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Effectiveness of large woody debris in stream rehabilitation projects in urban basins

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Abstract

Urban stream rehabilitation projects commonly include log placement to establish the types of habitat features associated with large woody debris (LWD) in undisturbed streams. Six urban in-stream rehabilitation projects were examined in the Puget Sound Lowland of western Washington. Each project used in-stream log placement as the primary strategy for achieving project goals; none included systematic watershed-scale rehabilitation measures. The effectiveness of LWD in these projects was evaluated by characterizing physical stream conditions using common metrics, including LWD frequency and pool spacing, and by sampling benthic macroinvertebrates. In all project reaches where pre-project data existed, pool spacing narrowed after LWD installation. All project sites exhibited fewer pools for a given LWD loading, however, than has been reported for forested streams. In project reaches where the objective was to control downstream sedimentation, only limited success was observed. At none of the sites was there any detectable improvement in biological conditions due to the addition of LWD. Our results indicate that, although LWD projects can modestly improve physical habitat in a stream reach over a time scale of 2–10 years, they apparently do not achieve commensurate improvement in biological conditions. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Stream restoration; Urban streams; Stream monitoring; Large woody debris; Watershed restoration; Biological monitoring; Invertebrate monitoring

1. Introduction

Urban streams in the Puget Sound Lowland (PSL) in northwest Washington state are unique in that many still support salmon, although in declining numbers. With the listing of Puget Sound Chinook (*Oncorhynchus tshawytscha*) as

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'endangered' under the federal Endangered Species Act in 1999 — the first time a species has been listed within a major metropolitan area — a greater importance has been placed on reversing urban impacts on waterways in the PSL. For this reason, engineered projects now being designed and constructed in urban streams are increasingly required to benefit salmon habitat, even if they are motivated primarily by more traditional concerns such as flood control or property protection.

In-stream rehabilitation projects are commonly built in response to problems that result from both local sources and diffuse watershed degradation. Local problems, such as an improperly sized culvert, are relatively easily identified and corrected. Reversing the consequences of watershed degradation, such as channel widening and incision, is much more difficult because conditions that led to stream degradation usually remain unchecked. Yet, because of numerous recognized problems on streams in urban or urbanizing basins, the interest of local communities in restoring the amenities these streams provide (MacDonald, 1995; Riley, 1998), and the relative ease and economy of site-specific in-stream work, large amounts of money are being spent on in-stream projects.

While the number of urban stream restoration projects is increasing across the nation, comparatively few examples of monitoring programs designed to measure the success of such efforts are documented (Kerschner, 1997). In western Washington, salmon recovery is an objective of the majority of rehabilitation projects, yet very rarely are salmon or any other element of stream biota directly monitored to assess restoration success. Of over 300 rehabilitation projects installed over the past decade in urban areas around the Puget Sound Lowland, less than 5% were evaluated with any sort of biological or habitat suitability data (Kropp, 1998).

This study investigates the effectiveness of one common technique, placement of in-stream large woody debris (LWD), to reverse local effects of watershed degradation in the absence of any systematic watershed-scale approaches to rehabilitation. To accomplish this, six stream rehabilitation projects in western Washington that employ LWD were examined with the objective of answering the following questions.

- Does in-stream placement of LWD produce physical channel characteristics typical of streams in less disturbed watersheds?
- Does biological condition improve immediately downstream of LWD addition?
- How can LWD project designs be improved?
- Does watershed disturbance exert greater control over physical and biological recovery of the channel than the local in-channel conditions addressed by added LWD?

1.1. Impacts of urbanization

Because of its permanence, urbanization poses a particularly ominous obstacle for stream protection and rehabilitation. The process of urbanization usually results in irreversible changes to the land surface and drainage pattern by increasing the impervious area, reducing vegetation cover, compacting soil, reducing areas of depression storage, concentrating and re-routing runoff, and straightening and piping streams. These changes cause a progressively greater fraction of precipitation to enter the channel rapidly as Horton overland flow (Leopold, 1968; Graf, 1975; Hollis, 1975). Particularly in geologic regions such as the PSL, where overland runoff is rarely generated and subsurface flow predominates, these changes can alter stream channels (Harr, 1976; Booth, 1990, 1991). Direct alterations to channels and riparian corridors include removing bank vegetation, clearing woody debris from streams, armoring stream beds and banks, straightening channels, reducing floodplain storage, and diverting extensive stretches of streams through culverts. Removing LWD, in particular, can modify channel morphology and increase sediment discharge, and has led to the widespread loss of once-prevalent wood in urban channels (fore example, Booth et al., 1997; Horner et al., 1997).

1.2. The use of LWD in channel enhancement

LWD plays prominent roles in regulating morphology and habitat in Pacific Northwest channels, from steep and narrow headwater streams to wide low-gradient rivers. These functions make it a critical component of current stream and river restoration, and enhancement efforts. The effects of LWD on moderate-gradient streams (0.5–4% slope) with bankfull widths of about 4–40 m have been studied in greatest detail. The steeper of these channels, dominated by riffle and glide features, are classified as 'plane-bed' by Montgomery and Buffington (1998). Lower gradient streams commonly display regularly alternating riffles and pools in a meandering planiform. The transition from 'plane-bed' to these flatter 'pool-riffle' channels, under a particular sediment-supply and flow regime, can be controlled by the presence of obstructions, notably LWD, that form scour pools, bars, sediment storage sites, and steps in channels that would otherwise maintain a relatively flat and uniform bed. In these channels, LWD can influence bank stability, pool and bar formation, sediment retention, and grade (Montgomery et al., 1995; Beechie and Sibley, 1997; Nelson, 1998).

The reported effects of re-introducing LWD (or other physical habitat structures) to a channel, particularly when watershed conditions have not been simultaneously addressed, is ambiguous. Several studies have reported that, at least in the short term, such habitat elements as pools, substrate for fish spawning or invertebrate colonizers, and cover for fish can be improved using in-stream structures alone (House and Boehne, 1986; Gortz, 1998; Hilderbrand et al., 1998; Shields et al., 1998). Some studies have shown that macroinvertebrate community structure changes and diversity increases when structures are added (Hilderbrand et al., 1997; Gortz, 1998), but they also report ambiguous responses in fish usage (Shields et al., 1998). In forested watersheds, studies have reported higher fish counts after habitat structures were installed in forested streams (House and Boehne, 1986; Crispin et al., 1993). In contrast, a comprehensive evaluation of in-stream rehabilitation projects (Frissell and Nawa, 1992) documented a high incidence of structure failure after floods of no more than a 10-year recurrence interval, and it emphasized the local and largely short-term benefits of LWD addition. House (1996) found similar shortcomings of in-stream structures. No studies have yet evaluated whether wood placed in urban streams can provide the range of functions observed in natural streams, such as increasing organic matter retention and attenuating the geomorphic effects of high flows.

2. Approach and methods

2.1. Study sites

Six in-stream rehabilitation projects were chosen for this study based on their location in watersheds with urban development, their use of in-stream log placement as a primary strategy for achieving local rehabilitation goals, and their inclusion of fish habitat enhancement as an objective (Fig. 1). The effectiveness of LWD in these projects was evaluated according to criteria for physical improvements, for biological response, and for meeting stated design performance standards.

The six evaluated projects lay in physically similar watersheds but with widely different levels of human disturbance (Table 1). But for the use of anchored LWD (i.e. buried or cabled) in the most developed basins, individual project characteristics were otherwise unrelated to watershed or stream characteristics. The streams in this study all had perennial flow and were classified as alluvial plane-bed or pool-riffle channels (Montgomery and Buffington, 1998).

The six rehabilitation projects included examples of both anchored and unanchored LWD, as well as different types of LWD, such as smooth logs, root wads, and tops of trees. Five of the projects had been built within 4 years of this study; the project at Forbes Creek was 10 years old (Table 2). Project lengths ranged from 210 to 430 m, except at Soosette Creek where wood was placed over a 1430 m long reach. Specific project objectives varied. However, all but one project identified 'habitat enhancement' as a primary or secondary goal, and most had some flood and sediment control objective. The degree to which the stream channels were constrained by residences, roads, or bank armor varied greatly between projects.

2.2. Analysis

Development intensity in the watershed area contributing to each project was determined from geographical information system (GIS) land-cover data layers based on 1995 Landsat satellite imagery, classified by King County Land and Water Resources Division (Jeff Burke, personal communication, 1998) at 30 m resolution. For this analysis, land cover was considered developed if classified as 'high-intensity', 'medium-intensity', or 'low-intensity' development; or 'bare rock/concrete', 'bare ground/asphalt', or 'recently cleared' land. The percentage of developed land in each basin upstream of the downstream end of the project was calculated using ArcView GIS.

To determine whether projects were successful in improving physical and biological conditions, monitoring was conducted in reaches at and upstream of where LWD was added. At the three projects where pre-project physical data existed (Laughing Jacobs, Soosette, and Swamp Creeks), pre- and post-project stream conditions were compared. For projects without pre-project data, post-project conditions were compared with data reported in the literature for Puget Sound Lowland streams (Montgomery et al., 1995; May, 1996; Karr and Chu, 2000) and/or to reaches upstream of each project. At most sites, the upstream reaches varied somewhat from pre-project conditions due to differences in valley width, slope, or encroachment, but all were geomorphically similar.

Two sections of stream, at least 20 times the bankfull width, were surveyed in the project and just upstream of the project on each stream. All pieces of wood greater than 10 cm diameter and longer than 1 m in any portion of the bankfull channel were counted, based on criterion for LWD used by Montgomery et al. (1995), Greenberg (1995), May (1996). Root wads greater than 0.02 m^3 in volume were also counted. The diameter and length of every piece was estimated; every five to ten pieces the lengths and widths were

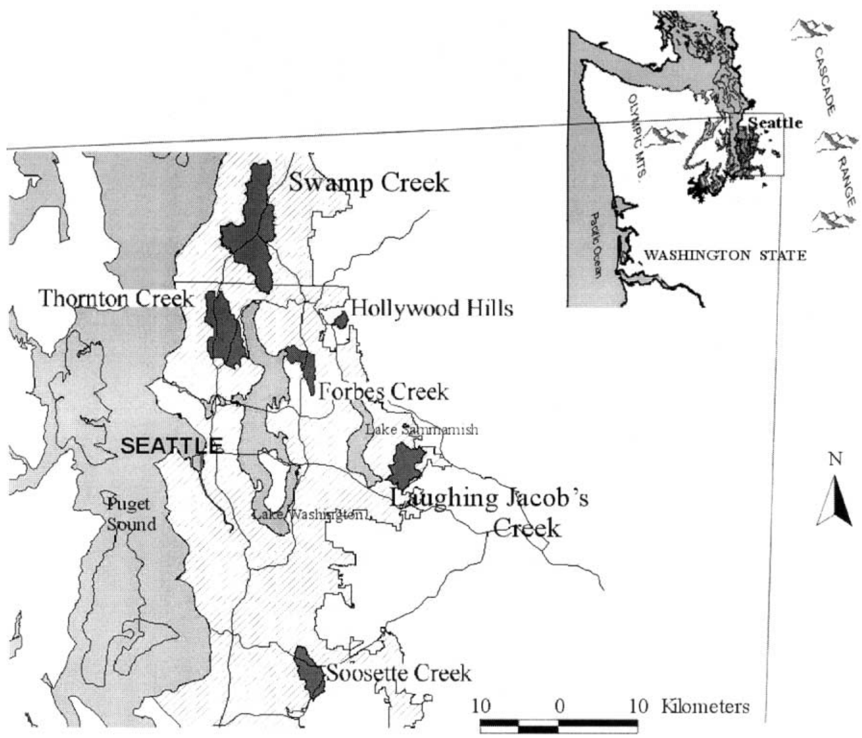

Fig. 1. Study location: western Washington state and the six rehabilitation project watersheds.

Table 1
Watershed and stream characteristics

	Forbes	Thornton	Swamp	Hollywood Hills	Laughing Jacob's	Soosette
Stream characteristics						
Average bankfull width (m)	3.5	5.4	10.4	4.1	6.4	8.7
Bed slope	0.037	0.006	0.005	0.046	0.028	0.019
Median grain size (mm)	14	18	14	11	39	51
Upstream drainage (km^2)	3.5	25.4	53.6	2.2	11.1	13
Percent upstream development						
Watershed (%)	82	93	72	62	52	58
Riparian buffer (100 m) (%)	70	75	47	44	43	34 (45)[a]
Basin relief (m)	45	45	150	50	40	40
Basin gradient (relief/basin length)	0.009	0.005	0.003	0.002	0.008	0.008

[a] Percent development in riparian buffer of the upstream end of the project.

measured with a tape to calibrate the visual estimate. 'Key pieces' were also identified; they are those pieces of LWD defined as being independently stable within the bankfull channel (i.e. not held or trapped by other material) and retaining or having the ability to retain other LWD (WFPB, 1997). The position of LWD in the project reaches with respect to the directions of flow was sketched in the field, as was any obvious association with bank scour.

Where pre-project data were available, the movement of LWD in the project reaches was estimated. Photographic documentation, sketched 'as-built' positions of logs, notes from longitudinal surveys, or notes on aerial photographs, were used to ascertain the mobility of the wood. To evaluate the flow conditions under which any documented LWD movement occurred, the magnitude of the largest flow after the project installation was determined from available gauges.

Residual pool depths (RPDs), the difference between depth of water in the pool and at the top of the downstream riffle (Lisle, 1987), were measured in the field and calculated from longitudinal thalweg surveys. Only depressions with a RPD of at least 25% of the bankfull depth and a minimum pool length at least 10% of the bankfull width were included in the final tally of pools (Montgomery et al., 1995). Pre-project information on pool numbers was taken from the Fish Habitat Relation surveys conducted by the King County Water and Land Resources Division at three of the projects. These counts were converted to an average pool spacing over each measured reach and expressed as the distance between pools in units of bankfull channel widths. This allowed direct comparisons between streams in this study and those in previously published studies.

The influence of LWD on the formation of pools was determined by field observation. Two categories were identified: pools formed by wood and pools formed by some other mechanisms (such as scour around a boulder or lateral scour against an armored bank). The number of pieces of wood associated with a given pool was also counted.

The influence of LWD on in-channel sediment storage was described by characterizing bars as either 'self-formed' if no LWD was present, or 'associated with LWD' if they were covered with or located immediately upstream or downstream of LWD. Where LWD was trapping sediment, the depth of the stored sediment was estimated by measuring the height of the step created by the LWD, and the total volume was estimated assuming the sediment was deposited as a wedge behind the LWD. The overall volume of sediment in the reach was estimated by measuring the total volume of all alluvial bars in the channel.

The influence of LWD in controlling grade in a given reach was estimated using a longitudinal profile of the channel thalweg. Steps in the longitudinal profile occurring at locations of LWD were specified in the survey. The change in the

Table 2
Project characteristics

Project characteristics	Anchored LWD			Unanchored LWD		
	Forbes	Thornton	Swamp	Hollywood Hills	Laughing Jacob's	Soosette
Year constructed	1988	1997	1997	1996	1995	1994
Project length (m)	210	280	370	240	430	1430
LWD placement	Cabled and in weirs	Cabled and in weirs	Anchored as deflectors	Unanchored, by crane	Unanchored, by crane	Unanchored, by helicopter
Number of pieces of LWD added	18	25	48	300	80	280
Approximate cost ($/m)[a]	$350[b]	NA	$160[c]	$580[d]	$120[c]	$280[c]
Project objectives						
Flood control	X	X	X	X	X	
Sediment/erosion control	X	X		X	X	X
Habitat enhancement	X	X	X		X	X

[a] Costs based on preliminary estimates of construction costs divided by project length.
[b] Source: Parametrix (1988).
[c] Source: KCDNR (1995, 1996, 1997).
[d] John Bethe, KCDNRl, personal communmication.

water surface elevation at LWD steps were summed and divided by the total drop in elevation over the reach to yield the percent of the elevation change controlled by LWD.

Biological condition at project sites was assessed with the benthic index of biological integrity (B-IBI) (Karr and Chu, 1999). The B-IBI is composed of ten metrics of taxa richness and evenness, disturbance tolerance, and life history attributes of benthic invertebrates. The B-IBI ranges in value from 10 to 50 and can detect five categories of watershed condition, from undisturbed to highly degraded (Doberstein et al., 2000).

Benthic invertebrates were collected at four of the rehabilitation projects. Monitoring sites were located immediately upstream and downstream of each restoration project. These paired sites were selected to be as similar as possible in all regards except for the presence of added LWD. All but Hollywood Hills were sampled in 1998, and two of the more recently completed projects (Swamp and Laughing Jacob's Creeks) were re-sampled in 1999.

Invertebrates were collected from each site in September when flows are typically stable and taxa richness is high (Fore et al., 1996). At each site, a Surber sampler (500-μm mesh, 0.1 m^2 frame) was used to collect three samples along the mid-line of a riffle (see Morley, 2000). Insect nymphs and larvae were identified to genus where practical; non-insect taxonomic identification varied from family to phylum. Following procedures first for fish (Karr et al., 1986), and then for invertebrates (Kerans and Karr, 1994; Fore et al., 1996), values from each of the ten metrics were summed to calculate a B-IBI score at each site.

3. Results

3.1. Installed LWD frequency, size, and mobility

LWD frequency was used to compare physical conditions in-stream and upstream of the project reach to those of geomorphically similar reference streams (Fig. 2). The forested reference streams allowed comparison with pre-urban conditions; urban reference streams allowed a comparison with a wider range of disturbed conditions than represented by the six study sites.

In the study reaches, LWD loadings were highest — in the range of least degraded urban streams — in unanchored projects (Fig. 3). Only

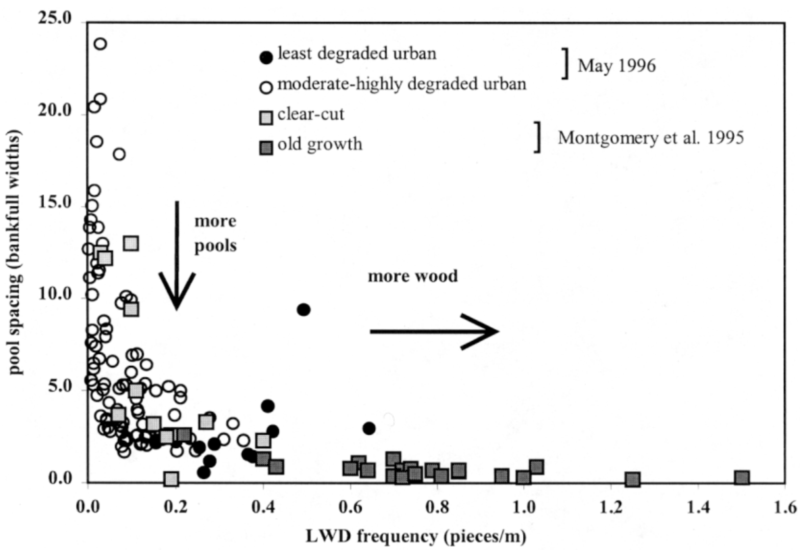

Fig. 2. Pool spacing versus LWD frequency in urban and forested streams in northwest Washington state (data from Montgomery et al. 1995; May 1996).

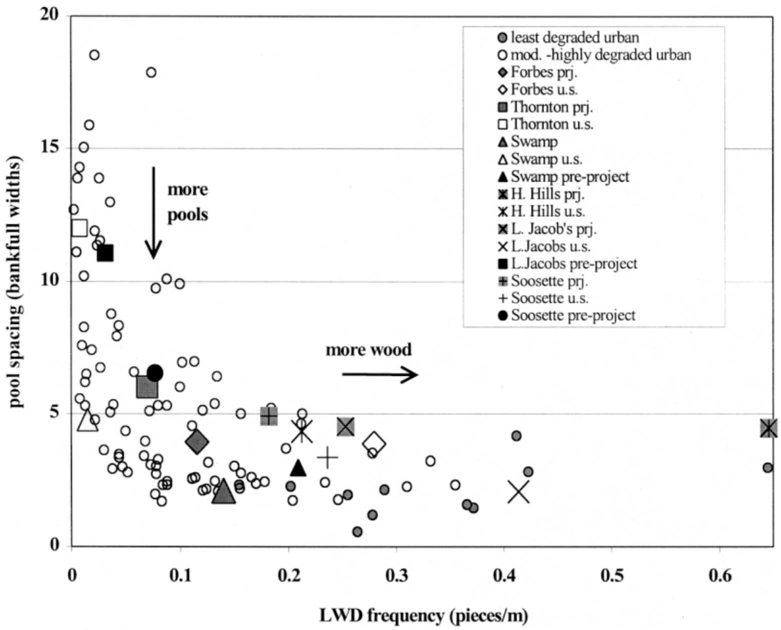

Fig. 3. Pool spacing versus LWD frequency: comparison over space (project and upstream sites) and time (pre- and post-project). Forbes, Thornton, and Swamp Creeks have anchored LWD. At the other streams, LWD is not anchored.

one of the streams (Hollywood Hills), however, had a LWD frequency considered ideal for a natural stream (Bisson et al., 1987; WFPB, 1997). At the projects where the wood was anchored, LWD loadings were lower and typical of moderate to highly degraded urban streams and clear-cuts.

The size of added LWD varied greatly between projects but showed no relationship either to the size of the project stream or to whether the LWD was anchored (Fig. 4). In particular, no logs of sufficient size to be 'key' pieces were added to the widest stream (Soosette) where LWD was not anchored, or to the widest streams (Swamp) where LWD was anchored. However, in the smallest stream, Hollywood Hills, roughly four times the number of 'key' pieces was added than typically found in forested streams (Bisson et al., 1987; WFPB, 1997).

At all projects, typically less than one-third of the added LWD came in contact with the low-flow channel or obstructed at least one-third of the channel width. Where LWD was anchored, as at Swamp Creek, or was large, as at Hollywood Hills, a higher fraction of the LWD was in the low-flow channel and did obstruct flow. Where LWD was the most mobile (at Soosette Creek), less than one-fifth of the pieces obstructed more than 30% of the flow.

Since the projects were installed, all experienced discharges greater than 2-year flows, and three sites experienced approximately 10-year flows. No anchored LWD moved at any of the project reaches and, where over 50% of the unanchored LWD were key pieces (Hollywood Hills), there was also no significant LWD movement. In the projects with unanchored LWD and few or no key pieces, however, LWD movement was documented. At Swamp Creek, two unanchored logs were transported out of the project reach. At Laughing Jacob's Creek, numerous pieces of LWD were transported tens of meters downstream, moved across the channel, or abandoned on adjacent banks. At Soosette Creek, dozens of smooth logs (as well as logs with branches drilled into them, ostensibly to mimic the form of 'real' trees) moved several tens of meters and several debris piles re-mobilized.

3.2. Pool spacing, formation, and depth

Post-project pool spacing was not correlated to LWD loading (Fig. 3). At three sites (Hollywood Hills and Laughing Jacob's and Soosette creeks), pool spacing was wide compared with the least degraded urban streams with the same amount of LWD. Forbes and Swamp creeks, where the LWD was anchored, had pool spacings most similar to those found in forested and least-degraded urban streams despite low LWD frequencies. In the three project reaches where pre-project data existed, pool spacing narrowed after LWD frequency was added.

Where there was no pre-project information on pools, the influence of added LWD on pools was evidenced by the high proportion of pools formed by added LWD. In each of the project reaches, 50–80% of the pools were formed by added LWD, which was comparable with forested streams (Montgomery et al., 1995; Beechie and Sibley, 1997; Nelson, 1998). More of the added LWD was associated with pools where the LWD was anchored (30–70%) than projects where LWD was unanchored (15–18%). In forested streams, 20–40% of LWD was associated with pools, suggesting that unanchored LWD in urban channels is not having an identical geomorphic effect as in undisturbed watersheds. Both types of LWD addition raised pool numbers, at least slightly, towards those of less disturbed streams. There was little difference in pool depth between pools formed by LWD or by other obstructions, between plunge or scour pools, or between pools formed by natural LWD or added LWD.

3.3. Sediment storage and grade control

About one-third of the estimated in-channel sediment storage was associated with LWD at most sites, although LWD generally did not retain sediment in the form of a discrete wedge. In all but one stream, sediment storage associated with LWD increased by 50–100% where LWD frequency increased. Added LWD contributed most to grade control (11–23%) on the highest gradient streams where wood spanned the full width of the channel, but it contributed little to grade control on the low-gradient streams. Although several projects sought to reduce downstream sedimentation by retaining sediment in the reach, only limited success was observed. LWD can retain sediment in some channel positions, but this storage was exceeded by high sediment loads.

3.4. Benthic index of biological integrity

Addition of LWD had little demonstrable effect on biological condition (see Fig. 5). Two projects had been in place only 1 year when this study was

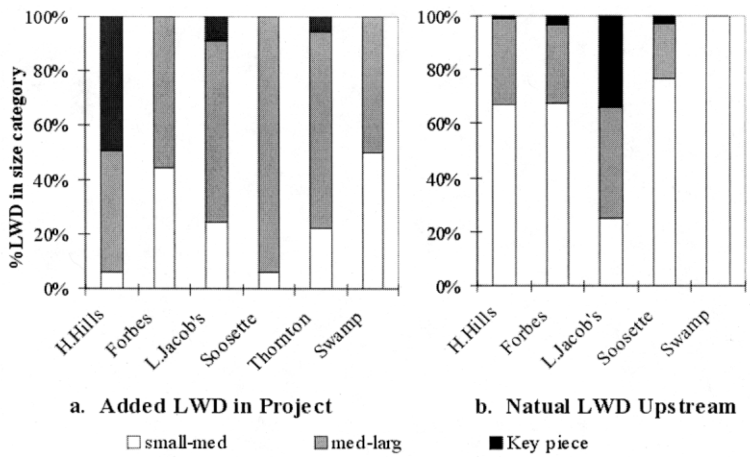

Fig. 4. Size distribution of added LWD and upstream natural LWD, listed from smallest to largest stream (no LWD was found upstream at Thornton Creek).

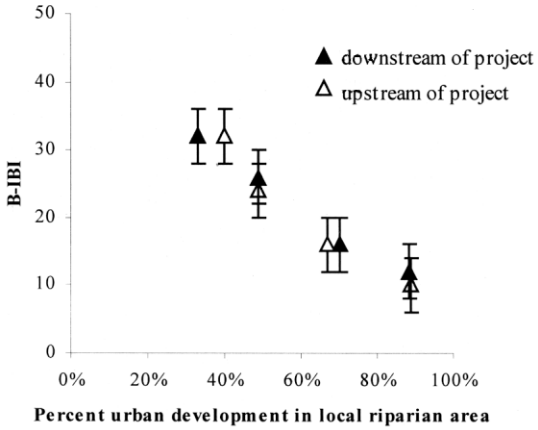

Fig. 5. Paired B-IBI scores at projects. Scores must differ by at least four points to conclude that sites are significantly different (Doberstein et al. 2000).

conducted and, although invertebrates rapidly recolonize the benthos following disturbance, this process may take longer if sources of colonizers are more distant (Gore, 1885) or if the channel is still re-equilibrating (Booth et al., 1997). Additional sampling in 1999, however, still showed no improvement in biological condition. There was also no detectable improvement in B-IBI scores when sampling sites were located within, rather than downstream of, project boundaries.

Local physical channel characteristics, particularly LWD frequency but also pool spacing and stored sediment upstream of the benthic invertebrate sampling sites, generally were not correlated with B-IBI. There was only a very weak positive relationship between B-IBI and extent of bank erosion, median grain size, or bed stability (indicated by a ratio of critical shear stress to boundary shear stress: see Olsen, 1997). In contrast, B-IBI was much better correlated with the level of urban development in the local riparian zone (Fig. 5), and with overall watershed urbanization. In total, these scores indicate that, although projects several hundred of meters long may improve some measures of physical habitat (i.e. pool spacing) in a stream reach over the evaluated time scales of 2–10 years, they have had little influence on the benthic invertebrate community.

3.5. Evaluation of project design

Limited project effectiveness may result when projects are built with an inadequate design, or if appropriate designs yield inadequate results. To weigh these two possibilities, criteria for the design of in-stream structures using LWD were extracted from research on the function of LWD in forested streams (Table 3). For example, studies have investigated the size ranges of stable logs at a given stream width (Bilby, 1984; Bisson et al., 1987; Hilderbrand et al., 1998), the obstruction angle associated with pool formation (Lisle, 1986; Cherry and Bilby, 1989; Gippel et al., 1996), the relationship between LWD frequency and pool spacing (Montgomery et al., 1995; Beechie and Sibley, 1997), the mechanics of log jam stability (Abbe et al., 1997), and the hydraulics of log spacing (Gippel et al., 1996).

These ‘design criteria’, inferred from research on LWD, were compared with conditions at the six rehabilitation projects to evaluate the success of each project in meeting them (Table 4). Meeting design criteria, however, is worthwhile only if those criteria are relevant to attaining actual project objectives. For example, ‘obstruction width’ was an important factor in pool formation at most sites; when that design criterion was met (shaded box in Table 4), this objective was also usually met (+). Conversely, ‘key piece frequency’ was also important; at most sites this criterion was not met (white box, Table 4) and nor were the associated objectives (−).

Yet most criteria are not sufficient to ensure that specific project objectives will be met. For example, the implied criteria for appropriate cross-bed position and burial of LWD were achieved at several projects (shaded box, Table 4) but the project objective of sediment retention was not (−). The same was true of log loading, where even adequate amounts of LWD did not ensure that all project objectives were achieved.

Finally, some criteria were almost universally not achieved at the project sites (blank box, Table 4), and yet the associated objectives were usually still met. This implies that these factors (such as obstruction angle for pool formation) are not as important as other design criteria (such as, in this example, obstruction width).

4. Discussion

The presented results have allowed us to address the original four questions of this study.

Table 3
Design criteria based on data reported for stable LWD in natural channels

Description	Inferred LWD design criteria	
	Value	Reference
Obstruction width		
Obstructing flow or W_{bk}[a]	$>30\%$	Lisle (1986)
Obstructing flow	$>10\%$	Cherry and Bilby (1989)
Log spacing		
Spacing in any direction	>10 log diameter	Gippel et al. (1996)
Downstream distance	$>3W_{bk}$	Lisle (1986)
Key piece sizes and frequency		
$W_{bk}=3$–5 m	0.4 m^3	Bisson et al. (1987)
$W_{bk}=6$–10 m	0.8 m^3	Bisson et al. (1987)
Minimum number of key pieces per meter	0.13 LWD/m	Bisson et al. (1987)
$W_{bk}=0$–5 m	1 m^3	WFPB (1997)
$W_{bk}=6$–10 m	2.4 m^3	WFPB (1997)
Minimum number of key pieces per W_{bk}	0.3 LWD/W_{bk}	WFPB (1997)
Log loading		
Volume per channel area	0.01 m^3/m^2	Lisle (1986)
Pieces per channel area	0.035 number/m^2	Montgomery et al. (1995)
Cross-bed position		
Angled to flow; on bed	90°	Gippel et al. (1996)
Burial and angle		
Angled to flow; mostly buried	$<30°$	Bisson et al. (1987)
Obstruction angle		
Angled to flow; partially elevated	90°	Cherry and Bilby (1989)

[a] W_{bk}, Bankfull width.

4.1. Does in-stream placement of LWD produce physical channel characteristics typical of streams in less disturbed watersheds?

In general, LWD is expected to have the greatest influence and range of functions on moderate-slope (0.01–0.03) alluvial channels classified morphologically as pool-riffle or plane-bed, which includes the streams studied in this study. Particularly in PSL streams, which tend to lack boulder or bedrock obstructions, and in urban streams, lacking deep-rooted woody bank vegetation, LWD is the primary pool-forming mechanism. Indeed, adding LWD to the urban streams in this study produced more physical channel characteristics typical of undisturbed streams, such as pools and sediment storage sites formed by LWD. Pool habitat and channel complexity also increased in most of the project reaches. However, any increase in sediment storage and grade control in these moderate-slope alluvial channels was less assured. The steepest project reaches studied in the present paper did not store more sediment, although LWD did provide more grade control in the steepest reaches. Stabilizing or retaining sediment to reduce downstream sedimentation and associated flooding was not accomplished by adding LWD to the channel.

4.2. Does biological condition improve immediately downstream of LWD addition?

Since fish habitat creation is usually named as the primary or secondary goal of an in-stream project utilizing LWD, project monitoring generally focuses on the physical expressions of this goal. In urban streams, however, structural habitat may be only one of numerous conditions that are lacking for fish survival, as well as survival of other aquatic species (such as benthic invertebrates) that are critical links in the aquatic food web. Since the ultimate goal of habitat restoration is biological recovery, direct measures of the biota are needed to determine whether structural measures alone are likely to be sufficient in the face of watershed-wide disturbances in biogeophysical processes. For the four projects of this study so evaluated, B-IBI analysis detected no positive ef-

Table 4
Objectives and LWD design criteria evaluated at project sites

LWD Design Criteria (and objectives)	Objectives & Criteria Met or Not						Suitability of Design Criteria for Meeting Project Objectives
	F	T	Sw	HH	LJ	So	
Obstruction width (pool formation)	?	?	+	+	+	+	Important for pool formation, whether as a result of size or position.
Log spacing (hydraulically independent effect)	+	+	–	–	–	+	Important in maximizing effect of added LWD.
Key piece frequency (stability, pool scour, LWD trapping, etc.)	–	–	?	+	–	–	Important for stability of unanchored LWD, and for flow influence and debris trapping of anchored LWD.
Log loading (various objectives)	–	–	–	–	–	–	Probably important, but depends on LWD position and size.
Cross-bed position (sediment retention)	–	–	–	–	–	–	Probably important for sediment retention, but not sufficient.
Burial and angle (stability)	NA	NA	+	+	–	–	LWD burial and position important for stabilizing smaller pieces.
Obstruction angle (pool formation)	?	?	+	?	+	+	Irrelevant for pool formation, particularly if LWD is too small.

Key:

+ objective usually met	– objectives usually not met	criteria met	criteria mostly met	Criteria not met	? not determined

* Forbes (F), Thornton (T), Swamp (Sw), Hollywood Hills (HH), Laughing Jacob's (LJ), Soosette (So).

fect on biological condition from the restoration activities at the time scales sampled. The physical characteristics in the reach that did change displayed no clear relationship to biological condition.

4.3. Does watershed disturbance exert greater control over physical and biological recovery of the channel than the local in-channel conditions addressed by added LWD?

The influence of watershed disturbance on physical channel response was evident and, in several instances, overwhelmed any potential benefits of LWD. High sediment loads buried some LWD, and high flows transported seemingly appropriately sized LWD out of the channel or incised underneath LWD formerly within the bankfull channel. Biological integrity was not affected by LWD additions, but it was strongly influenced by overall watershed disturbance. B-IBI here varied inversely with the increase in percent developed land, in full accord with other regional studies (Karr and Chu, 2000; Morley, 2000).

The degree to which watershed conditions influence project effectiveness varies with specific project objectives. Where the long-term goal of these habitat enhancement projects is to promote biological recovery, the extent of overall watershed development strongly limits the success of local LWD placement projects, independent of project design or execution. If the creation of more complex bedforms and stable banks is the main objective, watershed degradation can also limit project success. For example, several LWD structures intended to scour pools in the most urban streams in the study instead were filled with sediment, and severe bank erosion continued even where vegetation was planted for protection. Where project objectives included enhancement of riparian vegetation, however, watershed conditions were less important than local vegetation management.

At the projects in the least degraded watersheds (52–58% development), there was little evidence that the urban-modified flow pattern were undermining in-stream efforts to enhance the channel. The undeveloped riparian corridor in the least developed basins also aided the channel enhancement effort. Trees were naturally recruited to the stream from these buffers (although commonly not meeting minimum size criteria). Buried natural LWD and existing vegetation contributed significantly to pool formation and bank resistance. The deepest pools in several reaches were formed by formerly buried natural LWD, and by trees and remnant stumps on the banks. These features also emphasize the long-lasting influence of LWD in the channel and on the floodplain.

4.4. How can LWD project designs be improved?

In the relatively short time that most of the projects evaluated in this study have been in place, none experienced complete structural failure. Yet no project met all articulated objectives, most importantly because those objectives were too ambitious to be achieve simply by adding LWD. Where design problems hindered even modest improvements, the most common shortcomings were ineffective log spacing, failure of added LWD to remain within the bankfull channel, or placement of LWD too small to affect the flow. Studies documenting the size distribution and frequency of LWD found in natural streams should be used to inform designs in projects where LWD is added. Particularly where sufficiently large LWD is absent or sparse, anchoring should be considered to insure that LWD influences the flow in desired locations. When and where LWD is added should also be guided by an understanding of local sediment supply and transport conditions, tolerance for LWD movement, and articulated priorities for LWD function (e.g. grade control, high flow refuge, direct cover, etc.).

In our experience, pre-existing project monitoring was often inadequate for evaluating success in meeting project objectives, as other researchers have found (for example, Kondolf and Micheli, 1995). Only one of the projects studied here (Swamp Creek) specified any criteria for evaluating project performance (KCDNR, 1997). Furthermore, the project objectives named at most of the sites, particularly those related to habitat quality and complexity or to aquatic species recovery, could not be adequately evaluated using standard monitoring routines. Pool and LWD counts, for example, are not sufficient to evaluate biological or habitat conditions, as we have shown in the present study (see also Poole et al., 1997). Biologically, placing logs devoid of bark, roots, branches, or leaves into urban streams is not equivalent to natural recruitment, where in-stream obstructions and cover are but one benefit of a forested riparian corridor, and the organic input comes in a variety of forms, sizes, and configurations (Bilby and Ward, 1989; Gregory et al., 1991).

4.5. Management implications

Adding LWD to a degraded urban stream will not make it perform the same functions as in an undisturbed stream system. Whereas adding LWD is likely to achieve a number of specific objectives, a proliferation of in-stream LWD projects will not address the multitude of urban stressors nor ensure habitat protection or biological recovery. Therefore, it is critical to identify the primary factors causing degradation in a reach, to evaluate existing channel conditions, and to determine which, if any, objectives could be met with in-stream enhancement projects.

Added LWD can improve physical conditions in a channel, but only if the LWD affects conditions that were significant causes of initial degradation. These might include channel straightening and clearing that resulted in increased flow velocities or simplified habitat, or historic removal of LWD from the channel that resulted in loss of bank stability or cover. When the source of a problem originates from upstream or from watershed-scale disturbances, however, adding LWD does not appear either to solve the problem or to mitigate its consequences.

Not all placement techniques and types of LWD are equally suited to meet specific design objectives. For example, the potentially higher construction costs of anchored LWD may be justified along a constrained channel where bank protection is an objective, whereas larger unanchored LWD might be more desirable where access is limited and channel complexity is desired. The time frame over which improvements are desired must also be determined. Unanchored LWD that ends up in the floodplain might be useful additions to the riparian system in the long-term, but it will not contribute to channel enhancement objectives in the short term.

Although we found no obvious detriments to adding LWD to urban streams, resources should not be allocated to stream projects in the name of physical or biological recovery while overlooking source control of problems in the watershed.

5. Conclusions

This work evaluates the effectiveness of in-stream projects using LWD in urban streams where no systematic effort had been made to reduce degradation at the watershed scale. These types of projects are increasingly popular, particularly in the Pacific Northwest, where LWD is recognized as an important element in physical habitat for salmonids. Yet there is little evidence that these in-stream projects can reverse even the local expressions of watershed degradation in urban channels. Adding LWD to urban streams can be successful in increasing the number of pools in a reach, but it cannot be expected to increase sediment retention or to stabilize in-channel sediment over the time frames observed in this study. Biological conditions, as assessed by benthic macroinvertebrates, did not improve as a result of the in-stream rehabilitation projects; instead, they directly relate to the level of development in the upstream watershed. Although better placement, size and frequency of added LWD can increase the chances of meeting some project objectives, the most important consideration for these projects is the establishment of feasible goals in the context of existing and anticipated watershed disturbance.

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