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Disturbance regimes of stream and riparian systems — a disturbance-cascade perspective

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Abstract:

Geomorphological processes that commonly transport soil down hillslopes and sediment and woody debris through stream systems in steep, mountainous, forest landscapes can operate in sequence down gravitational flowpaths, forming a cascade of disturbance processes that alters stream and riparian ecosystems. The affected stream and riparian landscape can be viewed through time as a network containing a shifting mosaic of disturbance patches — linear zones of disturbance created by the cascading geomorphological processes. Ecological disturbances range in severity from effects of debris flows, which completely remove alluvium, riparian soil and vegetation along steep, narrow, low-order channels, to localized patches of trees toppled by floating logs along the margins of larger channels. Land-use practices can affect the cascade of geomorphological processes that function as disturbance agents by changing the frequency and spatial pattern of events and the quantity and size distribution of material moved. A characterization of the disturbance regime in a stream network has important implications for ecological analysis. The network structure of stream and riparian systems, for example, may lend resilience in response to major disturbances by providing widely distributed refuges. An understanding of disturbance regime is a foundation for designing management systems. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS debris flows; disturbance; landslide; riparian zone; sediment transport; stream ecosystems

INTRODUCTION

Ecosystem disturbances, processes that kill some organisms while providing opportunity for establishment of others, play vital roles in ecosystem development (Sousa, 1984; Pickett and White, 1985). Although many disturbance ecology studies have focused on the ecological effects of individual types of events, e.g. biotic response to landslides or wildfire, broader scale questions, such as influences of disturbance regimes within terrestrial landscapes and stream networks, are receiving increased attention.

The movement of materials through watersheds has been characterized in several ways. Sediment budget, routing and flux modelling studies have been concerned with sediment movement and storage at flood event to geological time-scales of resolution (Swanson *et al*., 1982; Reid and Dunne, 1996; Benda and Dunne, 1997a, b). Individual process types, such as debris slides, debris flows and woody debris transport, have been investigated through inventory and modelling studies (Sidle *et al*., 1985; Braudrick *et al*., in press). These geomorphological processes are important disturbance agents in many mountain and riverine landscapes (Nakamura, 1986, 1990; Nakamura and Kikuchi 1996). To our knowledge, however, no study has addressed specifically the sequencing of geomorphological processes that can operate as stream and riparian disturbances in mountainous terrain.

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A variety of geomorphological processes may be linked sequentially, forming 'disturbance cascades', which can propagate down gravitational flowpaths from hillslopes through stream networks, especially in geologically unstable, mountainous areas, such as Japan and the western USA. These disturbance cascades commonly occur during major floods when various types of landslides and transport of woody debris take place. The sequence of transport processes involves transformations from one process to another in response to changes in topographic influences and in content of water and other constituents. Each process can leave a distinctive disturbance imprint on stream and riparian biota and habitat.

Understanding of these disturbance cascades is useful in several respects. This understanding helps define the disturbance regimes in which these ecosystems have evolved and provides context for interpreting effects of land-use practices. Also, the disturbance cascade perspective puts an important focus on the critical, but little-studied transitions from one process to another. Traditionally, geomorphologists and ecologists have focused on individual processes (e.g., fire, landslides), rather than successive linkages among processes in time and space.

Our objectives in this paper are to elucidate:

(1) temporal and spatial patterns of geomorphological processes that disturb stream ecosystems in mountain landscapes;
(2) factors controlling the distribution of these processes, including transitions from one geomorphological process to another in disturbance cascades down a stream network;
(3) effects of land use and stream network structure on this disturbance regime;
(4) ecological implication of geomorphological disturbance.

We approach this task by developing a conceptual model based on experience in Japan and the Pacific Northwest of the USA. Results of field studies in these sites exemplify important relationships common to these steep, wet, forested, geologically unstable landscapes typical of temperate forest biomes of the Pacific Rim and elsewhere. This discussion of the disturbance-cascade concept emphasizes a distinctive suite of processes that are involved in movement of water, soil, sediment and large woody debris. These processes are particularly important components of disturbance regimes of stream and riparian systems in these landscapes, but elsewhere other processes may form disturbance cascades.

DISTURBANCE CASCADE: CONCEPTUAL MODELS

Geomorphological processes

The sequences of geomorphological processes that function as a disturbance cascade in the mountain landscapes we consider can be initiated by small, rapid debris slides from hillslopes and channel head environments or by large, slow moving earthflows (Figure 1). Small (10–1000 + m^3) debris slides (1a in Figure 1) triggered on hillslopes may move into steep, headwater stream channels, move rapidly (10 m s^{-1}) down those channels as debris flows (2), and ultimately deliver coarse sediment and logs to larger streams. Some debris flows may enter fourth- and fifth-order channels and be immediately entrained in part as rafts of large woody debris floated by stream flow in the large channel. Alternatively debris flow deposits may form jams at the confluence with larger channels (A). These jams may break during floods, triggering a flood surge (3), which pushes a mass of floating woody debris in a congested mode of transport (Coho, 1993; Braudrick *et al.*, in press). Transport of woody debris accumulations from debris-flow runout or from jam break-up may terminate in distinct accumulations of wood or may simply dissipate in the downstream direction as the transported wood is left along the banks in a series of smaller accumulations, such as wood levees (Wondzell and Swanson, 1999; Johnson *et al.*, 2000, this issue).

Disturbance cascades can also begin where large (1–100 + ha), slow-moving (millimetres to many metres per year) earthflows (4a) gradually constrict channels, increasing the potential for streambank erosion and streamside slides (5) during high flow events (Sidle *et al.*, 1985; Swanson *et al.*, 1985). The frequency of streamside

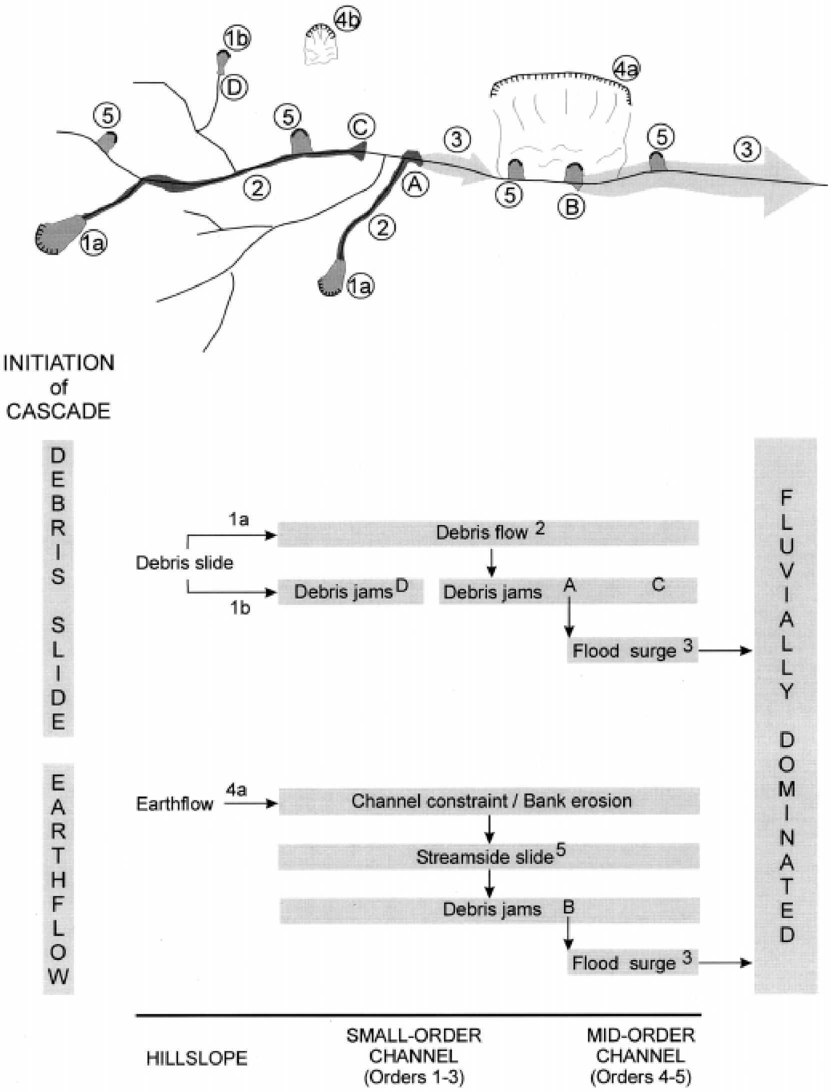

Figure 1. Schematic representation of interaction among processes (numbered) operating in disturbance cascades. Letters denote depositional sites at the end of debris slide and debris flow paths

slides at an earthflow toe may be proportional to the rate of earthflow movement constricting the channel (Swanson *et al*., 1985). These streamside slides can deliver > 1000 m^3 of sediment and trees, which form temporary (B) dams that can break up, triggering flood surges (3) downstream for a kilometre or more (Coho, 1993; Swanson and Swanston, 1977). The associated woody debris may move in a congested manner (sensu Braudrick *et al*., in press), accentuating its ability to disturb riparian vegetation (Johnson *et al*, 2000, this issue).

Transitions among these geomorphological processes are critical aspects of evaluating their potential to propagate through stream and riparian networks. The sequence of processes can be interrupted at any point along the flowpath. Debris slides may come to rest where they reach a channel (1b) and form a debris jam (D) or on areas of low gradient, such as slump benches or road surfaces, before reaching streams. Debris slides that do reach streams may stop if, for example, their angle of incidence is nearly

90°, so they climb the opposing hillslope and simply slump back into the channel without converting momentum in the down-channel direction (e.g. A in Figure 1) (Benda and Cundy, 1990). Debris slides that transform into debris flows down channels change character as valley wall constraint on flow width changes, thereby altering flow depth, and as sediment and woody debris is entrained along the channel. Debris flows may stop at critical points (C) where channel slope is too low to sustain flow; channel direction changes abruptly by 70° or more (Benda and Cundy, 1990); valley floor width increases, so flow thickness decreases, thus increasing resistence to flow; composition of the moving mass changes, making it impossible to sustain motion; or the debris flow encounters obstructions to flow, such as standing trees or road fills that can act as dams.

Most debris flows entering fourth- and fifth-order channels abruptly change character because the volume of flow in the receiving stream is great enough to separate constituents of the debris flow. The large wood may float downstream as a congested raft of debris, which may dissipate as wood is left in levees along the channel and a large jam may form at the terminus of a runout path.

Some mass movement processes do not trigger a cascade of events leading to stream and riparian disturbance (Figure 1). Slumps and debris slides on hillsides (4b) and cutslope slides along roads, for example, may not lead to delivery of soil to channels. Streamside slides along areas of wide valley floor may simply deflect the channel laterally without major downstream consequence.

One effect of the complexity of the disturbance cascades depicted in Figure 1 is that similar outcomes can arise from different sequences of processes. Flood surges, for example, can arise from extensions of the wood component of debris flow deposits down larger channels (Wondzell and Swanson, 1999) as well as the break up of streamside slide deposits.

Ecosystem disturbances

Processes involved in the disturbance cascade leave somewhat distinctive ecological disturbance patterns. Debris flows commonly produce high-severity disturbance by stripping riparian vegetation along their path and depositing woody debris, live vegetation, soil and sediment at their snouts (Swanson *et al*., 1998). Congested log transport downstream of debris flows can also result in severe disturbance to riparian vegetation, as indicated by removal of 30-yr-old red alder (*Alnus rubra*) trees of 20–40 cm diameter in some Pacific Northwest streams in a recent major flood (Swanson *et al*., 1998; Wondzell and Swanson, 1999). In larger channels, where wood transport is typically more dispersed, disturbance to riparian vegetation exhibits more varied severity with zones of removed, toppled and standing trees (Nakamura and Kikuchi, 1996; Johnson *et al*., 2000, this issue). In some sites floated woody debris appears to have been a critical factor in transfer of the force of flowing water against tree stems, leading to their toppling, but remaining partially rooted. Disturbance effects on aquatic habitat have not been characterized systematically, but debris flow tracks have conspicuously high severity disturbance in small channels. Flood flows and sediment transport in larger channels create a mixture of disturbance severity indicated by sites with a scour or deposition exceeding 1 m to patches of sediment with a surviving partial cover of moss, revealing little disturbance of benthic habitat (Swanson *et al*., 1998). These disturbance patterns appear to leave refuges of relatively undisturbed streambed and secondary channel environments. Thus, the disturbance cascades described here appear to produce a gradient of decreased overall severity and increased variability of severity of stream and riparian disturbance in the downstream direction.

DISTURBANCE CASCADES: EFFECTS OF LAND-USE PRACTICES

Land-use practices can potentially affect all stages of the disturbance cascade. Initiation sites may be affected and modification of channels along the flowpath may enhance or disrupt runout of disturbance-producing geomorphological processes. Land-use effects on earthflows and associated streamside slides are less well known and potentially less significant than effects on disturbance cascades initiated by debris slides. Here we consider some of the potential effects of various forestry and engineering practices on key components of the disturbance cascade.

Forest cutting can increase the frequency and volume of debris slides (Sidle *et al.*, 1985). One explanation is that tree roots that contribute to soil strength on marginally stable sites die and decay following cutting of many tree species (Sidle *et al.*, 1985; Tsukamoto and Minematsu, 1987). Thus, root strength may decrease markedly over several years after cutting, and clear-cut hillslopes become more susceptible to debris slides. Another potential effect of forest removal is to increase snow accumulation and melt rate with resulting increase in water discharge to soil and streams during rain-on-snow events (Harr, 1981). An increase in slides contributes to an increase of debris flow disturbances in low-order streams.

Roads can significantly alter hillslope hydrology and the distribution of soil and rock materials on slopes, increasing the rate of debris slide initiation. Cut-and-fill slopes constructed where roads traverse steep slopes commonly experience debris slides at a frequency that greatly exceeds background rates observed in forested areas in similar terrain (Sidle *et al.*, 1985). Road cuts can intercept groundwater drainage networks, collecting groundwater from upslope areas and diverting it into drainage ditches as surface water (Wemple *et al.*, 1996). This water enters the stream network where roads cross channels. The expanded drainage network moves groundwater into the stream network more rapidly than would the subsurface drainage system and could increase peak flows during storms (Jones and Grant, 1996). An abrupt supply of surface water from drainage ditches may contribute to debris slide initiation in headwater areas, where unstable colluvium accumulates (Montgomery, 1994). The net effect can be increased triggering of disturbance cascades.

Roads can affect the character of debris flows along their runout paths. Large debris flows moving at high velocity down steep channels may incorporate road fills, thus adding to debris flow volume (Wemple, 1999). In other circumstances, such as on the gentler slopes of valley floors, roads may function as small dams that stop debris flows before they can reach the main channel (Wemple, 1999). In this case roads not only trap sediment, but also interrupt the sequence of disturbance processes.

Removal of woody debris from channels can occur either by intentional extraction for wood value or inadvertently by removing streamside forest, hence the principle source of future wood supply. Change in woody debris may affect the disturbance cascade by affecting the volume and size distribution of wood transported by mass movement or fluvial processes. Very large pieces of wood, for example, can retard movement of organic and inorganic material, but absence of wood in debris flows limits the propagation of wood-mediated disturbance into large channels.

Straightening and channelization of meandering and anastomosing streams reduces the complexity of disturbance processes and biotic responses in areas of wide valley floors. Channel simplification may decrease bank erosion and the frequency of streamside debris slides at stream bends. However, shortening a meandering stream steepens the bed gradient, which results in an increase in stream power to transport sediment. Resulting degradation of the streambed may make adjacent slopes unstable and may set the stage for bank failures or streamside debris slides. If the channelized reach is connected with a natural reach downstream, having a gentle bed gradient, sediment can be deposited in this reach and the streambed may aggrade. Aggradation reduces the carrying capacity of a stream channel, resulting in innundation of lowland areas with sediment-laden flood water (Nakamura *et al.*, 1997).

Reservoirs and erosion-control check dams constructed for regulation of streamflow and sediment discharge have a great impact on the routing of water, sediment and wood through watersheds. In general, these structures restrict natural, seasonal and yearly fluctuations in discharge of water and sediment to downstream reaches. The stabilized hydrological regime downstream of reservoirs is completely different from the natural flow and disturbance regimes, which promote regeneration of certain vegetation species and maintenance of habitat for fish and aquatic invertebrates (Poff *et al.*, 1997). Sediment control dams built in low-order streams may alter the volume and size distribution of debris flows and, thus, restrict debris flow runout. The net effect of these structures is to moderate and even truncate the cascade of disturbance processes involving mass transport of sediment and wood.

EXAMPLES FROM NORTHERN JAPAN AND NORTHWESTERN USA LANDSCAPES

Effects of hillslope and valley floor geomorphology on disturbance regimes are illustrated by case studies in the upper Blue River watershed in the Cascade Mountains of western Oregon, USA, and Mount Tokachi and the Saru River basin in Hokkaido, Japan. Long-term records of debris slides and flows are a valuable study asset of the Oregon site. Japanese streams are intensively regulated and subject to frequent disturbance by volcanic debris flows, which have been well studied, so these channels illustrate disturbance and land-use effects at the downstream end of the disturbance cascade.

Disturbance-cascade processes in small channels — a USA example

A 50-year record of debris slide, debris flow and other landslide activity in the Blue River watershed provides a basis for examining the spatial patterns of the disturbance cascade concept (Dyrness, 1967; Swanson and Dyrness, 1975; Swanson *et al.*, 1998; Snyder, 1999; Swanson, unpublished data). The Blue River Watershed is steep terrain underlain by tertiary volcanic rocks, and ranges in elevation from 350 to 1640 m. Annual average precipitation of over 2500 mm supports dense conifer forests. In this area debris slides commonly begin in steep (30–40°), concave slopes and occur with higher frequency in clear-cut and roaded areas than in forested areas with similar soil and topographic conditions (Swanson and Dyrness, 1975). Similarly, earthflow landforms are associated with easily deformed, clay-rich soil and bedrock (Swanson and James, 1975). This watershed, therefore, can be zoned in terms of geomorphological disturbance regimes with high and low potential to experience the various disturbance-cascade processes, based on soil, bedrock and topographic conditions.

The extent of expression of the disturbance cascade can be assessed in terms of the probability of one process transforming to the next in the sequence, based on an observed history of events. To illustrate these relationships, we examine the linkages among the relevant processes occurring in the $>$ 50-year recurrence-interval flood of February 1996 (Figures 2 and 3). Debris slides, debris flows, streamside slides and flood surge events ($>$ 35 m^3 in volume) resulting from this flood were inventoried with field and aerial photographic interpretation in a 187 km^2 area in the upper Blue River watershed, including the Lookout Creek watershed, which encompasses the H.J. Andrews Experimental Forest.

The events of February 1996 were dominantly initiated by debris slides unassociated with earthflows (Figure 3). About 30% of the debris slides did not reach streams because they lodged on hillslopes or on roads. Nearly half (45%) of all the non-earthflow-associated debris slides transformed into debris flows down steep, first- through to third-order channels. Thus, about 70% of the initial population of debris slides and flows stopped on hillslope sites (26), at the slope–channel junction (19), in the channel at a downstream location (19), on roads (5), or on alluvial fans (6) before reaching large streams.

About 60% of all debris flows reached fourth- and fifth-order channels. Of these, seven debris flows traversed channels that experienced only one debris flow, and 15 debris flows occurred in channels with multiple events. In addition, five streamside debris slides occurred along debris flow paths and not associated with earthflows; but in most cases, we do not know their timing relative to debris flow passage and, therefore, do not show them in Figure 3. Only one distinct flood-surge event was observed (Wondzell and Swanson, 1999) (Figure 2), but others may have occurred in larger channels where their evidence was obscured by other flood effects.

Only 7 of 94 events inventoried occurred in association with earthflows, roughly reflecting the extent (about 10% of area) of earthflows in the analysis area; only the Lookout Creek part of the study area (Figure 2) has detailed mapping of earthflow terrain (Swanson and James, 1975), but we feel that this is representative of the entire area. Only one of these events was located at the toe of an earthflow encroaching on a larger channel (Figure 2). However, in major floods in December 1964 and January 1965 streamside slides at earthflow toes were much more common and resulted in a massive, wood-rich, flood-surge event that extended 1·5 km down Lookout Creek (Swanson and Swanston, 1977).

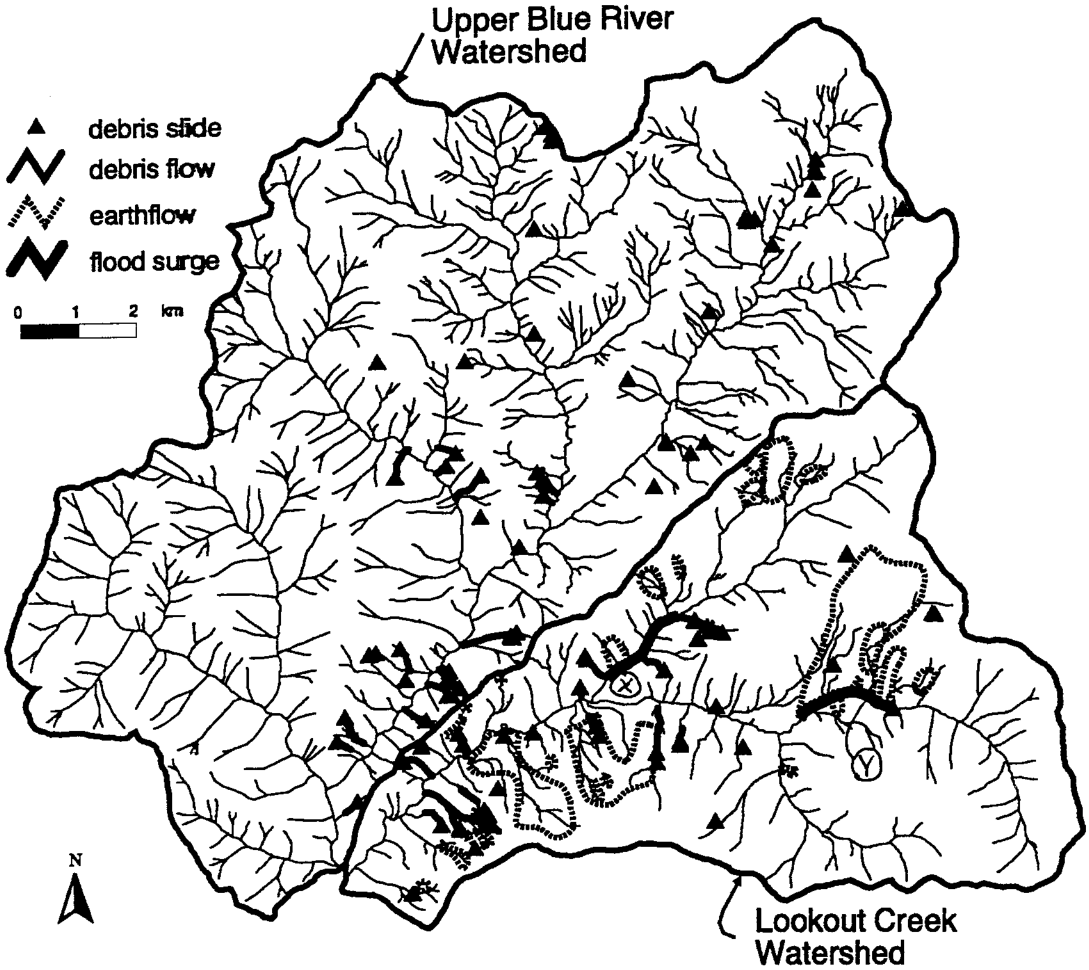

Figure 2. Map of upper Blue River watershed showing locations of debris slides and debris flows events in the February 1996 flood. X denotes location of debris-flow initiated flood surge in 1996. Y denotes earthflow-related, streamside-slide initiated flood surge in 1964–1965. Earthflows are shown for Lookout Creek watershed only

The ecological effects of these processes are varied. Disturbance severity ranges from complete removal of riparian vegetation and, undoubtedly, aquatic biota in steep, constrained channels affected by debris flows to more complex patterns along channels affected by flood surges. In the latter cases riparian trees up to 40 years in age were removed and toppled, old-growth trees were scarred, and piles of wood were strewn along the channel margins, culminating in a large debris jam lodged in old-growth riparian forest (Wondzell and Swanson, 1999; Johnson *et al.*, 2000, this issue). These events also altered the distribution of large woody debris, hence aquatic habitat structure, and hyporheic zone patterns and processes (Wondzell and Swanson, 1999).

In this mountain landscape major floods in 1964–1965 and 1996 each triggered nearly 100 mass movement events that are elements of the disturbance cascade. A very small fraction of these events resulted in full cascade sequences, but cumulatively these processes affected about 15% of the length of the stream and riparian network in the study area (Snyder, 1999). The sequence was interrupted by numerous natural (e.g. alluvial fan) and management-imposed (e.g. roads) features. Clear-cutting and roads had strong effects on

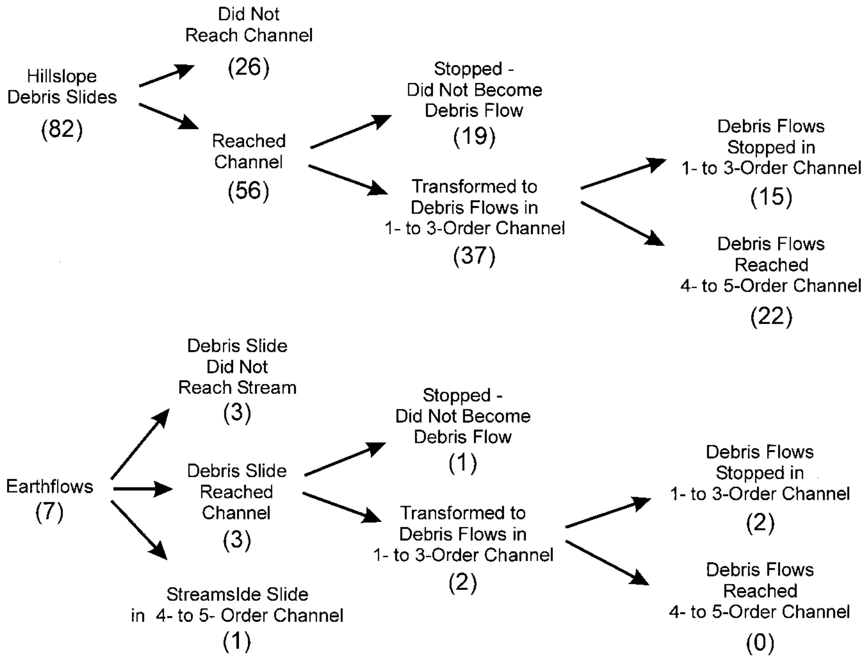

Figure 3. Numbers of events (shown in parentheses) along the disturbance cascade initiated as debris slides and from earthflows in the February 1996 flood in upper Blue River area (Figure 2), Cascade Range, Oregon

initiation of debris slides and flows, accounting for over 80% of the site conditions at points of initiation, although less than 30% of the watershed area had been subject to these land uses (Swanson and Dyrness, 1975; Swanson, unpublished data). Swanson and Dyrness (1975), for example, observed debris slide frequency several fold higher in clear-cut areas than similar forested terrain and frequency of sliding from road rights-of-way several tens of times higher than forested areas.

Examples of disturbance-cascade processes from Japan

Debris flows are major geomorphological disturbance agents in volcanic landscapes common in Japan where disturbance cascades start high on the steep flanks of volcanoes and may ultimately spread out on the surrounding, lower gradient terrain rather than enter a distinctly larger channel. These lower-slope alluvial and debris fans, such as those observed around Mount Tokachi, exemplify the complexity of disturbance and ecological response in the downstream end of disturbance cascades.

In 1926, snowmelt associated with an eruption triggered a debris flow from the 2077-m-tall volcano that destroyed mature coniferous forest and scoured the land surface in its path, leaving undulating earth surfaces formed by deposition and scouring. Regenerated forest types were classified using aerial photograph and field observation (Figure 4). Forests dominated by deciduous trees covered the northern margins of the disturbed zone, whereas conifers and mixed stands dominated near the stream and in southern margins, with scattered patches of bare land. These forests created a mosaic of elongated patches parallel to the stream itself, reflecting vegetation recovery controlled by the geomorphological habitat conditions, especially the size distribution of sediment in the debris-flow runout zone (Yajima *et al*., 1998). Birch (*Betula* spp.) stands dominated the sandy sediment at the margins of the debris flow deposits. Birch (overstory) and conifers (understory) stands dominated the areas of biomodal stony, sandy sediment. Cobbly sediment was most extensive in central areas of the debris flow deposits where pure spruce (*Picea glehnii*) stands were established. The gradient from coarse to fine sediment from the centre of the debris flow deposits to their edges suggested that central areas were disturbed more intensively than were marginal areas. Distributions of dwarf bamboo and sandy sediment overlapped closely because rhizomes of dwarf bamboo could easily penetrate sandy sediment. Dense cover of dwarf bamboo may inhibit the regeneration of conifers. In contrast, coarse sediment impeded rhizome extension. Thus, heterogeneity in habitat conditions created by the debris flow significantly influenced structure and composition of regenerated forests. Extensive debris fans on the lower flanks of volcanoes and in other geomorphological settings provide space for such complex patterns to develop and persist.

Detailed sediment budget studies in several small watersheds in Hokkaido, Japan, reveal effects of natural processes and erosion control dams on disturbance cascade processes. Shimizu (1998) documents volumes of sediment production and storage in the 2·08 km^2 Rubeshubenai Creek and 1·70 km^2 Paradai River watersheds for events triggered by an August 1992 rainstorm. In the Rubeshubenai watershed, he observed that 101 debris slides mobilized 47 700 m^3 of soil, 76% of which entered channels and much of this material moved downstream as debris flows. Deposition occurred along the main channel where slopes were less than 10% and two erosion-control dams at the mouth of the watershed trapped the remaining coarse material transported in the debris flows, effectively stopping their downstream progress. In the Paradai River, 86 debris slides delivered 14 400 m^3 to channels. This material moved downstream as debris flows and flood surges initiated by break-up of debris slide deposits in the channel network. These events scoured riparian forests, ultimately forming a large log jam, which trapped about 80% of the transported sediment near the mouth of the watershed. An erosion-control dam captured the remaining sediment.

OVERVIEW AND IMPLICATIONS

From these observations emerges a view of the stream and riparian landscape as a network containing a shifting mosaic of disturbance patches — linear and often parallel zones of disturbance created by cascading geomorphological processes. The frequency of disturbance and extent of freshly disturbed areas is determined by soil, topography and other factors controlling the initiation and runout of key geomorphological processes and the transitions between processes. Resulting disturbances range from debris flows completely removing alluvium and riparian soil and vegetation along steep, narrow, low-order channels to localized patches of trees toppled by floating logs along the margins of larger channels. Landscapes can be zoned in terms of high and low frequency of these processes, and results of this analysis can be represented as a map of the geomorphological disturbance regime of the stream and riparian network (Swanson *et al.*, 1997).

Land-use practices can affect the cascade of geomorphological processes that function as disturbance agents by changing the frequency and spatial pattern of events and the composition of material moved. Forestry practices, for example, historically increased the frequency of debris slides that initiated disturbance cascades and ultimately reduced the amount of large wood in debris flows and flood surges by direct removal of wood from streams and by intensive management of streamside forests, thus reducing long-term input of large wood to streams. Channel modifications by check dam construction and other techniques generally reduce the extent of natural complex geomorphological disturbance of riparian vegetation in ecologically rich, wide valley floor areas.

A characterization of the disturbance regime in a stream network has important implications for ecological analysis. The distribution of habitats, for example, can be identified for species that have disturbance-favoured requirements, such as those favouring high light and bare soil conditions, or disturbance-adverse requirements, such as shade-tolerant species. Flows of materials, such as sediment, nutrient and wood, may completely change with disturbance.

The network structure of stream and riparian systems may lend resilience in response to major disturbances (Swanson *et al.*, 1998). Debris flows in the upper part of the network have high severity of disturbance, but affect a small percentage of low-order channels in any one storm. Consequently, tributary streams that do not experience debris flows may serve as refuges during floods and sources of progagules for

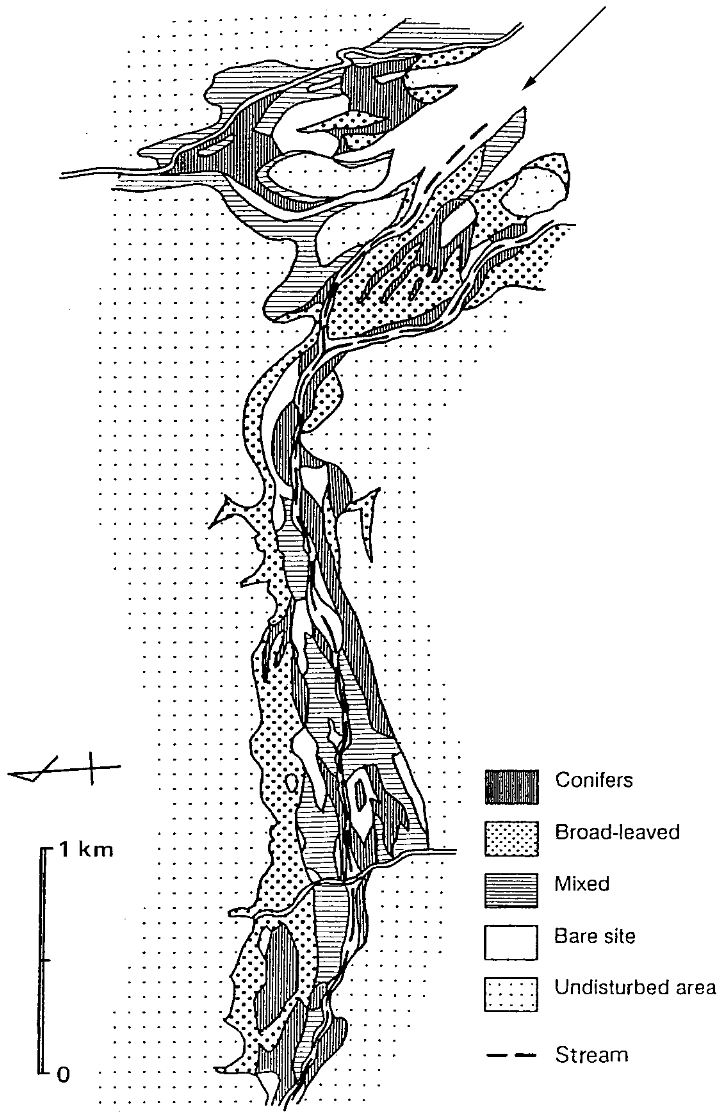

Figure 4. Map of a section of a debris-flow impacted channel draining from Mount Tokachi, Japan, showing types of post-disturbance vegetation. Flow is from top to bottom of figure

recolonization of severely disturbed reaches. Refuges may also be numerous in the downstream area affected by the disturbance cascade, particularly in areas of wide valley floor, where secondary channels and complex riparian vegetation patterns create the potential for extensive refuges during major disturbance events.

An understanding of disturbance regimes is a foundation for designing management systems. A strategy for managing landscapes to sustain biological diversity of natural systems will probably include some semblance of the natural disturbance regime. This is a challenge for management that commonly introduces new disturbance processes and increases or decreases the influence of processes that were integral to the system before human intervention.

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