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Effects Of Urbanization On Small Streams in the Puget Sound Ecoregion

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The Pacific Northwest, like many areas of North America, is experiencing an increase in urban development that is rapidly expanding into remaining natural aquatic ecosystems. In the Puget Sound lowland (PSL) ecoregion, the natural resources most directly affected by watershed development are small streams and associated wetlands. Stream ecosystems are critical spawning and rearing habitat for several species of native salmonids including coho and cutthroat trout and many salmon species. These fish, especially the salmon, hold great ecological, cultural, and socioeconomic value to the peoples of the region. Despite this value, the wild salmonid resource is in considerable jeopardy of being lost to future generations. Over the past century, salmon have disappeared from about 40% of their historical range and many of the remaining populations (especially in urbanizing areas) are severely depressed (Nehlsen, *et al.* 1991). There is no one reason for this decline. The cumulative effects of land-use practices including timber-harvest, agriculture, and urbanization have all contributed significantly to this widely publicized "salmon crisis."

The effects of watershed urbanization on streams are well-documented (Leopold, 1968; Hammer, 1972; Hollis, 1975; Klein, 1979; Arnold, *et al*. 1982; Booth, 1991) and include extensive changes in basin hydrologic regime, channel morphology, and water quality. The cumulative effect of these alterations have produced an instream habitat structure that is significantly different from that in which salmonids and associated fauna have evolved. In addition, development pressure has a negative impact on riparian forests and wetlands that are essential to natural stream function. Considerable evidence about these impacts exists from studies of urban streams in the Pacific Northwest, although most previous work has fallen short of establishing cause-effect relationships among physical and chemical impacts of urbanization and the response of aquatic biota.

The most obvious manifestation of urban development is an increase in impervious cover and the corresponding loss of natural vegetation. Land clearing, soil compaction, riparian corridor encroachment, and modifications to the surface water drainage network all typically accompany urbanization. Watershed urbanization is most often quantified in terms of the proportion of basin area covered by impervious surfaces (Schueler, 1994; Arnold and Gibbons, 1996). Although impervious surfaces themselves do not generate pollution, they are the major contributor to changes in watershed hydrology that drive many of the physical changes affecting urban streams. Basin imperviousness and runoff are directly related (Schueler, 1994). In previous studies, measures of total impervious area (%TIA) of about 10% have been identified as the level at which stream ecosystem impairment begins (Klein, 1979; Steedman, 1988; Schueler, 1994; Booth and Reinelt, 1993). Recent studies suggest that this potential threshold may apply to wetlands as well.

Stream Study Design

A key objective of the Puget Sound lowland stream study conducted between 1994 and 1996 was to identify the linkages between watershed conditions and instream environmental factors, including defining the functional relationships between watershed modifications and aquatic biota. The goal was to provide a set of stream quality indices for local resource managers to use in managing urban streams and to minimize resource degradation resulting from development pressure. For example, one study objective was to determine the conditions for maintaining a given population or community of organisms (such as native salmonids) at a specified level. This requires sustaining a certain set of habitat characteristics, which in turn depend on an established group of watershed conditions. A part of this overall objective was to identify any thresholds of watershed urbanization as related to instream salmonid habitat and aquatic biota. The study was designed to establish the linkages between landscape-level conditions, instream habitat characteristics, and biotic integrity. A conceptual model of this design is illustrated below:

Watershed and Riparian Characteristics => Instream Habitat Conditions => Aquatic Biota

A subset of 22 small-stream watersheds was chosen to represent a range of development levels from relatively undeveloped (reference) to highly urbanized. Researchers controlled for physiographic variability by

studying only streams in the Puget Sound lowland ecoregion (see Figure 1 for stream locations). Total impervious surface area (%TIA), because of its integrative nature, was used as the primary measure of watershed urbanization. The attributes of the stream catchments were established using standard watershed analysis methods including geographic information system (GIS) data, aerial photographs, basin plans, and field surveys. Impervious surface coverage, riparian integrity, instream physical habitat characteristics, chemical water quality constituents, and aquatic biota were analyzed on both watershed and stream segment scales. Discharge was continuously monitored by local agencies on 10 of the study streams. Chemical water-quality monitoring (baseflow and storm events) was conducted at 23 sites on 19 of the study streams. Biological sampling (macroinvertebrates) was performed in 31 reaches on 21 of the study streams. Extensive surveys of instream physical habitat and riparian zone characteristics were made on 120 stream-segments on all 22 PSL streams, each representing local physiographic, morphologic, and sub-basin land use conditions from the headwaters to the mouth of each stream. Salmonid abundance data were obtained from public, private, and tribal sources.

All streams were third-order or smaller, ranging in basin area from 3 to 90 km^{2}, with headwater elevations less than 150 meters. Stream gradients were less than 3.5% (most were < 2%). The study watersheds represented the two general types of geologic and soil conditions found in the Puget Sound region. The underlying geology and soil types are mainly a result of the last glacial period (15,000 years ago). All but three of the watersheds were dominated by poorly drained glacial till soils, with the remaining basins dominated by glacial outwash soil types (moderately well drained).

In the undisturbed, natural forested condition, PSL catchments are capable of providing adequate natural precipitation storage in the surficial "forest-duff" layer with little runoff resulting. Development typically strips away this absorbent forest soil layer and compacts the underlying soil and exposes the underlying till layer. The typical suburban development in the Pacific Northwest has been estimated to have roughly 90% less storage capacity than under naturally forested conditions (Wigmosta *et al.*, 1994). The latest (1990) stormwater mitigation and best management practices have the potential to recover only about 25% of the original storage capacity (Barker *et al.*, 1991). Because these standards affected very little new development that occurred between 1990 and the start of this study in 1994, the basin conditions observed largely reflected the pre-1990 situation with little effective stormwater control present. Therefore, no significant conclusions could be drawn about the effectiveness of current stormwater controls and regulations during this research.

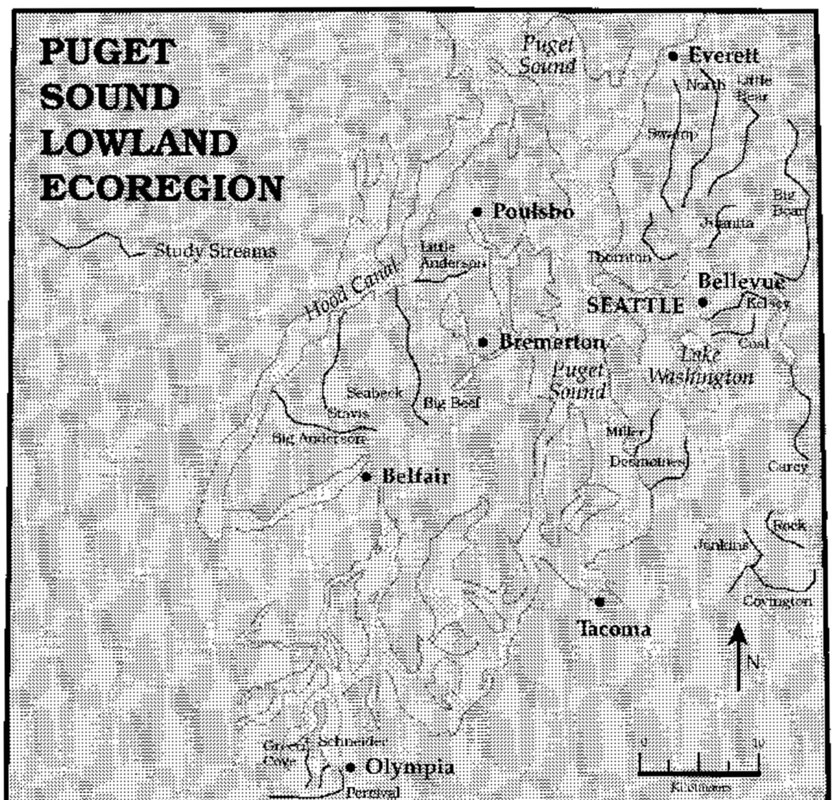


Figure 1: Puget Sound Lowland (PSL) Ecoregion

Results and Discussion

Watershed Conditions

Watershed imperviousness ranged from undeveloped (%TIA < 5%) to highly urbanized (%TIA > 45%). Imperviousness (%TIA) was the primary measure of watershed development; however, other measures of urbanization were investigated. Calculating impervious surface area can be costly, especially if computerized methods like GIS are utilized. In addition, the land use data required for calculation of %TIA may be unavailable or inaccurate. As part of this study, a low-cost alternative to imperviousness was also investigated. Analysis demonstrated that the relationships to be discussed were very similar if development is alternatively expressed as road-density (Figure 2). This is especially relevant in that the transportation component of imperviousness often exceeds the "rooftop" component in many land-use categories (Schueler, 1994). A recent study in the Puget Sound region has shown that the transportation component typically accounts for over 60% of basin imperviousness in suburban areas (City of Olympia, 1994).

Watershed urbanization results in significant changes in basin hydrologic regime (Leopold, 1968; Hollis, 1975; Booth, 1991). This was confirmed for streams in the PSL study. The ratio of modeled two-year

stormflow to mean winter baseflow (Cooper, 1996), was used as an indicator of development-induced hydrologic fluctuation (Figure 3). This discharge ratio is proportional to the relative stream power, and thus is representative of the hydrologic stress on instream habitats and biota exerted by stormflow relative to baseflow conditions. The modified basin hydrologic regime was found to be one of the most influential changes resulting from watershed urbanization in the PSL region.

In addition to an increase in basin imperviousness and the resulting stormwater runoff, urbanization also affects watershed drainage-density (km of stream per km^2 of basin area). This was first investigated by Graf (1977). Natural, pre-development drainage-density (DD) was calculated using historic topographic maps. This was compared to the current, urbanized DD which included both the loss of natural stream channels (mostly first-order and ephemeral channels lost to grading or construction) and the increase in artificial "channels" due to road-crossings and stormwater outfalls. Not surprisingly as imperviousness increases above the eight to 10% level in study watersheds so does the number of road crossings and stormwater outfalls per kilometer at a steady rate. The ratio of urban to natural drainage density was used as an indicator of urban impact.

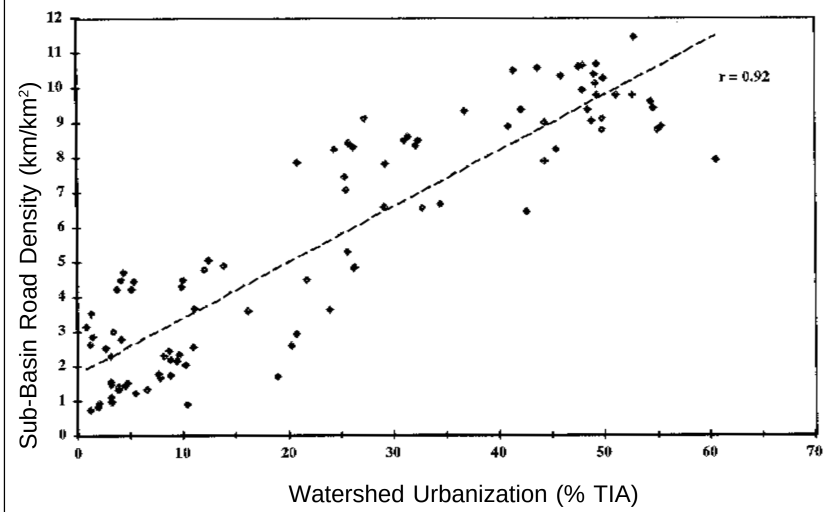


Figure 2: Relationship Between Urbanization (%TIA) and Sub-Basin Road-Density in PSL Streams

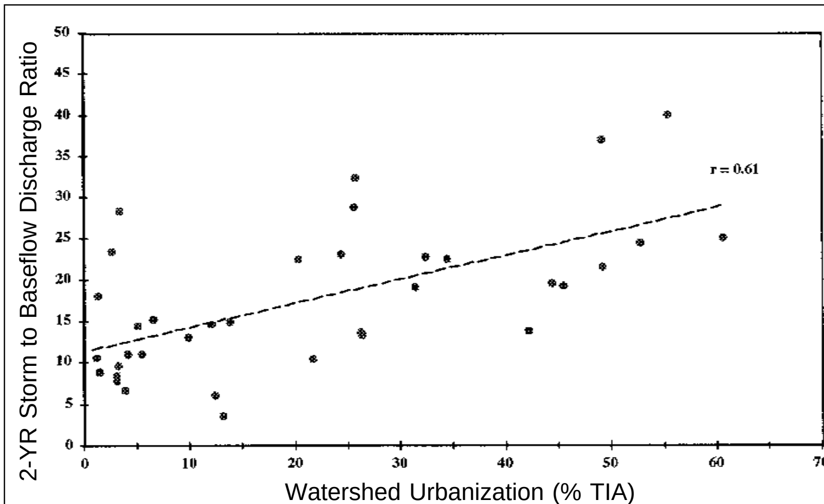


Figure 3: Change in Basin Hydrologic Regime with Urbanization in PSL Streams

Riparian Conditions

The natural riparian corridors along Pacific Northwest streams are among the most diverse, dynamic, and complex ecosystems in the region. Natural riparian integrity is characterized by wide buffers, a near-continuous corridor, and mature, coniferous forest as the dominant vegetation. The riparian corridor is frequently disturbed by flooding events, creating a naturally complex landscape.

Not surprisingly, riparian conditions were also strongly influenced by the level of development in the surrounding landscape. The impact of development activities on riparian corridors can vary widely. Very recently, regional development regulations did not specifically address riparian buffer requirements. Sensitive area ordinances, now in effect in most local municipalities, typically require riparian buffers of 30 to 50 meters (100 to 150 feet) in width. These recently adopted regulations had little influence on the urbanized streams in the PSL study. In general, wide riparian buffers were found only in undeveloped or rural stream watersheds (Figure 4). The actual size of riparian buffer needed to protect the ecological integrity of the stream system is difficult to establish (Schueler, 1995). In most cases, minimum buffer width "required" depends on the resource or beneficial use of interest and the quality of the existing riparian vegetation (Castelle *et al.*, 1994).

Encroachment into the riparian buffer zone is pervasive, continuous, and extremely difficult to control. At the same time, riparian forests and wetlands, if maintained, appear to have a significant capacity to mitigate some of the adverse effects of development. A buffer width of less than 10 meters is generally considered functionally ineffective (Castelle *et al.*, 1994). The fraction of riparian buffer less than 10 meters wide was used as a measure of riparian zone encroachment. In general, only streams in natural, undeveloped basins (%TIA < 10%) had less than 10% of their buffer in a nonfunctional condition. As watershed urbanization (%TIA) increased, riparian buffer encroachment also increased proportionally. The most highly urbanized streams (%TIA > 40%) in this study, generally had a large

portion (upwards of 40%) of their buffers in a nonfunctional condition.

The longitudinal continuity or connectivity of the riparian corridor is at least as important as the lateral riparian buffer width. A near-continuous riparian zone is the typical natural condition in the Pacific Northwest (Naiman, 1992). Fragmentation of the riparian corridor in urban watersheds can come from a variety of human impacts; the most common and potentially damaging being road crossings. In the PSL stream study, the number of stream crossings (roads, trails, and utilities) increased in proportion to basin development intensity. All but one undeveloped stream (%TIA < 10%) had, on average, less than one riparian break per km of stream. Of the highly urbanized streams (%TIA > 40%), all but one had greater than two breaks per kilometer. Based on current development patterns in the PSL, only rural land use consistently maintained breaks in the riparian corridor to < 2 per kilometer of stream length. In general, the more fragmented and asymmetrical the buffer, the wider it needs to be to perform the desired functions (Barton *et al.*, 1985).

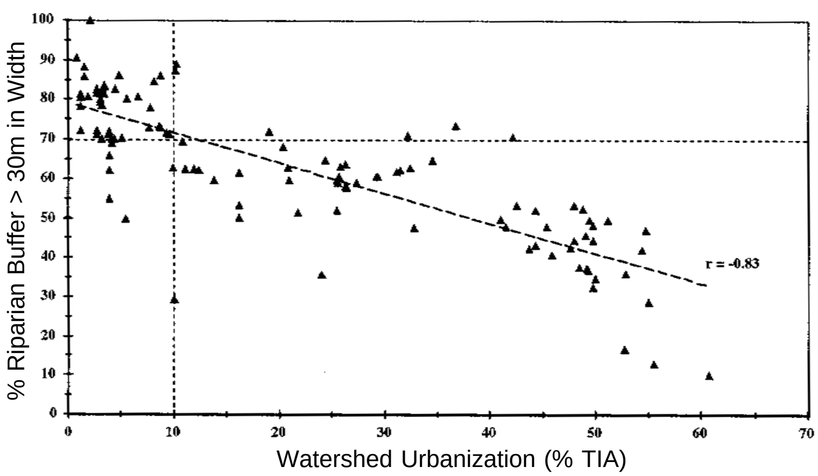


Figure 4: Relationship Between Riparian Buffer Width and Basin Urbanization (%TIA) in PSL Streams

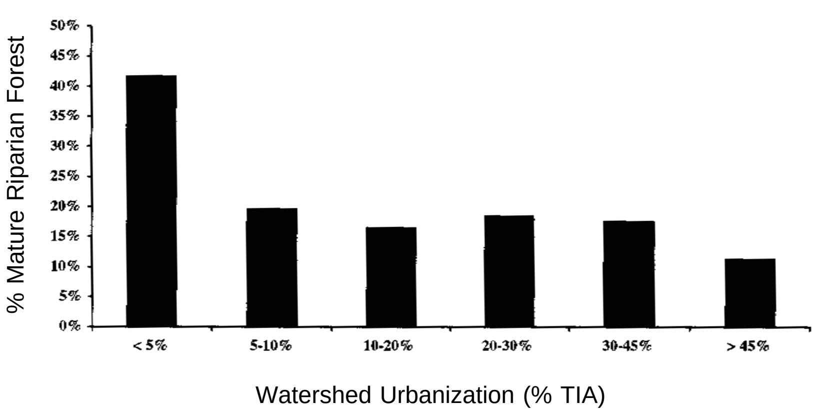


Figure 5: Relationship Between Watershed Urbanization (%TIA) and Riparian Quality (Maturity) in PSL Streams

The riparian zone was also examined on a qualitative basis. Mature forest, young forest, and riparian wetlands were considered "natural" as opposed to residential or commercial development. From an ecological perspective, mature forest or riparian wetlands are the two most ecologically functional riparian conditions in the Pacific Northwest (Gregory *et al.*, 1991). In the 22 PSL streams, riparian maturity was also found to be strongly influenced by watershed development. Only the natural streams (%TIA < 5%) had a substantial portion of their riparian corridor as mature forest (40% or greater), while urban streams consistently had little mature riparian area (Figure 5). In addition, none of the urbanized PSL streams retained more than 25% of their natural floodplain area.

Chemical Water Quality

Chemical water quality constituents were monitored under baseflow and stormflow conditions. Storm event mean concentrations of several chemical constituents were found to be related to both storm size (magnitude and intensity) and basin imperviousness (Bryant, 1995; Horner *et al.*, 1996). However, water quality criteria were rarely violated except in the most highly urbanized watersheds (%TIA > 45%). Total phosphorus (TP) and total suspended solids (TSS) also showed similar relationships. Sediment, zinc and lead also indicated a relationship with urbanization, again showing the highest concentrations in the most developed basins, although all were still below sediment quality guidelines. As with other recent studies (Bannerman *et al.*, 1993; Pitt *et al.*, 1995), these findings indicate that chemical water quality of urban streams is generally not significantly degraded at the low impervious levels, but may be a more important factor in streams draining highly urbanized watersheds.

Instream Salmonid Habitat Characteristics

Large woody debris (LWD) is a ubiquitous component in streams of the Pacific Northwest. There is no other structural component as important to salmonid habitat, especially in the case of juvenile coho (Bisson *et al.*, 1988). LWD performs critical functions in forested lowland streams, including dissipation of flow energy, streambank protection, streambed stabilization, sediment storage, and providing instream cover and habitat diversity (Bisson *et al.*, 1987; Masser *et al.*, 1988; Gregory *et al.*, 1991). Although the influence of LWD may change over time, both functionally and spatially, its overall importance to salmonid habitat is significant and persistent.

Both the prevalence and quantity of LWD declined with increasing basin urbanization (Figure 6a). At the

same time, measures of salmonid rearing habitat, including percent of pool area, pool size, and pool frequency, were strongly linked to the quantity and quality of LWD in PSL streams. While LWD quantity and quality were negatively affected by urbanization, even many of the natural, undeveloped streams also had a lack of LWD (especially very large LWD). This deficit appears to be a residual effect of historic timber-harvest and "stream-cleaning" activities. Nevertheless, with few exceptions (habitat restoration sites), high quantities of LWD occurred only in streams draining undeveloped basins (%TIA < 5%). It appears that stream restoration in the PSL should include enhancement of instream LWD, including addressing the long-term LWD recruitment requirements of the stream ecosystem.

An intact and mature riparian zone is the key to maintenance of instream LWD (Masser *et al.*, 1988; Gregory *et al.*, 1991). The lack of functional quantities of LWD in PSL streams was significantly influenced by the loss of riparian integrity (Figure 6b). In general, except for restoration sites, higher quantities of LWD were found only in stream-segments with intact up-stream riparian corridors. In addition, LWD quality was strongly influenced by riparian integrity. Very large, stable pieces of LWD (greater than 0.5 meter in diameter) were found only in stream segments surrounded by mature, coniferous riparian forests (Figure 7). This natural LWD historically provided stable, long-lasting instream structure for salmonid habitat and flow mitigation (Masser *et al.*, 1988).

The stream bottom substratum is critical habitat for salmonid egg incubation and embryo development, as well as being habitat for benthic macroinvertebrates. Streambed quality can be degraded by deposition of fine sediment, streambed instability due to high flows, or both. Although, the redistribution of streambed particles is a natural process in gravel-bed streams, excessive scour and aggradation often result from excessive flows. Streambed stability was monitored using bead-type scour monitors installed in salmonid spawning riffles in selected reaches (Nawa and Frissell, 1993). Basin urbanization in PSL streams was found to have the potential to cause locally excessive scour and fill. Urban streams in the PSL with gradients greater than 2% and lacking in LWD, were found to be more susceptible to scour than their undeveloped counterparts.

Streambank erosion was also far more common in urbanized PSL streams than in streams draining undeveloped watersheds. Using a survey protocol similar to Booth (1996), all stream segments were evaluated for streambank stability. Stream segments with >75% of the reach classified as stable were given a score of four. Between 50% and 75% stable banks were scored as a 3, 25-50% as a 2, and <25% as a 1. Artificial streambank protection (riprap), shown in the photo in the right panel below, was considered a sign of bank instability and graded accordingly. Only two undeveloped, reference

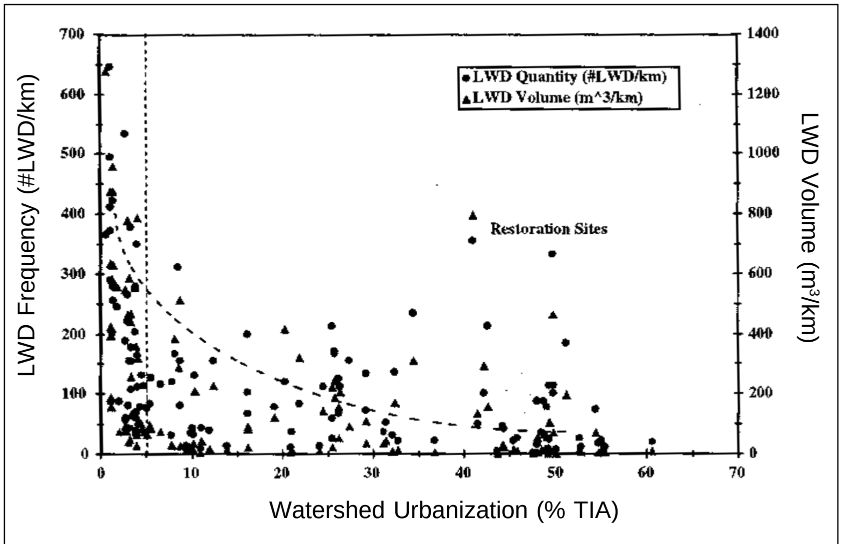


Figure 6a: LWD Quantity and Watershed Urbanization (%TIA) in PSL Streams

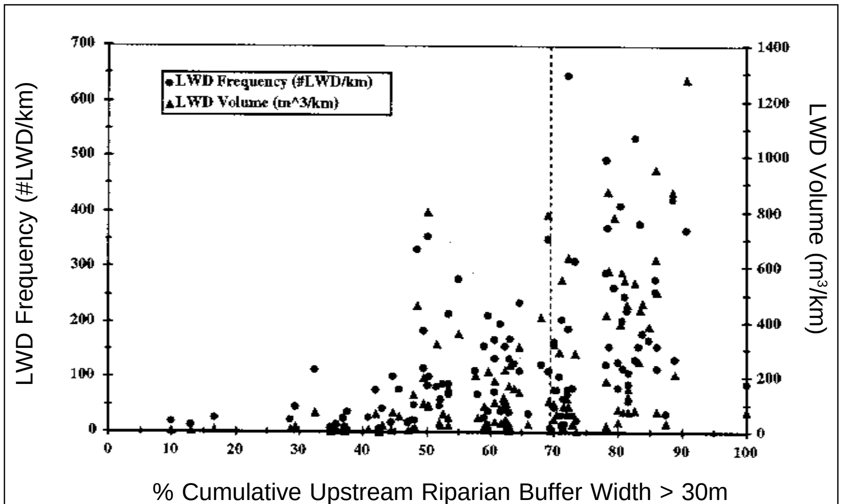


Figure 6b: LWD Quantity and Riparian Integrity In PSL Streams

(%TIA < 5%) stream segments had a stability rating less than three. In the five to 10% basin imperviousness range, streambank ratings were generally ranked three or four. When the sub-basin impervious area was between 10 and 30% there was a fairly even mixture of streambank conditions from stable and natural to highly eroded or artificially "protected." Above 30% TIA, there were no segments with a streambank stability rating of four and very few with a rating of three. These outliers were found only in segments with intact and wide riparian corridors. Artificial streambank protection (riprap) was a common feature of all highly-urbanized streams. Overall, the streambank stability rating was inversely correlated with cumulative upstream basin %TIA and even more closely correlated with development within the segment itself, perhaps reflecting the

local effects of construction and other human activities. Streambank stability is also influenced by the condition of the riparian vegetation surrounding the stream. In this study, the streambank stability was related to the width of the riparian buffer and inversely related to the number of breaks in the riparian corridor. While not completely responsible for the level of streambank erosion, basin urbanization and loss of riparian vegetation, contribute to the instability of streambanks.

Results of fine sediment sampling (McNeil method) indicated that urbanization can result in degradation of streambed habitat. Fine sediment levels (% fines) were related to upstream basin urban development, but the variability, even in undeveloped reaches, was quite high (Wydzga, 1997). Nevertheless, percent fines did not exceed 15% until %TIA exceeded 20%. In the highly urbanized basins, the percent fines were consistently > 20% except in higher gradient reaches where sediment was presumably flushed by high stormflows.

The intragravel dissolved oxygen (IGDO) was also monitored as an integrative measure of the deleterious effect of fine sediment on salmonid incubating habitat. A significant impact of fine sediment on salmonids is the degradation of spawning and incubating habitat (Chapman, 1988). The incubation period represents a critical and sensitive phase of the salmonid life cycle. A high percentage of fine sediment can effectively clog the interstitial spaces of the substrata and reduce water flow to the intragravel region. This can result in reduced levels of IGDO and a buildup of metabolic wastes, leading to even higher mortality. Elevated fine sediment levels can also have various sub-lethal effects on developing salmonids which may reduce the odds of survival in later life stages (Steward, 1983).

While low IGDO levels are typically associated with fine sediment intrusion into the salmonid redd, local conditions can have a strong influence on intragravel conditions as well as the distribution of fine sediment

Figure 7: Large Woody Debris in Undisturbed and Urbanizing Streams
Large woody debris (LWD) is an important structural element of undisturbed Puget Sound lowland streams (top panel). Urbanizing watersheds have much lower levels of LWD within the stream (bottom panel). ***Photographs by Chris May***

(Chapman, 1988). Spawning salmonids themselves can also reduce the fine sediment content of the substrata, at least temporarily. Measurement of instream dissolved oxygen (DO) coincident with IGDO allowed for the calculation of a IGDO/DO interchange ratio (Figure 10). In all but one case, the mean interchange ratio was > 80% in the undeveloped streams. Once TIA increased above 10%, a great majority of the reaches had a mean interchange ratio well below 80% (as low as 30%). While these DO levels are not lethal, low IGDO levels during embryo development can reduce survival to emergence (Chapman, 1988). Several urbanized stream-segments had unexpectedly high (>80%) IGDO concentrations (Figure 8). All of these segments were associated with intact riparian corridors and upstream riparian wetlands. Generally, these reaches also had stable streambanks and adequate levels of instream LWD.

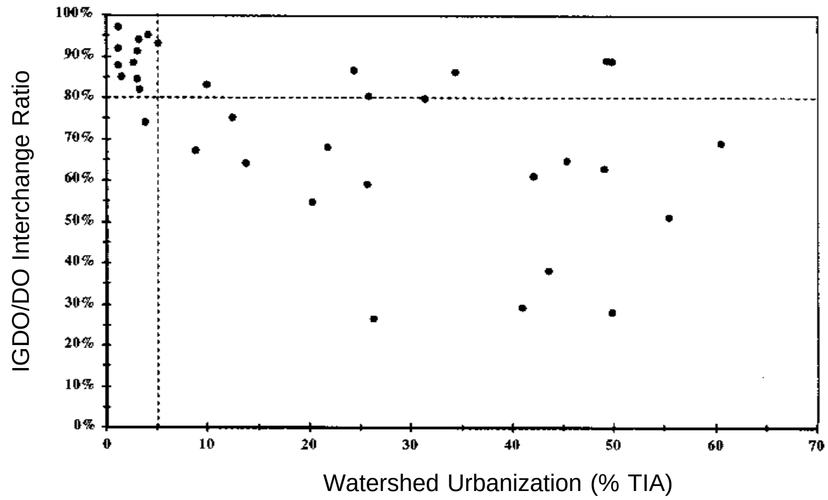
Coho salmon rely heavily on small lowland streams and associated off-channel wetland areas during their rearing phase (Bisson *et al.*, 1988). They are the only species of salmon that overwinter in the small streams of the PSL. Cutthroat trout are commonly found in almost all small streams in the Pacific Northwest. Cutthroat and coho are sympatric in many small streams and as such are potential competitors (adult cutthroat also prey on juvenile coho). In general, habitat, rather than food, is the limiting resource for most salmonids in the region (Groot and Margolis, 1991). In urban streams of the PSL, rearing habitat appears to be limiting. This study found all but the most pristine (%TIA < 5%) lowland streams had significantly less than 50% of stream habitat area as pools. In addition, the fraction of cover on pools decreased in proportion to sub-basin development. Coho rear primarily in pools with high habitat complexity, abundant cover, and with LWD as the main structural component (Bisson *et al.*, 1988). Urbanization and loss of riparian forest area significantly reduced pool area, habitat complexity, and LWD in PSL streams.

Biological Integrity

The biological condition of the benthic macroinvertebrate community was expressed in terms of a multimetric PSL Benthic Index of Biotic Integrity (B-IBI) developed by Kleindl (1995) and Karr (1991). The abundance ratio of juvenile coho salmon to cutthroat trout (Lucchetti and Fuerstenberg, 1993) was used as a measure of salmonid community integrity. Figure 9 shows the direct relationship between urbanization (%TIA) and biological integrity, using both measures. Only undeveloped reaches (%TIA < 5%) exhibited an B-IBI of 32 or greater (45 being the maximum possible score). There also appears to be rapid decline in biotic integrity with the onset of urbanization. At the same time, it appears unlikely that streams draining highly urbanized sub-basins could maintain a B-IBI greater than 15 (minimum B-IBI is nine). B-IBI scores between 25 and 32 were associated with reaches having a %TIA < 10%, with eight notable exceptions (Figure 9). These eight reaches had sub-basin %TIA values in the 25 to 35% (suburban) range and yet each had a much higher biological integrity than other streams at this level of development. All eight had a large upstream fraction of intact riparian wetlands and all but one had a large upstream fraction of wide riparian buffer (> 70% of the stream corridor with buffer width > 30 m = 100 feet). These observations indicate that maintenance of a wide, natural riparian corridor may mitigate some of the effects of watershed urbanization.

Urbanization also appears to alter the relationship between juvenile coho salmon and cutthroat trout. In this study, coho tended to dominate in undeveloped (%TIA < 5%) streams, while cutthroat were more tolerant of conditions found in urbanized streams. In 11 study streams where data was available, natural coho dominance (cutthroat:coho ratio > 2) was seen only at very low watershed development levels. Due to the lack of data, a more specific development threshold could not be established. Nevertheless, it is significant that both salmonid and macroinvertebrate data indicate that a substantial loss of biological integrity occurs at a very low level of urbanization. These results confirmed the findings of earlier regional studies.

Given that relationships were identified between basin development conditions and both instream habitat characteristics and biological integrity, it is reasonable to hypothesize that similar direct associations exist between physical habitat and biological integrity. As a general rule, instream habitat conditions (both quantity and quality) correlated well with the B-IBI and the



The IGDO/DO Ratio is an indicator of sediment intrusion into spawning redds.

Figure 8: Relationship Between Urbanization and Mean Intragravel Dissolved Oxygen (IGDO) Instream Dissolved Oxygen Ratio in PSL Streams

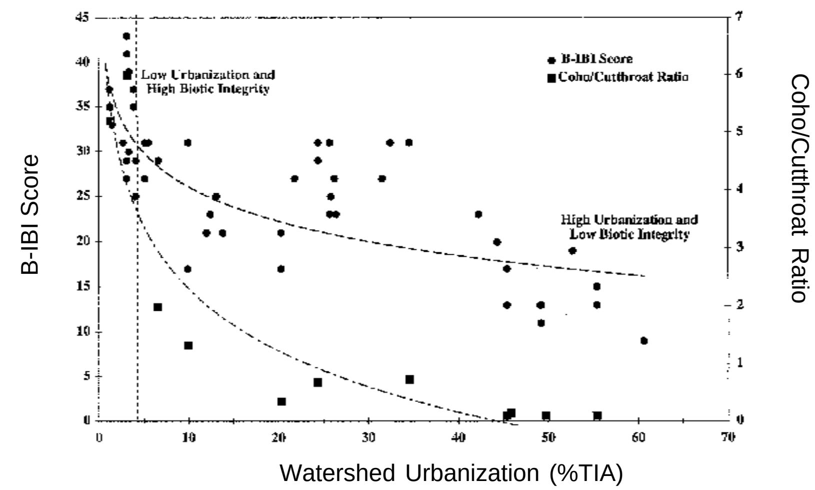


Figure 9: Relationship Between Instream Habitat Quality and Biotic Integrity

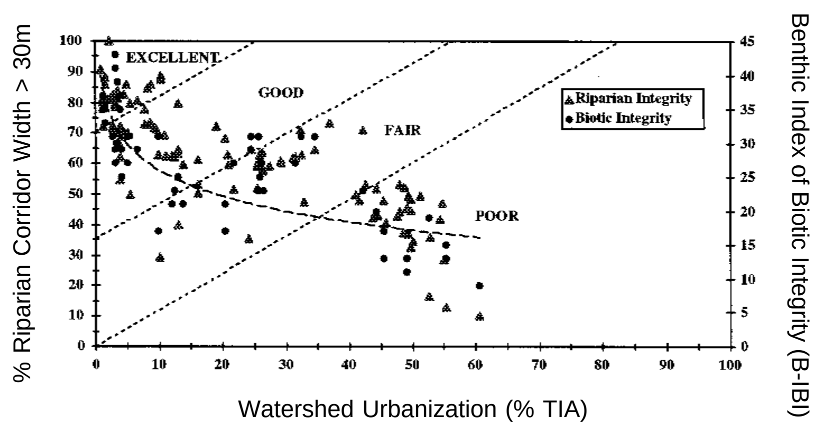


Figure 10: Relationship Between Basin Development, Riparian Buffer Width, and Biological Integrity in PSL Streams

coho:cutthroat ratio. Measures of spawning and rearing habitat quality were closely related to the coho:cutthroat ratio. As might be expected, measures of streambed quality were also closely related to the B-IBI (benthic macroinvertebrates). Chemical water quality may also influence aquatic biota at higher levels of watershed urbanization.

In addition to the quantitative habitat measures, a multi-metric Qualitative Habitat Index (QHI) was also developed for PSL streams. This index assigns scores of poor (1), fair (2), good (3), and excellent (4) to each of 15 habitat-related metrics, then sums all 15 metrics for a final reach-level score (minimum score of 15 and maximum score of 60). The QHI is similar in design to that which is used in Ohio (Rankin 1989) and as part of the U.S. EPA Rapid Bioassessment Protocol (Plafkin *et al.*, 1989). As was expected, biological integrity was directly proportional to instream habitat quality. Coho dominance is consistent with a B-IBI > 33 and a QHI > 47; conditions found only in natural, undeveloped streams. These results were consistent with the findings of a similar study in Delaware (Maxted *et al.*, 1994). The QHI has the advantage of being simpler (less costly) than more quantitative survey protocols, but may not meet the often rigorous requirements of resource managers. However, as a screening tool, it certainly has merit.

A major finding of this study was that wide, continuous, and mature-forested riparian corridors appear to be effective in mitigating at least some of the cumulative effects of adjacent basin development. Using the B-IBI as the primary measure of biological integrity, Figure 10 illustrates how the combination of riparian buffer condition and basin imperviousness explains much of the variation in stream quality. These observations suggest a set of possible stream quality zones similar to those proposed by Steedman (1988). Excellent (natural) stream quality requires a low level of watershed development and a substantial amount of intact, high-quality riparian corridor. If a "good" or "fair" stream quality is acceptable, then greater development may be possible with an increasing amount of protected riparian buffer required. Poor stream quality is almost guaranteed in highly urbanized watersheds or where riparian corridors are impacted by human activities such as development, timber-harvest, grazing, or agriculture. Because of the mixture of historical development practices and resource protection strategies included in this study, it was difficult to make an exact judgment as to how much riparian corridor is appropriate for each specific development scenario. More intensive research is needed in this area.

Summary

Results of the PSL stream study have shown that physical, chemical, and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion. Although the patterns of change differed among the attributes studied and were more strongly evident for some than for others, physical and biological measures generally changed most rapidly during the initial phase of the urbanization process as %TIA exceeded the five to 10% range. As urbanization progressed, the rate of degradation of habitat and biologic integrity usually became more constant. There was also direct evidence that altered watershed hydrologic regime was the leading cause for the overall changes observed in instream physical habitat conditions.

Water quality constituents and metal sediment concentrations did not follow this pattern. These variables changed little over the urbanization gradient until imperviousness (%TIA) approached 40%. Even then, water column concentrations did not surpass aquatic life criteria, and sediment concentrations remained far below freshwater sediment guidelines. Once

urbanization increased above the 50% level, most pollutant concentrations rose rapidly, and it is likely that the role of water and sediment chemical water quality became more important biologically.

It is also apparent that, for almost all PSL streams, large woody debris quantity and quality must be restored for natural instream habitat diversity and complexity to be realized. Of course, prior to undertaking any habitat enhancement or rehabilitation efforts, the basin hydrologic regime must be restored to near-natural conditions. Results suggest that resource managers should concentrate on preservation of high-quality stream systems through the use of land-use controls, riparian buffers, and protection of critical habitat. Enhancement and mitigation efforts should be focused on watersheds where ecological function is impaired but not entirely lost.

Biological community alterations in urban streams are clearly a function of many variables representing conditions in both the immediate and more remote environment. In addition to urbanization level, a key determinant of biological integrity appears to be the quantity and quality of the riparian zone available to buffer the stream ecosystem, in some measure, from negative influences in the watershed (Figure 10). Instream habitat conditions also had a significant influence on instream biota. Streambed quality, including fine sediment content and streambed stability, clearly affected the benthic macroinvertebrate community (as measured by the B-IBI). The composition of the salmonid community was also influenced by a variety of instream physio-chemical attributes. In the PSL region, management of all streams for coho (and other sensitive salmonid species) may not be feasible. Management for cutthroat trout may be a more viable alternative for streams draining more highly urbanized watersheds. The apparent linkage between watershed, riparian, instream habitat, and biota shown here supports management of aquatic systems on a watershed scale. The accompanying box outlines some key watershed management recommendations for PSL streams.

The findings of this research indicate that there is a set of necessary, though not by themselves sufficient, conditions required to maintain a high level of stream quality or ecological integrity (Table 1). If maintenance of that level is the goal, then this set of enabling conditions constitutes standards that must be achieved if the goal is to be met. For the PSL streams, imperviousness must be limited (< 5-10 %TIA), unless mitigated by extensive riparian corridor protection and stormwater management. Downstream changes to both the form and function of stream systems appear to be inevitable unless limits are placed on the extent of urban development. Stream ecosystems are not governed by a set of absolute parameters, but are dynamic and complex systems. We cannot "manage" streams, but instead should work more as "stewards" to maintain naturally high stream quality. Preservation and protection of high-quality resources, such as salmon, should be a priority. The complexity and diversity of salmonid life cycles and our limited understanding of them, merits additional caution in our efforts to mediate the effects of urbanization in stream environments. Engineering solutions in urban streams have utility in some situations, but in most cases cannot fully mitigate the effects of development. Rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds.

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Table 1: PSL Stream Study Recommendations for Ensuring Natural Stream Quality

Land Use and Transportation

- Reduce watershed imperviousness, especially targeting transportation-related surfaces and compacted pervious areas.
- Preserve at least 50% of the total watershed surface area as natural forest cover.
- Maintain urbanized stream system drainage-density to within 25% of pre-development conditions.
- Replace culverted road-crossings with bridges or arched culverts with natural streambed material.

Riparian Zone

- Limit stream crossings by roads or utility lines to less than 2 per km of stream length and strive to maintain a near-continuous riparian corridor.
- Ensure that at least 70% of the riparian corridor has a minimum buffer width of 30 m and utilize wider (100 m) buffers around more sensitive or valuable resource areas.
- Limit encroachment of the riparian buffer zone through education and enforcement (< 10% of the riparian corridor should be allowed to have a buffer width < 10 m).
- Protect and enhance headwater wetlands and off-channel riparian wetland areas as natural stormwater storage areas and valuable aquatic habitat resources (buffers).
- Actively manage the riparian zone to ensure a long-range goal of at least 60% of the corridor as mature, native coniferous forest.

Stormwater and Water Quality

- Allow no development in the active (100-year) floodplain area of streams. Allow the stream channel freedom of movement within the floodplain area.
- Continuously monitor streamflow and maintain two-year stormflow/baseflow discharge ratio much less than 20.
- Allow no stormwater outfalls to drain directly to the stream without first being treated by stormwater quality and quantity control facilities.
- Retrofit existing stormwater practices or replace with regional (sub-basin) stormwater control facilities with the goal of restoring the natural hydrologic regime.
- Adopt a set of regionally-specific stream assessment protocols including standardized biological sampling.
- Tailor monitoring of instream physical conditions to the specific situation. Habitat surveys should include a measure of rearing habitat (LWD and/or pools) and a measure of spawning/incubating habitat (% fines and/or IGDO); standard channel morphological characteristics should be measured; scour monitoring can be used to evaluate local streambed stability in association with specific development activity.

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Metric to English Conversion Table

Unit	To Convert	Multiply By	To Obtain
Length	km	.621	mi
Length	meters	3.281	ft
Area	km^2	247.1	acres
Area	km^2	.386	mi^2
Proportion	km / km^2	1.609	mi / mi^2