Published as: D.B. Booth, D.R. Montgomery, and J.P. Bethel, 1997, Large woody debris in urban streams of the Pacific Northwest: in Roesner, L.A., ed., Effects of watershed development and management on aquatic ecosystems: Engineering Foundation Conference, Proceedings, Snowbird, Utah, August 4–9, 1996, pp. 178-197.

Large Woody Debris in Urban Streams of the Pacific Northwest

Derek B. Booth[1,2], David R. Montgomery[2], and John Bethel[3]

ABSTRACT

Large woody debris (LWD) performs key functions in undisturbed streams that drain lowland forested watersheds, including dissipation of flow energy, stabilization of bedforms and channel banks, entrapment of sediment, and formation of pools. These functions vary between individual channels, however, depending on the size and morphology of the stream, which in turn depend on climate, watershed size, valley slope, geologic substrate, and relative inputs of water and sediment. Loss of LWD will alter channel form and processes, yielding greater sediment fluxes, more rapid bank erosion and incision, and loss of heterogeneity in bed morphology. Just as LWD is ubiquitous in undisturbed lowland streams of the Pacific Northwest, it is significantly depleted in urbanized systems where it is lost through washout, downcutting, and direct removal. Given the dramatic changes in runoff processes and sediment delivery that typify urban watersheds, we doubt that simple reintroduction of LWD will fully restore the lost functions of urban streams. Instead, projects that replace LWD may be best suited to recover a more limited set of rehabilitation goals; they are also necessary components of more comprehensive restoration efforts in once-forested lowland landscapes. Project designs range from the visually pleasing to the hydraulically engineered, but most approaches nonetheless fail rapidly in a dynamic stream environment. Stable configurations of LWD are best recognized through the careful observation of form and riverine context in natural systems, where years of varying water and sediment discharges have obliterated all but the most stable arrangements.

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[1] Director, Center for Urban Water Resources Management, Department of Civil Engineering, University of Washington, Box 352700, Seattle, Washington 98195
Phone (206) 543-7923; Fax (206) 685-3836; Email dbooth@u.washington.edu

[2] Department of Geological Sciences, University of Washington, Seattle, WA 98195

[3] King County Surface Water Management Division, Seattle, WA 98104

ROLE OF LWD

Logs, branches, and stumps are ubiquitous in undisturbed lowland humid-region stream and river channels. These pieces of large woody debris (LWD) can trap sediment, divert low and high flows, and provide cover and shading for aquatic organisms. Although the influence of any particular piece of LWD is difficult to predict and likely to change over time, both functionally and spatially, the collective effects of LWD can be substantial and very persistent. This discussion focuses on the *physical* effects of wood in channels, not because we judge the biological effects to be of lesser importance but because many of those biological effects result from the physical modifications to stream habitat that LWD imparts.

In the urban environment LWD is rare, and for many years the beneficial role of such material was ignored. Logs and branches were recognized only for their ability to block culverts or to lodge under bridges. Their presence in the active flow complicated any estimates of roughness or channel capacity, and the scour imparted by associated flow diversions was seen as a threat to bank stability and to an orderly channel geometry.

Those perceptions of LWD in urban channels are now undergoing significant revision, for several reasons:

- Recognition of adverse changes in stream-channel morphology and stability following the removal of LWD that normally accompanies land-use changes;
- Realization of the inadequacy of "traditional" mitigation for urban effects on stream channels (typically upland flow control via detention or retention ponds); and
- Increasing public interest in restored biological productivity, particularly fish, in urban stream channels.

Although the influence of LWD can be substantial, that influence is not uniform along the channel network from headwaters to river mouth. The same log that fully bridges a small mountain stream channel, suspended many feet above the water surface, could easily float down the center of the river in the broad alluvial valley below without ever touching the bed or banks. In between, that same log could wedge into both streambanks at the level of the bankfull flow, forming a step in the channel that controls bed elevations for many decades. Thus the position in the channel network is a critical determinant on the function(s) that LWD may perform: observations, analyses, management proscriptions, and rehabilitation strategies are *not* necessarily transportable from one location to another. The methodology for determining whether different sites on different streams are "equivalent" is the subject of *channel classification*, which we recognize as a necessary framework for any detailed discussion of the role and manipulation of LWD in urban stream channels.

Channel Types and Classification

Principles and Limitations. Geomorphologists and biologists have been organizing and categorizing the myriad array of stream channels for about a century. The purpose of such an organization is fundamental: if a channel of interest can be placed in a group, and the properties of that group are already known, then the properties of our new channel will also be known (Kondolf, 1995). Those "properties" depend on the organizational scheme, but they include such attributes as the channels' response to environmental change (increased sediment load, placement of an artificial habitat-enhancement structure, or removal of LWD) or its importance in supporting stream biota (Mosley, 1987).

Classification also can affect the communication between different workers, and between different disciplines, about the nature and condition of stream channels. The influence can be positive, by providing a common basis for discussion and a general agreement about the important attributes of a channel that must be recognized and evaluated in order to understand the channel's function (Platts, 1980). Yet the influence of classification also can be detrimental, by suggesting an overly simplistic range of channel conditions that obscures critical differences between channels that are ostensibly "the same." It may also impart a false understanding if the classification method is taken outside of where it was developed to where the dominant landscape processes are significantly different: channels may be "classified" but the predictive power of that classification will be low or misleading.

Two examples, both relevant to urban stream channels of the Pacific Northwest, illustrate this problem. The classification method of Rosgen (*e.g.*, 1994 and prior informal publications) has been applied widely throughout the United States by land managers because of its broad range of physical channel conditions that are included in the framework, its relatively straightforward application, and the hypothesized yet detailed channel-response matrix that accompanies the classification method. Yet nowhere in this method is the role of LWD recognized, reflecting the non-forested environment in which this method was first developed. This does not negate its utility in many settings but should remind us of its potential limitations in some.

The classification of Montgomery and Buffington (1993) was established explicitly to address the channels found in forested watersheds of the Pacific Northwest, where LWD is ubiquitous and one of the most important management needs is to evaluate the addition or removal of logs in the stream channel. Yet the same channel types in different lithologic units may appear very similar but *respond* very differently to changes in flow regime or sediment inputs. Some of the sediment-delivery processes and sources of channel roughness are very different in lowland urban channels than in the headwater channels of the Cascade Range, and so the utility of this (or any) classification may be limited for predicting specific channel response in different watershed settings.

Criteria. Despite these caveats, the related issues of channel types and channel classification are inescapable in addressing the role of LWD in urban channels. We will use the classification of Montgomery and Buffington (1993) because of its explicit recognition of the influence of wood and other such obstructions on channel morphology. We recognize, however, that the urban lowlands of the Pacific Northwest present a range of vegetation and geologic conditions that are necessary to consider in addition to the particular channel "type."

In an idealized watershed, the position of a channel in the drainage network is well correlated with (a) the sources of sediment, (b) the channel slope, (c) the role of LWD, and (d) the visible channel morphology (Figure 1). Thus a recognition of any of these characteristics, most commonly channel morphology, immediately yields information on the other characteristics as well. Conversely, in a disturbed watershed where channel morphology is no longer a good indication of the "appropriate" channel type, a less disturbance-sensitive parameter (normally channel slope) can suggest the type of channel morphology for which future restoration efforts should aim.

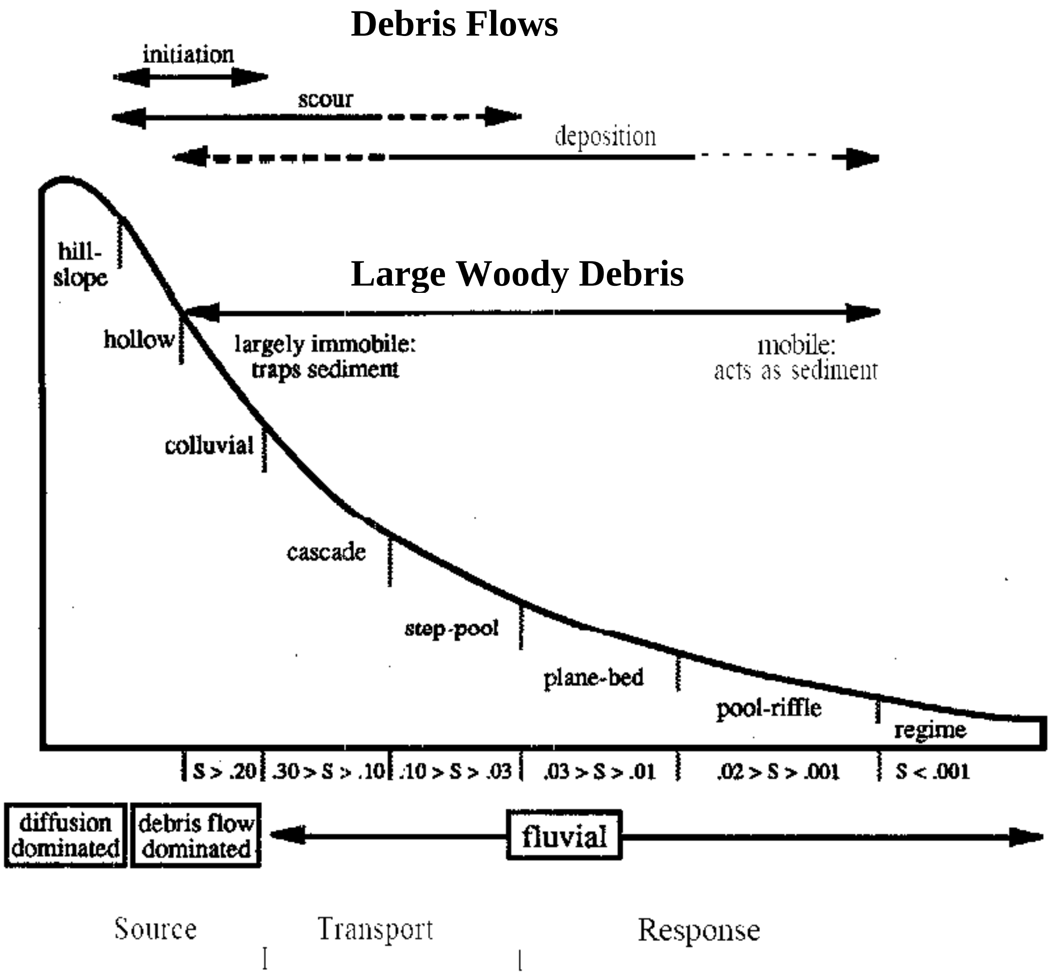

Figure 1. Characteristics of the channel types of Montgomery and Buffington (1993).

The different channel types are:

- **Colluvial Channels:** The small channels that are wholly surrounded by colluvium (*i.e.*, sediment transported by hillslope processes such as creep or landsliding and not by stream transport) that generally lie at the tips of the channel network.
- **Cascade Channels:** The steepest of the alluvial channels, characterized by large clasts that form the primary roughness elements and impose a strongly three-dimensional structure to the flow. Tumbling flow around individual boulders dissipates most of the energy of the flow; bed morphology is disorganized with at most small pools that span a fraction of the total channel width.
- **Step-Pool Channels:** Channels displaying full-width-spanning accumulations of coarse sediment that form a sequence of steps, typically one to four channel-widths apart, that separate low-gradient pools filled with finer sediment. The step-forming sediment is mobile but only at very high discharges; in contrast, sediment in the pools can be rapidly flushed downstream over the intervening steps. The spacing of the steps appears to maximize the flow resistance (Whittaker and Jaeggi, 1982) suggesting that this morphology is essential for maintaining a stable low-flow bed under slope and discharge conditions that would otherwise readily transport sediment downstream. Both “free” and “forced” step-pool channels can be identified, depending on whether alluvial (*i.e.*, episodically transported) sediment or immovable obstructions (*e.g.*, bedrock or large logs) form the majority of the steps.
- **Plane-Bed Channels:** Channels lacking well-defined bedforms and instead displaying long, and commonly channel-wide, reaches of uniform “riffles” or “glides.” In contrast to the steeper channels any flow oscillation is generally horizontal, not vertical, but the lateral variations are insufficient to produce pronounced meanders and associated pools.
- **Pool-Riffle Channels:** The most common of the lowland stream channels, with laterally oscillating flow producing a sequence of pools at the outside of bends with corresponding bars on the inside of bends. In the relatively straight reach between each bend a more laterally uniform riffle forms. Analogous to step-pool channels, the classification recognizes “free” pool-riffle channels, where this distinctive morphology forms simply by virtue of the inertial characteristics of the water moving in a sinuous or meandering channel; and “forced” pool-riffle channels where the presence of pools is closely tied to obstructions, such as LWD, but where the removal of such obstructions could yield a morphology more closely akin to plane-bed channels.
- **Dune-Ripple Channels:** The classic lowland sand-bedded channels typical of large rivers, where the character of the predominant bedform will change in response to increasing discharge from plane bed at low flows to ripples, sand waves, dunes, high-energy plane bed, and antidunes at highest flows.

In addition to channel type, the specific response of a channel to watershed changes or restoration efforts, will also depend on the geological context and the nature of bank-forming materials. For example, the effect of removal of LWD from a forced step-pool channel differs dramatically between channels in the Cascade Range, where there is a large supply of boulders capable of reforming steps, and in the Puget Lowland, where the available glacial sand and gravel are too fine to stabilize steps. Dramatic downcutting consequently follows log removal from steep, forced-alluvial channels underlain by glacial deposits, in contrast to the response of the "same" type of channel where a supply of large clasts is available. Hence, channel classifications based on channel morphology (Montgomery and Buffington, 1993) or on grain size and slope (Rosgen, 1994) do not always provide sufficient information to predict specific channel response.

The Role of LWD in Different Sizes and Types of Channels

When a tree falls into a stream channel, a variety of hydraulic changes occur. Typically, current is diverted over or around the obstruction, scouring the bed and banks. Other floating debris, too short to lodge against opposing banks of the channel, may be trapped against the log. Disruption of the flow will cause a local reduction in the transporting power of the flow, and so a sediment wedge may build on the upstream side of the log. The overall down-channel flux of sediment will reduce, because some of the elevation drop of the water surface in the channel will occur by abrupt wood-armored plunges which will reduce the capacity to transport sediment.

Biological changes follow hydraulic changes (see also Harmon and others, 1986). Fish will seek out the relatively deeper water in the scoured pools adjacent to the log, for refuge from both high flows and terrestrial predators. In addition, the decaying wood introduces nutrients into the aquatic food chain, and traps additional organic material that otherwise would be flushed downstream and out of the system altogether. Fish populations decline rapidly and precipitously following removal of LWD (*e.g.*, Bryant, 1983; Elliot, 1986). These changes, however, are not uniform across the range of channel types and sizes (Figure 2).

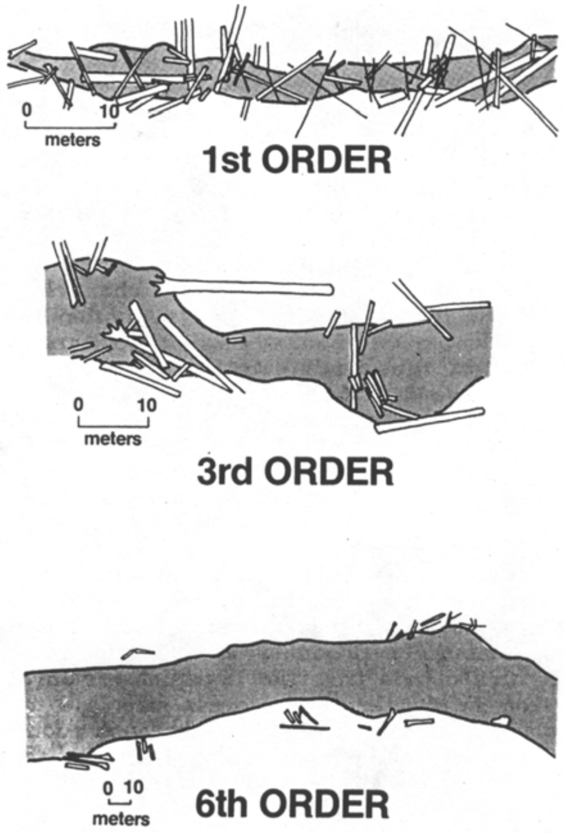

Figure 2. Position of large woody debris in channels of different sizes (redrawn from Salo and Cundy, 1987).

High Gradient Channels. In cascade and step-pool channels the role of LWD is highly variable. Where valleys are tightly confining, fallen trees are often suspended well above the active channel, bridging between the valley walls. Where they do contact the flow they become another obstruction, whose importance depends on their relative abundance: in a boulder-dominated channel, for example, the presence or absence of what minimal LWD falls into the stream may be of little consequence. Where large bedrock boulders are sparse or absent, however, logs may provide the primary control on bed morphology, forming the steps that account for most of the vertical drop, and dissipate most of the flow energy, in a step-pool channel (Heede, 1972 a, b; Swanson and others, 1976; Keller and Swanson, 1979; Keller and Tally, 1979; Bilby, 1981). In some channels, the distribution of bedrock channel reaches is controlled by log jams that force local deposition (Montgomery and others, 1996). If the steps are removed from the flow, either by direct human action or by channel incision that leaves the logs suspended above the now-confined channel, the consequences on channel morphology can be very dramatic (see below).

Dune-Ripple Channels. Where channels are large and individual pieces of LWD span but a fraction of the channel width, logs tend to move as sediment particles in most situations. Unlike most sediment particles, however, individual pieces have a somewhat greater opportunity to interact and interlock, which under favorable conditions can build a debris jam of massive, channel-spanning proportions (Lobeck, 1939; Keller and Swanson, 1979; Abbe and Montgomery, 1996). These conditions lie outside of the range of our concern in this discussion, but the urban environment is not immune to the consequences of debris jams on large rivers. Traditionally those jams have been viewed as threats to navigation and to efficient passage of flood flows, and so they have been removed whenever possible. They also can stabilize channel banks, however, and so their absence may also have negative consequences for land uses adjacent to the river.

Lowland Streams: Plane-Bed and Pool-Riffle Channels. It is within these channel types, typically spanning a range of gradients between about 0.1 and 3 percent, that LWD has the greatest range of functions (*e.g.*, Lisle and Kelsey, 1982; Keller and others, 1985; Montgomery and others, 1995). By observation of relatively undisturbed lowland channels, these functions include:

- ***Hydraulic roughness***, which may increase by 50 percent or more through the disruption of flow imposed by a high concentration of logs, stumps, or debris jams;
- ***Sediment storage*** behind channel-spanning logs that create a stepped bed profile with a wedge of trapped sediment just upstream, or individual obstructions that result in a (normally smaller) zone of deposition in the eddy just downstream (Keller and Swanson, 1979);
- ***Bank protection*** through a combination of flow deflection and general hydraulic roughness which reduces the rate of sediment transport (note also, however, that flow deflection may locally *increase* bank erosion); and
- ***Creation of habitat diversity*** by the variety of bedforms, sediment-transport zones, and sheltered areas that typically accompany LWD in the active flow. Pool formation, in particular, can be almost completely determined by the presence and location of LWD in forested channels of this type, with pool frequencies two or three times greater than in LWD-free streams (*e.g.*, Andrus and others, 1988; Robison and Beschta, 1990; Smith and others, 1993; Montgomery and others, 1995).

Conversely, the removal of LWD that commonly accompanies urbanization of a watershed and its associated riparian areas produces the opposite tendencies. Channels experience greater erosion and lateral instability, the flux of sediment is greater and more closely tied to individual high-flow events, and a diversity of physical habitat is replaced by uniformity in channel profile and channel cross-section. Many of these effects are also a product of the increased discharges that normally accompany urbanization, and we cannot always distinguish unequivocally the relative significance of increased flows and decreased LWD abundance in these settings. We will return to the implications of this uncertainty in our discussion of stream-channel restoration.

Quantifying the Role of LWD in Channel Hydraulics and Sediment Transport

Traditionally, hydraulic analyses of open-channel flow and sediment transport have assumed such "normal" simplifications as uniform channel cross sections and steady flow. In part these assumptions have been made to mimic original experimental conditions in laboratory flumes, on which these analyses are based. They also are made in recognition of the simplifications needed to find analytical solutions to the equations of motion in a three-dimensional fluid. Even the best field-based experimental data have generally been conducted on the most uniform, obstruction-free channels (*e.g.*, Milhous, 1973; Dietrich and Smith, 1983; Kinerson, 1990) to avoid the "complications" that would be inescapably imposed by irregularities such as LWD. Only recently has the role of log roughness been incorporated into some fluvial field studies (*e.g.*, Buffington, 1995).

In an effort to achieve analytical simplicity, however, we have sometimes lost site of the underlying goals: to understand the functions of real stream channels, to evaluate the ability of channels to achieve those functions, and to construct or reconstruct channels that achieve those functions to the best of their ability. It is precisely the *least* easily quantified aspects of open-channel flow and sediment transport that produce the heterogeneity necessary for habitat diversity and the attenuation of flow erosivity. So for example the channel types that must dissipate the greatest amount of flow energy per unit bed area, steeply dropping cascade or step-pool channels, attain this function within a stable form *not* by laying down a uniform pavement of immovable clasts but by an irregular, rapidly varying longitudinal profile (Figure 3).

Traditional analyses of LWD functions have followed a similar approach. The influences are removed from analysis not because they are unimportant but because the presence of LWD is inconvenient. When we exclude that influence in analyzing an existing channel, however, the representation is incomplete; and when we omit LWD in a reconstructed channel that would normally include it then the channel *functions* are incomplete (and likely inadequate as well).

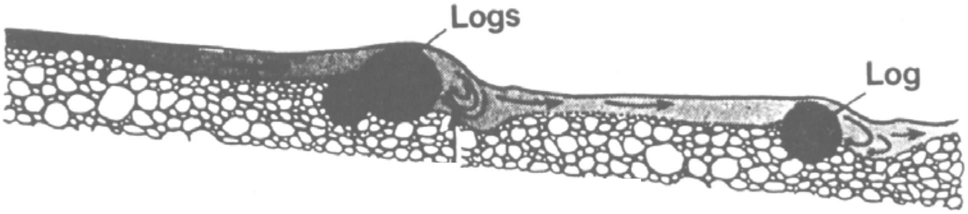

Figure 3. Cross-sectional view of logs in a step-pool channel.

LWD IN URBAN ENVIRONMENTS

The absence of LWD in developed and developing parts of the world is ubiquitous and long-standing, even where vast forests once blanketed the landscape (*e.g.*, Wiltshire and Moore, 1983; Petts and others, 1989). Hydraulic considerations, particularly land drainage and reduction of flood stage, motivated widespread removal of riparian vegetation and in-stream obstructions. On large rivers any logs or snags reduced navigability; on small streams mobile debris can be seen to lodge under bridges and clog culverts, encouraging local sediment deposition and flooding. In the Pacific Northwest even anadromous fish were thought to suffer from the migration-blocking effects of LWD accumulations, and so removal was mandated under commercial forestry permits of the 1970's and early 1980's.

The magnitude of LWD loss in urban streams is best demonstrated by the typical frequency of logs in their (relatively) undisturbed lowland counterparts. For example, the number of pieces of well-anchored LWD were tallied in successive 60-m stream segments of Huge Creek, a 5-m-wide channel draining about 12 km^2 in an area of very low urban development in western Washington. On average, log spacing was less than 7 m (*i.e.*, at least 9 pieces per 60-m segment) and commonly about equal to the channel width (*i.e.*, about 12 pieces per 60-m segment, or about 200 pieces per km). As we look to progressively more developed watersheds, the frequency of LWD tends to decrease. This can be displayed most simply by a plot of percent total impervious area, as a measure of watershed development, against the number of LWD pieces in a unit distance. Data from Horner and others (this volume) show abundant scatter but a clear general trend (Figure 4); in extreme yet all-to-common cases, there is no LWD whatever in an urban channel.

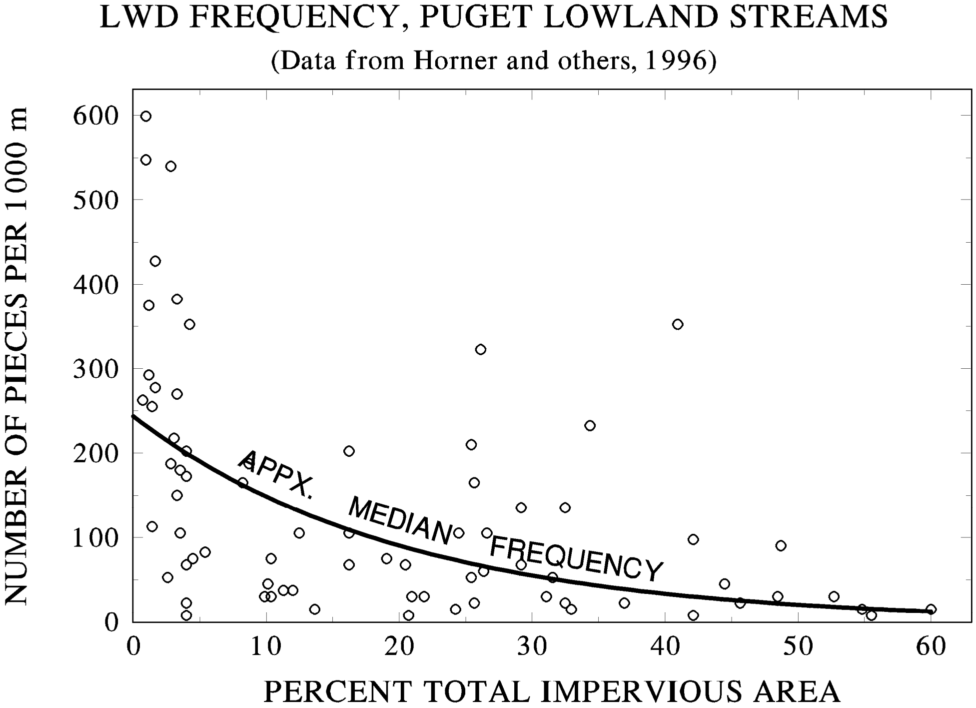

Figure 4. Site-specific measurements and median trend of measured LWD frequency in urban watersheds spanning a range of development intensity.

Loss Mechanisms

Although the processes by which LWD is lost from the active channel are not unique to urban streams, the nature of the changes that accompany urbanization make several removal processes particularly effective.

Washout. Increased discharges are the hallmark of watershed urbanization. By any measure the magnitude of channel flow increases: using the most common measure, the ***peak discharges*** of annual and multi-year floods increase by typically two- to five-fold (Hollis, 1975), depending on the degree of urban development and the frequency of the flood event. The aggregate ***duration of flood flows*** may increase more than ten-fold, as once-rare discharges become more commonplace (Barker and others, 1991). Finally, the ***frequency of major sediment-transporting events*** increases by as much as 50-fold, as discharges with a recurrence of five or ten years in the pre-urban condition can become monthly events after full watershed development (Booth, 1991).

The consequences of these flow increases include a dramatic increase in frequency at which very competent flows, capable of removing normally immobile obstructions, move down the channel. The change in the flow regime also tends to expand the cross-sectional area of the channel through both widening and deepening (Booth, 1990). Local data suggest that the increase in bankfull channel dimensions crudely follows the "downstream hydraulic geometry" relationships of Leopold and others (1964), wherein both width and depth increase in fractional proportion to the increase in bankfull discharge (normally approximated in hydrologic modeling by the 1.5-year or 2-year discharge) raised to a power of about 1.4. A 5-meter-wide channel, responding to a two- or three-fold urban-induced increase in two-year discharge, will therefore expand several meters in width and several tenths of meters in depth, which may expose and undermine most or all of any LWD that was previously well anchored or buried.

Stranding. A second consequence of the increased sediment transport of an urbanized channel affects those streams where the gradient has been established not by a nonerosive bed or a fixed base level, but by the balance between sediment resistance and flow energy, integrated over the suite of flows that has moved down the channel. Where that balance is disrupted by dramatically increased discharges then downcutting may proceed almost unchecked, until a much flatter gradient associated with a deeply incised new channel reduces the competence of the urban discharges (Booth, 1990). The immediate consequences of such a process is a deep and narrow channel that typically has dropped out from under any LWD that once was in contact with the bed. The LWD may be immobile still, but it is ineffectually suspended above the bed. This process is particularly pernicious, for as the incipient incision begins to strand LWD the very source of channel resistance is abandoned and so the rate of downcutting accelerates.

Human Removal. Although we are not aware of any controlled studies of the actions of neighbors on the persistence of LWD in channels, our collective observations suggest a marked correlation between suburban yards and adjacent LWD-free channel reaches that is best explained by intentional removal of debris. Whether motivated by aesthetics or a desire to “improve” the habitat for fish we can only speculate, but we suspect that visual appearances are particularly important.

The few studies on related subjects provide some useful details. Gregory and Davis (1993) asked people to rate the attractiveness of two lowland British streams. They found strong preference for more "natural" channels with clean flowing water and without artificially reinforced or armored banks. However, they also found that woodland channels *without* large woody debris were clearly favored over those with woody debris, despite the ecological advantages that such debris in fact provides. The preferred characteristics of bank vegetation, also among the British population, was investigated in more detail by House and Sangster (1991). They found preferences for (1) trees, ideally a deciduous canopy; (2) a multiplicity of understory vegetation that does not encroach of the channel itself; and (3) some degree of vegetation management (*e.g.* short mown grass rather than long grass). In general, a relatively undisturbed river setting is desirable but by no means mandatory (Mosely, 1989): some highly regarded rivers flow through heavily modified landscapes, and the most truly "natural" settings are not necessarily the most highly valued. Kaplan (1977) found that people already living nearby a stream were more likely to accept more natural, “unkempt” views of a channel than those without that prior experience. These subjective differences become especially important as water-resource design increasingly moves out of the forestland (where it has proceeded almost unnoticed for decades) into restoration and rehabilitation of urban systems (where everybody has an opinion).

Implications for Pervasive LWD Loss

Rarely does the loss of LWD occur in isolation--normally it accompanies upland changes, such as logging or urban development, that initiate significant changes in runoff and sediment-delivery patterns and in riparian vegetation. We can only partly isolate the consequences of LWD loss in channels, because those consequences are amplified by other, concurrent changes as well. Therefore, the mere *replacement* of lost LWD will not reverse all of the stream-channel changes, in large measure because only a fraction of the causal mechanisms are directly addressed by such an action.

Acknowledging the interrelationship between LWD loss and more pervasive watershed changes, we can nevertheless make some judgments about the consequences of that loss by observing the immediate response of channels to LWD removal and by deduction from the observed roles of LWD in undisturbed channels. Those responses include a rapid increase in the rate of channel shifting, both horizontally (typically by widening) and vertically (typically by incision). Changes in the bed morphology are also rapid but depend on the type of channel. Where logs form the “risers” of a step-pool channel their removal leads to immediate disruption of the fundamental morphology of the channel, a morphology that may eventually reform if other hard-to-transport material is available but more commonly will reestablish only after rapid erosion has first increased the channel dimensions and lowered the channel gradient (Booth, 1990). Where logs force pools and riffles in lower gradient streams their removal results in the simple, and relatively rapid, loss of those features.

Sediment discharges also increase following LWD removal or loss. If the change is as a result of riparian clearing then a delay of several years night be expected, as existing logs and jams deteriorate without concurrent replacement (for example, Hedin and others, 1988, report a three-year lag). If instead the LWD is actively removed then the corresponding increase in sediment transport is far more immediate and measurable within a single storm season (*e.g.*, Bilby, 1984; MacDonald and Keller, 1987; Smith and others, 1993).

The concept of *LWD budgets* provides a framework for examining the recruitment, transport, and decay of woody debris in forest stream channels. Analogous to a sediment budget (Dietrich and Dunne, 1978) an LWD budget characterizes any change in the stock of LWD within a channel as the difference between input, typically recruitment through blowdown and landsliding, and output, typically by washout and decay. Yet the dominant mechanisms of LWD input and output differ in urban and forested channels. Clearing of riparian forests and stabilization of channel positions typically dramatically reduce LWD recruitment in urban channels, unless deliberate placement occurs through rehabilitation projects. Even as input decreases the output increases, because of both the higher urban discharges that lead to greater transport rates and more pervasive direct removal of LWD in urban environments. Decreased recruitment together with enhanced transport inexorably result in lower LWD loadings in urban channels than in their comparable forest counterparts.

REHABILITATION OF URBAN CHANNELS

Principles

Reintroduction of LWD commonly is used in urban channel rehabilitation in an effort to recover lost form and function in the context of massive watershed changes. Whereas complete restoration is often unattainable, the efforts are not entirely misguided for two reasons:

1. Irrespective of what *else* has occurred in the watershed that affects the stream channel, loss of LWD probably has occurred in any once-forested lowland setting, and its functions will need to be replaced at some stage of a comprehensive rehabilitation effort.
2. LWD replacement is commonly the *only* practical stream-restoration activity that can occur in the early stages of a watershed enhancement effort. Other actions that directly address flow changes, sediment-delivery changes, or riparian conditions are much more expensive, contentious, and slow to implement.

The unanswered question, of course, is whether LWD placement *alone* produces any useful long-term effects in urban environments. The evidence from forested environments is not promising (*e.g.*, Frissell and Nawa, 1992; Beschta and others, 1994)--logs can be placed at relatively high densities without any corresponding improvement in the intended targets, typically fish use and production, and most log structures fail in time. A key shortcoming of most in-stream placement of LWD is the lack of geomorphic context and consideration of even the most basic information on channel type and size. The changes to the watershed imposed by urban development are even more disruptive than those resulting from logging, and so we anticipate little or no long-term improvement when LWD replacement is not designed with consideration of these factors.

Extreme increases in flow discharge complicate the use of LWD for channel rehabilitation in urban environments. Concern over local backwater effects and the influence of LWD movement on downstream infrastructure also influences design considerations in urban channels. These limitations are compounded by the fact that most of both what we know and our accumulated experience with reintroduction of LWD to stream channels comes from forest streams. Hence, it is important to consider what is different about specifically *urban* channels and whether these differences matter for channel rehabilitation projects.

Limitations of LWD Placement for Urban Channels

Management Concerns. Even though the long-term consequences of LWD removal are now better recognized among both stream scientists and (some) land managers, the original concerns that first motivated that removal still remain and plague stream-restoration projects that seek to reintroduce LWD into urban channels. Paramount among these concerns are the loss of flood conveyance, the potential for the wood to clog existing channel constrictions, and the possibility of flow diversion causing bank erosion. In the discussion that follows we address the theoretical and empirical basis for these concerns.

Hydrologic Changes. The changes in hydrology that accompany urban development are probably the most severe of the many alterations imposed by such land use. Replacing logs in a channel that experiences a “10-year flow” every month or two (Booth, 1991), and that dries up entirely in the summer, is unlikely to reestablish a robust aquatic-insect or fish population. Bank erosion may be reduced by an increase in flow roughness, local reduction in the water-surface slope by virtue of log steps, and mechanical armoring by careful (or fortuitous) LWD placement, but these factors alone are unlikely to compensate for ten-fold increases in the sediment-transporting capacity of urban channels or the likelihood that accelerated channel changes may abandon or strand the reinserted LWD altogether.

Sediment Fluxes. Related to the hydrologic changes that accompany urbanization, alterations to sediment movement will also compromise the intended functions. In erosional zones, LWD may be left unsupported by lateral channel expansion or stranded by vertical incision. In depositional zones, LWD may be episodically buried and reexcavated as pulses of sediment move down the channel network. In both settings the presence of the LWD may attenuate the response of the reach to the changes in sediment (and water) fluxes, but it cannot entirely mitigate extreme changes.

LWD Budgets in Urban Settings. In contrast to forested settings, opportunities to recruit new LWD are commonly quite poor in urban settings. In combination with concerns over LWD stability, this may result in project designs that seek an unrealistic degree of log stability. In the undisturbed streams that have yielded most of our understanding of the role of LWD, the debris is part of a dynamic system with recognized outputs and balancing inputs. Few urban restoration projects have adequately addressed the realistic need for long-term LWD inputs to maintain the form and function of the restoration effort.

Human Intrusion and Aesthetics. Even if a restoration project is supported by the members of the neighboring community, they may still destroy its functional and biological value in the name of visual improvement. Although the general public appears to value a "derelict but natural" landscape as a reminder of the large natural landscape beyond the urban fringe, people are likely to begin "caring for" these landscape by cleaning out woody debris and other desirable elements or by fashioning homemade retaining walls to stabilize eroding banks. In other words, while people generally like the idea of a stream nearby, they more likely want its appearance to fit into their neighborhood landscape, to look more “manicured” than “scruffy.” When public agencies attempt to restore degraded channels, they either complete the manicuring process with smoothed banks having no true rehabilitation value at all, or they build more "ecological" measures that seem unkempt, scruffy, and even more derelict to the nearby homeowner than the original degraded site.

Design Approaches for Urban Channel Rehabilitation

We judge that the rehabilitation of urban channels in the Pacific Northwest must acknowledge the following set of principles:

- In predevelopment time, LWD played a fundamental role in the function of most, but not all, lowland streams in the Pacific Northwest. Any rehabilitation effort must acknowledge those functions and reestablish them in a manner consistent with the geomorphic character of the channel and watershed setting.
- The watershed-scale alterations imposed by urban development cannot be corrected by in-channel, or even near-channel, means alone.
- LWD placement is commonly the most feasible and readily achievable component of a stream-restoration program; that it is not the only necessary action does not negate its value as an early action, as long as long-term rehabilitation targets are closely tied to the implementation of other, *watershed-scale* efforts.

The literature on channel-restoration techniques is replete with designs for “fish-habitat structures” such as single- and double-wing deflectors, notched weirs, and check dams. We find few analogs in undisturbed Pacific Northwest streams for these structures, and so we offer no additional guidelines for their construction. Instead, we focus on the guidelines behind recent projects to reintroduce LWD into urban channels, where the project objectives have been to mimic the character and function of LWD in undisturbed sites. Unfortunately, specific examples are relatively few in number and represent an early stage in our learning: failures are far more prevalent than successes. Nevertheless, they offer some indications for the directions we should be pursuing and should encourage others to follow these directions.

Natural LWD structures have been employed in channel rehabilitation projects using two distinct design philosophies. The first involves placing unanchored debris in the channel and letting high flow events reorganize the debris. The second approach involves the construction of LWD jams patterned after natural analogs (Abbe et al., 1993 and in prep; Abbe and Montgomery, 1996). Examples of the first approach from Washington State illustrate the potential for employing more natural designs in LWD-based stream rehabilitation projects.

Project Experience with LWD Placement in Urban Channels

Project Objectives. The King County Surface Water Management Division has experimented with placement of unanchored LWD in five stream enhancement and stabilization projects. In each case the projects were intended to both decrease sediment discharge and enhance in-stream habitat. The use of unanchored wood represented a distinct change in approach from more conventional channel stabilization projects; here, LWD was considered a dynamic element in the fluvial and riparian system, which had been depleted as a result of human activity. Woody debris was introduced with the explicit expectation that it would be moved, reoriented, and incorporated into the stream system through natural fluvial processes.

Creek Name	Watershed Upstream from Project	Predominate Land Use Upstream from Project	Channel gradient	Bankfull channel width	Predominant bed sediment	Channel Classification
Madsen	5.2 sq km	residential	4.0%	3m	gravel	plane-bed
Boise	22.3 sq km	timber production	3.0%	4 m	gravel	plane-bed
Soosette	14.3 sq km	residential	2.3%	4 m	gravel	plane-bed
Laughing Jacobs	14.6 sq km	residential	2.5%	5 m	gravel	plane-bed
Hollywood Hill	2.2 sq km	residential	7.1%	2 m	gravel	plane-bed

All of the project streams showed evidence of degradation consistent with the combined effects of LWD depletion and changes in basin hydrology as a result of changes in land use. All of the channels exhibited the characteristics of a plane bed channel, although in two cases (Madsen Creek and the Hollywood Hill tributary) the channel gradient exceeded the range typical of such channels. In all cases the project reach was selected to be a substantial distance upstream from the nearest bridge or culvert, in order to minimize the possibility of the debris blocking such a structure.

The size of material placed, and the number of pieces per unit length of stream were based generally on published descriptions of LWD in natural, undisturbed streams in the Pacific Northwest (Bilby and Ward, 1989; Nakamura and Swanson, 1993). Material availability, construction logistics, and budget constraints also significantly affected decisions regarding the type and amount of debris placed. Logs 6 to 12 meters in length in length, lacking both rootwads and branches, were readily available from commercial logging operations and constituted a majority of the pieces used. Rootwads without significant stems were also readily available from land clearing operations. Logs with attached rootwads are much more difficult to acquire and therefore were the used less than either of the bare logs or rootwads alone. All of the woody debris used in these projects was native coniferous species. Log and stump diameters were generally in the range of 0.25 to 0.75 meters.

Creek Name	Year Constructed	Length of Channel Treated (m)	Total # of Woody Pieces	Pieces / 100 Meters	# of Logs w/o Rootwads	# of Logs w/ Rootwads	# of Rootwads	Method of Construction
Madsen	1993	210	51	24	32	9	10	helicopter
Boise	1994	500	93	19	20	51	22	helicopter
Soosette	1994	1600	278	17	278	0	0	helicopter
Laughing Jacobs	1995	300	68	23	22	15	31	crane
Hollywood Hills	1995	80	53	66	17	4	32	crane

Table 1. Summary of LWD Placement Projects

As indicated in Table 1, two different methods were used to place the woody debris in the stream system with minimal disturbance to riparian vegetation. At project sites where access was available, it was possible to place material using a rubber-tired hydraulic crane, which could to reach over stream side vegetation. On the remaining sites, debris was placed by helicopters equipped for long line operation.

These projects have been subject to between one and three years of wet season flows, depending on their construction date. The largest storm to occur in this three year period occurred in February of 1996, subsequent to construction of all five projects. This recurrence interval for this storm (7 day rainfall) varied from 5 to 50 years depending on the project location.

Project Performance. Four of the five projects have achieved only limited success to date in reducing downstream sediment discharge. On these projects, the debris has been relocated by high flows to varying degrees. Much of the wood remains in contact with the channel and is contributing to increased roughness and causing local sediment deposition. In many cases the debris appears to have locally deflected flow, resulting in a more sinuous channel form, and consequently locally lower gradient . On the other hand, flow concentration or deflection by the debris, has caused local areas of bank erosion or channel incision, reducing or negating the net increase in sediment storage resulting from debris placement.

The one project where results to date have been less equivocal is the Hollywood Hill ravine stabilization. Sediment accumulation in the project area has been dramatic. Deposition has occurred throughout the project reach, with local deposition on the order of one-half meter. No significant erosion occurred in this reach. This project was different in several respects from the other four. The contributing basin was the smallest of the five, the number of pieces per unit length was roughly three times greater than the other projects, and a much higher percentage of the pieces used were rootwads rather than logs.

Conclusions. Qualitative evaluation the projects completed to date suggests several conclusions. These conclusions are preliminary, because on the short time period since these projects were completed, and on the lack of consistent, comparable monitoring information:

1) Placement of bare cylindrical logs, with no stems or rootwads seems to encourage streamflow to scour below the log rather than to flow over the top. As a result, such logs do not tend to form “steps” in the channel profile , and therefore do not lead to deposition of an upstream sediment wedge. This seems to be in contrast to natural tree fall, where the resulting debris is often a full length tree, with roughness and complexity provided by both branches and roots.

2) Use of pieces with greater complexity (rootwads, and logs with attached rootwads) and placement of more pieces per unit length both result increased effectiveness. In larger streams, where flow depths are sufficient for debris to become buoyant, rootwads are be more mobile than logs because they are less able to lodge on stream banks, or become wedged against streamside vegetation.

3) The intent of these projects was to simulate the natural input of wood to a channel system. One element which may be critical in this incorporation process is the passage of time. Much of the wood which forms structure in lowland stream channels occurs either as individual pieces which are largely buried in streambed sediment, or as a part of a jam constructed largely of woody debris transported by the stream. In both cases this occurrence implies that the wood was present in the stream for a period of time before it assumed its current role. It may be that it will be necessary to allow for a similar period of time for the debris introduced by these projects to be completely incorporated.

4) A significant effort has been made to evaluate the performance of these projects. Unfortunately the complexity of the physical system has made monitoring their geomorphic effects difficult at best. In addition, the monitoring program between projects has not been consistent, so that the data collected is not readily comparable. For these reasons, it is difficult at this point to draw clear, defensible conclusions about the effectiveness of these projects in meeting their objectives with respect to channel stability and sediment discharge. There is widespread interest in placement of LWD as one element of comprehensive urban stream restoration programs. Before such an approach should be widely adopted, the projects which have been completed to-date should be evaluated through a monitoring program designed to provide a consistent, comparable and meaningful characterization of the effects of such projects, and which yields clear direction for future project designs.

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