Although headwater streams can be found in a range of environments, including mountain meadows and lowland basins, attention is focused on the steepest portions of montane channel networks (Figure 1D). Currently, there is no universally accepted definition of headwater streams, and a simple definition is likely to be insufficient. Based on channel network analysis, Strahler (1957) defined headwater streams as first-order and second-order channels in the Horton-Strahler channel ordering system. However, the classification of stream order is usually based on map analysis and depends on map resolution. Most topographic maps do not include the majority of headwater channels that might be present in the landscape (Morisawa, 1957; Meyer and Wallace, 2001). This biases the identification of headwater channels, especially under a forest canopy. For example, analysis of drainage networks in Indian Creek, Oregon (Mapleton 1:62,500 quandrangle), and Sockeye Creek, British Columbia (Birkenhead Lake 1:50,000 quadrangle), yields drainage densities of 2.65 km/km^2 and 1.52 km/km^2, respectively, with corresponding constants of channel maintenance of 190 m and 330 m. Indian Creek lies in the Oregon Cascades, while Sockeye Creek is in the Coast Mountains of British Columbia. The summary figures all seem unreasonably low given the occurrence of identifiable stream courses every 100 m or so on hillsides. If it is supposed that the first-order streams are systematically absent, the constants of channel maintenance would become 98 m and 155 m; the latter figure still seems to be high.

Based on hydrological and geomorphological processes, Hack and Goodlett (1960) and Hack (1965) divided headwater systems into four zones: slopes; zero-order basins; transitional channels between zero-order basins and first-order streams (ephemeral or temporal); and first-order and second-order streams. In this context, "zero-order basin" refers to unchanneled and intermittent swales (Tsukamoto, 1973; Dietrich *et al.,* 1987). Steep unchanneled swales that are susceptible to shallow, rapid landslides have also been referred to as "bedrock hollows" (Dietrich and Dunne, 1978) and are a major initiation point for debris flows in low order streams. A hydrogeomorphic framework that identifies the transition to channeled flow has been proposed for such hollows by Sidle *et al.* (2000). The transition from an unchanneled swale to a channel has been referred to as the "channel head" (Dietrich and Dunne, 1993) and is typically a storm period or persistent seepage point. Montgomery and Buffington (1997) elaborated on the transitional channels of Hack and Goodlett (1960) by defining "colluvial channels" as ones flowing over a colluvial fill and exhibiting weak fluvial sediment transport. These elaborations make the anatomy of steep headwater channels seem fairly clear (Figure 2). Nevertheless, in glaciated regions, streamhead hollows frequently are replaced by bedrock headwalls.

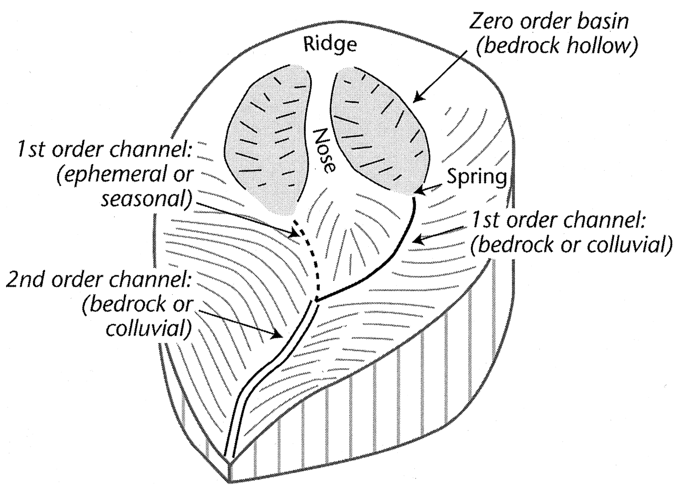

Figure 2. Anatomy of Headwater Drainage Systems (after Hack and Goodlett, 1960; Montgomery and Buffington, 1997).

Quantitative criteria by which headwater channels may be discriminated remain uncertain. From a hydrological perspective, Burt (1992) suggested defining headwater catchments as those that have flow strongly controlled by runoff production at the hillslope scale. Woods *et al.* (1995) suggested that the transition between hillslope and channel hydrological processes occurs at about 1 km^2. However, mixing of runoff from a range of hydrologic source areas obscures the process-response relation in small basins (Burt, 1992). Considering sediment transport criteria, Church (2002) noted that, according to the usual Shields competence criterion, channels with gradients greater than 7.5 percent cannot retain sediment that is not stored behind logs or boulders and suggested that this condition might be adopted as a suitable criterion for steep channel.

Montgomery and Foufoula-Georgiou (1993) developed a model for partitioning the landscape into drainage and slope regimes that includes hillslopes, unchanneled valleys, debris flow dominated channels, and alluvial channels. They reported an inflection in a log-log drainage area-slope relation at about 1 km^2 (20 to 30 percent slope). This inflection correlates well with the transition from debris flow dominated, colluvial channels to lower gradient channels flowing over stream (alluvial) deposits. Recent research by Stock and Dietrich (2003) interpreted the inflection point as a topographic signature of valley incision by debris flows. Consistent with these findings, May and Gresswell (2004) documented a transition from debris flow fans to alluvial fans in the Oregon Coast Range at a drainage area threshold of approximately 1 km^2, based on fan stratigraphy. Along larger mountain valleys, small headwater basins that often range in drainage area between 0.1 and 0.3 km^2 represent a more common transition between colluvial channels and alluvial channels (Benda and Dunne, 1997a).

In the foregoing discussion it is supposed that the extent of "colluvial channels" coincides with the extent of debris flow dominance in determining channel morphology. This assumption is reasonable insofar as fluvial processes have, by definition, limited efficacy in colluvial channels so that, if the channel is ever to be substantially cleared of sediment, then rapid mass wasting phenomena must be invoked. But many headwater channels on moderate gradients may remain permanently choked with colluvium while, on the other hand, it is possible for debris flows – once ignited – to travel well into normally "fluvial" channels.

The transition between debris flow dominated and alluvial channels likely depends on the local slope-area relation, which is influenced by climate, uplift rates, rock strength, and history (e.g., glaciation) of the fluvial system. Drainage basins dominated by debris flows may approach 10 km^2 in area in the glaciated southern Canadian Rockies (Kostaschuk *et al.,* 1986) and the British Columbia Coast Ranges (VanDine, 1985) and exceed 3 km^2 in northwestern British Columbia. These areas have high relief and long slopes. Therefore, absolute scales are only regionally indicative. Moreover, the transition between alluvial and colluvial processes may be a time dependent phenomenon. Debris flows and gully erosion that degrade headwater channels to bedrock can extend fluvial processes upslope for periods of decades while slow filling of channels with debris (including soil) will extend the colluvial/alluvial transition downhill (Dunne, 1991).

RECRUITMENT, TRANSPORT, AND STORAGE OF SEDIMENT AND WOOD IN MOUNTAIN HEADWATER STREAMS

Inputs of Sediment

In mountainous headwaters, channels are commonly bordered by steep slopes and rock walls. Such landforms are often referred to as gullies or hollows. Steep side slopes adjacent to channels typically reflect high rates of stream incision relative to surrounding hillsides (Kelsey, 1980). Sediment input to headwater channels is often dominated by mass wasting from the slope, including streamside landslides and small rotational failures, and the streams are said to be directly coupled to adjacent hillslopes. For example, in the Oregon Cascade Range, mass wasting processes (not including earthflows) accounted for 78 percent of sediment inputs into one first-order stream (Swanson *et al.,* 1982). A sediment budget constructed for first-order and second-order basins in the Oregon Coast Range estimated that streamside landslides accounted for 60 to 70 percent of long term sediment input (Benda and Dunne, 1987). In the Capilano watershed, British Columbia, Brardinoni *et al.* (2003) reported that 87 percent of slope failures entered first-order and second-order streams. Roberts and Church (1986) and Campbell and Church (2003) explored the nature of sediment delivery from hillslopes to stream channels and found that sediment delivery to coupled stream channels was dominated by mass wasting events.

Soil creep is another important process of sediment delivery into headwater streams. Soil creep occurs by rheological strain of the soil column and biogenic transport, the latter process including animal burrowing and tree throw, creating pit and mound topography. These processes can be a significant source of downslope soil movement (Reid and Dunne, 1996; Heimsath *et al.,* 2001). Estimates of soil creep integrated through the soil column range from 0.001 m/yr to 0.01 m/yr in the Oregon Coast Range (Dietrich and Dunne, 1978) to 0.002 m/yr in the Oregon Cascades (Swanson *et al.,* 1982) to 0.02 m/yr in northern California (Benda *et al.,* 2002). The range in soil creep rates is reflected in differences in watershed erosion rates that range from approximately 70 to 5,000 $t/km^2/yr$ from central coastal Oregon to coastal northern California.

Surface erosion along gullies can also supply sediment to headwater streams, particularly following scour of valley walls by debris flow. Bovis *et al.* (1998) reported an average surface erosion rate of 0.013 m/yr in headwater gullies in the Queen Charlotte Islands, British Columbia. The highest values recorded (0.025

m/yr) occurred in streams that had recent debris flows. More generally, inputs of soil to headwater streams were twice as high in stream valleys scoured by recent debris flows (Bovis *et al.,* 1998).

Inputs of Wood

Steep topography adjacent to headwater streams can promote a high influx of wood. In second-order channels in the Oregon Coast Range, landslides delivered over 50 percent of instream wood, which was recruited from distances of 20 to 60 m (approximately one to two tree heights) from the channel edge (May and Gresswell, 2003a). In headwater streams in the Oregon Cascades, most of the wood also originated from mass wasting (Nakamura and Swanson, 1993). Bank erosion and tree mortality can also be important tree recruitment processes to small streams (Benda *et al.,* 2002).

Defining the distances to wood sources in a riparian zone is important in the design of forest management and regulatory policies. The proportion of wood (either in length or volume) that enters a channel typically declines with increasing distance from the channel edge (McDade *et al.,* 1990); however, if streams are bordered by hardwood stands and large conifers grow farther back from the channel margin, the proportional volume of wood can increase with distance from the channel (May and Gresswell, 2003a). A cumulative distribution plot that indicates how the proportion of wood input changes with distance from the channel is referred to as a "source-distance curve" (McDade *et al.,* 1990). Source distance curves are sensitive to different recruitment processes and tree species composition (Benda *et al.,* 2002) and to the condition of the riparian forest. May and Gresswell (2003a) found that source distances of wood also were higher in headwater streams compared to larger, alluvial channels, presumably because of the strong downslope transfer effect.

Fluvial Transport and Storage of Sediment and Wood

Theoretically, steep channels that have a high sediment transport capacity should not accumulate sediment (Montgomery *et al.,* 1996; Church, 2002). Large wood supplied by riparian forests, however, can become the retainer for sediment accumulation in otherwise bedrock channels in Idaho (Heede, 1985), Oregon Coast Range (Benda, 1990; May and Gresswell, 2003b), coastal British Columbia (Millard, 2001), and coastal Alaska (Gomi *et al.,* 2001). Even in managed forests, small woody debris in headwater streams can store significant volumes of sediment (Jackson and Sturm, 2002). In addition, boulders can physically obstruct sediment transport and cause a local reduction in slope and surface water velocity, initiating a series of positive feedbacks that increase the sediment retentiveness of headwater channels. Coarse grained beds also have the potential to dissipate a substantial portion of the stream's energy and to trap sediment in interstitial spaces and behind stable bed forms such as interlocked cobble and boulder deposits (Chin, 1989, 1999; Grant *et al.,* 1990; Zimmerman and Church, 2001).

Numerous field studies have indicated that fluvial sediment transport is a minor process in headwater streams. It has been estimated that suspended load and bed load transport are responsible for only 20 to 30 percent of the long term sediment flux from headwater streams in humid landscapes (Swanson *et al.,* 1982; Grant and Wolff, 1991; O'Connor, 1993). In a study in the Queen Charlotte Islands, Bovis *et al.* (1998) estimated that fluvial transport accounted for approximately 10 percent of the long term export based on an average debris flow frequency of 50 years. In headwater streams in Idaho, Megahan (1975) determined that less than 10 percent of sediment stored behind obstructions appeared as sediment yield over a three-year period, suggesting a high rate of sediment retention. In first-order and second-order channels in the Oregon Coast Range, sediment deposits had a particle size composition more similar to hillside soil than to alluvial sediment, which also suggested high retention (Benda and Dunne, 1987). The capacity of headwater streams to retain sediment is also supported by an experimental study in which fine sediment was introduced into the upper reaches of a headwater stream in an attempt to mimic inputs of road surface erosion (Duncan *et al.,* 1987). For particles between 0.5 and 2 mm in diameter, only 10 percent of sediment was transported distances of 95 and 125 m to larger channels over one season. Approximately 35 percent of particles between 0.5 and 0.063 mm were transported out of the headwater stream. However, finer sediment (< 0.063 mm) was transported through the study reaches, presumably because it remained continuously suspended.

High sediment retention in headwater streams is believed to result from limited streamflow, a stepped longitudinal profile that limits shear stress, high surface roughness (associated with wood and boulders) that limits fluvial sediment transport and encourages sediment deposition, and accumulation of cohesive (landslide) sediments that is difficult to entrain (Benda and Dunne, 1987; Bovis *et al.,* 1998). The low potential for fluvial sediment transport in steep headwater channels favors the episodic occurrence of large debris flows that scour the long accumulated material (discussed below). There may, however, be local exceptions to the well documented and regionally pervasive high sediment retention in headwater streams. Modeling of sediment storage and routing in certain types of headwater morphologies (moderate gradient and broad valley floors) predicts a slow leakage of sediment from headwaters to larger, alluvial channels because of the storage capacity provided by large logjams (Lancaster *et al.,* 2003). On the other hand, little sediment may accumulate in headwater channels in friable lithologies where rock debris rapidly disintegrates to fine material and in drier regions where woody debris does not contribute effective channel blockage.

When fluvial sediment transport does occur in headwater streams, the transported load can be significantly coarser than in larger rivers. In headwater channels where fluvial transport has been recorded using bed load and suspended load samplers, the ratio of bed load to total load ranged between 0.21 and 0.63 in watersheds of 0.2 to 1 km^2 (Fredriksen, 1970; Gomi and Sidle, 2003). The higher bed load/total load ratios compared to those of larger rivers (where ratios commonly are less than 0.1) stems, in part, from the proximity of headwater streams to coarse textured sediment sources. For further discussion of fluvial sediment transport see Hassan *et al.* (2005).

The transport of large wood in headwater streams may be even more restricted than transport of sediment. Numerous studies have documented that wood shorter than bankfull width is much more likely to be transported by streamflow (e.g., Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993; Martin and Benda, 2001). Because headwater streams commonly have widths of only a few meters and contain wood that is substantially longer, transport in them of large wood by streamflow would be very rare (e.g., Millard, 2001). This leads to large buildups of wood in headwater streams (Hogan *et al.,* 1998; Jackson and Sturm, 2002; May and Gresswell, 2003b). However, in certain topographies, debris flows are an effective agent for scouring stored wood from headwater channels and transporting it downstream to larger channels.

Debris Flow Transport of Sediment and Wood

The steep topography that commonly surrounds headwater streams creates a high potential for landsliding in headwater channels and therefore for debris flows, a phenomenon that also has been referred to as "debris torrents" in some regions (VanDine, 1985). In small, steep, bedrock floored, unchanneled swales, soil may accumulate for thousands of years before being evacuated by shallow failures (Dietrich and Dunne, 1978; Benda and Dunne, 1987; Sidle, 1987; Reneau and Dietrich, 1991). Tree roots help stabilize landslide sites when soils are thin (< 1 m) but, over time, increasing soil development (> 2 m) contributes to eventual failure (Sidle, 1987; Dunne, 1991). Several models exist for predicting initiation of shallow landslides and debris flows (Montgomery and Dietrich, 1994; Dietrich *et al.,* 1995; Wu and Sidle, 1995; Pack *et al.,* 1998; Casadei *et al.,* 2003). The difficulty of reconstructing the history of landsliding, and therefore the soil depth, in any particular bedrock hollow limits the ability to predict landsliding at the scale of individual sites, and so one is practically restricted to predicting failure statistically within a population of sites (Benda and Dunne, 1997a).

Debris flows are defined as rapid to extremely rapid flows of saturated, nonplastic soil, rock, and vegetation (containing upwards of 70 percent solids by weight) occurring in a steep channel (Hungr *et al.,* 2001; Hungr, 2005). They are initiated by liquefaction of landslide debris concurrently with failure or immediately thereafter as the soil mass and reinforcing roots break up. They are distinguished from debris avalanches, which may develop similar characteristics on unconfined slopes, though not all practitioners or literature make this distinction. Confinement – as in a channel – considerably increases the mobility of debris flows, which can travel hundreds of meters in steep channels and are considered to be the most damaging form of mass wasting to aquatic resources in the short term; they also present the greatest risk to lives and property (Costa, 1984). As a geomorphic agent, debris flows are responsible for carving the narrow valleys in which headwater streams are located in steep, unglaciated terrain (Stock and Dietrich, 2003).

The path of a debris flow in a headwater basin can be divided into several distinct zones: initiation, which typically occurs on hillsides steeper than 60 percent gradient and often in convergent areas, but can occur on much lower gradients; erosion, which usually occurs in confined mountain channels on slopes between 15 and 60 percent; transport (without significant additional erosion) on gradients between 25 percent and approximately 10 percent; and deposition, which may begin on gradients around 25 percent but may extend to less than 3 percent. Hungr *et al.* (2005) give a review that demonstrates that there are no generalized limits for these process zones. Rather, zone limits depend upon the rheology of the debris flow mixture, especially on the readiness with which the material may drain, and on the size of the flow. Several models predict the transport and deposition of debris flows (Benda and Cundy, 1990; Fannin and Wise, 2001).

Erosion of sediment and organic matter in headwater streams can increase the volume of the initial landslide by tenfold or more, enabling debris flows to become more destructive as their volume increases with distance traveled (Fannin and Rollerson, 1993). Debris flows can entrain up to 50 m^3/m (though commonly less than 10 m^3/m) of material per meter of headwater stream length, and they deposit it in colluvial fans where channel gradient is reduced and valleys widen, commonly at junctions of first- and second-order channels with higher order streams (Hungr *et al.,* 1984; Benda and Cundy, 1990; Fannin and Rollerson, 1993; Bovis *et al.,* 1998; Hungr *et al.,* 2005).

Due to the branching nature of channel networks, recurrence intervals of debris flows may become shorter with increase in stream order (Reneau and Dietrich, 1987). For example, an individual first-order stream may have a recurrence interval of several centuries, but a second-order stream may have a recurrence interval of approximately half of that (Benda and Dunne, 1987; May and Gresswell, 2004) because of confluence of first-order source channels. Loss of tree root strength can increase the likelihood of debris avalanches and debris flows particularly in regions where winter storms can produce high pore water pressures (Ziemer, 1981).

Long term sediment storage in headwater channels and episodic scouring by debris flows creates high variability of sediment storage and transport characteristics of headwater streams over time (Figures 1C and 1D). For example, in a study of the temporal patterns of wood and sediment storage in headwater channels in the British Columbia, Bovis *et al.* (1998) showed that sediment storage increased nonlinearly following a scouring debris flow, in association with the supply of large wood. This study also illustrated how sediment transport in headwater channels can taper off over time due to an increasing accumulation of roughness elements that increase sediment storage. The tapering off of sediment export in concert with an accumulation of sediment and wood is associated with the evolution of the channel from one dominated by bedrock to one interspersed with deposits of wood, boulders, and sediment over at least one to two centuries (e.g., Reneau and Dietrich, 1991; May and Gresswell, 2003b).

Gullies and Hyperconcentrated Flows

Some headwater channels are susceptible to episodic erosion by floodwater, especially following fire (Meyer *et al.,* 2001; Cannon, 2001; Cannon *et al.,* 2001) (Figure 1B and Figure 3). Fires, which can completely burn small watersheds, can create hydrophobic (water repellent) soils (e.g., Letey, 2001), which may yield extraordinary surface runoff, particularly in regions where thunderstorms rain on dry soils (Cannon *et al.,* 2001; Istanbulluoglu *et al.,* 2003). Intense precipitation following hot burns can lead to extensive rill erosion and extreme discharge events in small, soil filled channels (Heede, 1988).

Sediment transport during extreme hydrologic events may cause floods to bulk with fine sediment up to 20 percent or more by volume (a condition referred to as a “hyperconcentrated flow”) (Costa, 1988); or to mobilize a gravel-transporting “debris floods” (Hungr *et al.,* 2001), which can evacuate all, or most of the sediment that has accumulated in unchanneled swales and headwater channels and this scouring of headwater streams can create upslope gullies, which focus further runoff and scour. Large pulses of sediment are delivered to downstream channels and valley floors (Klock and Helvey, 1976; Meyer *et al.,* 1995; Robichard and Brown, 1999; Istanbulluoglu, 2002). The physics of debris floods is not well understood but the process can be defined rheologically as an intermediate stage between debris flow and streamflow (Hungr *et al.,* 2001).

Another mechanism responsible for gully formation in headwater streams is the upstream progression of headcuts (Dewey *et al.,* 2002). A headcut is an abrupt change in elevation, or a “knickpoint,” at the leading edge of a gully (Bennett, 1999). Headcuts drive channel incision by migrating up the channel until a resistant structure such as large wood is encountered. Headcut progression results in a bottom-up control on channel erosion, which is the opposite of floods and associated hyperconcentrated flows that develop near the gully or channel head (a top-down control on gully formation). Once established, gullies can become chronic sources of fine sediment delivered by chronic fluvial transport processes over many years (Nistor and Church, 2005).

MOUNTAIN HEADWATER STREAMS: CHANNEL MORPHOLOGY AND CLASSIFICATION

Headwater streams containing a mixture of boulders, logs and soil and stretches of bedrock, including waterfalls, defy reach scale characterizations designed for larger channels dominated by fluvial processes (Jackson and Sturm, 2002). In addition, channel morphology can change significantly within a relatively short period. Vegetation that grows on deposits changes channel morphology by enhancing sediment storage (Abt *et al.,* 1993) and by narrowing

Figure 3. Post-Fire Gully Erosion in the North Fork Boise River, Idaho (photo taken by Steven Toth).

channels. Headwater gradients may vary locally from 50 percent to 1 percent (Heede, 1972). Moreover, shallow or ephemeral flow in headwater streams is commonly insufficient to mobilize material that is delivered from the adjacent hillslopes, resulting in headwater streams being filled with colluvium. Finally, a headwater channel can be transformed in minutes by debris flow from one filled with logs, boulders, and soil to a bedrock dominated one.

Therefore, headwater streams can generally be classified as "colluvial channels" (Montgomery and Buffington, 1997). A classification by Whiting and Bradley (1993) focuses on channel geometry necessary for debris flow initiation and propagation and channel properties that would affect sediment transport by floods (flow depth, slope, roughness, etc.). For instance, gradient thresholds must be exceeded for debris flow transport to occur (Benda and Cundy, 1990; Fannin and Wise, 2001), and particle size also dictates what flow magnitude is needed to fluvially transport sediment (Heede, 1972; Hassan *et al.,* 2005), although the application of the latter is complicated by the "stepped" nature of headwater streams.

Recently, Halwas and Church (2002) presented a classification and description of channel units in small, high gradient mountain channels in Vancouver Island, British Columbia (see also Grant *et al.,* 1990; Hawkins *et al.,* 1993). Falls, bedrock cascade, boulder cascades, rapids, chutes, riffles, glides, and pools were described according to their bed slope and dominant bed material texture and organization. Multiple pairwise comparisons showed that these morphologies have mean bed gradients distinct from each other and from those of corresponding units in larger streams. High gradient units (e.g., bedrock, boulder cascades) were dominant in steep, largely non-alluvial channels, whereas low gradient units (e.g., riffles, rapids) were common in semi-alluvial segments with more gentle slopes. Interestingly, wood did not play a large role in the morphology of these very small channels; mostly, wood spanned them above the level of hydraulic action.

In general, the spatially and temporally diverse morphology of relatively steep headwater channels precludes a strict classification according to process, since fluvial processes may dominate at certain times (although be relatively minor in terms of long -term sediment export), and debris flow scoured channels may characterize the system during other times. Consequently, channel morphology is highly sensitive to the time since the last scouring event, and it should vary with channel gradient and, hence, position in the headwater network (Figure 4). Therefore, debris flow prone headwater channels could be classified according to both spatial and temporal characteristics.

EFFECTS OF MOUNTAIN HEADWATER STREAMS ON LARGER CHANNELS AND RIVER ECOSYSTEMS

Episodic Sediment and Wood Supply

Punctuated erosion in hilly to mountainous terrains is common in coastal rainforests of Pacific Northwest, British Columbia, and Alaska (Dietrich and Dunne, 1978; Sidle and Swanston, 1982; Swanson *et al.,* 1982; Roberts and Church, 1986; Gomi *et al.,* 2004), in the Appalachian Mountains (Hack and Goodlett, 1960; Williams and Guy, 1973; Costa, 1974; Gupta and Fox, 1974; Jacobson *et al.,* 1989; Miller, 1990; Eaton *et al.,* 2003), in the intermountain region, and in southwestern highland deserts (Wohl and Pearthree, 1991; Meyer *et al.,* 1995; Kirchner *et al.,* 2001). Episodic erosion in headwater streams does not always result in an episodic flux of sediment to larger rivers because sediment can be stored on fans (May and Gresswell, 2004) and behind large logjams that effectively capture sediment (Lancaster *et al.,* 2003).

Nevertheless, because headwater streams are so abundant, they provide a substantial portion of the sediment and organic material that forms riverine habitats throughout whole drainage networks, and most of it is delivered during brief periods. For example, in the Queen Charolotte Islands, Schwab (1998) documented six storms over 180 years (1810 to 1991) that triggered debris flows in first-order and second-order channels that mobilized 77 percent of all sediment originating from all forms of mass wasting in a fifth-order basin. In Idaho, cosmogenic dating of stream sediments revealed an apparent long term

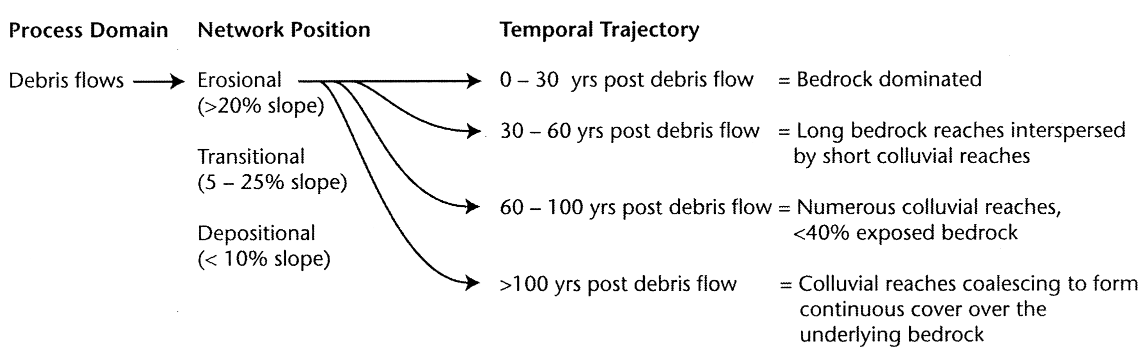

Figure 4. A Classification of Debris Flows in Headwater Streams Indicating the Slope Gradient Thresholds for Erosion, Transition Between Erosion and Deposition, and Deposition. Also shown are the temporal trajectories at different time intervals following scouring debris flow (after May and Gresswell, 2003b).

average erosion rate (10^3 years) 17 times higher than erosion rates measured over 10 to 84 years, indicating that mountain sediment yields are highly episodic and dominated by large erosional events in headwater basins (Kirchner *et al.,* 2001). Field studies by Meyer *et al.* (2001) also suggest that episodic erosion following fire was equivalent to several thousand years of sediment yield at the rates measured over short term sediment trapping and gauging in an Idaho batholith watershed. An important implication of these studies is that conventional programs of sediment transport and yield measurements are likely to miss the most significant events occurring in headwater channels unless they are continued for a long time.

Recognition that dynamic processes, termed "disturbances," can alter the physical environment and change ecosystem structure represents a maturing theme in the study of rivers (Pickett and White, 1985; Resh *et al.,* 1988; Reeves *et al.,* 1995) This framework coincides with a growing interest within the past several years in applying principles of landscape ecology to river corridors, leading to the consideration of "riverscapes" (Ward *et al.,* 2002) and spatially distributed fluvial processes and features that create habitat heterogeneity for aquatic and riparian species (e.g., Fausch *et al.,* 2002; Wiens, 2002). In the context of these emerging ecological frameworks, disturbances in forested mountain environments, such as landslides, debris flows, floods, and gully erosion in headwater channels, can be viewed as components in habitat formation, creating many landforms and associated habitats (i.e., fans, terraces, floodplains with secondary channels, large logjams, and boulder deposits) in channels and on valley floors (Hogan *et al.,* 1998; Benda *et al.,* 2004) that are not formed during more quiescent times. It should be clear, then, that long term habitat creation often entails shorter term disturbance. Shorter term negative effects of episodic erosion must be considered in the context of longer term goals for land management.

Headwater Tributary Junctions

The effects of headwater streams as sediment sources are most evident at the confluences of headwaters with larger channels where debris flow and alluvial fans form. In the context of "riverscapes," confluences of headwater streams with larger channels can be viewed as nodes of habitat heterogeneity (Benda *et al.,* 2003a). The ecological effects of debris flows have been documented in several studies, providing perspective on both destructive and constructive effects. Over short periods, debris flow deposits have destructive effects, including immediate burial of existing habitat and direct mortality of aquatic biota (Everest and Meehan, 1981); increased fine sediment deposition within gravels onsite and downstream that can suffocate fish eggs in gravel (e.g., Everest *et al.,* 1987); increased bed load transport and lateral channel movement due to heightened sediment supply that scours fish eggs; a loss of pools that reduces rearing habitat (Frissell and Nawa, 1992; Hogan *et al.,* 1998); loss of aquatic insects (Lamberti *et al.,* 1991); and the dewatering of pools due to channel aggradation (May and Lee, 2004). Over longer periods, constructive effects of debris flows on aquatic systems may include formation of temporary ponds that become occupied by rearing fish and beavers (Everest and Meehan, 1981); depositional areas that release nutrients from buried organics in anaerobic environments (Sedell and Dahm, 1984); deposition of woody debris that creates sediment wedges (Hogan *et al.,* 1998); deposition of boulders that trap sediments and create complex habitats (Benda, 1990; Reeves *et al.,* 1995); formation of wider valley floors that contain larger floodplains (Grant and Swanson, 1995); creation of gravel deposits and large pools (Benda *et al.,* 2003a); and increased biological productivity (Roghair *et al.,* 2002). Spates of debris flows contribute to watershed scale habitat diversity, including the structure and composition of riparian forests (Nakamura *et al.,* 2000; Nierenberg and Hibbs, 2000). In semi-arid environments, post-fire gully erosion in headwater streams can construct alluvial fans that create wide floodplains, side channels, and terraces in larger valleys (Benda *et al.,* 2003b).

The more or less irregular spacing of headwater confluences and the effects they have on the morphology of larger channels suggest that aquatic habitats in larger channels are not uniformly distributed. For example, in a fifth-order basin in the Oregon Coast Range, boulder deposits, logjams, and temporary ponds are focused at confluences with low order streams (Everest and Meehan, 1981; Benda, 1990). In third-order through fifth-order channels in the Queen Charlotte Islands, Hogan *et al.* (1998) showed that large logjams with associated sediment wedges occurred irregularly, their spacing dictated by the spatial distribution of headwater streams. Similarly, in third-order and fourth-order channels in managed basins in the Olympic Peninsula, Benda *et al.* (2003a) showed that the highest densities of large wood, large pools, wide floodplains, and gravel substrate occurred in the immediate vicinity of low order channels at a spatial scale of approximately 200 m (based on the average spacing of headwater streams).

In addition to tributary junction effects, spates of debris flows and gully erosion can lead to widespread (kilometer scale) channel aggradation. Large influxes of sediment can construct wide floodplains and side channels (Nakamura, 1986; Roberts and Church, 1986; Wohl and Pearthee, 1991; Miller and Benda, 2000; Benda *et al.,* 2003b) and can set the stage for subsequent terrace development. Fluctuations in bed load supply may also be manifest as coherent waves or pulses that migrate downstream (e.g., Madej and Ozaki, 1996; Miller and Benda, 2000). However, sediment pulses may also disperse downstream (Lisle *et al.,* 1997, 2001; Sutherland *et al.,* 2002). Channel aggradation can also occur preferentially upstream from large wood jams (Montgomery *et al.,* 2003) and culluvial and alluvial fans (Benda *et al.,* 2003a,b).

Long Term Perspectives of Headwater Dynamics

Sediment supply from headwater streams impacts the form and function of larger, fish bearing channels (Everest and Meehan, 1981; Swanson *et al.,* 1987; Benda, 1990; Rice *et al.,* 2001; Gomi *et al.,* 2002). Given the relatively short time horizons of many natural resource studies, a common perspective is that episodic erosion and the punctuated supply of sediment and wood during storms or following fires and timber harvest is inherently destructive. However, the longer term consequences of erosion, including the material transfer from headwaters to larger channels, cannot be evaluated over short time horizons (Dunne, 2001).

Most of the field studies reviewed in this paper represent snapshots in time. For a longer term perspective, the role of headwaters on larger, fish bearing streams can be examined using simulation models. Benda and Dunne (1997b) used numerical models to illustrate how, over decades to centuries, a probabilistic sequence of rainstorms coupled with a sequence of fires generates a stochastic sequence of erosion and sediment transport events in headwater streams in a 200 km^2 basin in the Oregon Coast Range. The model predicted that the probability distribution of sediment export from headwaters would be right-skewed and characterized by frequent small sediment fluxes punctuated by infrequent large fluxes (triggered by fires and storms). Other predictions suggest that following spates of storms and fires, sedimentation would be concentrated in certain parts of the network, particularly near tributary junctions, and that those deposits would interfere with transport of sediment and wood from upstream.

Other models are being used to understand the long term effects of events such as fires, landslides, debris flows, wood recruitment, and gully erosion on the behavior of watersheds. Lancaster *et al.* (2000, 2003) constructed models to show how debris flows exported sediment and wood. Because sediment was captured by logjams, there was less sediment delivery downstream, at least in the short term. Stochastic simulation is being utilized to create visual graphics of watershed dynamics over decades to centuries as an educational tool (USFS, 2002). Simulation modeling is also being extended to more arid environments where post-fire gully erosion is an important process (Gabet and Dunne, 2003; Istanbulluoglu *et al.,* 2003). Theoretical models of wood recruitment over centuries have also been developed (Benda and Sias, 2003). For example, in the Oregon Coast Range, debris flows in headwater streams are predicted to contribute approximately 10 percent of the century-scale wood budget in larger channels. However, these long term predictions have not been tested, and short term studies suggest that wood recruitment from debris flows can be a much larger component of the wood budget (May and Gresswell, 2003a; Reeves *et al.,* 2003).

Influences of Land Management on Mountain Headwater Streams

Timber harvest, road networks, and severe fires influence the frequency, magnitude, and composition of mass wasting in headwater systems. Landslide frequency typically increases after construction of forest roads and timber harvest (summary of early work in Sidle *et al.,* 1985; Jakob, 2000; Guthrie, 2002; Brardinoni *et al.,* 2003). An increase in landslide frequency often leads to an increase in debris flow frequency (Swanson and Dyrness, 1975; Swanson *et al.,* 1977). Harvesting of large, old trees adjacent to headwater streams (and maintaining the managed forest in younger, smaller trees) can reduce the supply of large instream wood in headwater systems. In the glaciated landscapes of British Columbia and Alaska, rerouting of the drainage system as the result of forestry activities (principally road building) is responsible for triggering landslides and may also contribute to gullying.

Increasing the frequency of debris flows in managed forests can alter the morphology of larger river systems. May (2002) documented a higher proportion of wood delivered by debris flows (relative to other sources of wood in the mainstem channel) for catchments that had been clear-cut. Montgomery *et al.* (2003) found that debris flow deposits assumed a greater relative importance in logjam formation in managed forests due to the inability of small, locally recruited wood from young riparian forests to provide stable foundations for logjam development. Debris flows in managed forests on the Olympic Peninsula led to increases in large wood, gravel deposits, and large pools in proximity to low order confluences (Benda *et al.,* 2003a). These studies imply increased delivery by debris flows of residual large wood in the decades following forest harvest, but the effect is widely expected to give way to smaller flows carrying smaller wood later.

If forest management activities are increasing the occurrence of debris flows, then headwater streams may be transformed to a bedrock state more frequently. The reduction of wood recruitment to headwater streams due to harvesting of large trees should lead to a reduction in sediment storage. Hence headwater streams may become more of a chronic source of sediment to downstream, fish bearing systems because bedrock streams have a high transport efficiency and the lack of large wood reduces their storage capacity (May and Gresswell, 2003b). The effect of more punctuated versus less punctuated delivery of sediment and wood from headwater to larger channels in managed versus unmanaged watersheds is not well understood. A reduction in large wood in headwater systems will also reduce the amount of large wood that can be delivered to larger streams by debris flows, thereby negatively impacting fish habitats (Reeves *et al.,* 1995), though possibly not for decades.

Land management influences on headwater streams go beyond mass wasting. Because headwater watersheds are small, it is feasible to log all or a significant proportion of low order catchments at one pass. Given that headwater catchments in some regions are rain-on-snow or snow dominated watersheds, there is significant potential to increase peak flows (Berris and Harr, 1987; Jones and Grant, 1996; Jones, 2000). Moreover, roads can alter runoff patterns and supply more flow to headwater streams (Wemple and Jones, 2003). Increases in flood magnitude have the potential to further increase erosion and sediment transport.

It is imperative that forest managers recognize the role played by headwater systems in the supply of water, sediment, and nutrients downstream, understand the intensity of impacts from forestry practices, and adopt practices to ensure the integrity of headwater systems. Management practices need to ensure that when disturbances do occur, the essential processes (e.g., coarse sediment and large wood inputs, nutrient and fine organic matter transfers) and linkages (e.g., floodplain connections) that promote channel reorganization and habitat recovery are not disrupted (Reeves *et al.,* 1995; Ebersole *et al.,* 1997).

CONCLUSIONS

Small headwater channels have received considerably less study than larger streams. Reasons include lack of fish, difficult access, and generally harsh working conditions. Based on their sheer numbers in a watershed, headwater channels have important consequences for the ecology of larger streams and rivers (Gomi *et al.,* 2002). In addition, the protection of headwaters has important ramifications for the forest industry and the regulatory agencies.

A rapidly growing body of literature analyzes the hydrology, geomorphology, and ecology of headwater systems. In many important respects, headwater streams are different from their larger counterparts located lower in river networks. Headwater streams can be highly retentive of both sediment and wood, and in steeplands the episodic release of material may occur infrequently during debris flows, flash floods, and gully erosion. Because of high sediment and wood storage, the morphology of steep headwater channels is an amalgam of logs, soil, boulders, bedrock, and waterfalls, and the morphology varies temporally due to debris flows and flash floods. Therefore, headwater streams defy simple classification of their morphology. Although the episodic and catastrophic nature of sediment and wood transport in headwater channels often appears as an environmental threat to downstream resources, the supply of sediment and wood by mass wasting processes is an important ecological process in both unmanaged and managed forests.

Because of their episodic dynamics, the behavior of headwater streams may best be understood over large spatial and temporal scales. For example, it is difficult to evaluate effects of a debris flow or post-fire gully erosion in a single headwater channel over only a few years. Because of the century long time scales involved in the disturbance of headwater streams, event histories are best understood over decades to centuries at the scale of the river basin (i.e., incorporating hundreds to thousands of headwater channels). Only then can the inherently stochastic nature of sediment and wood supply from hillslopes and headwater channels be put into the context of the geomorphological and ecological behavior of entire mountain drainage basins. Only with that understanding can viable, long term management strategies be developed for headwater landscapes.

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