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Dynamics of Wood in Rivers in the Context of Ecological Disturbance

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Abstract.—Disturbance relevant to dynamics of wood in rivers can take many forms. We consider effects of ecosystem disturbance related to wood in river systems in geographic settings, which include high-gradient, boulder-dominated streams, braided, gravel-bed streams, and low-gradient, sand-bed streams. Disturbances of forests affect delivery of wood to streams and rivers directly by causing wood input or wood removal and indirectly by limiting source material. Disturbance of the fluvial system, either the channel form or flow regime, alters the transport and standing crop of wood. Change in wood distribution by processes of deposition, transport, and removal can disturb riparian, benthic (streambed), hyporheic, and water-column habitat. Human actions, such as harvesting trees, building roads, and regulating water flow, can substantially alter the types, frequencies, spatial patterns, and severity of the natural disturbance regime. We summarize the current status of knowledge on these points and identify knowledge gaps in studies of wood in rivers within the context of ecological disturbance. Finally, we offer a framework for future work and management that integrates processes that shape the spatial and temporal dynamics of wood at a series of scales.

Introduction

Disturbance can be defined ecologically as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (Pickett and White 1985) and thus creates "space" for other organisms. Principal attributes of disturbances include timing, spatial aspects, intensity of the force that triggers change, and severity of response. This concept of disturbance is ecological and is not commonly used in geomorphology. Disturbance processes are so integral to the highly dynamic riverine and riparian ecosystems being considered here that absence of disturbance, such as elimination of peak flows by reservoir management, can itself be considered a disturbance (Resh et al. 1988).

Previous studies of wood in rivers have focused on the amounts and distribution of wood and its ecological and geomorphic effects. Few studies have considered wood explicitly in terms of disturbance processes and effects, though implications for interpreting disturbance appear in many published studies.

Disturbance relevant to dynamics of wood in rivers can take many forms. For example, the frequency and magnitude of flooding can be reduced by natural factors, such as drought, or management, such as dams and dikes, to regulate or divert flows. Human actions, such as cutting forest, building roads, and regulating water, can substantially alter the natural disturbance regime (that is, the types, frequencies, spatial patterns, and severity of disturbance). Human actions can increase or decrease the frequency and magnitude of natural processes, and they can introduce entirely new (exotic) factors.

Three effects of ecosystem disturbance related to wood in river systems can be significant. Disturbances of forests affect delivery of wood to streams and rivers directly or indirectly by limiting source material. Disturbance of the fluvial system, either the channel form or flow regime, alters the transport and standing crop of the wood. Change in wood distribution, including deposition, transport, and removal, can disturb riparian, benthic (streambed), hyporheic, and water-column habitat.

In this chapter, we first describe the geographic settings in which disturbance processes in river landscapes operate. We then summarize the current state of knowledge about wood-related processes, both as they are affected by disturbance (wood input) and as disturbance agents that affect the river landscape (wood transport and change in wood structure). For each of these wood-related processes, we discuss their spatial patterns and how they are influenced by management. We conclude by defining some major gaps in knowledge related to managing wood in rivers and present a framework for interpreting and applying results in different geographic and management situations.

Geographic Settings of Wood-Related Disturbance Processes

For many ecological phenomena, especially disturbance in stream and riparian networks, a geographic context is an important framework for analysis. Here, we consider relevant processes in terms of the size and type of the river landscape and the associated channel conditions. River landscapes are classified into three dominant morphologies. The relative importance of mechanisms that deliver wood to streams varies among these types: (1) high-gradient, boulder-dominated streams with very narrow valley floors, so hillslopes constrain the stream channel and hillslope processes directly influence channel morphology and wood dynamics; (2) braided, gravel-bed streams with a relatively steep channel bed and banks commonly dominated by a gravel-dominated stream, and also shows some development of multiple channels where wood dynamics are controlled mainly by fluvial processes; (3) low-gradient, sand-bed streams characteristic of low-gradient, meandering rivers (Figure 1). We refer to these three morphologies as mountain, boulder-bed streams; braided, gravel-bed streams; and meandering, sand-bed streams.

The concept of "disturbance cascades" is a complementary geographic perspective that considers the wood moving through stream networks by a sequence of transport processes (Nakamura et al. 2000). These sequences can pass from one of these stream types to another. A broader, landscape-ecology perspective also can be adopted to assessing disturbance effects on wood in rivers. For example, transport of wood in floods can contribute to forming patches of disturbed riparian vegetation, making a shifting patch-mosaic, landscape-dynamic model relevant (Bormann and Likens 1979). This landscape view of the river and riparian landscape is addressed in Swanson 2003, this volume.

Disturbance Effects on Wood Input to Rivers

Input processes include both geophysical and biotic processes, some highly influenced by vegetation structure and composition and others less so. Stage of vegetation succession can affect vulnerability of a stand to disturbance that leads to wood delivery to streams. Stage of succession of streamside forest also affects the size and spatial distributions and amount of wood available to be delivered to streams. Hedman et al. (1996), for example, showed that instream amounts of wood increased linearly with increasing forest age through a chronosequence of forests spanning a 165-year interval in a series of study sites in the southern Appalachian Mountains, USA. Similar observations have been made in conifer forests in the Pacific Northwest, USA (Harmon et al. 1986).

Mountain, boulder-bed stream type

Processes that deliver wood into the mountain, boulder-bed streams are dominated by disturbances to upland and riparian forests, such as windthrow, fire, and landslides. Lateral cutting by the stream may not significantly contribute wood to mountain streams because the channels are tightly constrained by the adjacent hillslopes.

Windthrow dominates the agents of delivery in many mountain streams. Lienkaemper and Swanson (1987), for example, observed that about 69% of the wood volume added to the stream was delivered by wind, possibly coupled with stem or root decay, which make trees more vulnerable to toppling. Instability imposed by the tilt of trees growing into the open canopy space over a chan-

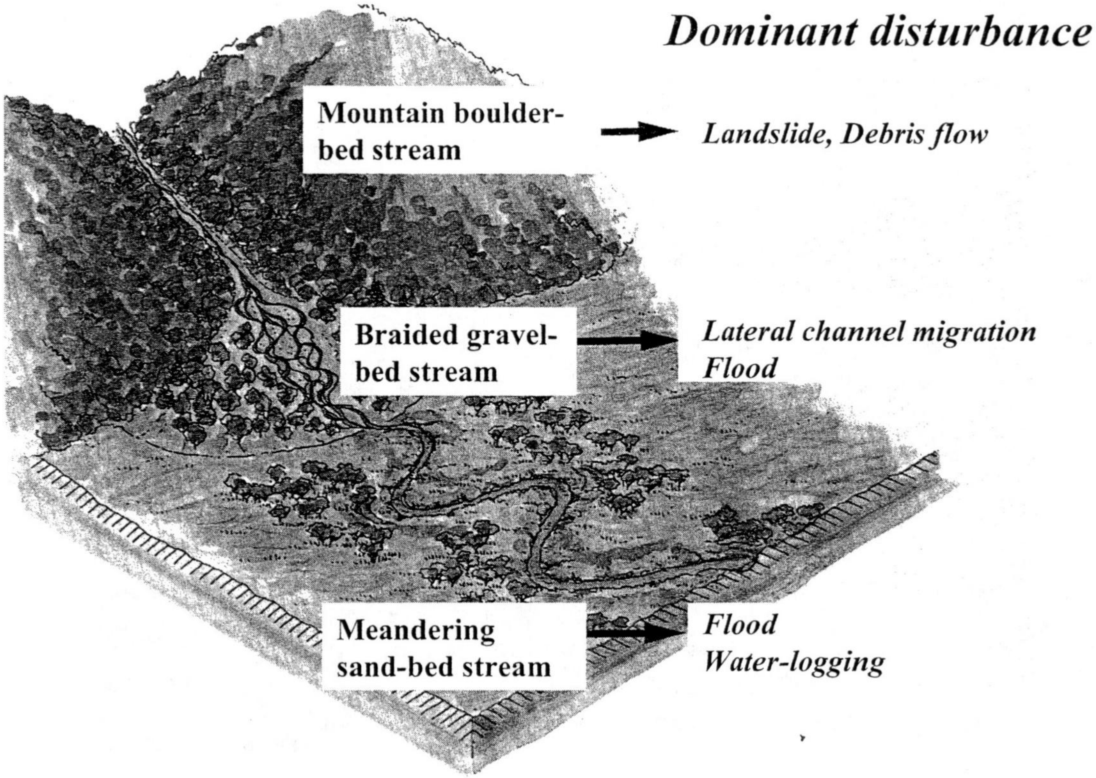

FIGURE 1. Classification of river landscape into the three dominant morphologies.

nel can increase the susceptibility of large trees to windthrow. Catastrophic windstorms, such as typhoons and hurricanes, are common in both temperate and tropical forests, and their effects are closely related to landform. Forest stands established on steep slopes facing the direction of strong winds and valley bottoms running parallel to the wind direction are particularly susceptible to windthrow (Tokyo Forestry Branch 1959). Strong typhoon winds in Japan create large patches of fallen trees (Figure 2) and abruptly supply large amounts of wood to streams in association with landslides (Miyabuchi et al. 1999). Stands planted in Japan after World War II now form densely stocked, 50-year-old stands on steep slopes; the trees are highly vulnerable to toppling into streams as large patches, perhaps in part by a domino effect under the influence of the high winds and intense rainfall of typhoons (Ishikawa 1989). Under these conditions, distinguishing influences of wind and landslides is difficult. In some stands, large trees are more susceptible to windthrow than small ones, creating individual small canopy gaps and occasional tree fall into streams.

Large wildfires, such as the Yellowstone fires of 1988, can burn forests over tens to thousands of square kilometers, affecting extensive areas of the mountain, boulder-bed and other stream types (Romme and Despain 1989). These fires substantially alter the amount and quality of the wood in streams over a long period. Minshall et al. (1989) evaluated the wood in stream channels before and after wildfire in a lodgepole pine forest in the Yellowstone area. Large amounts of wood accumulate in old-growth forest streams in periods leading up to fires. Because of its high moisture content, most of this material remained intact even after hot fires, and it was rapidly augmented by branches and trunks brought down by the fire (Figure 3). Thus, wood volume in the streams increases sharply immediately after fires (Spies and Franklin 1988). Although fallen, fire-killed snags continue to accumulate in streams for several decades after a fire; the new growth in the riparian forest contributes little large wood to the stream. Burned wood may readily break down into small pieces with greater stream instability, faster in the first few years after a fire than later. As forests

FIGURE 2. Catastrophic windthrow by the typhoon in September 1991, Ooita Prefecture, southern Japan (photo provided by Akira Shimizu).

mature and naturally thin, additional wood of increasing diameter and mass accumulates in streams. This process accelerates when old-growth forest conditions are attained. This process can take about 300 years in some of the forest types of the Yellowstone region (Romme and Despain 1989). Simulation modeling of forest stands replicates this temporal pattern of instream wood loading after disturbance (Bragg 2000; Benda et al. 2003, this volume).

Heavy rainfall and rapid snowmelt can initiate landslides, which deliver wood and sediment to mountain streams. The potential for landslides can be increased by windthrow and wildfire in steep landscapes. Typical landforms with landslides are bedrock hollows (zero-order basins; Tsukamoto 1973, Dietrich and Dunne 1978) and steep (>30 degrees), convergent slopes created by channel incision and then filled with colluvium after the last glacial period (Hatano 1974). Many of the wood pieces moved by landslides may be delivered directly to stream channels because there are few geomorphic surfaces, such as fans and terraces, that act to intercept wood delivery. The frequency of landslides at a particular site can range from a few decades (Shimokawa 1984; Yanai and Usui 1989) to 10,000 years or more (Reneau and Dietrich 1990), depending on the geological and geomorphological setting. Slope positions with very frequent landslides may supply smaller pieces of wood than slopes with rare landslides because of the limited time for accumulating live and dead wood for transport by the slides. Ishikawa (1989) studied three heavy rainfall disasters in Japan and concluded that most of the mobilized wood pieces were delivered by landslides adjacent to stream channels and also included old, remnant wood that was in the channel before the storm. Landslides seem to be an important process supplying wood to streams, especially in geologically unstable terrain, such as Japan and the Pacific Northwest, USA (Benda 1990; May 2001).

Volcanic eruptions and associated mass movements can dramatically increase wood volume in mountain streams in volcanic landscapes,

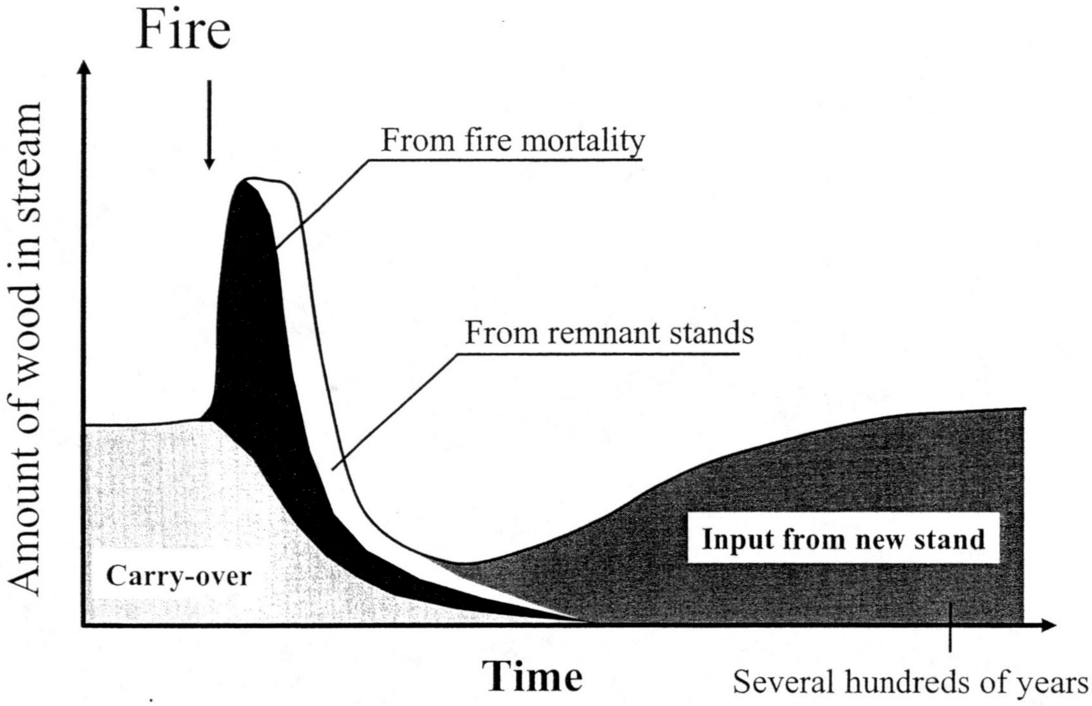

FIGURE 3. Postulated response of instream large wood in lodgepole pine forest after wildfire (modified from Spies and Franklin 1988 and Minshall et al. 1989).

such as in Japan and northwest USA. The timing of inputs of wood, however, can vary widely. The 1977 eruption of Usu Volcano—Hokkaido, Japan—ejected a large amount of ash and pumice, covering a forest landscape near the volcano with several meters of ash fall. Trees buried by deep ash fall were killed, but they were not instantly supplied to the deep gully systems created by rapid runoff after the eruption because most of the trees were standing dead. The wood pieces from broken limbs delivered right after the eruption were relatively short and thin and therefore contributed little to the large debris flows from the flanks of the volcano. In contrast, the 1980 eruption of Mount St. Helens included a much greater variety of volcanic processes that immediately delivered large volumes of wood to rivers draining the volcano and transported that material downstream in some of these rivers. A lateral blast leveled forest over 550 km^2, greatly increasing the wood in river networks (Figure 4). Massive volcanic mudflows raced down most major channels draining the mountain, entraining riparian forest and moving vast amounts of wood many tens of kilometers downstream. The magnitude of the Mount St. Helens 1980 eruption was far greater than recent activity at Mount Usu, and trees near Mount St. Helens were large conifers, up to 60 m (197 ft) in height and 2 m (6.6 ft) in diameter. Wood is still a very important component in streams and some lakes of Mount St. Helens 20 years after the eruption (Figure 4).

Braided, gravel-bed stream type

Forest disturbance processes that operate along mountain, boulder-bed stream types also affect wood in braided, gravel-bed streams, but the braided type additionally experiences disturbances resulting from lateral channel migration and the development and abandonment of secondary channels. Wood falls into streams where banks are eroded and live trees undermined, and wood enters primary channels where fallen trees in secondary channels and on floodplains are floated into the main channel. Multiple channels appear in this stream type at low water, and they may unite during flood flows.

An example of fluvial, wood-related disturbance in the braided, gravel-bed stream type has been described for the Saru River, Japan (Naka-

FIGURE 4. Wood pieces in an area where the 1980 eruption of Mount St. Helens blew down old-growth forest. The photograph was taken in the upper Green River 20 years after the eruption and after recent flooding caused some redistribution of wood in the channel.

mura and Kikuchi 1996). A major flood in 1992 inundated the entire valley floor with water, filling abandoned channels and knocking down the trees in its path. The degree of riparian forest disturbance by the 1992 flood varied according to the age of forest stand (Figure 5). Disturbance severity was described in three rankings: high severity, where trees and even soil were completely removed; moderate severity, where trees were toppled but not removed from the site; and low severity, where trees remained standing, but understory vegetation was removed. Younger riparian forests tended to be more extensively and severely disturbed than older forest stands. In general, mature forests are away from the active channel and on higher geomorphic surfaces, which limits the depth, velocity, and force of water on the trees. In contrast, younger forests are close to the stream channels and, therefore, disturbed frequently by flooding and impacts from floating logs. Thus, small wood pieces dominate braided, gravel-bed streams because the forest is frequently disturbed in the main zone of wood recruitment and the forest does not have time to grow trees of large size.

These observations in Japan parallel trends reported for braided rivers in southeast France by Piégay and Gurnell (1997) and in the Pacific Northwest of the United States (Acker et al. 2003). In alluvial channels in northwest Washington State, however, large "key member" logs (potentially >4 m in diameter, >70 m in length) initiate formation of stable bar-apex (head of gravel bar) and meander jams that alter local flow hydraulics, resulting in bar and pool formation. Individual jams are remarkably stable, providing habitat for trees to mature within a dynamic valley floor environment characterized by frequent channel migration and disturbances (Abbe and Montgomery 1996).

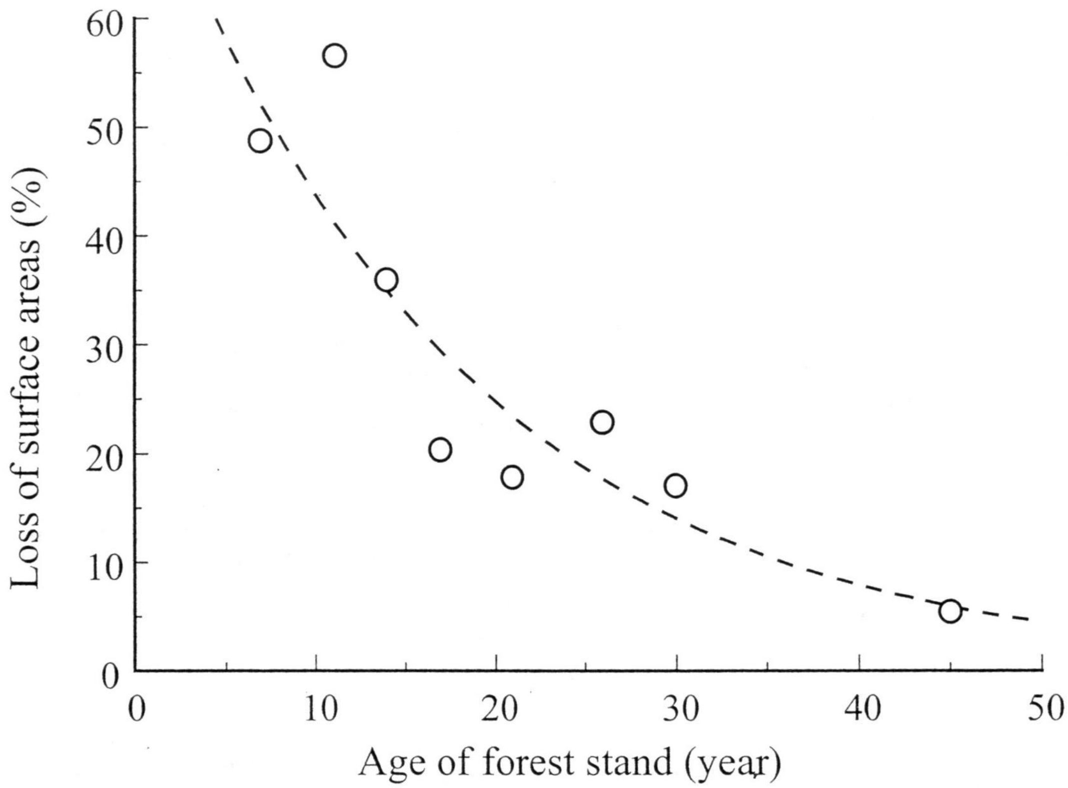

FIGURE 5. Areal percentage of eroded floodplain areas of the Saru River with respect to the stand age (from Nakamura and Kikuchi 1996).

Meandering, sand-bed stream type

River pattern dynamics along the meandering, sand-bed stream type strongly influence the spatial pattern and rate of wood input to channels. Point bars composed of fresh sediment deposits are formed one after another on the inside of meander bends, and progressively older plant communities are developed at increasing distance from the channel. As the entire meandering belt shifts downstream through time, however, older stands grow at the outside of bends where strong currents undercut the banks. This process produces large wood pieces that fall into the channel and may collect on downstream point bars. Thus, wood pieces are individually delivered from the outside banks of the channel, and fresh sand bars providing regeneration sites develop on the inside of meander bends.

Keller and Swanson (1979) suggested the importance of bank erosion in supplying wood to low-gradient, meandering streams. In a study of a meandering, sand-bed stream in northern Japan, Abe and Nakamura (1996) observed that about 78% of the wood volume was produced by bank erosion. Mortality and windthrow contributed only 3% of the total pieces for which supply processes could be identified in this study. Everitt (1968) documented wood entrainment and destruction of riparian forests in association with lateral migration of meandering, sand-bed channel in the Little Missouri River.

Management effects on wood inputs

Forestry activity has the potential to strongly influence wood in the mountain, boulder-bed stream type. Clearcutting, thinning, cleaning streams, and building roads, for example, can alter stand conditions that affect input of wood to streams. Removing large trees and using management schemes that operate on short rotation lengths can reduce the amount and size of wood in channels. If logging debris is left in channels, it may be more vulnerable to movement than natural wood, which includes large pieces, some with rootwads that can stabilize the entire wood supply of the channel. The amount of logging slash in a channel decreases over time as it is transported by debris flows or floods, however, and the wood source areas on adjacent hillslopes are limited to smaller pieces after intensive forestry (Murphy and Koski 1989). A rapid decline of the amount of wood in the first 7 years after harvesting has been reported (Bilby and Ward 1991). The selective removal of instream wood in association with timber harvesting and establishment of red alder trees in riparian zones shifts the size-class distribution of wood toward smaller pieces in low-order streams (Bilby and Ward 1991; Ralph et al. 1994).

Forest roads used to be built along the riparian areas in many countries in the 1950s and 1960s, resulting in removal of riparian trees and reduction of the source of wood input to streams. Even if the roads were removed, the influence of this activity could continue for a century until the re-established riparian trees reach maturity. More recently, forest roads are built away from the riparian zone and on the ridges, to minimize detrimental effects on streams.

Monocultural, even-aged plantations of commercial trees develop a uniform canopy layer. This simple structure may be vulnerable to windthrow, occasionally producing large and abrupt delivery of wood pieces to streams. Moreover, the edges of clearcut patches are particularly susceptible to windthrow where trees grown in fully stocked stands are exposed to strong winds moving through the new opening (Franklin and Forman 1987; Sinton et al. 2000).

In many areas, it is now common practice to leave buffer strips along streams in forest harvest sites to maintain stream and riparian habitat and processes, including wood delivery to streams. This practice has not been widely examined in terms of its long-term ability to meet these objectives, however. One concern is that narrow riparian buffer strips may be subject to substantial toppling of trees by wind and high levels of associated input of wood pieces because the buffer-strip edges are vulnerable to windthrow.

In some areas, such as Japan, regulations for management of both braided and meandering alluvial channel types require clearing of the riparian forests, and roads and agricultural lands are then developed to the edges of the river banks. The riparian forests, therefore, cannot regenerate on these sites, and grasses dominate the streambank vegetation. In Juyonsen Creek, for example, the length of streamside areas bordered by forested riparian zones decreased by half from 1947 (11.6 km [7.6 mi]) to 1989 (6.6 km [4.1 mi]). In the Toikanbetsu River basin, including the Juyonsen Creek tributary, the volume and number of wood pieces were different among stream reaches flowing through three forest-cover types—no forest cover, second-growth forest, and old-growth forest (Figure 6). The numbers of wood pieces in second-growth forest were significantly higher than those in reaches with no forest cover, and wood volume was significantly higher in old-growth forest (Nagasaka and Nakamura 1999). Field studies of the distribution of wood pieces and modeling studies have shown that the successional stage of riparian forests is an important factor limiting the amount of wood because these forests are the major source of wood for streams (Andrus et al. 1988; Murphy and Koski 1989; Bilby and Ward 1991).

After streamflow is regulated by dams, lateral channel change is suppressed and the frequency of modification of gravel bars and associated vegetation are limited. Effects of altered flow regimes on valley-floor inundation are exemplified by damming of the Satsunai River in Japan. Floods with a 1-year return period before the dam was built recurred only once every 5 years or so after the dam went into operation (Figure 7A). Because the maximum discharge below the Satsunai River dam is regulated at only 150 m^3/s (5,300 ft^3/s), flood disturbances as large as those every 2 years before the dam are not expected in the future. A large gravel bar 2.0 km (1.2 mi) downstream from the dam site was used to observe effects of a considerable drop of water level after the dam was built (Figure 7B). Before the dam, a flood once every 5 years would submerge the entire river bed, except for 8% of the higher elevations on the gravel bar. In contrast, the regulated flows resulted in only 55% of the river bed submerged by a flood occurring once in 20 years (Nakamura and Shin 2001). Thus, production of wood pieces by fluvial processes will be limited by the regulated streamflow regime.

Disturbances Caused by Transport of Wood

Once wood pieces are supplied to streams from hillside slopes and floodplains, they may be transported and redistributed by processes operating in the channel. The mode of transport,

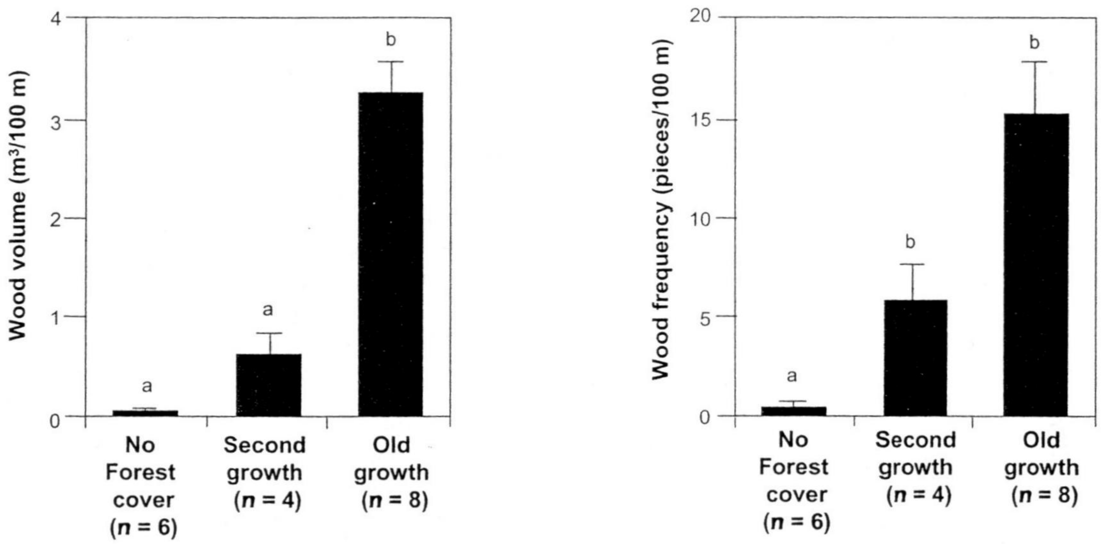

FIGURE 6. Comparison of wood volume and numbers of wood pieces among the three stand age-classes along tributaries in Toikanbetsu River basin, Japan. Values followed by the same letter are not significantly different using Mann-Whitney *U*-test ($p < 0.05$), conservatively adjusted with a Bonferroni procedure (from Nagasaka and Nakamura 1999).

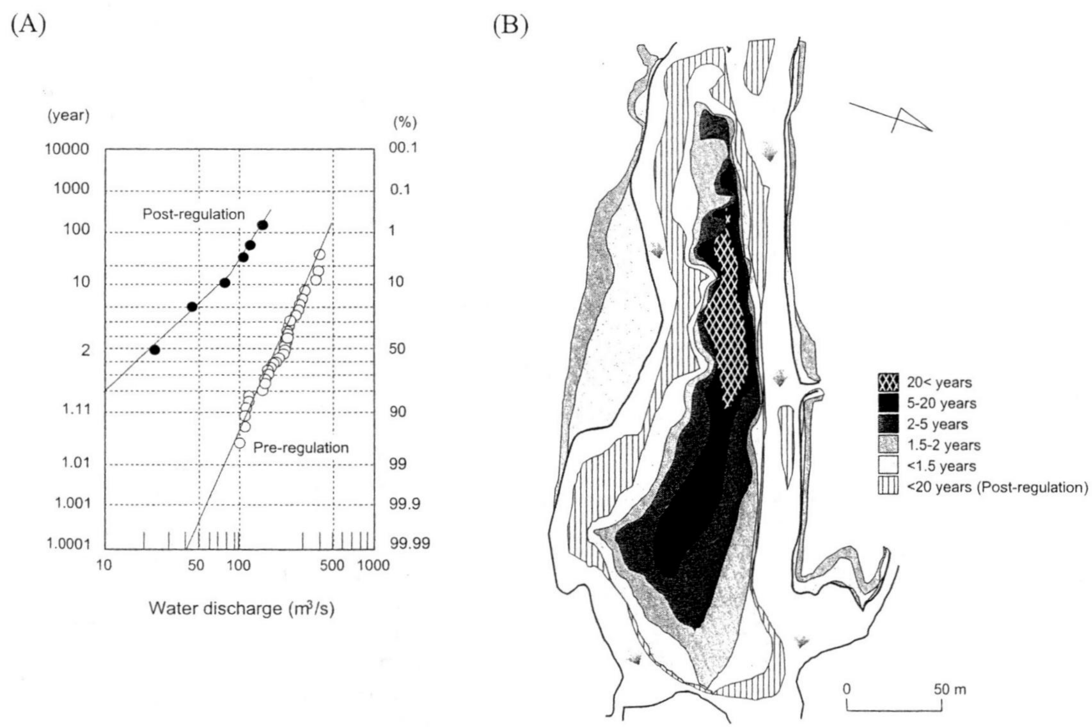

FIGURE 7. Return periods of peak discharge before and after Satsunai River dam (Japan) construction (A) and the resultant decrease in water level (B). The water level in flows with 20-year recurrence intervals was far lower than the water level during 1.5-year flows before flow regulation (Nakamura and Shin 2001).

including the abundance of wood and the type and amount of associated material in transit, can strongly influence the type and extent of disturbance it creates for in stream and riparian organisms and habitat structure (see Gurnell 2003, this volume).

Wood is transported by processes operating over a continuum of concentrations of wood and sediment in water. At least three classes of wood transport conditions are recognized: debris flows, floating wood moving in a congested manner in streamflow, and floating in an uncongested manner in streamflow (Braudrick et al. 1997). "Congested" transport refers to a high concentration of logs moving together as a single mass of pieces in contact with one another; "uncongested" transport refers to logs moving in sufficiently low densities that log–log contacts are infrequent. This spectrum of flow and transport conditions parallels to some extent the classification scheme of Scott (1988) for sediment transport, and we build on that framework by including wood.

Debris flows can transport large amounts of wood pieces as they flow down channels with abundant wood that can be entrained from the streambed and banks. This wood can move at the front of a debris flow as a pile of logs pushed forward by the force of the sediment-rich core of the debris flow. In steep mountain landscapes, debris flows pushing wood at their fronts can be 2 to more than 6 m (20 ft) thick and may therefore overflow the channel, exerting intense scour on streambed and banks. In steep channels with narrow valley floors, debris flows can maintain sufficient thickness to continue moving for many hundreds of meters into channels of lower gradient and wider valley floors. As debris flows spread laterally and become thin, frictional resistance to flow increases and standing trees interact with the moving boulders and wood to stop movement.

In larger channels, buoyant wood pieces can float during high flows in congested or uncongested modes of transport (Braudrick et al. 1997). Important mechanisms of disturbance by floating wood involve the impact force of a floated log against a standing tree and the "sail effect" of the transfer of force of flowing water on a horizontal, floated log lodged against a standing tree. In the latter case, the standing tree may gradually topple, making it possible for the floated log to slide up the tipping tree. This may cause the floated log to be lifted out of the water somewhat, thereby reducing the cross-sectional area affected by streamflow and reducing the force of streamflow against the toppling tree. This negative feedback mechanism may be responsible for formation of patches of tipped, still partially rooted saplings and small trees along channels where wood floatation events recently occurred (Johnson et al. 2000). Congested transport has the greater potential for disturbing riparian vegetation because groups of floating logs can have higher impact force on standing trees and may be less likely to pivot on impact and float away than is the case of a single piece of wood hitting a riparian tree. Floating wood is less likely to disturb benthic habitat than are debris flows because the floating wood is generally moving in the upper part of the water column and above the streambed.

The type of riparian vegetation disturbance depends on the vegetation itself and the amount and size distribution of transported wood. For example, young forests, such as 10–40-year-old alders, are flexible and have root systems that allow trees to be commonly found partially toppled but still rooted on gravel bars. This finding may be common where the channel has transported floated wood of sufficient size to knock the trees down, especially large, cylindrical pieces of conifer wood lacking massive, complex branch systems more typical of hardwoods. Large conifer trees in riparian zones may topple as a result of erosion of soil from their root systems. When they fall, their full length reaches the ground and may shatter on impact, but some pieces may not move because of their size relative to the amount of water available to float them. An important control on mobility of young, toppled hardwood trees, on the other hand, can be the stabilizing effect of partial rooting.

Johnson et al. (2000) investigated the role of floated wood on disturbance severity in riparian forests affected by a major flood in 1996 in the Cascade Range in Oregon, USA. Some riparian trees were removed by the flood, some were toppled, and others remained standing. The percentage of trees affected in these ways differed with transport processes, such as fluvial disturbance, uncongested transport, and congested transport. Stream reaches with uncongested wood transport had more toppled riparian trees than reaches experiencing high flow with very little wood transport and less than reaches with congested wood transport. Therefore, the availability of wood pieces to function as disturbance "tools" and the way they are transported influence the degree of disturbance in riparian forests.

Spatial perspectives of transport

Debris flows are a common wood transport and disturbance process in many steep, narrow channels of the mountain, boulder-bed stream type. On the other hand, floatation of wood pieces dominates transport in higher-order streams of the braided and meandering alluvial stream types. The factors controlling stream power (such as discharge, width, and gradient) and large obstructions or roughness elements (such as boulders, riparian trees, bars, and sinuosity) play major roles in redistributing wood pieces in streams (Nakamura and Swanson 1994; Piégay et al. 1999; Gurnell et al. 2000, 2002).

These different transport processes and their geomorphic settings can result in distinctive deposits of wood (Gurnell et al. 2002). Debris flows commonly produce tightly knit logjams at their snouts, which may accumulate at channel junctions (Benda and Cundy 1990), on roads, on valley floors, or in receiving channels. Floated wood transported in an uncongested mode commonly results in scattered deposits along the banks of rivers or in discrete trapping sites, such as at the heads of islands or mouths of secondary channels. Wood moved in a congested manner may form a series of log levees along the channel with pieces oriented parallel to it or pointing downstream and toward the channel (Johnson et al. 2000). Where streamside slides instantly deliver soil and many trees into a stream, they may dam the channel temporarily, followed by a dam-break flood (Coho 1993). This geomorphic process can transport logs in a congested manner. When the logs are deposited, they tend to be oriented perpendicular to the channel at the toe of the deposit and parallel to the channel at the lateral marginal levees. Floated wood pieces can be efficiently trapped on gravel bars in braided rivers, resulting in distinctive wood accumulations, bar forms, and patches of riparian vegetation (Nakamura and Swanson 1993; Abbe and Montgomery 1996). Wood may be preferentially deposited along floodplains adjacent to meandering streams (Piégay and Gurnell 1997; Gurnell et al. 2002).

Spatial and temporal interactions of transport processes

Sequences of geomorphic processes transport wood through stream networks. These sequences also function as a cascade of disturbances in mountain landscapes (Nakamura et al. 2000). Such disturbance cascades can be initiated by small, rapid landslides from hillslopes and channel head environments or by large, slow-moving earth-flows (Nakamura et al. 2000; Figure 8). Small landslides (1a) triggered on hillslopes may move into steep, headwater streams, move rapidly down those channels as debris flows (2), and ultimately deposit coarse sediment and logs in larger streams or on mainstem valley floors. Some debris flows may enter fourth- and fifth-order channels and be immediately entrained in part as rafts of wood 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 logs in a congested mode of transport. Transport of wood accumulations from debris-flow runout or from jam break-up may end in distinct accumulations of wood or may simply dissipate in the downstream direction as the wood is left along the banks in a series of smaller accumulations, such as wood levees (Johnson et al. 2000).

Disturbance cascades can also begin where large, slow-moving earthflows gradually constrict channels (4a), increasing the potential for streambank erosion and streamside slides during high flows (5). These streamside slides can deliver sediment and trees, which form temporary dams (B) that can break up, triggering flood surges downstream for a kilometer or more (3). The associated logs may move in a congested manner, accentuating their ability to disturb riparian vegetation.

Transitions among these geomorphic 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. Landslides may come to rest where they reach a channel (1b) and form a debris jam (D) or, in areas of low gradient—such as slump benches or road surfaces—before reaching streams. Debris flows may stop at critical points where the channel slope is too low to sustain flow, channel direction changes abruptly by 70 degrees or more, valley floor width increases, or the debris flow encounters obstructions to flow, such as standing trees or road fills that can act as dams (C).

The extent of expression of the disturbance cascade can be assessed in terms of the probabil-

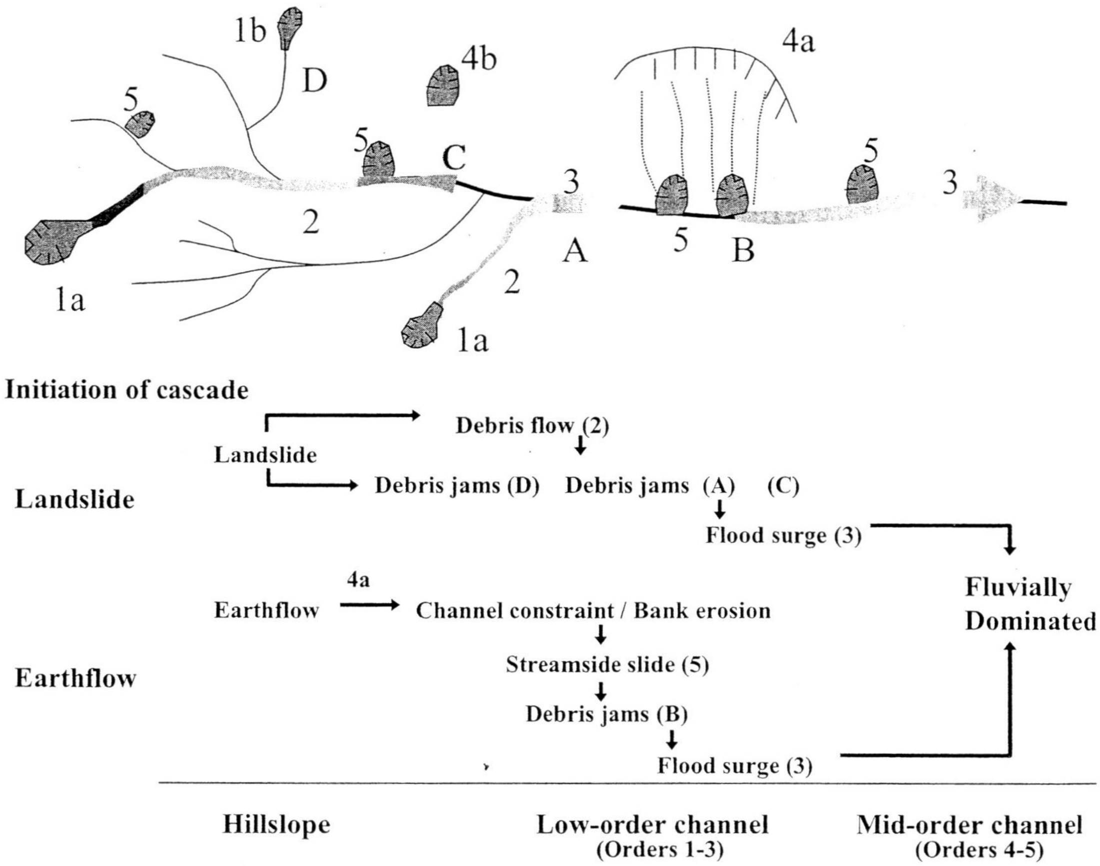

FIGURE 8. Representation of interaction among processes (numbered) operating in disturbance cascades. Letters denote depositional sites at the end of landslide and debris flow paths (from Nakamura et al. 2000).

ity of one process transforming to the next in the sequence, based on an observed history of events. To illustrate these relations, we examined linkages among the relevant processes in >50-year-recurrence-interval flood of February 1996 in the Oregon Cascade Range (Nakamura et al. 2000). The events were initiated mostly by shallow landslides unassociated with earthflows. About 30% of the landslides did not reach streams because they lodged on hillslopes or on roads. Nearly half of all the landslides transformed into debris flows down steep, first- through third-order channels. Thus, about 70% of the initial population of landslides and debris flows stopped at hillslope-channel intersections, in the channel at a downstream point, or on roads and alluvial fans before reaching large streams. Only 7 of 94 events inventoried were associated with earthflows. These observations suggest the relative importance of different flowpaths through the watershed in terms of wood transport by mass landslide-related processes and associated disturbance to stream and riparian habitat in this mountain stream network.

Management effects on wood transport

Management actions of various types—including forestry, erosion control, and recreation-related—can affect the rates, frequencies, and types of wood transport in watersheds and the size distribution of material moved. These factors affect disturbance regimes of stream and riparian systems. Forest clearcutting, for example, can increase the probability of landslides by a factor of two or more (Sidle et al. 1985), and the associated reduction of large trees in landslide deposits may increase the potential for these landslides to develop into debris flows. Forestry practices may also reduce the size of wood pieces in a stream, making the material more mobile during high flows.

Roads passing through headwater areas of mountain stream networks can be sources of landslides when roadfills collapse during heavy rainfall and snowmelt (Sidle et al. 1985, Wemple et al. 2001). Roads on valley floors of larger channels can serve as small dams that block downstream transport of wood in debris flows (Wemple et al. 2001). Roads may also increase peak flows in some situations by increasing the stream drainage density in a watershed (Wemple et al. 1996), thus potentially increasing the capacity of a stream to transport wood.

A comparative watershed study by Nakamura and Swanson (1993) showed that a third-order watershed with no landslides along its mainstem after clearcutting developed a wide valley floor with many wood pieces, including logging slash. A nearby watershed with many, large debris flows had relatively little instream wood remaining on the narrow, bedrock streambed.

Check dams for sediment control in Japan trap wood pieces on the flat areas of the sediment storage area behind the dam (Shimizu 1998). Slit dams designed to sieve large inorganic and organic materials from streamflow and debris flows capture wood pieces efficiently. Large reservoirs for power generation and flood control trap all wood pieces transported from the upstream drainage areas, resulting in substantial decrease in wood delivery to the downstream reaches.

Not only the wood supply from upstream, but also the entrainment of wood by lateral channel migration and high flow peaks can be greatly reduced by regulating water discharge. Straightening, revetment, and bed stabilization work in association with channelization projects can simplify channel margin features and bed roughness, increasing channel capacity for downstream wood transport, and leaving very few pieces after flooding in channelized reaches. The subsequent degradation of the riverbed by vertical erosion commonly forces a river into a single channel. Such hydrologic and geomorphic changes dramatically alter the frequency and magnitude of flood disturbances.

Disturbance Caused by Changes in Structure of Wood Accumulations

Because wood plays important roles in the habitat structure and ecological function of stream ecosystems, change in the arrangement of instream wood can amount to ecosystem disturbance. Effects of modifying wood have been examined in various ways, such as studies of processes and experimental manipulations of the wood, including both introducing and removing it.

Wood efficiently retains the particulate organic materials delivered from upstream and adjacent hillslopes, especially in low-order streams. This function is important in regulating energy flows in forested streams. In a study in Japanese low-gradient, small streams, hydrologic factors—such as velocity and depth—were shown not to regulate the amounts of leaf litter in streams; rather, wood volume best explains the standing stock of leaf litter in the three seasons studied (Kishi et al. 1999).

Wood pieces were experimentally removed from streams at Hubbard Brook Experimental Forest, New Hampshire, USA to investigate effects on particulate-matter storage and export and other factors (Bilby and Likens 1980). The results showed a striking increase in fine-particulate organic-matter export, especially when water discharge was high. Removing wood pieces not only decreased the ability of the channel to retain these materials, but also destroyed most of the pools in the stream, thereby removing depositional areas for particulate material. Wood also serves as a major mechanism for retention of salmon carcasses in the Pacific Northwest (Cederholm et al. 1989).

The abundance of dams not only regulates organic-matter storage, but also macroinvertebrate abundance. Macroinvertebrate density and biomass in wood dams of a headwater stream in Virginia were 5 to 10 times greater than on sandy sediments because of higher retention of particulate organic matter associated with wood dams (Smock et al. 1989). Thus, functional feeding groups also varied with wood dam abundance; for example, the density of leaf shredders was eight times higher in dams than on sediment.

Removing wood pieces initiates substantial changes in channel morphology and sediment transport (Beschta 1979, Abe and Nakamura 1999). Experimentally removing wood from a small, gravel-bed stream resulted in a fourfold increase in bedload transport at bank-full discharge (Smith et al. 1993).

Natural fluvial disturbance of wood can also greatly alter the characteristics and the extent of the hyporheic zone. Wondzell and Swanson (1999) observed changes in hyporheic zones before and after the major 1996 flood in the Oregon Cascade Range, USA (Figure 9). Before the flood, the active

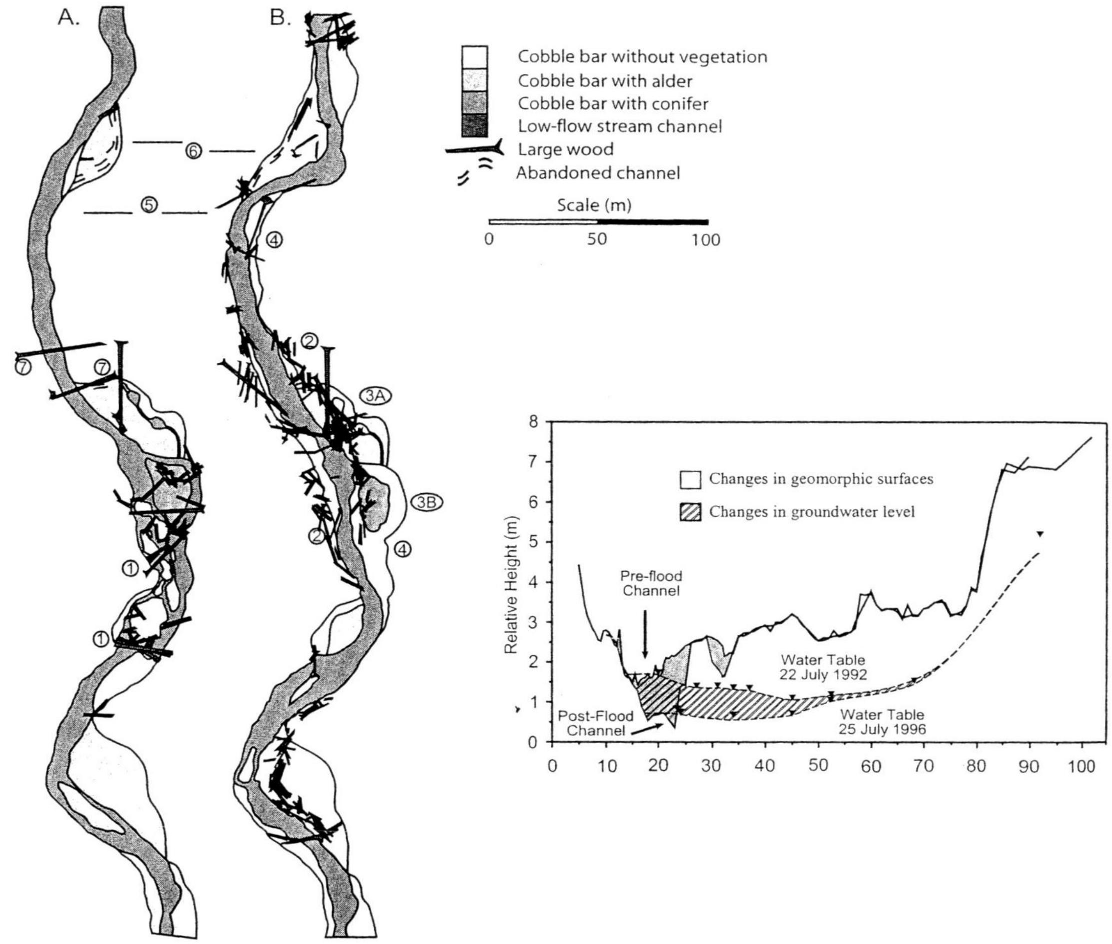

FIGURE 9. Lower McRae Creek showing the general planform of the active channel, locations of key large wood, secondary channels and gravel bars (A) before and (B) after the flood of February 1996. Cross-sectional profile indicates the drop in water table before and after the flood (from Wondzell and Swanson 1999).

channel was somewhat braided around small gravel bars and logjams. The flood of 1996 breached the logjams, and the channel cut down through the wedge of accumulated sediment. This downcutting altered subsurface flow paths and limited the extent of the hyporheic zone.

Wood pieces control instream habitat conditions for fish by creating pools and providing refuge during floods and cover in nonflood periods. Studies in the United States and Canada clearly indicate that wood provides salmonid habitat and influences fish abundance (Elliott 1986; Riley and Fausch 1995; Dolloff and Warren 2003, this volume). These results were experimentally confirmed by adding wood pieces or removing them. Observed increases in fish populations were attributed to an increase in pool volumes (Fausch and Northcote 1992). This function of wood pieces was not fully examined in Japanese streams where all riparian trees are small. Inoue and Nakano (1998) examined the relation between wood volume and juvenile salmon density in a small stream and concluded that wood affected fish more by providing cover than by creating pools. In the volcanic, pumice-bed streams of this study area, however, even small woody pieces could create pools and increase biomass of rainbow trout *Oncorhynchus mykiss* (Urabe and Nakano 1998), probably because the low-density, pumice bed material could be easily scoured. Removal of wood by river regulation detrimentally affect fish populations and communities.

Spatial aspects of change in wood accumulations

Mountain boulder-bed channels, and especially bedrock channels, can be highly influenced by wood because these systems have high transport capacity, which wood can impede. Wood can trap sediment, creating benthic habitat, and retain floated organic litter in a system otherwise limited in substrates. Thus, removing wood from these systems is likely to strongly affect these processes and features. Disturbance of wood in this channel type is likely to have little effect on recruiting additional wood to the stream, except in the case of reduction of wood for inclusion in debris flows, which can affect their impact and extent. Modifying wood in this channel type may have limited effect on fish where the boulders are providing high channel complexity and fish populations are limited by high velocity and gradient and by limited habitat space.

Disturbance of wood structures in braided, gravel-bed streams is likely to affect both wood input and transport processes, which are sensitive to the presence of floated wood in these systems. Disturbance of wood structures in secondary channels can be particularly important in terms of loss of water-column habitat for fish. Secondary channels can trap small wood pieces that contribute to pool formation (Nakamura and Swanson 1994) and provide refugia during floods.

Disturbance of wood in the meandering, sand-bed channel type may have an impact on complexity of water-column habitat along the outside banks of bends in the channel where certain fish species may reside. In general, however, wood plays less significant roles in this channel type than in the other two, so disturbance of wood would be of less consequence. Experimentally removing the wood in the meandering, sand-bed channel decreased small pools associated with wood in one Japanese study but recreated large pools by lateral scouring, and total pool volume remained unchanged (Abe and Nakamura 1999).

Management effects on wood accumulations

Channelization projects common in developed countries can greatly reduce the ability of a channel to retain material transported by flowing water (such as organic matter, nutrients, and sediment) by removing wood pieces from stream channels. After channelization, further changes in channel structure are limited because of wood removal, straightening of the channel path, and revetment of stream banks. Thus, transport capacity in the channelized reaches, in general, is high, and wood pieces supplied from upstream are easily transported.

Check dams for sediment control create a large hyporheic zone behind (upstream of) the dams. Check dams, however, are commonly impermeable, and therefore, they can almost eliminate exchange flows because water cannot flow through the accumulated sediment behind dams. The residence time of groundwater in the dam-created hyporheic zone may be very long, so anaerobic conditions commonly occur in the stagnant groundwater. On the other hand, wedges of sediment accumulated behind permeable, step structures, such as logjams, permit complex subsurface water flow through the structure.

Knowledge Gaps and Framework for Future Work

Research on the influences of disturbance on patterns and processes of wood in rivers and stream is growing, but many knowledge gaps remain. Only little work on wood in rivers has taken a disturbance perspective, especially at the time scale of the disturbance regime and the spatial scale of whole watersheds. Few studies link wood production, storage, decay, and transport at the watershed scale (Snyder 2000; Benda et al. 2003). An important next step is to incorporate a disturbance perspective in the general view of the production and routing of wood pieces. Some components of the wood-routing system (Benda et al. 2003; Gurnell 2003) result in ecosystem disturbance and other components do not.

A further critical knowledge gap is the cumulative effects of management actions. Effects of management actions—intended and unintended—are poorly understood in terms of wood quantities, arrangements, movement, and effects. In general, management tends to reduce wood pieces in streams in the long term, though it may initially increase them. Many complexities of the temporal and spatial dynamics of wood in natural and managed systems remain to be unraveled, however. One valuable perspective would be an understanding of how the relative behavior of wood-related disturbance regimes compares with other disturbances in terms of types, degrees, and consequences. This information could benefit efforts to restore watersheds and biodiversity.

A disturbance-cascade perspective (Nakamura et al. 2000) may provide a good framework to advance understanding of the links between wood-transport processes and disturbance. We know little about effects of management activities on the frequency and intensity of disturbances and the continuity and connectivity of disturbances processes cascading through river networks. An assessment of management effects on wood-related disturbances would examine the roles of wood for each process and the transitions from one process to another.

Critical elements of a framework for future study and management of wood must include geographic, temporal, and process views at a series of scales. These elements are shown in a single figure encompassing the geographic sequence down the gravitational flow path from hillslopes to small streams to large rivers (Figure 10). Natural disturbances—such as fire, windthrow, and landslides—on hillslopes and in mountain creeks contribute wood pieces to streams, and fluvial processes like channel migration and flooding are responsible for producing wood in braided and meandering streams. Management activities, like timber harvesting and road building, influence both production and transport processes, and check dams and slit dams in mountain creeks interrupt transport of log pieces by debris flow. Embankment, revetment, and channelization constrain channel migration and flooding frequency. Time is another important factor affecting current conditions of wood in streams under a disturbance regime. From a watershed perspective, time can be expressed as a disturbance cascade providing a disturbance history in a stream network. Scaling reflects geographical differences, such as decay rate, tree size versus channel width, wood density, and bed material density, affect temporal changes in the standing stock of wood in the stream and residence time in a storage.

All of these factors eventually affect the stream and its riparian ecosystem, including habitat loss and creation, refugia and sources of propagules for recolonization, energy flows, and the dynamics of hyporheic zones.

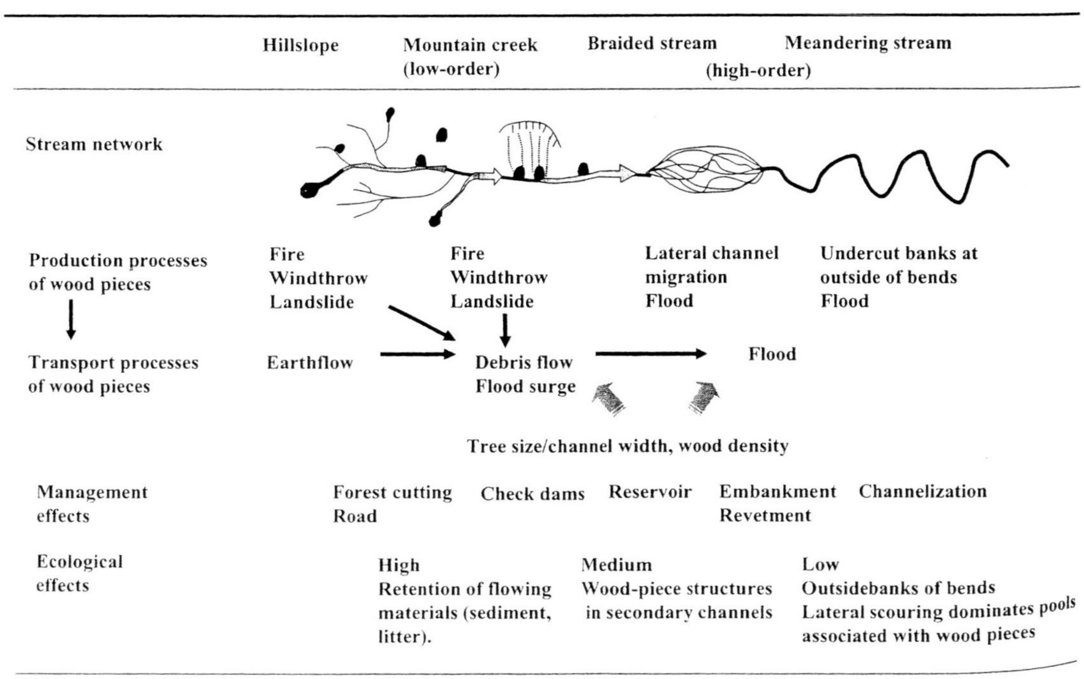

FIGURE 10. A framework for applying results in different geographic and management settings.

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