

BRIDGES

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Challenges and prospects for restoring urban streams: a perspective from the Pacific Northwest of North America

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Abstract. Undoing harm caused by catchment urbanization on stream channels and their resident biota is challenging because of the range of stressors in this environment. One primary way in which urbanization degrades biological conditions is by changing flow patterns; thus, reestablishing natural flow regimes in urban streams demands particular attention if restoration is to have a chance for success. Enhancement efforts in urban streams typically are limited to rehabilitating channel morphology and riparian habitat, but such physical improvements alone do not address all factors affecting biotic health. Some habitat-forming processes such as the delivery of woody debris or sediment may be amenable to partial restoration, even in highly disturbed streams, and they constitute obvious high-priority actions. There is no evidence to suggest, however, that improving nonhydrologic factors can fully mitigate hydrologic consequences of urban development. In the absence of effective hydrologic mitigation, appropriate short-term rehabilitation objectives for urban channels should be to 1) eliminate point sources of pollution, 2) reconstruct physical channel elements to resemble equivalent undisturbed channels, and 3) provide habitat for self-sustaining biotic communities, even if those communities depart significantly from predisturbance conditions. Long-term improvement of stream conditions is not feasible under typical urban constraints, so large sums of money should not be spent on unrealistic or unreachable targets for stream rehabilitation. However, such a strategy should not be an excuse to preclude potential future gains by taking irreversible present-day development or rehabilitative actions.

Key words: stream enhancement, urbanization, rehabilitation, restoration, watershed hydrology, aquatic invertebrates, land cover.

Catchment urbanization has long been known to harm aquatic systems, but reversing the degradation imposed on the physical channel and resident biota remains elusive. Other papers in this series focus on particular aspects of urban stream degradation; my intent is to emphasize what may be needed to reduce such degradation and to acknowledge constraints on successful restoration in urban catchments. Those constraints are not well incorporated into management goals for urban streams; all too commonly, urban systems become orphans of neglect (i.e.,

“nothing can be done”) or, conversely, of unrealistic optimism (e.g., “the salmon will return”). Review of recent studies, however, suggests that other perspectives may be warranted that offer both promising and achievable outcomes.

The context of my discussion is temperate, humid-region lowland streams where urban or suburban development is the primary human disturbance. Most of my examples are taken from the Puget Sound region of western Washington, with the city of Seattle as the geographic and demographic center. The climate is maritime and mild, with 75% of the annual rainfall (~1000 mm) falling in autumn and winter.

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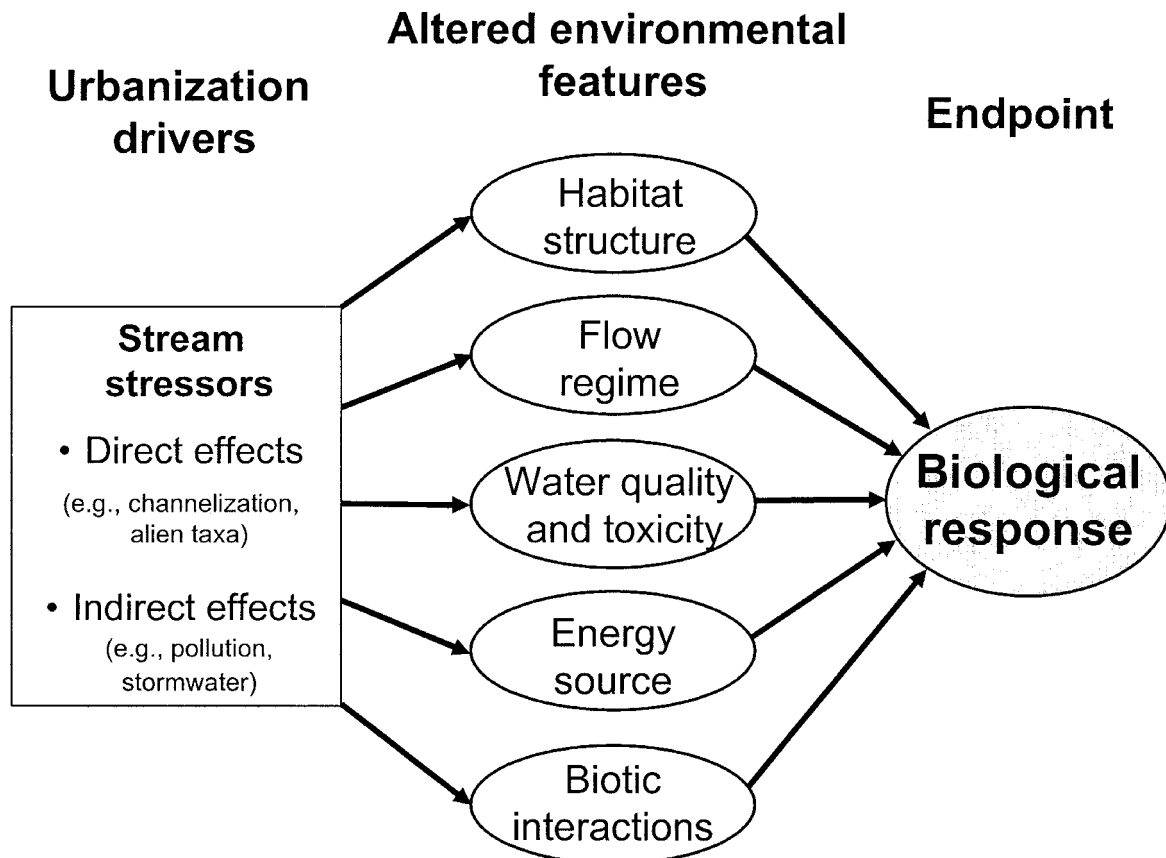


FIG. 1. Five environmental features that are affected by urban development and, in turn, affect biological conditions in urban streams (from Booth et al. 2004, reprinted with permission of the American Water Resources Association; modified from Karr 1991, Karr and Yoder 2004).

Catchments in this region share relatively uniform soil, climate, and topography, allowing direct comparisons among streams. All study streams have, or once had, diverse natural biota, including anadromous salmonids; even streams in moderately developed catchments still support valuable biotic resources that are protected by local, state, and/or federal laws, and are widely appreciated by the public. State and local government expenditures for stream enhancement have expanded dramatically over the past decade because of both legal requirements and public support, reflecting increased social and political interest (National Marine Fisheries Service 2004, WDFW 2004).

Many human actions can disrupt the chemical, physical, and biological processes that influence stream biota. These processes, and their interactions, can be grouped into 5 classes of environmental features (Fig. 1; Karr et al. 1986, Karr 1991, NRC 1992, Yoder and Rankin 1998).

This classification provides a tractable framework for analyzing the condition of water resources such that, when one or more environmental feature is affected by human activities, the result is ecosystem degradation. Following Karr (1999), biological conditions are judged as either healthy or progressively less healthy compared with analogous reference conditions. Using an endpoint of biological integrity acknowledges, but does not concede, the damage already done by human intervention (cf. Rapport et al. 1998, Carpenter et al. 2003). However, no one environmental feature determines biological health a priori (Boulton 1999); conversely, improving any one feature does not guarantee improvement in biotic condition of the catchment as a whole.

Changes in the urban environment can be imposed on any or all of the above features by many human activities, through a number of pathways at multiple spatial scales (Walsh et al.

2005a). For example, changes in land cover integrated over an entire catchment will alter both stormwater inflows to streams and recharge of groundwater (Konrad et al. 2005). Adjacent to stream channels, changes to riparian land cover can affect localized input of energy from organic matter and sunlight; at a single site, the structure of the channel itself can be disrupted by direct modification.

Any of the 5 features shown in Fig. 1 can be responsible for reduced biological health in an urban stream, but changes in flow regimes, in particular, are an important pathway by which urbanization influences biotic conditions. This premise is based on the magnitude of change in hydrology commonly imposed by urbanization (Hollis 1975, Leopold 1968, Booth and Jackson 1997, Konrad and Booth 2002) and the close connection between stream biological health and hydrologic alteration (Power et al. 1988, Poff and Allan 1995, Resh et al. 1988, Poff and Ward 1989, Horner and May 1999, Roy et al. 2005). My focus on the hydrologic regime in this paper should not imply that understanding hydrology allows a complete explanation for urban stream degradation; however, it does provide a useful starting point for evaluating stream-enhancement efforts in the Pacific Northwest and, likely, for other humid-area regions of the world. Flow is a key factor in aquatic systems and one that is almost universally altered by urban development, so it demands particular attention if stream restoration is to have any chance of success.

Chemical water-quality alteration has received considerable attention in urban streams (Paul and Meyer 2001). However, data from all but the most highly urbanized catchments in the Pacific Northwest suggest no clear relationships between a broad suite of conventional water-chemical parameters and biological health (May et al. 1997, Horner and May 1999). Increases in conductivity and nutrients commonly are associated with increases in urbanization (May et al. 1997, Herlihy et al. 1998, Walsh et al. 2005a) but corresponding ecological effects are relatively weak, closely correlated with hydrologic responses, and generally cannot be explained solely in relation to chemical water-quality standards.

The purpose of my paper is to review past and ongoing studies in terms of 1) assessing the prevalence and importance of hydrologic alter-

ation in urban catchments, and 2) evaluating the nature and outcome of common enhancement approaches in urban streams. In combination, these studies suggest a framework for approaching urban stream restoration, in particular one that recognizes not only the importance of the hydrologic regime but also the unique constraints of the urban environment on achievable goals and objectives for restoration.

Sources of Data

Relationships between urban land cover, biological condition, and hydrology are evident in several studies across the Puget Lowland (see Booth et al. 2004), with data collected from 45 sites on 16 second- and third-order streams in King and Snohomish counties. Streams have similar catchment areas (5–69 km²), local channel gradients (0.4–3.2%), soils, elevation, and climate typical of the central Puget Lowland, and urban development as the dominant human activity (American Forests 1998). Total imperviousness (TI, the % of a catchment covered by impervious surfaces) was used to characterize degree of urban development in the catchments draining to each site; TI values were determined from a classified 1998 Landsat image (30-m resolution; Hill et al. 2003). Paved land cover in the contributing catchments ranged from near 0 to almost ¾.

Benthic macroinvertebrate assemblages were sampled at all 45 sites from 1997 to 1999 (Morley and Karr 2002). The biological condition of each site was quantified by the 10-metric benthic index of biotic integrity (B-IBI, Karr 1998), which includes measures of taxon richness, tolerance to disturbance, and selected ecological attributes (e.g., proportion of clingers and predators). Hydrologic analyses were conducted at all of the macroinvertebrate sites that were close to gauging stations and without intervening input of tributaries ($n = 18$ total sites; Konrad 2000). Equivalent hydrologic analyses also were conducted for 10 additional lowland streams with similar gradients and catchment geology, but some with catchment areas up to 171 km², to allow a more thorough assessment of the influence of contrasting catchment urbanization on flow regime.

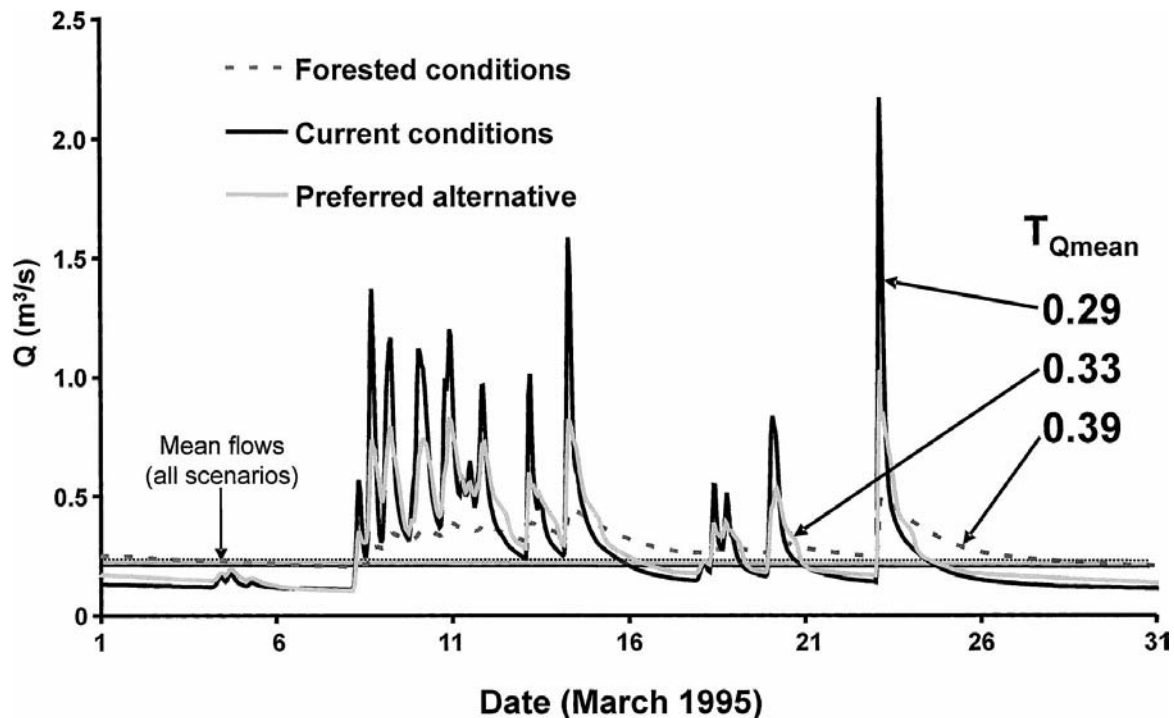


FIG. 2. Example of variation in the fraction of a year daily mean discharge exceeds annual mean discharge (T_{Qmean}) as a result of urban development, displayed with simulated hydrographs for Des Moines Creek in the central Puget Lowland (lat $\sim 47^{\circ}24'N$, long $122^{\circ}20'W$). Hydrographs and corresponding values of T_{Qmean} compare predevelopment (forested) condition for this 14-km² catchment, current (degraded) condition, and full catchment urbanization with a hypothetical detention pond and high-flow bypass pipeline (preferred alternative; estimated cost = \$8 million US). Simulation results courtesy of King County Department of Natural Resources (King County 1997). Note that traditional hydrologic mitigation (i.e., preferred alternative) effectively reduces flood peaks, but its influence on T_{Qmean} values is significantly less pronounced.

Quantifying Hydrologic Alteration

Changing flow patterns over time scales of months to years potentially imposes a long-term regime of frequent disturbances to stream biota (e.g., Pickett and White 1985, Poff et al. 1997). In contrast, the long-term ecological consequences of a single 1- or 2-d flood are likely to be unimportant because episodic high flows are part of most riverine systems, irrespective of human disturbance. Published hydrologic statistics that represent long-term storm and baseflow patterns relevant to stream biota include baseflow stability, daily discharge variability, and spate frequency (Poff and Allan 1995); the ratio of flood-to-baseflow volume, the frequency of high flows, and the product of frequency and duration of high flows (Clausen and Biggs 1997); and the fraction of a year daily mean discharge exceeds annual mean discharge (T_{Qmean}) (Konrad and Booth 2002, Konrad et al. 2005).

T_{Qmean} provides an intuitive index of urban influence on flow regimes because it reflects the annual or decadal distribution of runoff between storm flow and base flow. As such, it reflects the degree of flashiness in a stream hydrograph (Fig. 2). T_{Qmean} is expected to decrease with urban development because annual mean discharge changes little in response to urbanization, whereas duration of individual flood peaks shortens greatly (Konrad and Booth 2005). This metric was used to characterize hydrologic conditions in the study catchments because of its demonstrated responsiveness to urbanization.

The correlation of biological conditions (as B-IBI) with T_{Qmean} in the Puget Lowland study sites was about as good as with TI ($R^2 = 0.67$ for B-IBI vs T_{Qmean} , $R^2 = 0.70$ for B-IBI vs TI, both $p < 0.001$; Booth et al. 2004). However, T_{Qmean} is a more useful parameter than TI for understanding degradation processes because it more

closely represents a likely causal mechanism for stream degradation. T_{Qmean} is not a gross measure of human disturbance, but instead expresses a disturbance signal for a specific environmental feature (e.g., Roy et al. 2003). Urban stream degradation has multiple causes, but the consistency of the $B-IBI-T_{Qmean}$ relationship coupled with the ubiquity of hydrologic alteration in urban and urbanizing catchments (Booth and Jackson 1997) suggest that hydrologic alteration is a fundamental determinant of biotic changes in these systems.

Historical Approaches to Restoring and Rehabilitating Urban Streams

Goals for stream enhancement projects vary both spatially and temporally. They are sometimes articulated in terms of restoration, namely the return to predisturbance conditions (Cairns 1989). More typically, however, such goals offer only the more modest objective of rehabilitation, the measurable improvement of a limited number of elements, with the associated hope of some overall improvement in stream biological health. In either scenario, the focus is typically on the channel's physical condition, with little or no corresponding evaluation of the biological response. Yet, synoptic reviews and specific examples both demonstrate the inadequacy of physical enhancement approaches alone.

Bethel and Neal (2003) noted the following prevailing goals for stream-enhancement projects in the Puget Sound region: "1. to establish the channel morphology appropriate to the topographic, geologic, and hydrologic setting, and 2. to establish the channel and riparian habitat that support a diverse native plant and animal community appropriate to the setting". This perspective was affirmed by most stream-enhancement projects in the Puget Sound region during the 1990s (CUWRM 1998). Of the nearly 400 stream-enhancement projects reviewed in CUWRM (1998), 90% fell into 4 broad categories involving physical rehabilitation: riparian enhancement (planting and fencing; 35% of all projects), instream habitat augmentation (large woody debris [LWD] installation, gravel placement, and large rocks; 22%), bank stabilization and grade control (18%), and fish passage enhancement (15%). Each of these project categories typically affects only a few tens to, at most, hundreds of meters of stream channel. The

CUWRM (1998) study also reported very limited construction of flow-control projects such as regional detention ponds, presumably because of their high financial and environmental cost (e.g., King County 1994) and dubious effectiveness in hydrologic restoration (Booth and Jackson 1997). In this context, Fig. 2 is an example of how very high project cost results in only modest hydrologic improvement. More integrative and potentially more effective flow-control strategies, notably low-impact development (LID; USEPA 2000) or the disconnection of impervious surfaces from the stream network (Walsh 2004, Walsh et al. 2005a), are poorly represented by projects during this period (CUWRM 1998), although implementation is now becoming more widespread (e.g., Puget Sound Action Team 2003).

Despite the high abundance of stream-enhancement projects, reported evaluations are remarkably limited, and available monitoring results are not very encouraging (Beschta et al. 1994, Kondolf and Micheli 1995). For example, Frissell and Nawa (1992) evaluated rates and causes of physical impairment or failure for 161 fish-habitat structures in 15 streams in southwest Oregon and southwest Washington. Their study catchments generally had been affected more by logging rather than by urbanization, yet despite this generally less severe form of catchment disturbance, functional impairment and outright project failure was common (median damage rate = 60% following a single flood, with a 2- to 10-y recurrence interval; Frissell and Nawa 1992). In particular, Frissell and Nawa (1992) found that damage to restoration projects was most widespread in streams with signs of recent catchment disturbance, high sediment loads, and unstable channels. They argued that restoration of alluvial streams with the greatest potential for fish production in the Pacific Northwest requires reestablishment of natural catchment and riparian processes rather than the construction of instream features. Larson et al. (2001) reviewed 6 projects in which LWD was placed into small suburban and urban streams and reported that these projects produced, at best, only modest changes in channel structure but generally no improvement in biological condition. Hession et al. (2003) reported that urban stream reaches with forested riparian corridors in Pennsylvania and Delaware displayed differences in a few benthic

macroinvertebrate metrics compared with non-forested sites, but only at the lowest levels of catchment TI. The common theme of these and other stream-restoration projects is their narrow symptomatic focus (e.g., bank erosion or lack of pools or LWD at a site) in response to an underlying disturbance at a much larger, typically catchment scale (e.g., logging or urbanization).

Anecdotal examples graphically demonstrate the challenges involved in restoring streams using only symptomatic, local-scale approaches. Madsen Creek drains 6 km² of largely urban and suburban upland plateau in the Puget Lowland, ~20 km southeast of Seattle. In 1989, the lowermost kilometer of the channel was relocated as part of a road-widening and fish-enhancement project designed to recreate salmon-spawning habitat. The stated project objective was simply to deploy the specified quantities of logs, stumps, riparian plants, and streambed gravel to the site. Logs and rootwads were placed in the channel, gravel of a size deemed suitable for salmon spawning was spread over the bed, and fast-growing native riparian species were planted along the banks (Fig. 3A). A large rainstorm that winter created significant flooding and erosion in the stream, and erosion of a steep ravine below the upland deposited hundreds of m³ of sand and silt throughout the project reach that destroyed most of the constructed habitat elements (Fig. 3B). Eight years of relatively benign flows later, the channel offers an instructive case both for and against site-scale rehabilitation (Fig. 3C): the riparian corridor is healthy and provides shade, litter, and protection to the stream, but the large manmade structures are either buried or eroded, and the channel bed remains sandy, ill-suited for salmon spawning, and reflects the sediment load of the upper catchment under present flow and erosion conditions. The project achieved only a subset of its goals, but not necessarily those of greatest concern or those that required the most costly actions.

Longfellow Creek, draining a heavily urbanized catchment in Seattle, provides another example of a local-scale action motivated by broad ecological goals but, at best, showing only marginal success. In- and nearstream projects to date on a 2-km reach include removing fish-migration barriers, planting riparian vegetation, reconstructing the channel, addition of spawning gravel, and placement of instream LWD

(Fig. 4), for a cost of \$8 million US. Post-restoration biotic conditions, however, have yielded massive pre-spawning death of returning (or stray) coho salmon (Seattle Post-Intelligencer 2003), with only a small fraction of salmon surviving long enough to spawn, and with virtually no smolt production (Fig. 5).

Consequences for Urban Stream Restoration

Habitat elements and habitat-building processes

The lessons of Madsen and Longfellow creeks and elsewhere are clear and should not be surprising. Certain instream conditions are easier to improve than others, but local actions cannot reverse the consequences of broadly degraded urban catchments. Given the financial and technological obstacles to fixing catchment-scale degradation, particularly hydrologic alteration, urbanization often promotes the inescapable consequence of limiting efficacy of local-scale actions (Barker et al. 1991, Booth and Jackson 1997, Maxted and Shaver 1999, Booth et al. 2002, Morgan and Cushman 2005).

The difficulty in managing multiple scales of degradation has long been explored in forestry-dominated landscapes, where the distinction between aquatic-habitat “elements” and habitat-building “processes” usefully discriminates the construction of channel features from the establishment of self-sustaining improvements (Cederholm et al. 1997, Roni et al. 2002). For example, fish habitat in Pacific Northwest streams includes such elements as LWD, pools, riparian and instream cover, gravel deposits, floodplains, and riparian vegetation. Each of these habitat elements can be built on-site, but neither their longevity (Frissell and Nawa 1992) nor their biological effectiveness (Larson et al. 2001) can be documented. Roni and Quinn (2001) noted that streams subject to outmoded forest practices and with initially low amounts of instream wood generally showed the most dramatic increases in habitat quality and fish abundance following local-scale LWD introductions. This outcome is logical for channels where the absence of LWD occurred primarily by physical removal (e.g., Collins et al. 2003). Yet, catchment processes that create and must permanently support such features (i.e., forest succession, sediment input, flow regime, geomorphic evolution of alluvial channels) operate at such broad

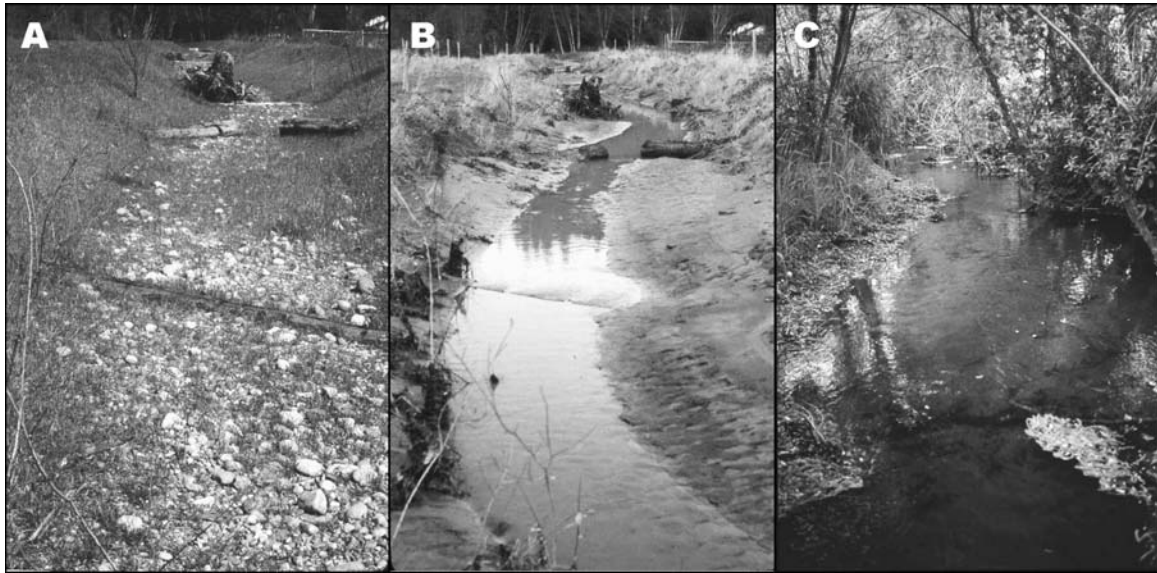


FIG. 3. Reconstruction, disturbance, and partial recovery of lower Madsen Creek, southeast of Seattle, Washington. Photographs taken September 1989 (A), February 1990 (B), and April 1998 (C).



FIG. 4. Longfellow Creek, in the city of Seattle, Washington, shortly after channel reconstruction with log deflectors, imported channel-bed sediment, and riparian plantings.

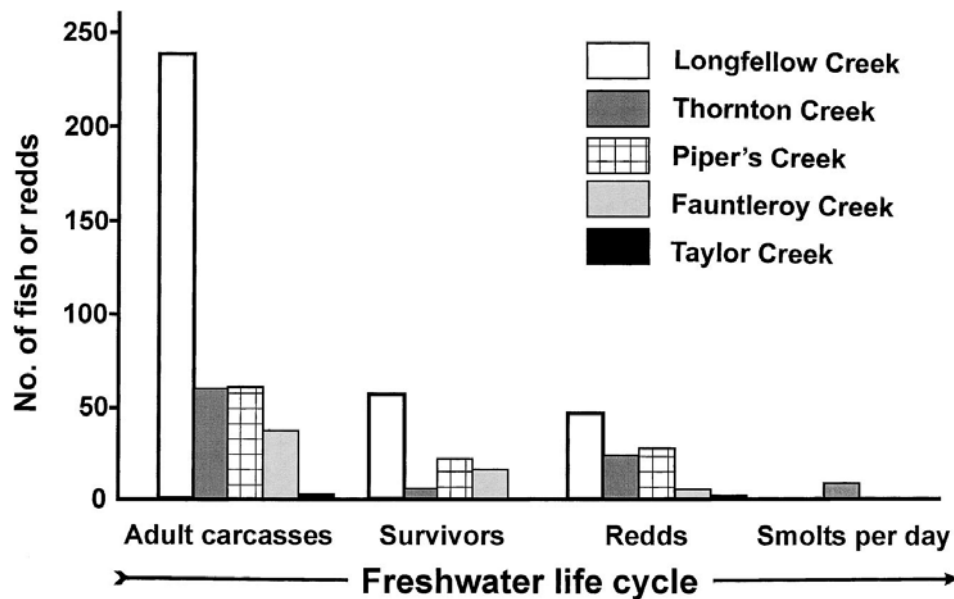


FIG. 5. Decline in survival at successive life stages of coho salmon in the 5 major streams of Seattle, Washington (2003 data from the City of Seattle).

spatial and temporal scales that their products will not persist if simply built or replaced (Kauffman et al. 1997, Roper et al. 1997, Beechie and Bolton 1999, Kondolf et al. 2001), particularly in flashy, unstable urban systems.

Short- and long-term enhancement of urban streams

This distinction between habitat elements and habitat-building processes suggests an alternative perspective to urban stream enhancement: short- vs long-term restoration activities. The former actions are generally feasible under many different management settings but unlikely to produce permanent effects; they include riparian fencing and planting, water-chemistry source control, fish-passage projects, use of instream structures, and construction of social amenities. Short-term actions address acute problems typical to stream channels in urban and urbanizing catchments (Miltner et al. 2004) and so are normally worthwhile, although they only provide immediate solutions that are necessary yet are insufficient to restore biotic integrity.

Short-term actions also must acknowledge the presence of people in urban environments. Actions enhancing the quality of interactions between people and urban streams, particularly those justified in terms of quality of life or by

their value as a public amenity, are likely to be supported and maintained; indeed, such actions commonly result in financial outlays far in excess of likely ecosystem benefits (Middleton 2001). Conversely, actions degrading or limiting interactions between surrounding human communities and streams are more likely to fail. This situation is particularly relevant for short-term actions because they often are unlinked to catchment processes and so typically require continued maintenance to achieve even their transitory objectives. Use of public education to guide community actions in maintaining sustainable and ecologically beneficial streams and stream-enhancement projects is sorely needed (Purcell et al. 2002), which is a particular urgency in the Pacific Northwest because most urban streams flow across private property and thus lie beyond the jurisdiction of public agencies (Schauman 2000).

In contrast, long-term actions are, by definition, self-sustaining, and they address catchment processes at their relevant scales. However, they also must address each potentially degraded environmental feature (Fig. 1) if they are to achieve enhanced biological health. Examples include landuse planning such as preserves or zoning (King County 1994), avoiding road- and utility-stream crossings (Avolio 2003), rehabilitating upland hydrology (e.g., stormwater rein-

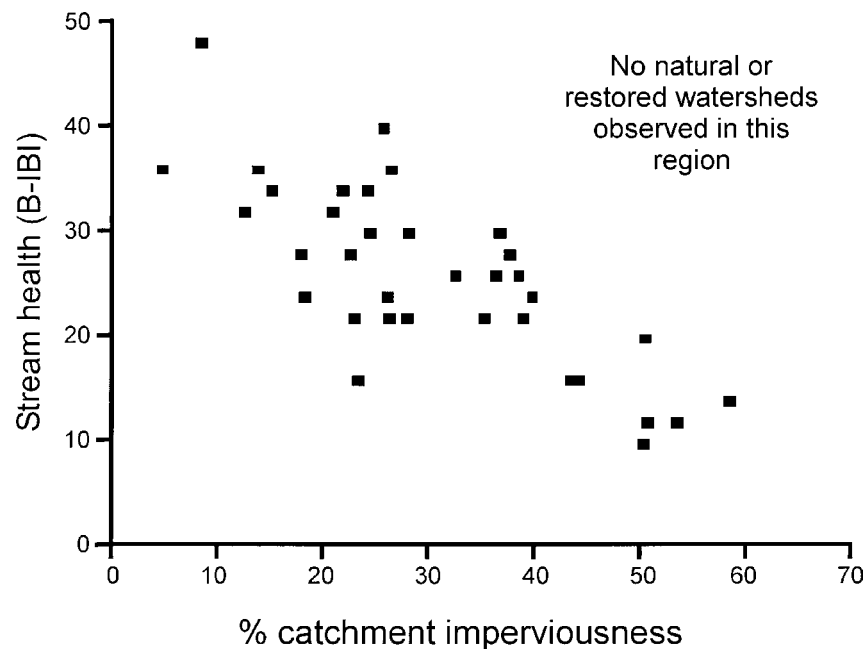


FIG. 6. Percent catchment imperviousness plotted against stream health (as benthic index of biotic integrity [B-IBI]) for Puget Lowland stream data. Management goals are commonly articulated for the upper right-hand corner of this graph (i.e., high-quality streams in highly urbanized watersheds), although no evidence suggests that this condition exists (modified from Booth et al. 2004; B-IBI data from Morley and Karr 2002).

filtration or LID; Walsh et al. 2005a), establishing riparian-zone vegetation communities, and reconnecting floodplains with their channels (Buffington et al. 2003).

Stewardship by the surrounding human community is as important with long-term as with short-term actions; however, it must emphasize instream biotic health over direct human interaction with stream channels (Schauman and Salisbury 1998). A long-term focus on enhancement, therefore, tends to exclude people from stream and riparian environments, even though enhancement requires social support to ensure ecological success. There are few examples or case histories to guide the development of this task.

Despite good intentions, strong public interest, and massive funds, we have virtually no examples of having achieved or retained biotic integrity—i.e., ecological health akin to that in undisturbed streams—in degraded urban channels. An example of this pattern comes from streams in the Puget Lowland (Morley and Karr 2002), where catchment imperviousness plotted against stream health (as B-IBI) showed no high-quality streams in highly urbanized catchments (Fig. 6). Clearly, we have not yet devel-

oped nor implemented a truly effective stream-enhancement strategy, a failure that echoes a long-recognized conclusion in ecological restoration regarding the challenge of achieving pre-disturbance ecosystem conditions in human-modified landscapes (Cairns 1989).

Towards better urban streams

The above perspective raises 2 key management questions for degraded urban catchments. First, can a natural flow regime ever be reestablished in an urban catchment and, if so, how? Second, if such a flow regime *cannot* be reestablished in urban catchments, what outcomes might be expected from other management actions that either construct short-term elements or reestablish some long-term processes (e.g., water-quality treatment, improved instream habitat, replanted riparian zone), but that do not address reestablishment of a natural flow regime?

A retrospective view suggests that the answer to the 1st management question is *no*, but failure of the last century's management of hydrologic alteration should not condemn us to the same future. Instead, it merely emphasizes the need

for new approaches to stormwater management, preferably those integrating multiple scales of catchment planning, site layout, and infrastructure design. Such efforts are now beginning throughout the world (e.g., Puget Sound Action Team 2003, Walsh et al. 2005a), although their effectiveness is yet to be demonstrated. Determining the optimal combination and resulting effectiveness of such stormwater-management strategies should be a priority because their promise is great, alternatives are lacking, and confirmatory data for design guidance are presently sparse.

Yet full, or at least partial, long-term restoration of some habitat-forming processes, with subsequent biological recovery, may be possible even in highly disturbed urban environments. Such restorative actions include controlling of landslides and surface erosion to minimize changes to sediment-delivery processes, protecting mature riparian buffers to maintain delivery of coarse and fine organic debris and to moderate solar input (Jones et al. 1999, Parkyn et al. 2003), and disconnecting the pipes linking impervious areas to natural channels (Walsh et al. 2004, 2005a, b). For example, a B-IBI increase from "very poor" to "fair" over <2 km along a single suburban Puget Lowland stream channel was strongly explained by riparian land cover but not by overall catchment land cover (Morley and Karr 2002). Avolio (2003) and McBride and Booth (2005) have documented good correlations between physical condition of channels and frequency of stream-road crossings. Such results point to actions that are generally sensible to implement, even under existing management constraints, because they are often economically feasible and may provide long-term benefits. Furthermore, the absence of abrupt thresholds in biological responses to urbanization (e.g., Booth et al. 2002, Morley and Karr 2002) suggests that even incremental improvements can have direct, albeit commensurately modest, ecological benefits.

In the absence of effective hydrologic mitigation, however, what are appropriate objectives for urban streams (e.g., see also Osborne et al. 1993)? Point sources of pollution should be eliminated. In addition, channels should have the same physical elements (e.g., pools, substrate, logs, accessible floodplains) as their equivalent undisturbed counterparts, with the recognition that these elements are necessary

but not sufficient to support future biotic improvements. Urban streams also should be considered neighborhood amenities that inspire passion and ownership from their nearby residents, and they can be self-sustaining to biotic communities, even though those communities depart significantly from predisturbance conditions.

Last, urban streams should also retain the possibility, however remote, of one day benefiting from the long-term actions that can produce greater, sustainable improvements. This final goal cannot be achieved for most urbanized catchments under present socioeconomic constructs, at least not in the Pacific Northwest. This constraint should be a reminder not to spend large sums of money on targets that can never be reached by paths that are all-too-commonly followed. This excuse is not sufficient, however, to continue building the kinds of urban developments or traditional rehabilitation projects that permanently preclude future long-term stream improvements.

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