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Geomorphic Effects of Wood in Rivers

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Abstract.—Wood has been falling into rivers for millions of years, resulting in both local effects on channel processes and integrated influences on channel form and dynamics over a wide range of spatial and temporal scales. Effects of stable pieces of wood on local channel hydraulics and sediment transport can influence rates of bank erosion, create pools, or initiate sediment deposition and bar formation. At larger spatial scales, changes in the supply of large wood can trigger changes in both river-reach morphology and the interaction between a river and its floodplain. Over long time scales, wood-rich rivers may retain more sediment and have lower sediment transport rates and steeper slopes than comparable wood-poor channels. Most geomorphic effects of wood in rivers arise from large, stable logs that catalyze changes in the routing and storage of both smaller wood and sediment. The size of a log relative to the channel provides a reasonable gauge of the potential stability of in-channel wood. Channels with a high supply of large, potentially stable wood may experience substantial vertical variability in bed elevation independent from external forcing (e.g., climate variability, temporal variations in sediment supply, or tectonic activity). In some river systems, changes in the wood regime, as described by the size and amount of wood supplied to a river, can result in effects as great as those arising from changes in the sediment supply or the discharge regimes. Consequently, an understanding of the geomorphic effects of wood is crucial for assessing the condition and potential response of forest channels.

Introduction

Over the past several decades, researchers have recognized that large wood has a significant effect on many channel processes. Recent studies show that wood affects channel processes at scales from channel roughness (Shields and Gippel 1995; Buffington and Montgomery 1999b; Manga and Kirchner 2000) to bed-surface grain size (Lisle 1995; Buffington and Montgomery 1999b), pool formation (Keller and Tally 1979; Lisle 1995; Montgomery et al. 1995; Abbe and Montgomery 1996), channel-reach morphology (Keller and Swanson 1979; Lisle 1986; Nakamura and Swanson 1993; Montgomery et al. 1996; Montgomery and Buffington 1997, 1998; Piégay and Gurnell 1997), and the formation of valley-bottom landforms (Abbe and Montgomery 1996; Montgomery et al. 1996; Gurnell et al. 2001). This chapter addresses the geological context of wood in fluvial environments, the extent of historical changes in wood loading, and the geomorphic effects of wood across this range of scales. We also propose a framework for using the relative size of large wood for assessing its geomorphic effectiveness in rivers. Our intent is not to simply review the recent literature on the geomorphic effects of wood in rivers, but to focus on developing a framework for interpreting both general and region-specific geomorphic effects of large wood across a range of scales. We begin with overviews of the geological and historical contexts in which to consider the changing roles of wood as a geomorphic agent in river systems.

Geological Context

Modern forests cover almost a third of Earth's land surface (Atjay et al. 1979), and wood has been entering streams and rivers for more than 400 million years, although its relative influence on freshwater ecosystems has varied substantially and becomes progressively more speculative back through geologic time (Figure 1). Indirect evidence suggests that primitive plants first colonized the land surface in the Middle to Late Ordovician (470–438 m.y.a.), but fossils document the existence of terrestrial plants by the Late Silurian (423–408 m.y.a; DiMichele and Hook 1992). The evolution of land plants coincides with the first appearance of meandering stream deposits in the geologic record, before which only braided channel deposits appear in fluvial deposits (Schumm 1968; Cotter 1978). Development of a meandering channel pattern requires bank cohesion (Schumm 1963), which, with the advent of terrestrial vegetation, was presumably provided by riparian root strength. By the Late Devonian (384–360 m.y.a.), forested areas dominated by small trees had become common, although trees with diameters up to 1 m were present in low abundances (DiMichele and Hook 1992). Vegetation covered much of the world's land mass during the Carboniferous (360–286 m.y.a), and logjams probably were common in many Carboniferous rivers, such as those whose deposits have been mined for coal in recent history. Presumably, the geomorphic role of wood in rivers increased as trees grew larger and more abundant later in the Paleozoic, at least until the Permian-Triassic (P/T) extinction event (Figure 2), when meandering channels worldwide reverted to the

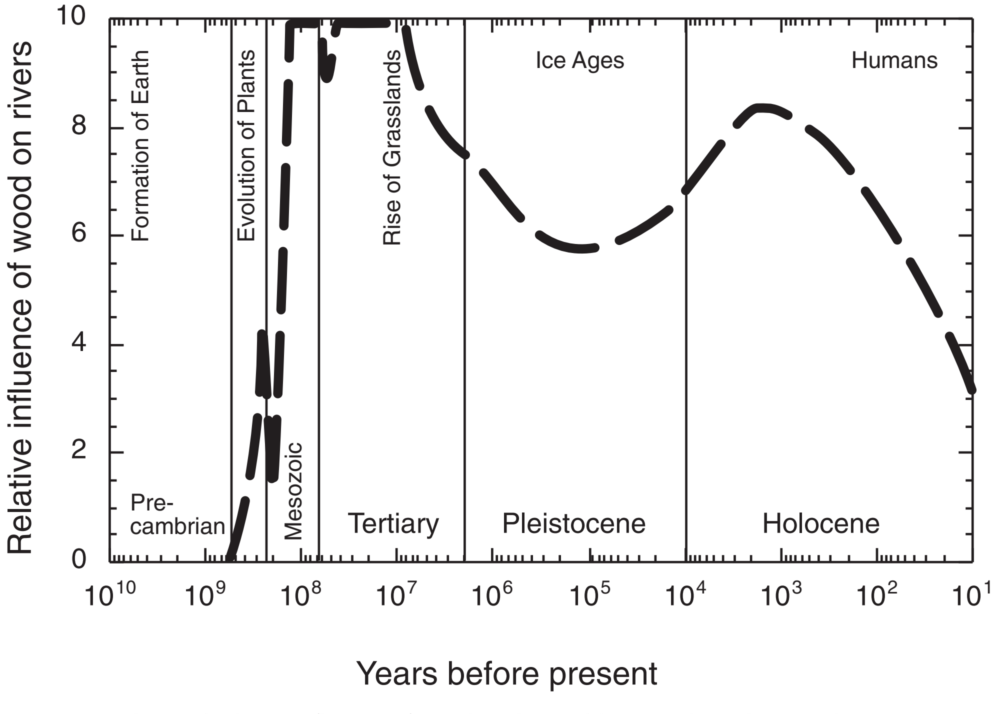

FIGURE 1. Hypothesized relative influence of wood on the world's rivers throughout geologic time.

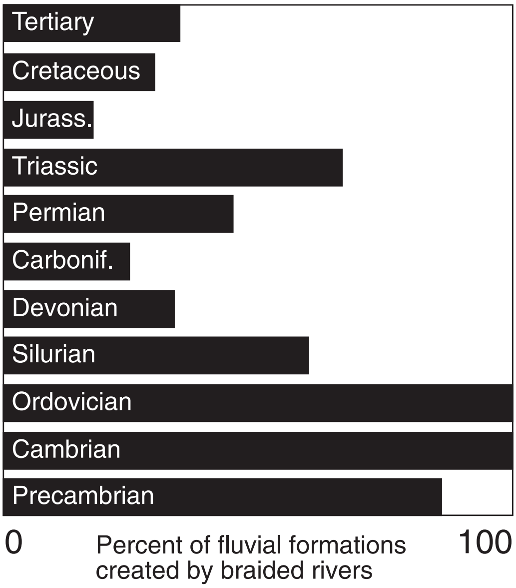

FIGURE 2. Plot of the percentage of fluvial deposits interpreted as deposited by braided channel systems for periods of geologic time from the Precambrian to the Tertiary (data from Cotter 1978). Note the original dominance of braided channel deposits, their gradual decline in relative abundance as they were replaced by meandering channel deposits, and the increase in the relative abundance of braided channels at the Permian/Triassic boundary (Ward et al. 2000).

braided morphology typical of Precambrian fluvial deposits (Ward et al. 2000). The apparent global die-off of terrestrial vegetation at the P/T event would have dramatically reduced the role of wood in world rivers.

After the P/T event, trees generally increased in size during the Mesozoic (248–65 m.y.a.), hence we hypothesize that so did the influence of wood in rivers. Temperatures were warmer than at present, especially at high latitudes, and the equatorial regions were more arid than today. Primitive conifers were the largest trees in Triassic forests, and some Late Triassic (228–208 m.y.a.) floodplain forests supported dense stands of trees up to 60 m tall (Wing and Sues 1992). In the warm Jurassic climate (208–144 m.y.a.), vegetation assemblages that included numerous conifer species extended to high latitudes (Gee 1989). Conifers were still the dominant large trees, and Late Jurassic (175–148 m.y.a.) forests of northwestern China supported conifers up to at least 2.5 m in diameter (McKnight et al. 1990). Spicer and Parrish (1987) report fossil conifer logs up to 50 cm in diameter in Late Cretaceous fluvial deposits as far north as 80° to 85° latitude. Moreover, they show evidence that logs were not transported far from their site of growth, which implies that they were relatively stable in the streams in which they were deposited. The diversity of smaller angiosperms increased during the Cretaceous to the point that they accounted for most of the species in typical fossil assemblages and particularly those from riparian corridors. The asteroid impact at the Cretaceous/Tertiary (K/T) boundary 65 m.y.a. caused devastating ecological disruption in western North America but less severe effects on terrestrial biota in the Southern Hemisphere (Wing and Sues 1992). After the K/T event in the Early Tertiary, floral diversity recovered gradually, but preferential extinction of conifer species at the K/T boundary is hypothesized to have enriched Northern Hemisphere floras in deciduous taxa (Wolfe 1987). All told, the influence of wood in rivers is likely to have been substantial throughout the Mesozoic.

Cenozoic changes in global vegetation patterns seem likely to have imparted significant variability to the role of wood in world rivers. In the Early Oligocene, broad-leaved forests expanded into areas previously covered by conifers (Wolfe 1985) and ultimately came to cover large regions of the Northern Hemisphere (Potts and Behrensmeyer 1992). The global climate began cooling in the Oligocene (37–23 m.y.a.), a trend that accelerated in the latter half of the Miocene (14–5 m.y.a.). Extensive savannas and grasslands became established by the Pliocene, and closed canopy forests were increasingly replaced by more open woodlands (Potts and Behrensmeyer 1992). With the onset of Pleistocene glaciations 2 m.y.a., the extent of forests oscillated in the temperate and polar latitudes, with forest cover expanding during warm interglacial periods and contracting during glacial periods (Porter 1983; Velichko 1984; Huntley and Webb 1988). During glacial maxima, only a few European rivers in small isolated areas of forest refugia would have had significant wood loading. In contrast, parts of eastern Australia have been continuously forested for more than 100 million years. The recession of glaciers in regions such as northern Europe was followed by rapid forest expansion early in the Holocene, about 10,000 years ago (Wright 1983; Velichko 1984). European forests reached their maximum Holocene extent before the onset of deforestation that fueled the rise of human civilization (Perlin 1989). Humans have reduced global forest cover to about half its maximum Holocene extent and eliminated all but a fraction of the world's frontier forest (Figure 3). The influence of wood on world rivers during most of the Holocene was likely intermediate between the more extensive effects hypothesized for the warm Mesozoic climate and the more limited influence during major glaciations.

Historical Context

In most of the industrialized nations, the primeval character of rivers is lost or unknown because ancient deforestation and river clearing to improve navigation changed the input of wood to rivers long before recorded history. The United States and Australia are unusual in that they were technologically advanced bureaucracies at the time that many of their rivers were first modified and their forests first cleared. Consequently, historical records of instream wood removal and clearing of riparian forests can now be used to reconstruct and evaluate how the role of wood in some river systems has changed in the last two centuries. We must rely on more indirect methods for regions cleared in earlier times.

The effect of forest clearing on soil erosion in the ancient Mediterranean had dramatic long-term effects on the region and its inhabitants (Dale and Carter 1955). The famous cedars of Lebanon once covered nearly 2,000 square miles, but by Roman times the forest had been so extensively cutover that Emperor Hadrian protected groves for the use of the Roman fleet (Lowdermilk 1950). The Lebanese cedars were enormous; around 2600 B.C., a shipment from Phoenicia to Egypt arrived with logs 100 cubits long (just over 170 ft; Perlin 1989). By 1950, this ancient forest was reduced to several tiny groves (Lowdermilk 1950). The similar, but more recent, forest destruction in the Chinese Province of Shansi caused extensive soil erosion and substantial adverse effects to regional river systems (Lowdermilk 1926).

Human alteration of forests in Europe has been significant for at least 6,000 years (Williams 2000), and river clearing and engineering date to the Roman era (Herget 2000). Forests in southern Europe were already confined to mountainous areas by classical times, and the clearing of central and western European forests that began in the Neolithic expanded dramatically in the Middle Ages (Darby 1956). Even with such early forest clearing, logs and logjams were depicted in early European books on rivers (Figure 4). By the 18th century, the fortunes of European naval powers were influenced by access to distant sources of timber for building ships, particularly trees large

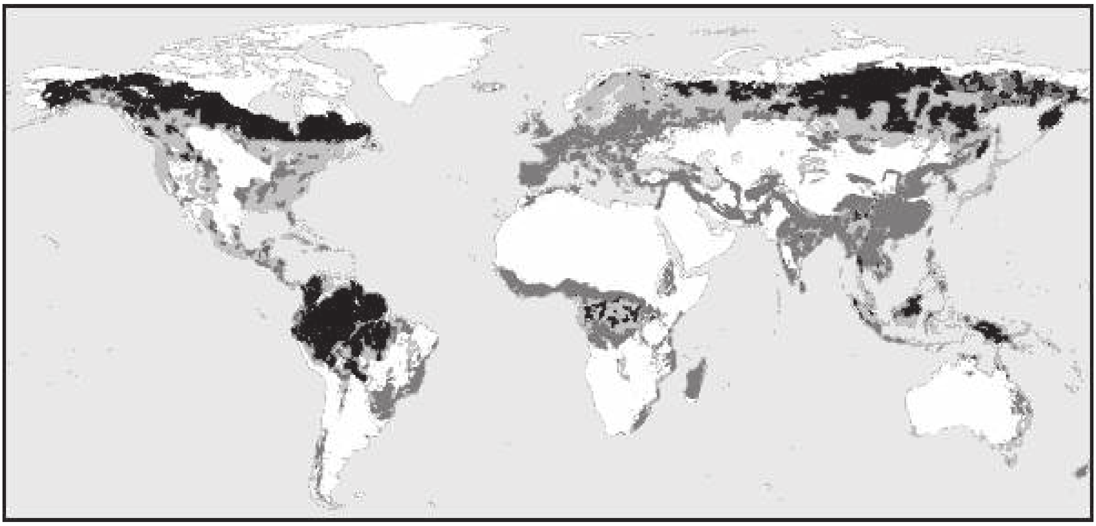

FIGURE 3. Global extent of frontier forest today (darkest shade), nonvirgin forest (medium shade), and forest cleared during the Holocene (lightest shade), showing that about half of the original Holocene forest cover is gone and about one-fifth remains in large tracts of relatively undisturbed forest. Modified from World Resources Institute (http://www.wri.org/wri/ffi/maps/).

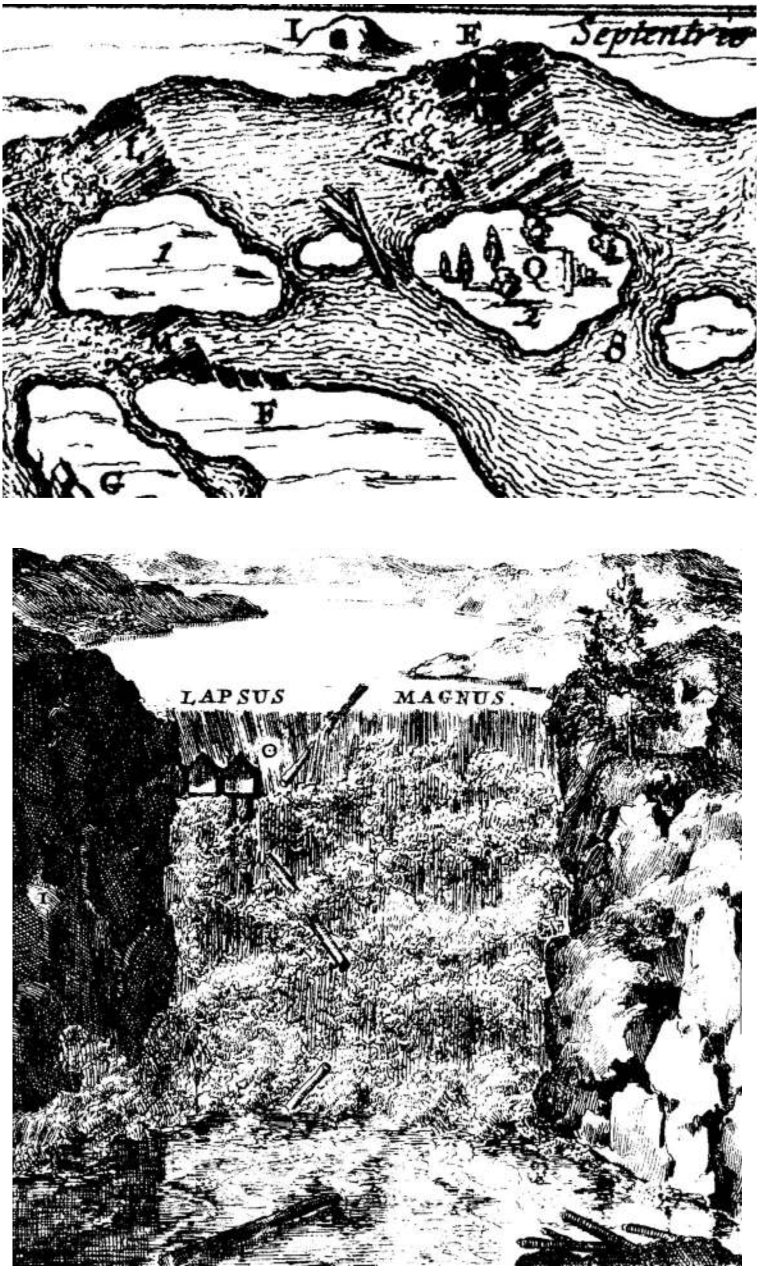

FIGURE 4. Portions of woodcuts showing logs and log jams in 17th century European rivers (Herbinio 1678).

enough to be suitable for masts (Albion 1926; Bamford 1956). The English navy, for example, depended on large, old-growth white pine from the American colonies to provide masts for their ships (Albion 1926).

The forests of eastern North America were vast and dense; John Bartram writing in 1751 characterized the tree tops as "so close to one another for many miles together, that there [was] no seeing which way the clouds drive, nor which way the wind sets: and it seem[ed] almost as if the sun had never shown on the ground, since the creation" (quoted in Whitney 1996). Remnant stands of eastern old-growth mixed conifer-hardwood or hemlock-white pine stands have a biomass of 560–820 t/ha (Whitney 1996), nearly as much as that of the dense, highly productive coniferous forests of the Pacific Northwest (Franklin and Dyrness 1973). White pine often grew to diameters of 2–3 m and heights of 45–60 m, while sycamore attained diameters greater than 4 m, tulip tree diameters of almost 2 m, and cottonwood and oak reached diameters well in excess of 2 m (Whitney 1996).

Although the European forests were cleared over centuries and millennia, the vast forests of North America vanished much more rapidly, often over the course of decades (Whitney 1996). The earliest known clearings by indigenous populations began about 1,000 years ago (Williams 2000). European settlers began more widespread clearings for farming and fuel in the 18th and early 19th centuries. Forest stands near rivers were usually among the first logged because early transport was primarily by log rafts (beginning about 1600) and log drives (from about 1800) on rivers. Industrial timbering greatly expanded the rate of clearing in the late 19th century, due in part to the development of canals and railroads for timber transport (Whitney 1996). Harvest of the eastern forests was complete and thorough; by 1920, the Northeast and Midwest had lost 96% of their old-growth timber. By late in the 20th century, estimates of original old-growth forest remaining in individual states ranged from less than 0.01% to 0.36% (Table 8-4 in Whitney 1996).

Trees that had accumulated in the rivers draining these massive forests were cleared throughout the 19th and 20th centuries. The large rivers of the eastern and Midwestern United States were perceived as "national highways and arms of the sea," and their clearing was a matter of great commercial and military importance (Hill 1957). In 1824, Congress made its first appropriation to remove snags from the Mississippi and Ohio rivers, and the first snagboat designed for that purpose was built by 1829. More than 800,000 snags were pulled in a 50-year period along the lower Mississippi alone; these cottonwood and sycamore snags averaged 1.5 m in diameter at the base and 0.6 m at the top and had an average length of 37 m (Sedell et al. 1982). Triska (1984) reported that the largest logs in the Red River, Louisiana were up to 36 m long and 1.75 m in diameter. In the following decades, snagging extended to rivers throughout the Southeast and Midwest.

Later in the 19th century, snagging extended to rivers in the West Coast region (Sedell and Froggatt 1984; Collins et al. 2002). Rivers were sometimes snagged and massive log rafts dismantled, even before the surrounding forests were logged, because rivers were the primary means for settlers and loggers to access upstream lands. In the Puget Sound region, river clearing began around 1880 and was followed immediately by clearing of valley-bottom forests. By 1900, essentially all virgin low-elevation riparian forests were gone (Plummer et al. 1902). Snagging was part of a general effort for channelization that also included plugging and disconnecting secondary channels and floodplain sloughs (Sedell and Froggatt 1984). Snagging records attest to the giant sizes that trees could attain in the Pacific Northwest; snags removed from rivers in western Washington were as large as 5.3 m in diameter (Collins and Montgomery 2001). Snagging records also suggest wood loading in large Pacific Northwest rivers 100 times greater than now (Sedell and Froggatt 1984). A similar difference was found in several Puget Sound rivers by comparing present-day wood loading in a protected reach of the lower Nisqually River to cleared reaches of the Stillaguamish and Snohomish rivers (Collins et al. 2002).

While large rivers were being cleaned of snags and jams, smaller tributary streams were catastrophically cleared through the ubiquitous practice of splash damming, in which a dam-break flood was induced to transport trees to the larger rivers from where logs were then rafted to market. Splash damming was common in the Northwest (Sedell and Duvall 1985), Midwest, and Northeast (Sedell et al. 1982). These torrents scoured sediment and wood from streambeds and banks and reduced roughness and obstructions to flow, leaving some channels scoured down to bedrock.

Few places remain where the effects of wood can be studied in rivers relatively unmodified by human actions. The Queets River on the Olympic Peninsula, Washington is one such river where extensive field work has documented that logjams trap sediment and deflect flow and thereby affect channel morphology and processes throughout a mountain channel network (Abbe and Montgomery 1996, 2003). We have observed wood accumulations identical to types found in the Queets system in gravel-bed rivers that drain old-growth rainforest in the coast range of northern New South Wales, Australia and in the southern Alps of New Zealand. The Rio Beni, Bolivia, a large tributary to the Amazon, has huge snags that create navigation hazards in some reaches and that armor riverbanks or form large logjams in other reaches. Types and patterns of in-channel wood seen by the senior author during a reconnaissance expedition down the Rio Beni resemble those portrayed in Karl Bodmer's paintings of the Mississippi River in the 1840s (Bodmer et al. 1984), suggesting that rivers of the upper Amazon may offer reasonable analogs for the prehistoric role of wood in other large rivers. Areas in far eastern Siberia and central Africa may offer additional sites to study the dynamics and effects of wood in rivers that flow through relatively pristine forests, but these regions are being deforested rapidly. Although the role of wood has been studied in some relatively undisturbed forest streams, most of the research to date on wood in large rivers has been from relatively altered systems.

Geomorphic Effects of Wood

Three themes dominate any discussion of the geomorphic effects of wood on rivers: changes in sediment routing and storage, channel dynamics and processes, and channel morphology. These different effects are produced through direct and indirect influences of wood across a wide range of scales. Our discussion will proceed from small length scales to large because the local direct effects of wood are easiest to see. Indirect effects generally become apparent over larger spatial and temporal scales, but they have been more widely affected and obscured by historic changes and are generally less well recognized.

When a tree falls into a river, it may remain intact or break into smaller, more mobile pieces. Depending on the size of the tree and the size of the channel it fell into, the tree may remain stable at or near where it entered the channel or it may be transported downstream to lodge against the bank or in a logjam, become stranded on a bar top or floodplain during falling flow, lodge in the riverbed as a snag, or transit the river system and leave the basin. Many of the geomorphic effects of wood in rivers arise from the influence of large stable wood as obstructions to flow and sediment transport. The influence of "key" pieces of large wood on stabilizing other debris in logjams has been recognized for many years (Habersham 1881; Deane 1888; Russell 1909; Keller and Tally 1979; Nakamura and Swanson 1993; Abbe and Montgomery 1996). The distribution of instream wood and the accumulation of logs into logjams have been studied extensively in Europe and North America (Gregory et al. 1985, 1993; Robison and Beschta 1990; Gregory and Davis 1992; Piégay 1993; Abbe and Montgomery 1996; Gurnell and Sweet 1998; Piégay and Marston 1998; Downs and Simon 2001). A number of workers have noted how the organization of wood, the changes catalyzed by its introduction into channels, and styles of wood transport vary with position in the channel network (Keller and Swanson 1979; Swanson et al. 1982; Abbe and Montgomery 1996, 2003; Wallerstein et al. 1997; Gurnell et al. 2001). Many of the commonly recognized effects of wood on aquatic habitat are manifest at the scale of individual channel units (Bisson et al. 1982), but these local influences can generate emergent properties at larger spatial scales of channel reaches, valley bottoms, and even at the landscape scale (Figure 5).

Channel unit

At the channel-unit scale, wood can dramatically affect the size and type of pools, bars, and steps in coarse-grained channels (Lisle 1986; Keller et al. 1995; Montgomery et al. 1995; Woodsmith and Buffington 1996; Hogan et al. 1998).

Pool scour.—Wood is an effective flow obstruction that alters channel hydraulics and enhances scour of pools (Figure 6). Depending on its orientation and position above the bed, wood can form four basic obstruction types (vertical, pitched, horizontal, and step), each of which corresponds with common channel unit types (Figure 7).

Vertical obstructions behave like bridge abutments and piers, creating horseshoe vortices and turbulent eddies that scour the channel bed (Melville 1992, 1997), with scour depth increas-

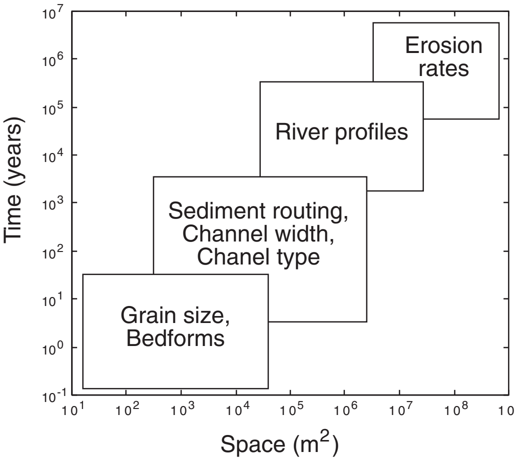

FIGURE 5. Scales of geomorphic influences of wood in the world's rivers.

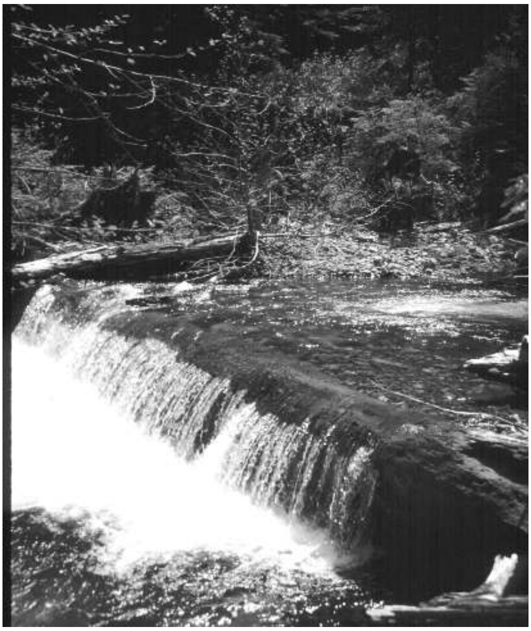

Figure 6. Plunge pool formed by log step in headwater channel.

ing as the obstructed width increases relative to flow depth (Buffington et al., 2002 b). Lateral vertical obstructions (abutments) can be formed by wood jams sutured to one or both banks: isolated vertical obstructions (piers) can be created by in-channel rootwads and debris piles (Buffington et al. 2002b). In the channel-unit vernacular, vertical obstructions form scour pools, eddy pools, or dammed pools (Robison and Beschta 1990).

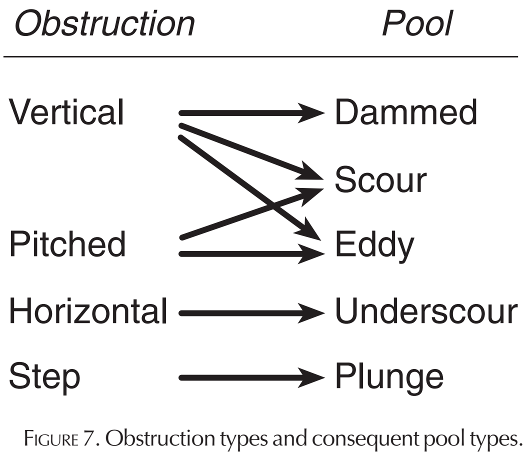

Figure 7. Obstruction types and consequent pool types.

Logs located above the bed and subparallel to the water surface form horizontal obstructions that advect flow downward toward the bed. Pitched obstructions are logs oriented obliquely to the water surface. The flow structure and scouring mechanisms of pitched logs are similar to pier-type vertical obstructions, but they are complicated by flow accelerations over, under, and around the debris. Pool scour for both horizontal and pitched obstructions depends on log diameter, angle of attack, flow velocity, height above the bed, and pitch from horizontal (Beschta 1983; Cherry and Beschta 1989). Pitched logs create scour pools and eddy pools, and horizontal logs form underscour pools (Robison and Beschta 1990; Woodsmith and Buffington 1996).

Wood steps create downstream turbulent jets that scour plunge pools (Heede 1972; Marston 1982; Chin 1989; Wohl et al. 1997). The depth to which plunge pools are scoured depends on jet energy, flow depth, and the degree of turbulence (Mason and Arumugam 1985; Bormann and Julien 1991). Pools scoured by flow around large debris jams typically have larger and more variable depths than other types of pools (Abbe and Montgomery 1996; Collins et al. 2002). In addition to the orientation and size of wood, scour depth is influenced by channel geometry, bed-surface grain size, particle form drag (relative roughness), supply and caliber of bed load, and channel gradient (Buffington et al. 2002b).

Bar deposition and sediment storage.—Wood can force the formation of bars by creating organic dams that physically block sediment transport or by forcing local flow divergence and consequent sediment deposition. Where flow deflection by wood scours a pool, a complimentary bar will develop, partially defining the boundaries of the associated pool. Sediment deposition forced by wood can be significant. In some systems sediment storage associated with wood exceeds the annual sediment yield by more than 10-fold, thereby regulating the transport of sediment through the channel system (Megahan and Nowlin 1976; Swanson et al. 1976; Mosley 1981; Hogan 1986; Bilby and Ward 1989; Nakamura and Swanson 1993; Keller et al. 1995; Pitlick 1995). In a channel system with a high load of wood, sediment storage associated with logs and logjams can act as a sediment capacitor and significantly damp variability in sediment transport rates (Massong and Montgomery 2000; Lancaster et al. 2001). Conversely, the destruction of debris dams can result in large decreases in storage and related increases in sediment transport (Beschta 1979; Bilby 1981; Megahan 1982; Heede 1985; Smith et al. 1993a). Whether or not the failure of an in-channel debris dam causes a debris flow depends, in part, on the volume and stability of wood in a channel (Swanston and Swanson 1976).

Channel width.—Wood influences channel width by either armoring channel banks and maintaining relatively narrow sections or by locally directing flow into the banks, causing localized erosion and channel widening. Consequently, channel width can vary considerably within a single reach of a forest channel. For example, reach-scale variations in the bank-full width along portions of the Tolt River, Washington, flowing through old-growth forest, show that logjams can superimpose dramatic local variability on the hydraulic geometry of river systems (Figure 8). Zimmerman et al. (1967) also found that local channel widening due to flow deflection by vegetation dominated the variability of channel width at drainage areas less than about 1 km^2. Similar observations have been made in forest channels in northern California (Keller et al. 1995), western Oregon (Nakamura and Swanson 1993), coastal British Columbia (Hogan 1986), and southeastern Alaska (Robison and Beschta 1990; Buffington and Montgomery 1999b). Independent studies from Wisconsin (Trimble 1997) and New Zealand (Davies-Colley 1997) have shown that forested channel reaches are both wider and have greater variance in width than do channels flowing through grasslands. Murgatroyd and Ternan (1983) found that reforestation increased bank erosion and channel width of Narrator Brook, England. In contrast, Stott (1997) reported that erosion rates of forested streambanks in Scotland were less than in moorland channels because a forest canopy inhibited the formation of frost that triggered bank failure. In a series of field experiments, Smith (1976) found that riverbank erosion rate was inversely related to the percent of roots in channel banks, indicating that vegetation can substantially retard bank erosion. Triska (1984) reported that the huge raft jams on the Red River dramatically narrowed the channel; above and below the reach influenced by the raft the channel was 180–230 m wide,

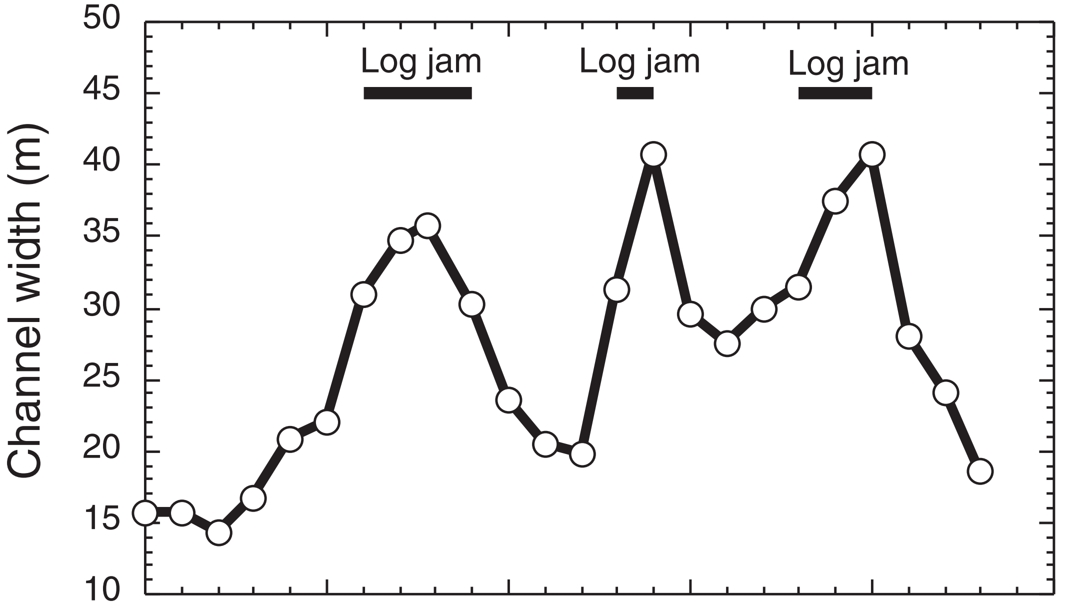

FIGURE 8. Channel width measured every 10 m along a reach of the Tolt River, Washington on 3 August 1993.

whereas the channel width in the area of the raft was only 27–46 m. After removal of the raft, the constricted portion of the channel widened dramatically. Flow splitting by stable logs or logjams can reduce channel widths by increasing the number of channels and splitting a single-thread channel into a system of smaller anastomosing channels (Harwood and Brown 1993). Hence, inchannel wood and riparian vegetation can either increase or decrease both the local and average width of channel reaches depending upon the geomorphic context of the reach in question (Thorne 1990).

Channel reach

Pool spacing.—At the reach scale, wood can control the frequency of pools and bars in gravel-bed rivers. Previous studies have shown that, in forest rivers, mean pool spacing is inversely related to wood frequency (Montgomery et al. 1995; Beechie and Sibley 1997). However, pool spacing can be quite variable for a given wood frequency (Figure 9), reflecting both regional and site-specific differences in channel and wood characteristics. Regional differences in mean pool spacing

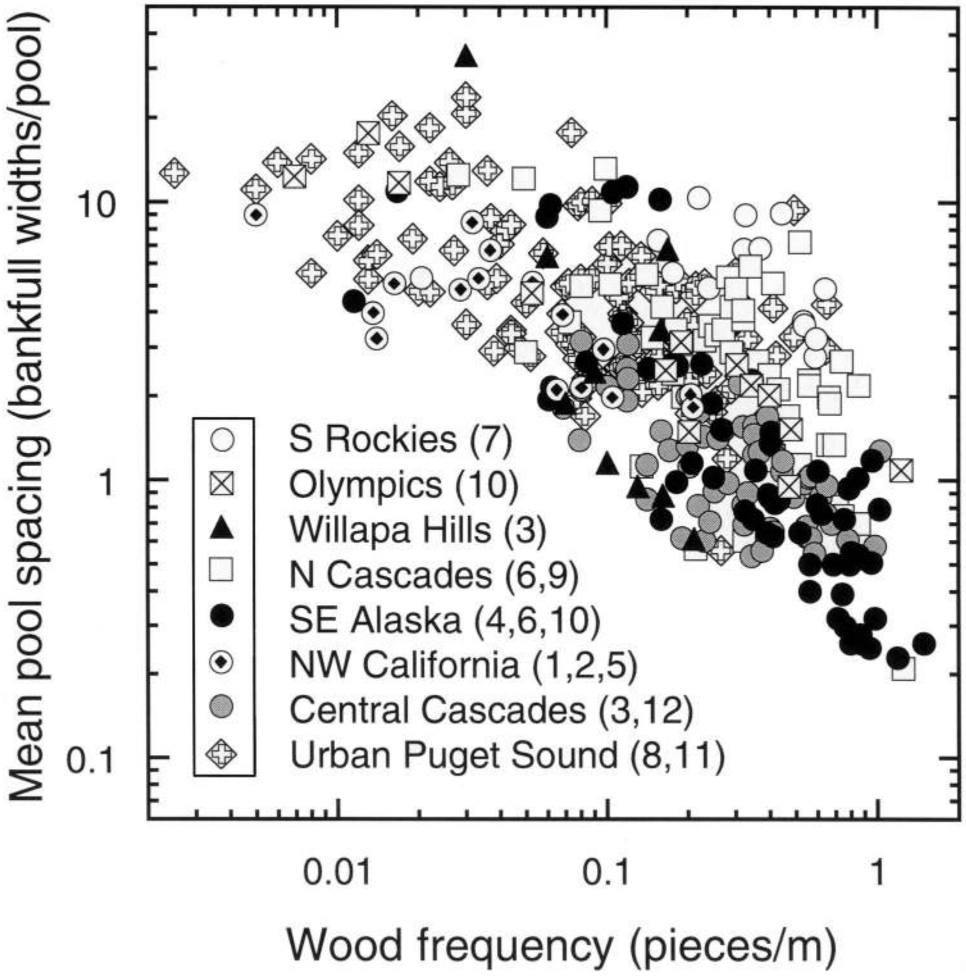

FIGURE 9. Mean pool spacing versus wood frequency. Numbers in parentheses show data sources: (1) Keller and Tally (1979); (2) Florsheim (1985); (3) Bilby and Ward (1989, 1991); (4) Buffington and Montgomery (unpublished data); (5) Keller et al. (1995); (6) Montgomery et al. (1995); (7) Richmond (1994); (8) May (1996); (9) Beechie and Sibley (1997); (10) Buffington and Montgomery (1999b); (11) Larson (1999); (12) Turaski (2000). Modified from Buffington et al. (2003a).

also reflect differences in lithology, climate, tree species, wood size, and land management.

Hydraulic roughness, channel competence, and bed-surface grain size.—Wood can create significant hydraulic roughness, which influences flow velocity, discharge, and shear stress. In a study of gravel-bed channels in old-growth forests of southeastern Alaska, Buffington (2001) found that nearly 60% of the total bank-full shear stress was spent on form drag caused by wood. Manga and Kirchner (2000) report a similar value for a spring-fed channel in the Oregon Cascades. Assani and Petit (1995) found that removing logjams in a small gravel-bed channel in Belgium caused a more than 50% increase in near-bed shear stress and commensurately reduced bedload transport rates. Shields and Gippel (1995) report that historical wood removal from rivers in Australia, the United States, and the United Kingdom reduced values of Manning's *n* by 10% to more than 90% in those channels. Loss of large wood in alluvial channels, however, may be partially compensated for by development of larger amplitude bedforms or coarser bed-surface grain sizes after wood removal (MacDonald and Keller 1987; Smith et al. 1993b). Smith et al. (1993b) found that removing wood from a small pool-riffle channel reorganized pool and bar topography and increased bed-load transport rates, both from release of sediments previously stored behind wood dams and from increased boundary shear stress and greater transport capacity.

In addition to creating its own hydraulic resistance, wood can force spatial variations in shear stress and stream power that alter bed and bank topography. Specifically, wood increases the number of pools and bars and forces spatial variations in channel width. Consequently, wood creates more irregular bed and bank topography, generating additional form drag that further increases channel resistance (Buffington and Montgomery 1999b).

The combined effects of roughness caused by wood, the bed, and banks can significantly reduce bed shear stress and channel competence, diminishing reach-average surface grain sizes (MacDonald and Keller 1987; Assani and Petit 1995; Lisle 1995; Buffington and Montgomery 1999b; Manga and Kirchner 2000). Buffington and Montgomery (1999b) found that diminished channel competence resulting from bar, bank, and wood roughness can cause up to a 90% reduction in median surface grain size relative to that predicted for a low-roughness, wide, planar channel (Figure 10). At subreach scales, wood can force strong spatial variations in shear stress and sediment transport, resulting in spatially variable textural patches (grain-size facies; Figure 11). The effect of wood on both absolute grain size and spatial variability of particle sizes may influence both the availability and diversity of aquatic habitats in forest channels. For example, recent theoretical models indicate that bar and wood roughness can lead to the deposition of spawning gravels in steep mountain drainage basins that otherwise would only have large bed material inhospitable to salmonids because of high shear stresses (Buffington 1998).

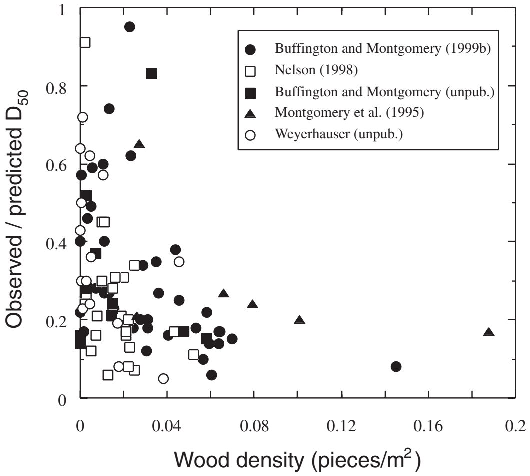

FIGURE 10. Ratio of observed to predicted median surface grain size (D_{50}) versus wood pieces/m^2. The predicted D_{50} is the competent value for the total bank-full shear stress (that of a wide, planar channel): it is determined from the Shields equation for a dimensionless critical shear stress of 0.03. Bar and bank roughness as well as sediment supply limitations cause the D_{50} ratio to be less than 1 at zero wood loadings.

Channel type.—The effect of wood on channel hydraulics and sediment transport provides a strong control on reach-scale channel morphology in forested basins. For example, wood may create steps that dissipate energy otherwise available for sediment transport (Keller and Swanson 1979; Heede 1981; Marston 1982). Such organic steps may trap sediment and maintain an alluvial bed in channels with an otherwise bedrock bed due to either rapid downstream fining or lack of coarse sediment. Removing organic steps can transform a forced step-pool channel into either a step-pool, cascade, or bedrock channel depending on slope, discharge, and sediment load. Similarly, wood may force a pool-riffle morphology in otherwise plane-

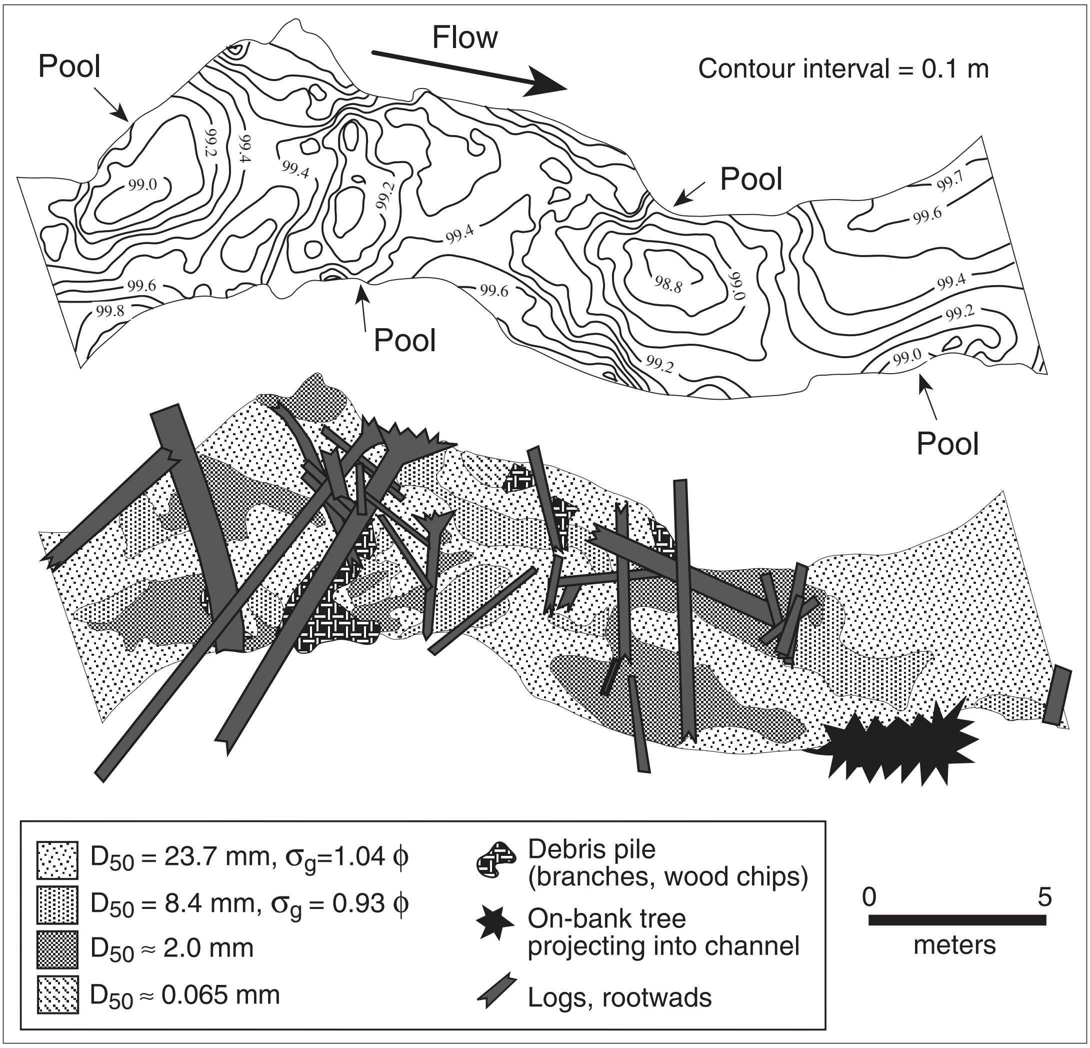

FIGURE 11. Channel topography, wood loading, and bed-surface textures in Mill Creek, western Washington (modified from Buffington and Montgomery 1999a). σ_g is the graphic standard deviation of particle sizes (Folk 1974).

bed or bedrock reaches (Swanson et al. 1976; Montgomery et al. 1995, 1996).

Because of the major influence of wood on channel morphology, finding free-formed pools and bars can be difficult in moderate-gradient (i.e., >0.01), cobble- and gravel-bed forest rivers. Many studies indicate that most pools in such channels are either formed by or strongly influenced by wood (Zimmerman et al. 1967; Keller and Swanson 1979; Lisle 1986; Andrus et al. 1988; Robison and Beschta 1990; Keller et al. 1995; Montgomery et al. 1995; Abbe and Montgomery 1996; Woodsmith and Buffington 1996).

Valley bottom

In his revolutionary *Principles of Geology*, English geologist Charles Lyell commented on the geological significance of vast accumulations of logs in North American rivers (Lyell 1837). Wood rafts that completely blocked large lowland rivers significantly influenced the channel and valley-bottom morphology, gradient, and sediment transport capacity (Veatch 1906; Guardia 1933; Triska 1984; Harvey et al. 1988). These effects could be both extensive and persistent. Spanish explorers reported a large, channel-spanning wood raft on the lower Colorado River, Texas, in 1690 (Clay 1949). In the three decades after the raft was removed by the U.S. Army in 1927, sediment eroded from the channel created a delta extending all the way across Matagorda Bay (Hartopo 1991). Early European explorers also recorded massive wood rafts on the Red River, Louisiana and reported that Native Americans could not recall a time when jams did not block the river (Lowrey 1968). Veatch (1906) estimated that the "Great Raft" of the Red River, which in 1875 affected 390–480 km of the river, began accumulating in the late 1400s. Veatch also reported incision of 1–5 m over a 24-km reach of the Red River in the two decades after the last logjam was removed. In addition to incision following raft removal, Triska (1984) reported how channel blockage by logjams on the Red River flooded large tracts of riparian lands creating a series of lakes where tributaries entered the main river. Consistent with this observed entrenchment, Harvey et al. (1988) estimated that removing the Red River jams increased the river's transport capacity by sixfold. A raft jam that blocked more than 1 km of the Skagit River, Washington was observed to cause "the river to overflow its banks annually, flooding 150 square miles, more or less, of rich bottom lands" (Habersham 1881, p. 2606). After the jam was removed, even the highest spring flood in the memory of local settlers did not overtop the riverbanks, though before jam removal, the floodplain was often inundated during "snow floods" (Habersham 1881). These large raft jams strongly influenced interaction between the channel and the valley bottom.

When accumulated in jams, wood can influence channel pattern and floodplain processes in large forest channels (Figure 12) and especially the formation of side channels and channel avulsions (Bryant 1980; Sedell and Froggatt 1984; Harwood and Brown 1993; Nakamura and Swanson 1993; Abbe and Montgomery 1996; Collins et al. 2002). Harwood and Brown (1993) found that stable logs and logjams split flow into multiple channels and maintain an anastomosing channel form in a wooded, seminatural channel in Ireland. Although anastomosing channels are now rare in northwest Europe, they were more common earlier in the Holocene (Brown and Keough 1992). Studies of the historical characteristics of valley bottoms in the Puget Sound area show that logjams can maintain floodplain sloughs, trigger avulsions, and thereby both create and maintain an anastomosing channel pattern (Collins and Montgomery 2001, 2002). Sedell and Froggatt (1984) showed

FIGURE 12. Large meander jam on Queets River, Washington.

how the Willamette River was a complex of anastomosing channels in 1854 that was progressively confined to a single-thread channel as debris jams were removed, the channel dredged, the side channels closed off, and the valley-bottom forest cleared. In many areas, anastomosing channel patterns appear to have been more common in natural forest channels than they are today.

The naturalist John Muir also recognized how wood on valley bottoms affected small mountain streams. In describing an early visit to the sequoia groves of the southern Sierra Nevada, he noted that

> a single trunk falling across a stream often forms a dam 200 ft long and ten to thirty feet high, giving rise to a pond which kills the trees within its reach; these dead trees fall in turn, thus clearing the ground; while sediments gradually accumulate, changing the pond into a bog or drier meadow… In some instances a chain of small bogs rise above one another on a hill-side, which are gradually merged into one another, forming sloping bogs and meadows. [Muir 1878, p. 827.]

The changes Muir described parallel those observed in the different context of confined headwater channels on the Olympic Peninsula, where sediment impounded by logjams can form terraces that exceed 10 m in height and store more than 10,000 m^3 of sediment (Abbe 2000). Even in unconfined reaches of large channels, sediment deposited in the lee of individual logjams can become integrated into a patchwork mosaic of individual surfaces that coalesce to form a multilevel floodplain with substantial local relief (Abbe and Montgomery 1996). Brooks and Brierley (2000) showed that removing instream wood and riparian forest in a river in southeastern Australia resulted in a 10-fold increase in channel size and sediment transport capacity. The formation of valley-bottom landforms—from pieces of a floodplain to entire floodplains and even terraces—can be catalyzed by a single log, logjam, or the integrated effects of many logjams.

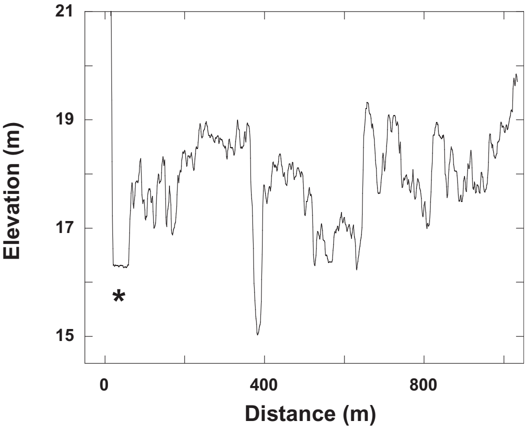

FIGURE 13. Topographic cross-sections across the floodplain of the Nisqually River, Washington, showing the multi-elevation nature of the active floodplain surface due to flow splitting and deposition associated with logjams.

Deposition associated with stable logs and logjams adds an intrinsic vertical dynamic to forest channels in which the channel can incise or aggrade without changes in external boundary conditions such as climate or tectonics. The effect of such vertical variation in bed surface elevation on valley-bottom topography is shown by cross-sections from detailed elevation transects across active river floodplains in western Washington (Figure 13). In the Nisqually river system where logjams maintain an anastomosing channel morphology, the floodplain surface is a patchwork of surfaces with a net relief of 2–4 m. This vertical dynamic complicates predicting channel migration because past meander migration rates do not provide ready guidance for projecting future channel migration. Local aggradation of the channel bed in response to sediment deposition associated with a logjam can affect the potential for the channel to avulse into a side channel or cause the river to simply carve a new channel across the floodplain. Due to such influences, changes in the age structure of riparian forests, and thereby the supply of large trees available to a river, can dramatically influence the dynamics of channels and ultimately lateral channel migration.

A channel unconfined by valley walls can aggrade to at least the level of two stacked logs before avulsing across the floodplain surface. Hence, a minimum estimate of the long-term portion of a valley bottom potentially occupied by forest channels can be defined as the area with elevations lower than twice the diameter of the site-potential tree diameter above the bank-full elevation. Vertical changes in riverbed elevation due to deposition around or behind logjams are higher in confined channels, where there is little leeway for such channels to move laterally around the jams. In addition, the potential for wood-mediated vertical changes in bed-surface elevation complicates the assessment of channel conditions, as a wood-rich channel can incise after logjam removal (e.g., Stover and Montgomery 2001). Hence, interpretation of the causes of entrenchment in forest channels requires consideration of how wood loading has changed. Evaluations of where forest channels are likely to move in the future need to consider the role of local aggradation associated with logjams in affecting the potential for channel avulsion.

Landscape

Over time, the integrated effects of wood on erosion and sediment transport processes can translate into geomorphic effects at the landscape scale. For example, log steps provide for dissipation of potential energy otherwise available to transport sediment, and studies of the total elevation drop attributable to flow over log steps report a range of from 6 to 80% of the total elevation drop in stream systems (Keller and Tally 1979; Keller and Swanson 1979; Marston 1982; Abbe 2000). In small streams, wood can also trap and store more sediment than the average annual rate of bedload transport (Marston 1982), and log removal can trigger increased transport of formerly stored material (Bilby 1984). Lancaster and others (2001) showed that sediment storage associated with logjams could transform a stochastic input of sediment into a relatively steady sediment output in mountain channel networks. In steep channel systems developed on weak or unconsolidated substrate, such as in the glacial sediments of the Puget Lowland, loss of the roughness attributable to wood can lead to catastrophic incision, especially when combined with increased discharges due to urbanization (Booth 1990, 1991). Hence, wood can influence watershed-scale patterns of erosion and sediment transport and can greatly influence channel response to disturbance.

Recognition of the potential for large-scale effects of forests to influence landscape evolution is not new. At the dawn of the 20th century, Toumey (1905, p. 94) argued that a forest cover decreased the ability of mountain streams to incise bedrock by moderating both streamflow and the supply of “grinding material carried by the moving water.” He concluded that the effects of a forest cover on erosion rates were such that, over geologic time, a forest cover influences physiographic form. More recent work on the processes controlling the distribution of bedrock and alluvial channels offers support to Toumey’s conclusion. Montgomery et al. (1996) found that, in mountain channel networks, logjams can convert bedrock reaches to alluvial reaches by trapping bedload sediments. Rates of bedrock river incision will be lower if a streambed has a thick alluvial cover because the bedrock surface beneath the stream will be protected from abrasion (Sklar and Dietrich 1998). The effect of such influences of wood on the steepness of river systems can be addressed by formalizing the controls on the form of river profiles.

The longitudinal profile of mountain channel systems, and thereby landscape relief, is controlled by both the erodibility of the bedrock surface and the ability of the channel to cut into rock. The equilibrium stream profile will be that for which the bedrock erosion rate equals the rock uplift rate set by tectonic processes. An analytical solution for the form of river profiles can be based on a general expression for the rate of river incision (E) as a function of drainage area (A) and local slope (S):

$$E = KA^mS^n, \tag{1}$$

where K is a constant that incorporates climatic factors and erodibility and m and n are thought to vary with different erosional processes. For steady-state topography, where E equals the rock uplift rate U, equation (1) can be recast as

$$S = (U/K)^{(1/n)}A^{-m/n}. \tag{2}$$

Equation (2) shows that a less erodible (or “harder”) streambed with a lower erodibility coefficient (a lower value of K) will lead to a steeper equilibrium river profile. Hence, a channel network with extensive, stable, and persistent deposits of wood that trap sediment and shield the bedrock surface will have a lower K and maintain steeper profiles than comparable channels lacking wood. In addition to altering stream gradients, forests can also influence the surrounding topography. The maximum stable angle predicted by limit-equilibrium models of slope stability increases with increased soil strength due to the apparent cohesion of an interlocking root network. Hence, vegetative cover with substantial root strength, such as a forest (e.g., Schmidt et al. 2001), can allow soil-mantled hillslopes to stand at steeper angles than would be predicted based on soil strength alone. In these ways, a forest cover can allow steeper topography, and therefore greater relief, to develop and persist than would occur without a forest cover.

Controls on Wood Stability and Flux

The species of wood and its size relative to the channel in which it lies are primary controls on the stability of wood. Although dry wood generally has a specific gravity less than water and therefore readily floats, saturated wood has an effective density greater than water and can therefore be stable in some circumstances, even if submerged. Saturated wood can have an effective density greater than water, and some species, such as teak and some varieties of eucalyptus, have dry densities exceeding unity and sink without being saturated. The geometry of wood also influences its stability. A rootwad raises the center of mass of a wood piece to well over that for a simple log with the same bole diameter. The presence of a rootwad is therefore a fundamental control on log stability (Abbe 2000; Braudrick and Grant 2000).

The size of stable wood changes as a river widens and deepens downstream, and the style in which large wood is organized in river systems changes commensurately (Bisson et al. 1987; Abbe and Montgomery 1996, 2003). In headwater channels, even relatively small logs can remain where they fall, and wood is therefore arrayed in random orientations; in larger channels, wood is more mobile and tends to form both snags and become reorganized into different types of discrete logjams. Some jams have an exquisite architecture of pieces laid in one after another as if woven together. Other accumulations, such as many debris-flow-deposited jams, are chaotic jumbles of logs oriented at all angles to one another. Based on field observations in the Pacific Northwest, New Zealand, Australia, and South America, we recognize a generalized downstream change from randomly oriented wood, log steps, and debris flow jams in steep headwater channels to progressively larger, more organized jams in mainstem channels.

Several workers have identified different types of wood accumulations. Abbe and Montgomery (1996) described the development of bar top (BTJ), bar apex (BAJ), and meander (MJ) jams on the Queets River, a more than 1,000-km^2 old-growth watershed on the Olympic Peninsula, Washington. They noted that chaotically organized BTJs were relatively unstable and had little impact on channel morphology, whereas the more organized and stable BAJs and MJs created deep pools, bars, and patches of floodplain. Abbe and Montgomery (2003) later described 10 distinct types of logjams based on the orientation of key, racked, and loose wood mapped in field surveys along the Queets River (Figure 14), where stable wood accumulations dominate alluvial morphology from the scale of pool formation to channel anabranching and floodplain topography. Wallerstein et al. (1997) developed a wood jam classification based on the functional relation of the jam to the channel, with underflow jams causing local scour but limited deposition, dam jams trapping a wedge of sediment and forming log steps in the stream profile, deflector jams causing local pool scour and bar formation due to flow deflection, and parallel/bar head jams, which encompass Abbe and Montgomery's (1996) bar apex and meander jams. The relative abundance of these different wood jam types changes systematically downstream through a channel network (Abbe and Montgomery 1996, 2003).

The geomorphic effects of wood jams can change through time. Hogan et al. (1998) described patterns in the temporal evolution of logjams deposited by debris flows in small gravel-bed streams of coastal British Columbia. They observed that channel morphology changes from morphologically diverse prior to jam formation to simplified morphology following emplacement of a logjam by a debris-flow, followed by a progressive change back to a complex channel morphology as a jam decays (Hogan et al. 1998). In contrast, Abbe (2000) documented increased morphologic complexity of channels influenced by the development of valley jam complexes in the headwaters of the Queets River, Washington. Hence, the temporal evolution of wood jams, and their attendant geomorphic effects, varies according to processes governing jam formation, preservation, decay, and destruction.

Key pieces appear crucial for altering channel morphology and processes in large rivers. River systems filled with stable wood can trap and retain smaller, mobile debris. A comparison of wood loading in Puget Sound rivers showed strong contrasts in the influence of wood between relatively undisturbed rivers and those that had been both cleared of debris and no longer have a forested floodplain (Collins et al. 2002). The Nisqually River, which retains a source of key-member-size trees in its floodplain, has numerous logjams and a wood loading (pieces of large wood per unit river length) one to two orders of magnitude greater than the Snohomish and Snoqualmie rivers, which lack key-member-size

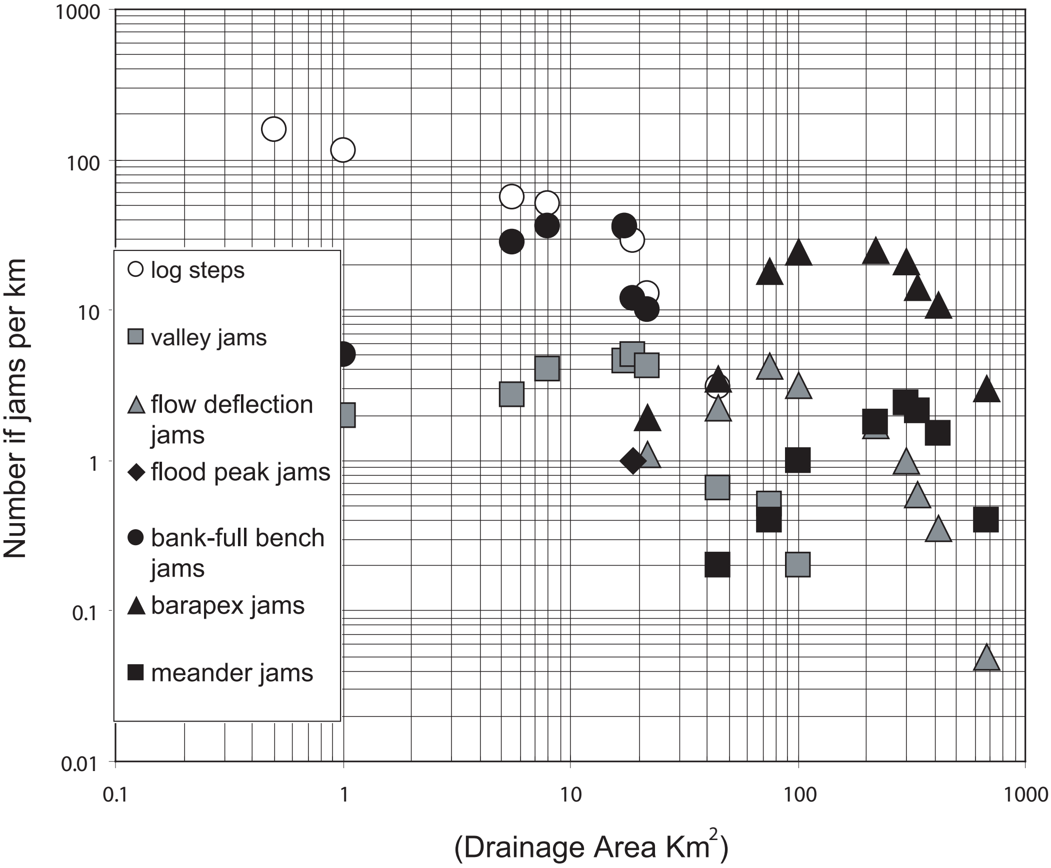

FIGURE 14. Downstream variations in the style of log accumulations in the Queets River, Washington based on field surveys from 1993 to 1996. Modified from Abbe and Montgomery (in press): open symbols represent in situ jams that remain close to where they were introduced to the channel; gray symbols represent *combination* jams composed of transported wood racked onto in situ key pieces; and black symbols represent *transport* jams in which key pieces of wood were transported within the channel.

debris because of snagging, prevention of channel migration (and thus wood recruitment) due to levee construction, and floodplain forest clearing. If even a small portion of the wood load supplied to a river is large enough to prove stable, these pieces can catalyze retaining additional mobile wood that racks up onto the stable pieces. An example of such an effect is the trapping of more than 400 pieces of wood by a single "engineered logjam" built on the North Fork Stillaguamish River in the first year after the structure was built (Abbe et al. 2000).

Shape is another primary influence on the stability of wood. Based on observations in areas with large deciduous trees, we suggest that widely spreading or multiple-stemmed hardwoods are more prone to forming snags than accumulating as racked members in large logjams because their geometry makes them extend laterally to well beyond their bole diameter. In contrast, conifers tend to create longer, more cylindrical pieces more readily transported and routed through river systems, resulting in enhanced development of logjams. Although both snags and jams form in many forested regions, regional forest composition influences the relative tendency for large wood to form either individual snags or large logjams in river systems.

The effects of wood debris on channel morphology depend on wood stability, which is, in turn, a function of wood dimensions and wood size relative to channel size (Bisson et al. 1987). The typical definition of large wood based on uniform size criteria (for example, >0.1 m in diameter and 1 m in length) does not account for wood stability relative to channel size and stream power. A 0.3-m-diameter, 5-m-long log may have significant geomorphic effects in a small headwater channel but be ineffective flotsam in a large river. Abbe and Montgomery (2003) showed that in the drainage basin of the Queets River, the relative size of key piece sizes varies with wood dimensions relative to channel size (Figure 15). They found that, for wood longer than about half the bank-full width, those pieces with a diameter larger than about half the bank-full depth tend to form key pieces. Progressively larger relative diameters are required to form stable pieces of shorter wood. Abbe and Montgomery (2003) also found that wood size relative to channel size differentiates metastable pieces that tend to form racked members of logjams from unstable wood that provides little, if any, structural integrity to wood accumulations. Controls on wood stability, and thus its geomorphic effects, depend on both regional factors (such as the size and shape of wood delivered to the channel) and location in the channel network.

Wood regime

The supply and size of wood delivered to a channel system defines a wood regime, analogous to the sediment or discharge regimes, respectively

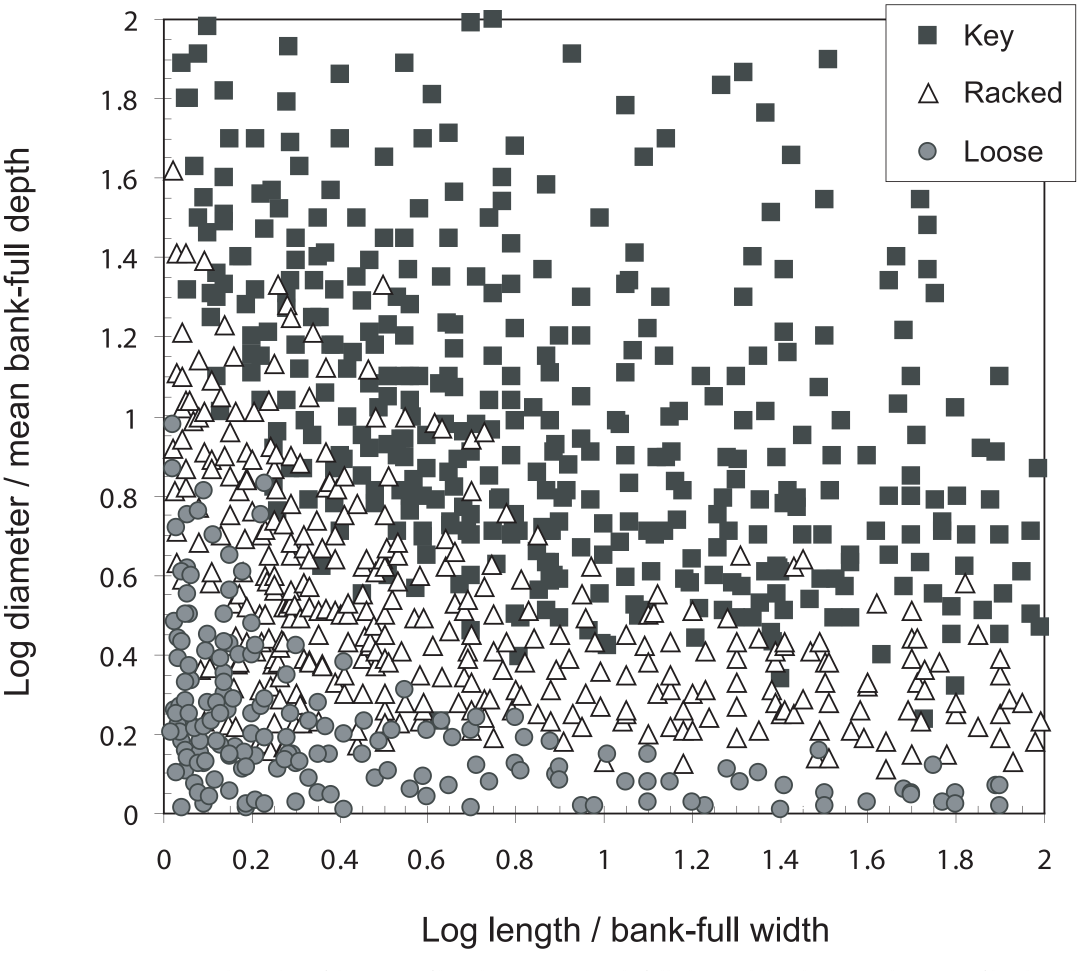

FIGURE 15. Dimensionless plot of the ratio of log diameter to bank-full channel depth versus the ratio of log length to channel width, showing distinct fields defined by loose, racked, and stable key members of logjams from throughout the Queets River system, Washington. Modified from Abbe and Montgomery (in press).

determined by the caliber (size) and volume (amount) of sediment delivered to the channel and the discharge magnitude and variability. In forested landscapes, the wood regime interacts with the sediment and water regimes to set channel morphology and control channel dynamics. Channels with a large supply of stable logs would be expected to have different characteristics, dynamics, and sensitivity to changes in land use than channels supplied only with small wood, or little wood at all.

The quantity and characteristics of wood delivered to a channel depend on the nature of the forest supplying the wood and the processes that introduce wood into the channel. Tree fall can directly deliver trees to channels from streamside forests (McDade et al. 1990). Slope instability and particularly debris flows or large earthflows can deliver substantial amounts of wood to headwater channels from hillside forests (Grant and Swanson 1995; Johnson et al. 2000). Bank erosion can introduce both standing trees and wood stored in floodplain sediments into channels (Murphy and Koski 1989; Piégay et al. 1999). The relative importance of processes that directly or indirectly deliver wood to rivers and streams vary by region but, in general, include biological processes (such as insect outbreaks and disease), fire, floods, landsliding, wind storms, and snow avalanches. Different processes deliver wood to different portions of a river system, with a typical pattern of landsliding and tree fall dominating wood inputs in steep headwater channels and bank erosion dominating wood inputs to larger floodplain rivers. Riparian stand growth models have been used to predict in-channel wood loading based on recruitment of nearstream trees under a range of land use and disturbance histories (McDade et al. 1990; Beechie et al. 2000; Bragg 2000). These processes affect the age, amount, diameter, and species of trees recruited to channels, as well as where wood enters the channel system. Natural or anthopogenic changes to the recruitment, transport and storage of wood can affect a stream’s physical and biological condition.

As discussed above, the size of wood is the primary control on its stability and transport in a river. The strong influence of large “key” pieces of wood debris on stabilizing other debris in logjams is well known (Keller and Tally 1979; Nakamura and Swanson 1993; Abbe and Montgomery 1996). The role of key pieces of wood appears crucial for triggering geomorphological effects of wood in large rivers, as river systems filled with stable wood debris can trap and retain smaller, mobile debris (Abbe and Montgomery 1996; Collins et al. 2002). In addition to wood size and channel size, the species of wood also influences the stability of instream wood through both its density and shape. The controls on wood stability and transport—wood size relative to the channel, shape, species, and recruitment mechanism—vary both with position in a channel network and regionally.

The amount of wood stored in a river system varies greatly between catchments and can exhibit substantial variability over time. Harmon and et al. (1986) compiled reported values of wood biomass stored in natural (unmanaged) channel systems in temperate forests and found substantial differences in wood loading between redwood forest (>1,000 m^3/ha), other coniferous forest (200–1,000 m^3/ha), and deciduous forest (<200 m^3/ha). The frequency of logjams also varies widely both within and among river systems. Wood dam frequencies as high as 400/km have been reported in small channels, and the frequency of organic obstructions typically decreases with increasing channel size, or basin area (Bilby and Likens 1980; Gregory et al. 1993), although the size of stable jams likely increases with increasing channel size. Deforestation and debris clearing have reduced wood jam frequency by 3-fold to more than 10-fold in different regions (Hedin et al. 1988; Webster et al. 1992; Gregory et al. 1993; Collins et al. 2002). In addition to storage in the active channel, substantial amounts of wood can be buried in floodplain sediments where wood can persist for thousands of years under anaerobic conditions (Becker and Schirmer 1977; Nanson et al. 1995).

The transport and decay of wood debris also varies greatly among river systems, and much of this variability is due to the influence of both wood size and channel size in controlling the stability and retention of wood delivered to channels. In small channels flowing through old-growth forests in the Pacific Northwest, key pieces of wood can remain stable for hundreds of years (Keller and Tally 1979; Murphy and Koski 1989). Studies on the Queets River, Washington, have shown that decay-resistant species can last centuries to more than 1,000 years in even large rivers (Abbe 2000; Hyatt and Naiman 2001). In contrast, wood storage on the Drôme River, France is only several times the annual wood input, and therefore, the residence time of wood accumulations is on the order of just several years (Piégay et al. 1999), most likely due to the small size of forest trees recruited to the channel. The transport and decay of wood also depends on the environment; hardwoods generally decay faster than coniferous species; small wood is more mobile than larger wood; and wood decay rates are high in tropical forests due to high temperatures and rainfall.

Just as for sediment, the wood regime can be assessed using a mass balance approach to characterize the wood budget for a channel (Swanson et al. 1982; Cummins et al. 1983; Gregory 1992; Piégay et al. 1999). A wood budget is a straightforward quantitative statement of the inputs, outputs, and changes in storage of wood in a river system. A wood budget can be constructed for a particular reach of river or for a whole river system and used to characterize or explore differences in the recruitment, storage, or export of wood. The relative mobility and potential for wood transport and storage can be modeled using analyses of buoyant and drag effects (Abbe 2000; Braudrick and Grant 2000). The transport of logs by debris flows also has been incorporated into simulation models (Lancaster et al. 2001). A key consideration for interpreting wood budgets is the potential for wood storage to depend on the presence of key pieces of wood, which strongly influences retention of organic matter in a river system (Figure 16).

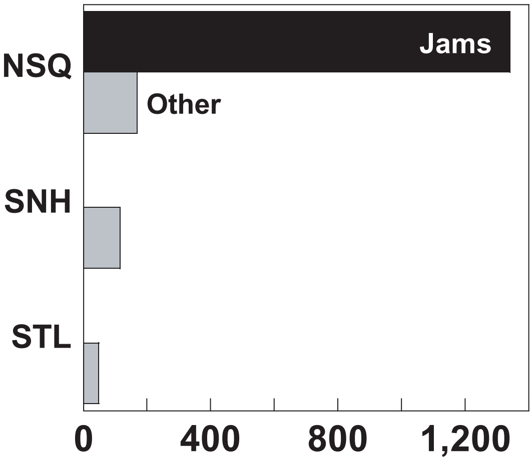

FIGURE 16. Comparison of wood loading in the Nisqually (NSQ), Stillaguamish (STL), and Snohomish (SNH) rivers (from Collins et al. 2002).

Regional patterns in the influence of wood on rivers

Regional variation in the size and shape of trees and the characteristics of their wood imparts global patterns to the geomorphic influence of wood. Rivers flowing through boreal forests are likely to be less influenced by wood because the trees are generally small. The effect of small-wood jams in tropical forest channels may be more short lived and ephemeral than in temperate latitudes because of the rapid breakdown and decay of debris in equatorial regions, although equatorial regions also have many decay-resistant hardwoods. Forest stand density will also strongly influence wood recruitment, with channels in open woodlands less influenced by wood than channels flowing through dense closed-canopy forests. The greatest effects of wood in rivers may be in the old-growth temperate rainforests dominated by massive, decay-resistant wood such as cedar in the Pacific Northwest of North America and eucalyptus in Australia. Regional biogeographic patterns are therefore primary determinants of the geomorphic effects of wood in rivers.

Different zones of wood influence should shift up and down river systems based on the absolute size of the available wood. In this sense, variations in the geomorphic effects of wood in different regions may correspond to variations in different environments and positions in a single watershed through the common currency of relative wood size. Hence, the geomorphic effectiveness of wood in rivers has two independent dimensions: tree size (and shape) and river size. Tree size sets regional limits on how much of the channel network could be influenced and in what way. Regional geography controls drainage-basin size and therefore the size of the rivers. Coastal mountains have small rivers; thus, the available wood should have a relatively large influence on fluvial processes and morphology. Huge continental rivers such as the Amazon are less influenced by wood, even if their tributaries are (or were) strongly influenced by wood. But the potential for even large rivers to be influenced by logjams emphasizes the need to incorporate the effects of wood into geomorphic models and thinking across all scales in forest river systems.

Wood, History, and the Landscape

The role of wood on fine-scale geomorphological features such as pools has been widely recognized for decades. Such effects can be observed directly in the field without specialized training or consideration of geologic time. But the recently recognized importance of wood in influencing channel geometry, channel patterns, and floodplain topography has been masked by decades to centuries of river cleaning and forest clearing in Europe and North America. Geomorphologists tend to downplay the potential effects of vegetation on landform evolution, but the stabilizing effects of forests and wood on sediment transport and storage processes could require increased river slopes to counteract a given rate of rock uplift. Such large-scale effects remain somewhat speculative, but vegetation and its effects on earth surface processes may be a greater influence on landscape evolution than typically imagined. Although the geomorphic effects of wood on rivers has been obscured by a legacy of anthropogenic changes to river systems, wood has been entering and affecting fluvial systems for more than 100 million years. Fluvial geomorphology is only now starting to link wood to channel properties and processes at spatial scales larger than individual habitat units (e.g., single pools and bars). Just as the sediment and water regimes are widely acknowledged to influence channel systems across a wide range of scales, the wood regime is an important component of fluvial systems.

Acknowledgments

Our discussion of the effects of wood on bar deposition and sediment storage is based on a literature summary developed by R.D. Woodsmith.

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