THE INFLUENCE OF LARGE WOODY DEBRIS ON FOREST STREAM GEOMORPHOLOGY

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ABSTRACT

In forest streams large woody debris (LWD) commonly functions as an in-channel obstruction to stream flow and an agent of stream channel and riparian zone interaction, thereby strongly influencing channel processes, morphology, and location. LWD can significantly influence energy dissipation, pool formation, local base level, bank erosion, frequency and duration of overbank flow, bed surface texture, and sediment transport, deposition, and storage. Other effects on channel morphology include influences on pool and bar type, location, size, and spacing. In addition to static LWD, moving pieces and clusters transported by high streamflow or debris flow have significant geomorphic and ecological effects. An understanding of the geomorphic function of LWD in forest streams can be applied to a variety of land use problems relating to fluvial and riparian processes.

INTRODUCTION

Some aspects of traditional fluvial geomorphic thinking have been modified to accommodate the case of forest streams, owing to their unique attributes including, (1) the presence of in-channel pieces and accumulations of large woody debris (LWD), (2) toppling of large trees along stream banks and within streamside forests, and (3) debris flows, dam-break flood surges, and other transport processes rich in LWD. Broad-scale concepts of fluvial geomorphic interactions with riparian vegetation are reviewed in Gurnell et al. (1995) and Hupp and Osterkamp (1996). Reviews that focus primarily on the biological and nutrient cycling functions of LWD in forest stream ecosystems include Harmon et al. (1986), Bisson et al. (1987), and Sedell et al. (1988).

Rates of deposition and erosion of fluvial surfaces are strongly affected by LWD and rooted riparian vegetation (Osterkamp and Costa, 1987). Channel equilibrium conditions, in turn, control riparian vegetation patterns, which are indicative of specific landforms (Swanson et al., 1982). These relationships can be critical to stream channel recovery from disturbance (Swanson et al., 1982; Fetherston et al., 1995). The location of debris and debris-related geomorphic features is determined by fluvial processes including bank erosion and transport from upstream sources as well as by several non-fluvial processes including windthrow, stem breakage, beaver activity, mass soil and snow movements, and land use activities.

The influence of LWD on channel width and channel diversions is attributable, in large part, to toppling of trees along the banks and flow deflection by tree stems or debris dams in the channel (Zimmerman et al., 1967). These effects on channel shape affect frequency and duration of overbank flow (Zimmerman et al., 1967), and flow diversions can lead to extreme incision into floodplain deposits (Hack and Goodlet (1960). Some LWD pieces defend the channel bed and banks from erosion, while others enhance erosion by deflecting and concentrating flow, thereby delivering sediment to the channel and in some cases scouring pools. In contrast to the hydraulic geometry relationships of non obstruction-controlled streams (Leopold and Maddock, 1953), in low-gradient (generally less than 0.03), forest streams meandering, avulsions, braiding, and changes in width are commonly attributable to the influence of LWD, rather than variation in upstream drainage area or discharge (Zimmerman et al., 1967; Heede, 1972; Keller and Swanson, 1979; Robison and Beschta, 1990).

LWD provides important buttressing of sediment storage sites, which, depending on stream size, can account for the majority of sediment stored in a channel, in some cases exceeding 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; Bilby

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and Ward, 1989). Mosley (1981) reports that episodic releases of debris-stored sediment and related variation in bedload transport are caused by shifts in LWD location in a New Zealand stream. Debris dams form particularly important sediment storage sites in steep streams with limited floodplain width (Keller and Swanson, 1979). Removal of this debris can result in large decreases in storage and related increases in sediment transport (Beschta, 1979; Bilby, 1981; Heede, 1985). Smith et al. (1993a) find that experimental removal of LWD from a forest stream in southeastern Alaska results in a four-fold increase in bedload transport at bankfull discharge, owing to elimination of LWD buttressing of sediment storage sites, elimination of LWD-related, low-energy hydraulic environments, bank erosion, and an inferred reduction in LWD-imposed roughness.

Function of LWD is affected by piece size and position. Piece length relative to channel width is a key factor determining the amount and distribution of in-channel LWD and thereby the number and volume of sediment storage sites (Bilby and Ward, 1989). Generally, most mobile pieces are shorter than bankfull width and longer pieces are resistant to flood transport (Lienkaemper and Swanson, 1987). Smith et al. (1993b) report that debris suspended above bankfull flow has relatively little effect on the bed or on sediment storage, and debris oriented in a streamwise direction tends to buttress smaller sediment storage sites than more stable pieces oriented perpendicular to the channel.

Most geomorphology and ecology research on LWD has focused on its role while static. LWD also has important functions while moving as individual pieces at high stream flow, in movement of collections of LWD, or with transport at the fronts of debris flows. These processes are in early stages of study with flume experiments (Braudrick et al., in press), computer modeling (Ishikawa et al., 1991), and field studies (Coho, 1993). Floated LWD can damage streamside vegetation and create highly dynamic interactions among LWD, bedforms, and inorganic sediment in transport. LWD transport mechanisms may have distinct effects on channel and riparian conditions and may produce distinct organic and inorganic deposits. Fluvial transport of LWD commonly results in debris "levees", accumulations of sub-parallel LWD along the channel margins at the high flow level.

Debris flows and dam-break flood surges occur in both forested and non-forested channels, however in forest streams occurrence of debris flows depends on volume and stability of LWD in the channel as well as hillslope stability, channel slope, and peak discharge characteristics (Swanston and Swanson, 1976). Destructiveness appears to depend primarily on volume of the triggering landslide. Debris flows commonly entrain LWD as they move down steep channels. During some high flow events debris jams are transported several kilometers downstream, while in other cases entrained debris reduces travel distance, resulting in shorter, wider debris flow tracks than in non-forest areas (Swanson et al., 1976; Keller and Swanson, 1979).

Sudden breakup of LWD accumulations can trigger both debris flows and dam-break flood surges (Coho, 1993). The presence of abundant LWD can increase the erosive consequences of these events by enhancing scour of the channel bed and banks and damage to riparian vegetation. Masses of moving LWD in debris flows or dam-break flood surges can substantially increase the height of a flood surge to levels exceeding that of flood waters alone. This phenomenon can result in extensive removal and damage to streamside vegetation, similar to the case of floated ice (Smith, 1980). Such wood-fronted debris flows alter channel form and sediment storage and can leave large, organic-rich, long-lived deposits at channel junctions, alluvial fans, and riparian areas (Hack and Goodlett, 1960; Benda, 1990).

MECHANISMS OF POOL SCOUR

One distinction between streams in forest and non-forest areas is the effect of LWD on pool distribution. Because processes maintaining LWD-related pools appear to differ from those in pools not related to obstructions, patterns of channel morphology and routing of sediment may differ substantially between the two cases. Maintenance of non obstruction-related pool morphology in low-gradient, alluvial streams is commonly explained using the well-known shear stress (or velocity) reversal hypothesis, which attributes pool maintenance to a reversal in location of maximum boundary shear stress (or velocity) from riffles to pools as discharge increases to approximately bankfull (Leopold and Wolman, 1960; Keller, 1971). More quantitative approaches involve modeling the interactive adjustments of velocity, boundary shear stress, sediment transport, and water surface and bed topography (Dietrich and Whiting, 1989; Nelson and Smith, 1989).

Interaction of stream flow with LWD results in energy dissipation and the production of channel-scouring turbulence (Zimmerman et al., 1967). A large portion of stream energy can be expended over short distances at debris-defended steps in the stream profile, commonly creating a scour pool at the downstream edge of the step (Heede, 1972).

Many studies in small. forest streams observe that pools are commonly associated with LWD and other in-channel obstructions. Indeed. obstruction-related pools are the rule rather than the exception in these streams (Keller et al.. 1981; Lisle. 1986a; Robison and Beschta. 1990; Montgomery et al.. 1995; Wood-Smith and Buffington. 1996). Beschta (1983) reports that in flume experiments obstructions create a wide variety of hydraulic environments ranging from zones of low-velocity backwater to zones of exceptionally high turbulence capable of scouring and removing gravel. even though mean. near-bed velocities indicate otherwise. This suggests that entrainment with rising discharge is caused largely by an increase in obstruction-related turbulence rather than solely by increased average shear stress (Beschta. 1983).

Hydraulic characteristics of obstruction-related pools resemble those at bridge piers (Lisle. 1986a). where bed material is mobilized by a combination of time-averaged boundary shear stress and turbulent agitation near the pier (Melville, 1984). Large-scale vortices are the primary mechanism of local scour at piers. where scour occurs at average velocities of about 50 percent of the critical average velocity for material transport in the part of the stream unaffected by the pier (Breusers et al.. 1977). In an analysis of an obstruction-associated pool in north-coastal California. Smith (1990) supports this analogy to processes at bridge piers. He reports no systematic reversal. with increasing discharge, of maximum near-bed velocity or shear stress. bedload transport. bedload competence. or significant scour pool morphology.

OBSTRUCTION-POOL RELATIONSHIPS

In undisturbed. forest streams the thalweg path and location and characteristics of pools are commonly controlled by LWD. Flume experiments indicate that pool depth. volume. and length of time required for scour are functions of complex interactions between obstruction diameter. orientation. and position above the bed. channel constriction. and flume discharge (Beschta. 1983; Cherry and Beschta. 1989). Field investigations indicate that pools are linked to obstruction location. and stationary obstructions tend to stabilize pool and gravel bar locations (Lisle, 1986a). Magnitude of channel constriction and obstruction orientation relative to the flow affect the hydraulic characteristics of associated pools. pool size. and the stabilization of bars (Lisle. 1986a; Sullivan. 1986). Pool area has been shown to correlate with volume of LWD forming the pool (Bilby and Ward. 1989). Pool-obstruction relationships can be quite complex. Wood-Smith and Buffington (1996) report that a single LWD obstruction can influence the development of as many as five distinct pools, and as many as ten obstructions affect a single pool.

Studies of the effects of debris removal confirm that LWD can exert a strong influence on local hydraulics, on the location, spacing, and size of pools, bars. and other sediment storage sites. and on stream bed surface texture (Lisle, 1986b; MacDonald and Keller, 1987). Heede (1985) reports the formation of new gravel bars that replace hydraulic resistance lost through debris removal. Similarly, Smith et al. (1993b) report that debris removal causes initial degradation of a low-gradient stream bed. however the loss of LWD-related. scouring turbulence and development of an alternate bar-pool sequence result in a net. long-term increase in sediment storage. These results are strongly dependent on low gradient and sufficient water depth necessary for alternate bar development (Ikeda, 1984).

Pool spacing in LWD-affected streams is commonly less than the expected 5-7 channel widths for bar-pool type channels (Leopold et al., 1964), owing to the pool forming function of LWD. Robison and Beschta (1990) employ time series analysis to determine that spacing of pools in a forest stream in southeast Alaska varies in an irregular way, as a function of the random spacing of LWD rather than a predictable function of channel size or discharge. Published values for pool spacing in forest. bar-pool streams fall within a fairly consistent range despite inconsistencies in how pools are defined. These values include 1.8 to 6.6 channel widths for northwestern California streams (Keller et al., 1981), 1.7 to 3.5 widths in the Queen Charlotte Islands. British Columbia (Hogan, 1986), 1.0 to 1.6 widths (derived from a regression equation) for undisturbed streams in southwestern Washington (Bilby and Ward. 1991), 4 widths in the western Cascade Mountains of Oregon (Nakamura and Swanson. 1993), 0.2 to 3.7 widths in southeastern Alaska and western Washington (Montgomery et al.. 1995), and 0.3 to 3.3 widths in southeastern Alaska (Wood-Smith and Buffington, 1996). Montgomery et al. (1995) find that in addition to LWD distribution. pool spacing depends on channel type, slope, and width.

APPLICATION TO FOREST LAND USE ISSUES

A primary concern regarding effects of land use on forest streams is the potential response of the stream and riparian zone to altered LWD loading. Comparisons between undisturbed streams and those affected by timber harvesting activities indicate that land management can increase or decrease in-channel LWD concentration and change size distribution and orientation of pieces. Such effects can alter hydraulics, channel geometry, and sediment transport, as well as frequency and size of pools, riffles, and sediment storage sites, thereby affecting riparian vegetation and lotic biota, including economically important salmonids (Lisle, 1986b; Hogan, 1986; Hogan and Church, 1989). For channels with abundant LWD, Buffington (1995) reports a 4.5-fold decrease in median surface grain size resulting in increased spawning habitat availability relative to model predictions for the same channel without debris. Land use impacts can also affect distribution and variability of pool types through altered LWD frequency and size distribution (Bilby and Ward, 1991; Wood-Smith and Buffington, 1996).

Geomorphic response to land use can be highly variable. Carlson et al. (1990) compare channel features in five relatively undisturbed stream segments in northeastern Oregon with paired segments having one-quarter to one-half of their riparian forest removed. They find no significant difference with respect to pool frequency or percent stream area in pools. Reeves et al. (1993) report a non statistically significant decline in pool frequency with increasing timber harvest level. They find reduced LWD loading and salmonid diversity in the most highly disturbed basins. Wood-Smith and Buffington (1996) report that loading of LWD is generally greater in pristine streams, where scour at LWD obstructions accounts for 80% of the number of pools, in contrast to stream reaches intensely affected by timber harvesting, where 55% of pools are LWD related. The authors successfully discriminate these highly-disturbed from undisturbed reaches based on LWD-affected differences in pool frequency, pool depth, and bed surface texture.

Land use effects on LWD transport can only be speculative at this stage of knowledge. In some northwest-coastal areas of North America, earlier logging practices increased the amount of transportable LWD in channels and frequency of debris flows. This increased the frequency and extent of LWD movement and associated disturbance of channels and streamside vegetation. These and other processes, such as salvage logging and other LWD removal from streams and riparian zones, may result in reduced effect of LWD movement in the future. However, scientists and land managers have yet to determine optimum levels of LWD movement in streams to balance ecosystem dynamics and protection of transportation systems. Land management agencies are becoming increasingly aware of the importance of LWD in fluvial-riparian ecosystems and are strongly urged to incorporate this information into management practices as well as increase research examining these relationships (Bisson et al., 1987; Gregory and Davis, 1992).

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