Flood Disturbance in a Forested Mountain Landscape

Interactions of land use and floods

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Recent flooding in the Pacific Northwest vividly illustrates the complexity of watershed and ecosystem responses to floods, especially in steep forest landscapes. Flooding involves a sequence of interactions that begins with climatic drivers. These drivers, generally rain and snowmelt, interact with landscape conditions, such as vegetation pattern and topography, to determine the capability of a watershed to deliver water, sediment, and organic material to downstream areas (Figure 1). Land-use practices can affect watershed responses to flooding through the influences of managed vegetation patterns and roads on delivery of water, sediment, and wood to streams. Watershed responses to floods include geophysical processes, such as landslides and channel erosion, and related disturbances of aquatic and riparian organisms and their habitats. We explore these geophysical–ecological interactions using a recent flood in the Pacific Northwest as an example of flood effects in a managed mountainous landscape.

Floods trigger cascades of physical processes that alter streams and riparian zones of mountain landscapes, yet affected species are resilient

Floods in forested mountain landscapes are distinctly different from lowland floods. Flood peaks in mountain streams are brief (hours to days in duration) and high, reflecting rapid movement of water down steep hillslopes and channels. Steep topography facilitates triggering of debris slides down hillslopes, and steep channel gradients permit rapid movement of coarse sediment and woody debris through stream networks. Consequently, flood disturbances in mountain landscapes are dominated by mechanical damage to stream and riparian habitats. Despite the continuous passage of a flood peak through stream networks, disturbance patterns are very patchy. Where soil, boulders, trees, and large woody debris do not move during floods, they provide refuge for diverse aquatic and riparian species.

In large, lowland rivers, on the other hand, floods are commonly more tranquil, seasonally predictable, and of much longer duration (weeks to months). These features have permitted aquatic and riparian species to undergo evolutionary adaptations to flooding to such an extent that the absence of flooding becomes a disturbance (Bayley 1995).

The biota of mountain and lowland stream and riparian systems respond to flooding as a disturbance process in many ways. Physical processes of erosion and deposition during a flood create disturbance patches and refuges in which aquatic and riparian organisms either recolonize or survive (Townsend 1989). Biotic responses are characterized by both resistance to change during the event and resilience (recovery) after the event (Sousa 1984, Pickett and White 1985, Reice 1994). Postdisturbance biological responses are determined by the distribution of disturbance patches and refuges across the landscape; by species–habitat relations; by dispersal among patches in the river network; by reproductive strategies; by biotic interactions, such as competition; and by the availability of food resources.

A major flood in February 1996 in the Pacific Northwest affected areas of long-term ecological and geophysical research, providing a historical context for interpreting flood effects in mountain landscapes. Our detailed observations at the H. J. Andrews Experimental Forest, a National Science Foundation–sponsored Long-Term Ecological Research site, and in other parts of the upper McKenzie River basin in Oregon (Fig-

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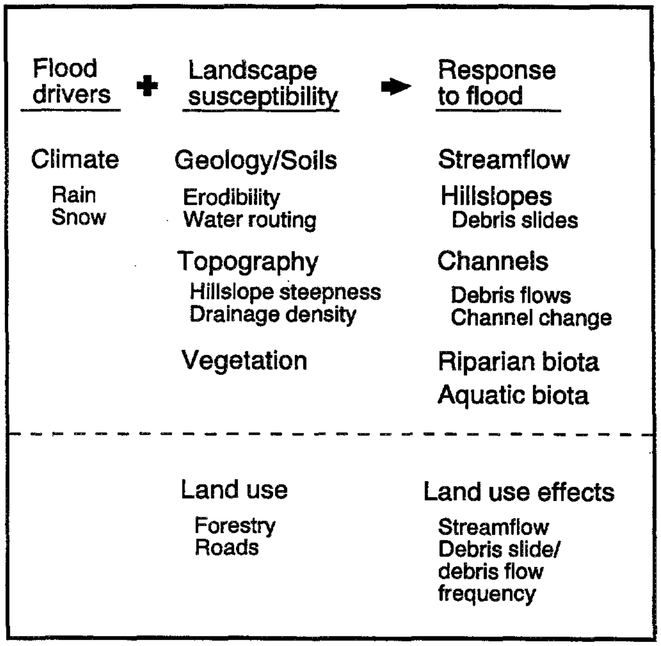

Figure 1. Climate factors (flood drivers) interact with landscape conditions that affect landscape susceptibility to rapid movement of water, sediment, and woody debris through stream systems. Flood responses include processes that transport these materials and the biological consequences of their transport. Forest land uses (below dashed line) can alter landscape susceptibility and, therefore, watershed responses to floods.

ure 2) are representative of flood effects observed elsewhere in the Pacific Northwest and in other mountainous regions, such as the central Appalachians (Hack and Goodlett 1960).

In this article, we examine selected effects of the February 1996 flood on a forested mountain landscape in western Oregon. We describe geophysical processes in stream and riparian networks and flood effects on taxa that represent a variety of types and rates of response. Finally, we consider the interactions of land use and floods. These observations derive from a larger set of studies of flood effects on ecosystems and interactions of floods with forest land-use practices.

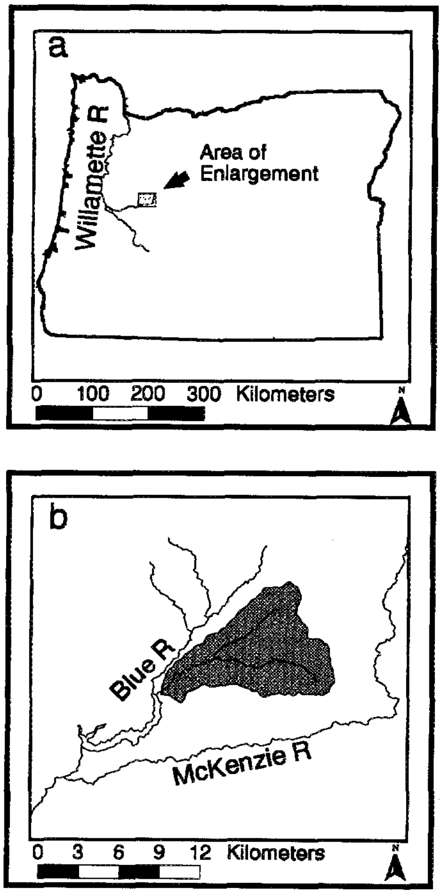

Figure 2. The Willamette River watershed in Oregon. (**a**) Map of Oregon showing the Willamette River. (**b**) Area of enlargement showing the west-flowing McKenzie River, a tributary to the Willamette River, and the Andrews Experimental Forest (shaded), which drains into the Blue River.

The setting and the flood

The upper McKenzie River basin is representative of much of the Cascade Range of Oregon and Washington, both in general terms and with respect to responses to the February 1996 flood. This study area is characterized by elevations from 300 to over 1600 m; by tall, native conifer forests ranging in age from 80 to over 500 years since the last major wildfire; and by the development of scattered conifer plantations after clear-cut logging of the area during the past 50 years. The steep hillslopes are underlain by soils derived from volcanic bedrock, which in some areas are subject to small-scale soil movement by debris slides. On average, the area receives more than 2500 mm of precipitation annually, 80% of which falls in winter, mainly in the form of snow at elevations above 1000 m and as rain at elevations below 400 m. The transitional transient-snow zone can experience high levels of water delivery to soil and streams as snowmelt augments rainfall runoff (Harr 1981). Runoff flows rapidly through the steep stream network.

The 6–8 February 1996 flood in the Pacific Northwest involved a sequence of events typical of major floods in the region (Harr 1981). Following an early winter period of little snow accumulation, prodigious snowfall in late January brought the snowpack for the Willamette River basin to 112% of the long-term average. On February 6, a strong jet stream delivered subtropical moisture to the northwest, resulting in four days of intensive rainfall (290 mm) while the air temperature was well above freezing. This one–two punch of rain and snowmelt triggered flood flows with return periods of 30 to more than 100 years in many river systems in Oregon, Washington, and Idaho. On a more local scale, flood magnitudes varied with precipitation patterns, watershed structure, and snow hydrology. For example, cold, dry snow in the upper elevations stored rainfall during early periods of the storm, while warm, rain-saturated snow at lower elevations melted rapidly.

These large quantities of water moving through this steep, forested landscape set off movement of soil, sediment, and large pieces of wood. The initiation of this movement, the transport of these materials, and their ultimate deposition commonly involved interactions between the mobile material and standing forest vegetation. The resulting complex patterns of flood disturbance, interspersed with refuge sites experiencing minor flood effects, were substantially influenced by vegetation conditions in watersheds at the time of the flood.

Geophysical disturbance processes and patterns

Geophysical processes that alter streams and riparian zones during floods operate with highly heterogeneous patterns of disturbance sever-

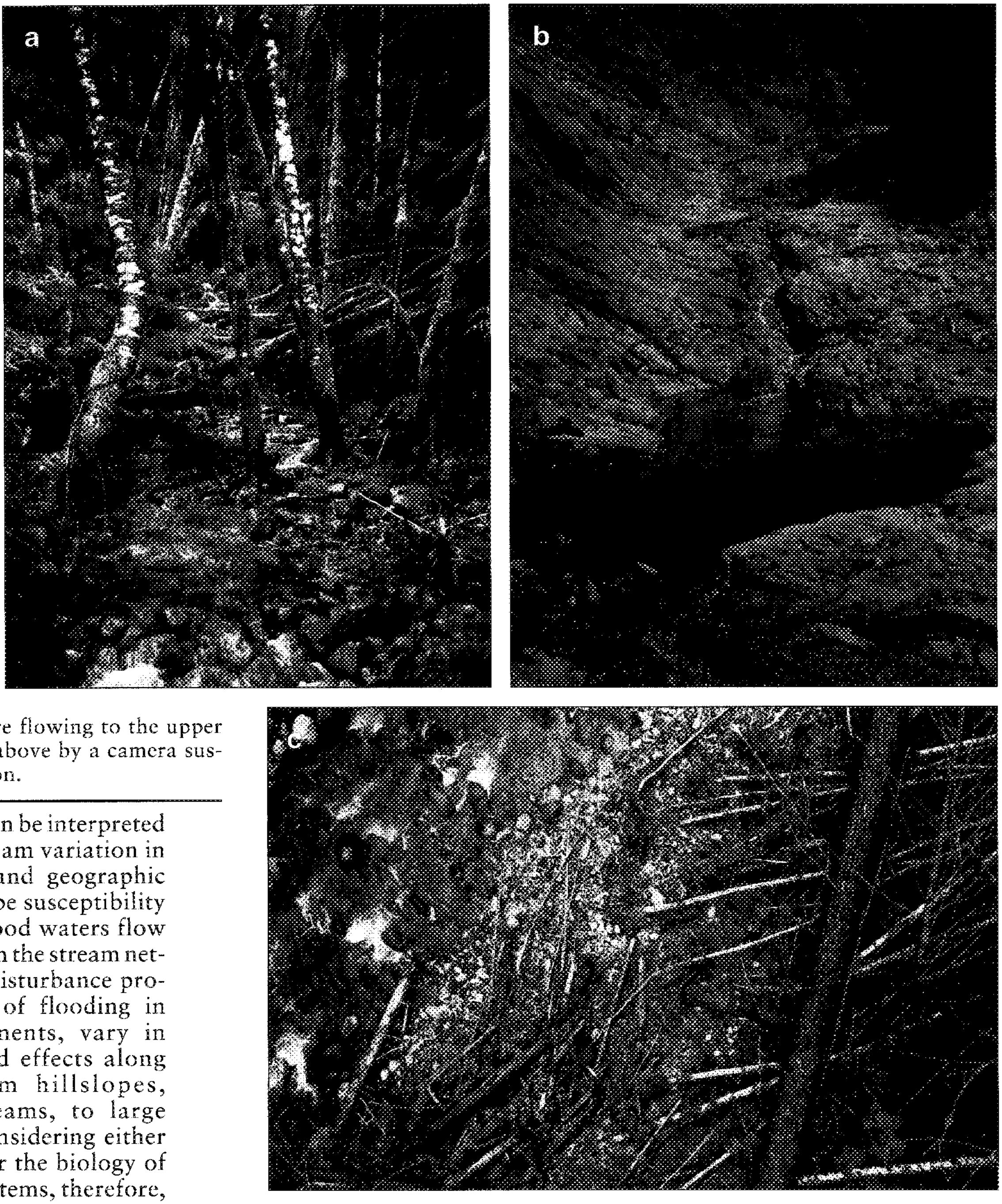

Figure 3. Flood effects on stream channels and riparian vegetation. (a) A small stream and alder (*Alnus rubra*) riparian zone that experienced the February 1996 flood but no debris flow. Alder trees, even those growing in the channel, survived the flood and created complexity that provided refuge for some species. (b) A small bedrock stream after passage of a debris flow in February 1996. Streambed sediment and riparian vegetation, including alder trees of the stature shown in (a), have been removed. (c) High streamflow rotated a 1.5 m diameter conifer log from left to right, toppling riparian alder trees. This stream reach, here flowing to the upper right, is viewed from above by a camera suspended below a balloon.

ity. These patterns can be interpreted in terms of downstream variation in physical processes and geographic variation in landscape susceptibility to key processes. Flood waters flow progressively through the stream network, yet physical disturbance processes, a hallmark of flooding in mountain environments, vary in their properties and effects along the gradient from hillslopes, through small streams, to large channels. When considering either physical processes or the biology of mountain stream systems, therefore, it is useful to distinguish steep headwater streams draining 1–100 ha from larger, lower-gradient streams (drainage areas of 1–1000 or more km^2) because some key processes (e.g., debris flows or movement of floating logs) and biota are restricted largely to one or the other.

Water, soil, sediment, and woody debris move down hillslopes and stream channels by a cascade of processes, following the gravitational flow path. Moving solid material may have variable disturbance effects. Sediment and wood, for example, may move as individual particles with little ecological impact or as large mass movements with the force to substantially disturb ecosystems. Soil mass movement by debris slides originating on hillslopes may enter steep headwater channels and change into debris flows. Varying in size from hundreds to thousands of cubic meters, debris flows are water-charged masses of sediment and organic matter that move down headwater channels at velocities of up to 10 m/s or more (Hack and Goodlett 1960, Sidle et al. 1985), scouring channel sediment and riparian vegetation (Figures 3a and 3b). Debris flows may enter larger, lower-gradient channels that carry sufficient water to float large logs on the water surface, while gravel and boulders roll audibly along the streambed. Generally, in wet landscapes, an increasing amount of water is available along this flow path to dilute the sediment in transit and to float larger pieces of woody debris. Moving woody debris can become a significant agent of disturbance in larger channels as floating logs ram into or lodge against standing trees, acting

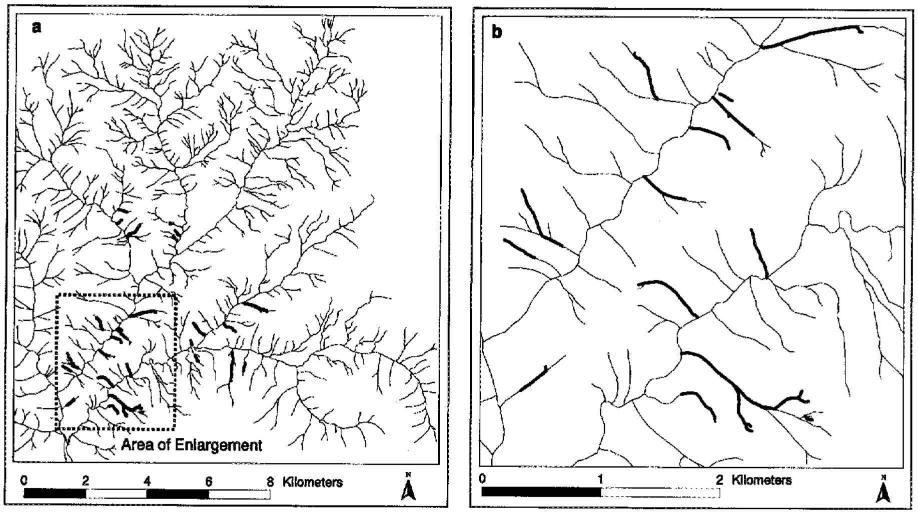

Figure 4. Map of 1996 debris-flow paths in the Blue River area reveals two scales of disturbance patterns. (**a**) A zone of high–debris flow frequency occurs in the southwest quadrant at lower elevations, where weak rocks and soil, high rates of snowmelt during the storm, relatively high road density, and steep slopes create debris flow–prone areas. (**b**) Area of enlargement shows that even within the high–debris flow zones, most small tributary networks have some channels that experienced debris flows and others that did not. Thick lines indicate debris-flow paths; thin lines indicate the rest of the stream network.

as levers to increase the water's force until trees topple (Figure 3c).

Phenomena operating at several geographic scales create the complex patterns of disturbance severity observed among steep headwater streams. Some streams may experience high flows but escape major disturbance entirely, whereas other streams and riparian zones are severely scoured by debris flows (Figures 3a and 3b). The disturbance cascade may be interrupted if the debris slides or flows pile up on roads or on the edges of the floodplains, for example, obstructing further flow. In the Blue River watershed, areas of slide-prone soils or high rates of water delivery to soils in the transient-snow zone create predictable geographic zones of high slide and debris flow frequency (Figure 4a; Hack and Goodlett 1960, Swanson and Dyrness 1975). Geographic patterns of debris flows in the 1996 flood were nearly identical to patterns triggered by floods in the 1950–1995 period, indicating that the geography of controls on debris-flow occurrence causes some but not all headwater streams to experience repeated, severe disturbance.

On a finer scale, debris flows commonly affect only parts of the stream networks of small watersheds, even within a landscape with a high incidence of debris flows (Figure 4b). The small tributaries that do not experience debris flows may serve as refuges for organisms that can contribute to the recolonization of channels that were severely affected by debris flows.

Much of the heterogeneity of disturbance severity in larger channels occurs along lateral gradients from the channel axis to the floodplain and from reach to reach along the main channel. Both lateral and along-stream variation in flood disturbance are regulated in part by the width of the valley floor: Narrow valley floors confine flood waters, limiting lateral channel migration and extent of disturbance, whereas wide valley floors have room for both the zone of severe disturbance and areas of more tranquil flow. In wide valley floor areas (unconstrained reaches; *sensu* Swanson and Sparks 1990, Gregory et al. 1991, Grant and Swanson 1995), sections of the main channel experience severe disturbance by complete reworking of the streambed and removal or toppling of riparian vegetation, commonly red alder (*Alnus rubra*), that had established after previous major floods. Flood waters may also inundate areas of riparian forest in which water velocity and the momentum of entrained wood and coarse sediment are not sufficient to damage standing vegetation. Narrow valley floor areas with steep, rocky stream banks may record fewer effects of flooding simply because they have less floodplain and riparian vegetation, although physical disturbance can be intense.

Biotic response to flooding

Landforms and geophysical processes establish the physical template within which aquatic and riparian ecosystems operate (Gregory et al. 1991). The disturbance history of the landscape strongly influences patterns of upland, aquatic, and riparian biota in Pacific Northwest landscapes (Schoonmaker and McKee 1988, Morrison and Swanson 1990, Lamberti et al. 1991, Swanson et al. 1992). Floods are the most frequent and intense natural physical disturbances that alter communities of aquatic organisms.

A fundamental ecological question related to flood disturbance is: How do spatial patterns of flood disturbance and refuges in a river network affect the survival and recovery of aquatic and riparian organisms? Species differ greatly in their responses to floods, depending on the type of refuge available to them, their dispersal capabilities, their mode of reproduction, and other life-history traits that affect persistence through floods and subsequent recovery (Table 1). We address the variability of biotic response to floods by examining several types of taxa that represent a range of interactions with floods—riparian vegetation and several groups of aquatic vertebrates.

Riparian vegetation. Natural riparian forests in many Cascade Mountain landscapes are commonly composed of narrow bands of red alder that established after flooding in previous decades. Adjacent to these flood-reset alder stands are taller, older conifer forests that typically established after wildfire (Swanson et al. 1992). Thus, spatial patterns of species and age classes of trees strongly reflect past flooding and other disturbances.

Surveys in major tributaries of the McKenzie River after the 1996 flood revealed heterogeneous patterns of disturbance to riparian forests. Nu-

Table 1. Some hypothetical species response mechanisms and timing of responses to flood disturbances as constrained by refuges, dispersal, and reproduction.

Taxon	Refuges	Dispersal mechanism	Reproductive strategy	Recovery time
Conifers	Upland; undisturbed riparian patches	Fall seed dispersal	Seeds	More than 30 years
Giant salamanders (*Dicamptodon tennebrosus*)	Secondary channels; streambed interstices	Limited crawling; terrestrial phase	Nest building, guarding (slow egg development)	More than 5 years
Sculpins (*Cottus* spp.)	Streambed interstices	Swimming (weak)	Spawning—broadcast (low fecundity)	More than 5 years
Red alder (*Alnus rubra*)	Upland; low-disturbance riparian areas	Fall seed dispersal	Seeds	Less than 5 years
Cutthroat trout (*Oncorhynchus clarki*)	Secondary channels; channel margins	Swimming (strong)	Spawning—nest building (high fecundity)	1–3 years
Caddisflies (Trichoptera)	Shallow stream margins; floodplains	Behavioral drift; catastrophic drift	Terrestrial mating (26–52-week generation time)	1–3 years
Midges (Diptera)	Crevices in rocks; shallow stream margins	Behavioral drift; catastrophic drift; aerial dispersal	Terrestrial mating (4–12-week generation time)	3–6 months
Aquatic algae	Crevices in rocks	Sloughed cells	Vegetative reproduction; sexual reproduction	Less than 3 months

merous steep headwater streams experienced channel-scouring debris flows that damaged riparian forests, but other channels did not (Figures 2, 3a, 3b, and 4a). The larger tributaries also exhibited a heterogeneous pattern of riparian disturbance severity. For example, zones of complete toppling of riparian alder trees were interspersed with areas of standing alder or mixed standing and toppled alder (Figure 5). The most complete disturbance of riparian trees commonly occurred in sites where the channel is confined within a narrow valley floor area containing riparian stands dominated by young (less than 30 year) alder (Figure 5, zone b). Standing alder remained in wide valley floor areas, where secondary channels and extensive floodplain area could accommodate flood waters outside the zone of severe disturbance (Figure 5, zones a and d). In the 1996 flood, these wide valley floor areas experienced disturbance to riparian vegetation by lateral channel changes; the common occurrence of large, floated logs on toppled alder trees (Figure 3c) implicates floated wood as another disturbance mechanism. Few alder trees occur in constrained, bedrock-defended reaches because of limited rooting medium and frequent scouring (Figure 5, zone c).

Long-term riparian vegetation plots reveal fine-scale details of tree response to the 1996 and earlier floods. A 2.4 ha vegetation plot (Reference Stand 38) in the Andrews Forest, for example, contains distinct zones of differing forest composition and disturbance severity. Areas of conifer-dominated old-growth forest on upper terrace and floodplain areas (collectively termed "upland" in Figure 6) are above the damaging flood waters. On the active valley floor areas, young alder stands dominate the forest established after floods in 1964, 1972, and other years (Figure 6) because they have the potential to establish profusely on the fresh gravel substrates left by receding flood waters. Alder trees in these near-channel riparian areas experienced approximately 20% mortality in the 1996 flood as a result of channel erosion and toppling by floating woody de-

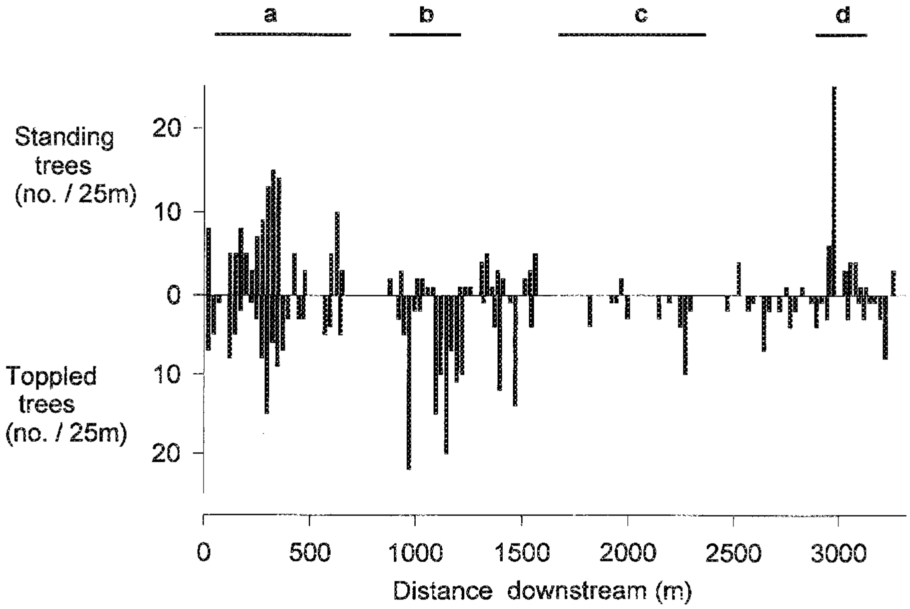

Figure 5. Distributions of standing and toppled alder (*Alnus rubra*) trees along lower Lookout Creek, the stream draining Andrews Forest. Zone a is a riparian area of mixed flood-disturbance severity (both standing and toppled trees); zone b shows high flood-disturbance severity (dominantly toppled trees); zone c is a bedrock-constrained reach with little habitat for alder, so few trees were available to record flood severity; and zone d exhibits low flood-disturbance severity (standing trees predominate).

bris. The quiet valley floor area was inundated by flood waters, but flow was so tranquil that mortality was limited to several large conifers that fell after their root systems were undercut by bank erosion. This pattern of alder patches dominating in areas of recent flood disturbance and conifers dominating other valley floor forests is typical of riparian zones across the region.

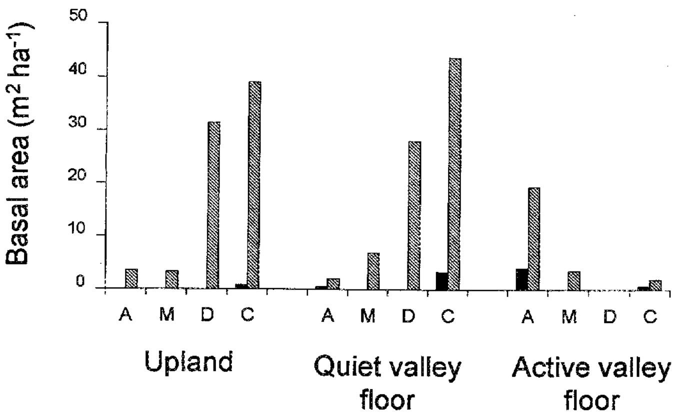

Figure 6. Preflood tree species distributions and postflood tree mortality in different areas of a 2.4 ha riparian vegetation plot straddling Lookout Creek in the Andrews Forest. Areas included uplands (outside of flooded area) and quiet (no or low severity of flood disturbance) and active (high severity of flood disturbance) valley floor areas. Hatched bars, 1990 survey of tree species; solid bars, mortality in post-1996 flood survey. A, red alder (*Alnus rubra*); M, broadleaf maple (*Acer macrophyllum*); D, Douglas-fir (*Pseudotsuga menziesii*); C, shade-tolerant conifers.

The varied interactions of standing trees and downed woody debris with geophysical features and processes produced complex patterns of disturbance and refuge. Although floated wood pieces caused major disturbance in some stands, toppled and standing vegetation combs floated wood from flood waters in other places, creating zones of low disturbance in their lee despite inundation by flood waters. These interactions produced a heterogeneous patchwork of zones of high and low severity of disturbance, providing both refuge for surviving species and new sites for establishment.

Aquatic vertebrates. The impact of the flood in tributaries of the McKenzie River varied by species for the most abundant vertebrates: cutthroat trout (*Oncorhynchus clarki*), Pacific giant salamanders (*Dicamptodon tennebrosus*), and sculpins (*Cottus beldingi* and *C. bairdi*). The highly mobile cutthroat trout are most abundant in pool habitats and are found in the water column, although during winter high flows they move into relatively quiet, shallow water along the stream margin or adjacent to wood and boulder accumulations. Trout are strong swimmers that are capable of moving quickly in the stream, even in areas of high water velocities. Sculpins, which are benthic dwellers, are most abundant in the spaces among boulders on the bottoms of pools and riffles. These fish move down into the streambed during high winter flows. In addition, they are less mobile and swim more slowly than trout and are therefore less able to move to side-channel refuges during floods. Pacific giant salamanders, like sculpins, are bottom dwellers, disperse primarily by crawling, and are not strong swimmers. During winter high flows, giant salamander larvae seek cover under boulders and gravel, while the adults seek cover in the litter and soil of adjacent forests.

Long-term population studies of aquatic vertebrates in and near the Andrews Forest provided a context for measuring the responses of these aquatic vertebrates to the flood of 1996. Densities of adult cutthroat trout following the flood were within the range of year-to-year variability observed before 1996 (n = 7–24 sample years) in a sample of nine stream reaches in which flood conditions ranged from only high streamflow and gravel movement to severe disturbance by debris flow deposition. Although the average densities in the summer of 1996 were slightly less than in the preflood year (approximately 8% lower after the flood), the average lengths and weights of adult cutthroat were slightly greater. The percentage of marked trout recaptured in an old-growth and harvested reach of Mack Creek in 1996 (30%) was similar to year-to-year survival over winters without major floods (23%). The Mack Creek site experienced high flows and movement of sediment, but most major habitat features, such as large logs and boulders, remained in place. Overall, these observations suggest that cutthroat trout exhibited high resistance to flood disturbance.

Sculpin densities in the main stream of the Andrews Forest were more adversely affected by the flood, declining by an average of 70% compared to the previous year (for reference, the average range of variability between years is 30% [n = 7 years]). Although it is not possible to study the behavior of these vertebrates during a flood, it is known that their preferred habitat during high winter flows is in spaces among cobbles and boulders. When flood discharge is great enough to cause movement of cobbles and boulders along the streambed, organisms limited to that habitat may be killed by moving particles.

Densities of giant salamander are much more variable among years (average range of variability between years is 70% [n = 7 years]), so it is difficult to assess the impacts of the flood on that species. The adults are terrestrial and have the potential to disperse to other sites, possibly leading to high year-to-year variability in densities of larval forms within a stream. In some small, steep streams, where the only vertebrates are salamanders, debris flows severely damaged salamander habitats and densities were very low. But even in these sites, some salamanders were observed. Perhaps these were new colonists or survivors from riparian or hillslope soil refuges.

Flood responses can differ among age classes of a species. Other studies have found that young of the year are most vulnerable to flood flows (Harvey 1987). However, the 1996 flood in the Pacific Northwest occurred prior to the cutthroat spawning season; therefore, young-of-the-year fry observed in the summer of 1996 were not exposed to the high flows in February and were the progeny of adult survivors. Cutthroat fry biomass after the flood was, on average, 43% greater than biomass before the flood. Fry populations after the 1996 flood were the highest observed in the 24-year period of investigation at Mack Creek. Several mechanisms may account for these increases in fry population, including reduced competition from species that were more negatively affected by the flood and enhanced reproductive success as a result of the flood flushing fine sediment from spawning gravels.

Ecosystem interactions. The complexity of responses of individual taxa to floods is mirrored by the complexity of the sets of ecosystem and community interactions that occur over subsequent years and decades. Interactions develop among species with slow responses and species with more rapid responses to floods (Table 1). Aquatic communities often recover to predisturbance densities more quickly than streamside riparian vegetation, which may have provided a major food resource before the flood. Most in-stream food resources are sensitive to flooding (Fisher et al. 1982, Power and Stewart 1986) and to channel complexity (Bilby and Likens 1979, Golladay et al. 1987). The relatively slow recovery of woody riparian vegetation and the shade it casts over streams favor aquatic species able to take advantage of altered food resources, such as increased aquatic primary productivity and reduced terrestrial leaf litter, that occur after removal of the riparian canopy. Community composition may shift due to differential responses of species to floods. Biotic interactions of competition and predation might be reduced initially by flood disturbance, which might counteract the changes in aquatic species composition due to changing food resources.

Long-term studies of severe debris flow impacts in 1986 on a tributary of the McKenzie River provide an example of longer-term ecological responses and interactions (Lamberti et al. 1991; Stanley V. Gregory, unpublished data.) Debris-flow disturbance of riparian vegetation opened up the canopy, resulting in increased light levels in the stream (Lamberti et al. 1991), which led in turn to several years of increased primary productivity by aquatic plants and increased secondary productivity in communities of invertebrates that graze on aquatic plants. Trout populations were initially greatly reduced in the most severely disturbed reaches, but they recovered to higher than preflood abundance within three to five years. Enhanced food resources and possibly increased foraging efficiency under high light levels (Wilzbach et al. 1986) may have contributed to the temporary increase in trout population and biomass, apparently offsetting the possible detrimental effects of elevated temperature and of the accumulation of fine sediment delivered from upstream areas for a few years after the 1986 debris flow. Ultimately, we expect that riparian vegetation cover will increasingly shade the stream and return stream productivity to preflood levels.

Such patterns of ecosystem response will play out over the next few decades at the sites disturbed by the 1996 flood, which are scattered over the flood-affected region. These immediate responses, longer-term recovery processes, and the patchiness of disturbance create a complex mosaic of habitats and biotic diversity along stream and riparian networks.

Land-use effects, assessment, and mitigation

Floods can be ranked along a continuum from largely natural, as on the Tanana River in Alaska (Yarie et al. 1998), to managed, such as the experimental flood on the Colorado River initiated by water release from the Glen Canyon Dam (Schmidt et al. 1998). In the February 1996 flood in the Pacific Northwest, many forested mountain headwater basins experienced a hybrid event—wild (unregulated) flooding in a managed landscape. The watersheds we have studied have experienced road construction, and 20–30% of the natural forest cover has been converted to plantations after clear-cutting. Forest management affects many of the processes involved in flooding, responses to a flood, and effects of subsequent floods on ecosystems and human systems (Figure 1). Forest cutting and road development can increase the delivery of water to soil and streams, increasing streamflows (Jones and Grant 1996, Wemple et al. 1996), the initiation of debris slides and debris flows (Swanson and Dyrness 1975, Sidle et al. 1985), and the availability of sediment (Grant and Wolff 1991) and coarse, woody debris in streams.

Despite forest land use in many tributaries of the upper McKenzie River basin, the aquatic and riparian taxa considered in this article persevered through the 1996 flood at a wide range of sampled sites. We believe that several factors mitigate land-use effects on biota during major floods in this landscape:

- The heterogeneity of habitats in this mountain landscape provides numerous diverse, widely distributed refuges. Where boulders, logs, and soil move during floods, disturbance can be severe; however, many areas of the flooded landscape were not severely disturbed.
- Forests of the McKenzie River basin and other Cascadian landscapes have experienced extensive past disturbances, such as large-scale wildfire (Agee 1993). Clearly, these watersheds have repeatedly experienced the interactions of floods and other forest disturbance processes. Many native species are well adapted to flooding, and some species may benefit from flooding at specific points in their life histories because it may help them to reproduce and recruit successfully.
- Management activities in Pacific Northwest forest lands have influenced primarily the frequency and magnitude, rather than the types, of processes and materials that affect stream and riparian ecosystems. Processes and materials completely exotic to the ecosystem, such as exotic chemicals or species, could have more detrimental effects on native biota.
- Some management effects may increase or decrease impacts of some disturbance processes. For example, we have observed that roads on upper and middle hillslope areas may be sources of debris flows, but roads on valley floors may trap debris flows before they encounter larger channels.

How will future floods interact with land use to determine overall watershed responses to flooding? Some legacies of forest roads, forest cutting, and other land-use activities of past decades appear to diminish with time for many important processes, such as frequency of debris slides and debris flows (Swanson and Dyrness 1975). However, other management effects may last a long time, such as hydrologic effects of roads and reductions in large, woody debris in streams, an important component of forested stream ecosystems (Gregory et al. 1991). New federal policy for watershed management directs substantial reductions in the rate of forest cutting and major efforts in watershed restoration, with objectives that include mitigation of road effects and enhanced quality of stream habitats (FS and BLM 1994). Successful implementation of this policy, which is contingent on many factors, would probably reduce but not eliminate land-use effects on future floods.

Recognition of the ecological importance of the natural dynamics of ecosystems in response to such processes as streamflow and fire is leading to new approaches to assessing and mitigating land-use effects (Poff et al. 1997). Land use is now often evaluated in terms of how it has altered natural, historical disturbance regimes. In the case of flooding, for example, dams most commonly reduce peak flows, but extensive road development may increase them. River restoration projects have increasingly included some degree of return to a more natural flow regime (Poff et al. 1997). This change represents an important about-face in approaches to managing disturbance-prone ecosystems—from suppressing disturbances to accepting them as integral to ecosystem integrity.

Implications for research and resource management

Floods, like other large-scale disturbance processes (Turner et al. 1997), are highly complex in their physical aspects and ecological effects, reflecting the overlapping factors of predisturbance ecosystems, the disturbance processes themselves, and patterns of recolonization and geomorphic adjustment. Floods in mountain watersheds have particularly heterogeneous spatial patterns of transport of soil, sediment, and large logs down steep hillslopes and through stream channels. Biotic responses to flood-created mosaics of disturbed sites and refuges are species specific, depending on life-history attributes, mobility, availability and accessibility of refuges, and other factors. The complex mix of positive and negative flood effects and their interactions with land use points to the need for long-term, interdisciplinary studies to understand ecological and geophysical roles of floods in natural and managed landscapes.

River and riparian ecology and management will benefit by considering several points that overlap both mountain and lowland environments. It is important to understand the function of habitat complexity across the full range of riverine environments. Information is also needed about ecological and other functions of natural and controlled-flow regimes. In both of these cases—habitat and flow regime—reference to natural, historic variability will provide useful information for watershed management. The importance of natural habitat complexity in the response of biota to flooding implies that managers should seek to maintain natural types and levels of habitat complexity so that flooding can provide its ecological benefits (Bayley 1995, Poff et al. 1997).

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References cited

Agee JK. 1993. Fire ecology of Pacific Northwest Forests. Washington (DC): Island Press.

Bayley PB. 1995. Understanding large river–floodplain ecosystems. BioScience 45: 153–158.

Bilby RE, Likens GE. 1979. Effect of hydrologic fluctuations on the transport of fine particulate organic carbon in a small stream. Limnology and Oceanography 24: 69–75.

Fisher SG, Gray LJ, Grimm NB, Busch DE. 1982. Temporal succession in a desert stream ecosystem following flash flooding. Ecological Monographs 52: 93–110.

[FS and BLM] US Forest Service and US Bureau of Land Management. 1994. Record of decision for amendments for Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. Washington (DC): US Government Printing Office.

Golladay SW, Webster JR, Benfield EF. 1987. Changes in stream morphology and storm transport of seston following watershed disturbance. Journal of the North American Benthological Society 6: 1–11.

Grant GE, Swanson FJ. 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. Pages 83–101 in Costa JE, Miller AJ, Potter KW, Wilcock P, eds. Natural and Anthropogenic Influences in Fluvial Geomorphology: The Wolman Volume. Washington (DC): American Geophysical Union. Geophysical Monograph no. 89.

Grant GE, Wolff AL. 1991. Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA. Pages 31–40 in Peters NE, Walling DE, eds. Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation. Oxfordshire (UK): International Association of Hydrological Sciences. Publication no. 203.

Gregory SV, Swanson FJ, McKee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones. BioScience 41: 540–551.

Hack JT, Goodlett JC. 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians. Washington (DC): US Geological Survey. Professional Paper no. 347.

Harr RD. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. Journal of Hydrology 53: 277–304.

Harvey, BC 1987. Susceptibility of young-of-the-year fishes to downstream displacement by flooding. Transactions of the American Fisheries Society 116: 851–855.

Jones JA, Grant GE. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32: 959–974.

Lamberti GA, Gregory SV, Ashkenas LR, Wildman RC, Moore KMS. 1991. Stream ecosystem recovery following a catastrophic debris flow. Canadian Journal of Fisheries and Aquatic Sciences 48: 196–208.

Morrison PH, Swanson FJ. 1990. Fire history and pattern in a Cascade Range landscape. Portland (OR): US Department of Agriculture Forest Service, Pacific Northwest Research Station. General Technical Report no. PNW-GTR-254.

Pickett STA, White PS, eds. 1985. The Ecology of Natural Disturbance and Patch Dynamics. Orlando (FL): Academic Press.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. BioScience 47: 769–784.

Power ME, Stewart AJ. 1986. Disturbance and recovery of an algal assemblage following flooding in an Oklahoma stream. American Midland Naturalist 117: 333–345.

Reice SR. 1994. Nonequilibrium determinants of biological community structure. American Scientist 82: 424–435.

Schmidt JC, Webb RH, Valdez RA, Marzolf GR, Stevens LE. 1998. Science and values in river restoration in the Grand Canyon. BioScience 48: 735–747.

Schoonmaker P, McKee A. 1988. Species composition and diversity during secondary succession of coniferous forests in the western Cascade Mountains of Oregon. Forest Science 34: 960–979.

Sidle RC, Pearce AJ, O Loughlin CL. 1985. Hillslope stability and land use. Washington (DC): American Geophysical Union. Water Resources Monograph no. 11.

Sousa WP. 1984. The role of disturbance in natural communities. Annual Review of Ecology and Systematics 15: 353–391.

Swanson FJ, Dyrness CT. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3: 393–396.

Swanson FJ, Sparks RE. 1990. Long-term ecological research and the invisible place. BioScience 40: 502–508.

Swanson FJ, Wondzell SM, Grant GE. 1992. Landforms, disturbance, and ecotones. Pages 304–323 in Hansen AJ, di Castri F, eds. Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows. New York: Springer-Verlag.

Townsend CR. 1989. The patch dynamics concept of stream community ecology. Journal of the North American Benthological Society 8: 36–50.

Turner MG, Dale VH, Everham EH III. 1997. Fires, hurricanes, and volcanoes: Comparing large disturbances. BioScience 47: 758–768.

Wemple BC, Jones JA, Grant GE. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin 32: 1195–1207.

Wilzbach MA, Cummins KW, Hall JD. 1986. Influence of habitat manipulations on interactions between cutthroat trout and invertebrate drift. Ecology 67: 898–911.

Yarie J, Viereck LA, Van Cleve K, Adams PC. 1998. Flooding and ecosystem dynamics along the Tanana River. BioScience 48: 690–695.

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