THE CUMULATIVE EFFECTS OF URBANIZATION ON SMALL STREAMS IN THE PUGET SOUND LOWLAND ECOREGION

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BACKGROUND

The Pacific Northwest (PNW), like many areas of North America, is experiencing an increase in urban development that is rapidly expanding into areas containing much of the remaining natural aquatic ecosystems. In the Puget Sound lowland (PSL) ecoregion, the natural resources most directly affected by the current pattern of watershed land use, are small streams and associated wetlands. These stream ecosystems are critical spawning and rearing habitat for several species of native salmonids (both resident and anadromous) including cutthroat trout (*Oncorhynchus clarki*), steelhead trout (*O. mykiss*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), chinook salmon (*O. tshawytscha*), pink salmon (*O. gorbuscha*), and sockeye salmon (*O. nerka*). These fish, especially the salmon species, hold great ecological, cultural, and socio-economic value to the peoples of the PNW. Despite this value, the wild salmonid resource is in considerable jeopardy of being lost to future generations (Figure 1). 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".

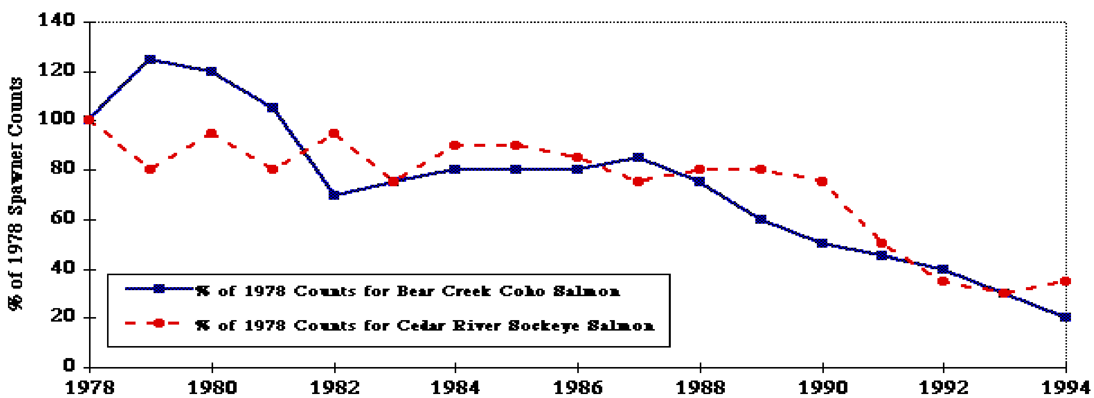

Figure 1: Representative data showing the decline in salmon stocks in the Puget Sound lowland (PSL) region u**sing 1978 as the base year** for spawner counts (Washington State Department of Fisheries data).

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 morphologic features, and physio-chemical water quality. The cumulative effects of these alterations has 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 functioning. Considerable evidence of these effects exists from studies of urban streams in the PNW (Perkins 1982; Richey 1982; Steward 1983; Scott et al. 1986; Booth 1990; Booth and Reinelt 1993; Taylor 1993). Nevertheless, most previous work has fallen short of establishing cause-effect relationships among physical and chemical variables resulting from urbanization and the response of aquatic biota.

The most obvious manifestation of urban development is the 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 the change in basin hydrologic regime that drives many of the physical changes affecting urban streams. Basin imperviousness and runoff are directly related (Schueler 1994). The two most common measures of imperviousness are total impervious area (%TIA) and effective impervious area (%EIA). The distinction between the two lies in the linkage between the impervious surface and the drainage network. Effective impervious surfaces are those which are directly connected to the surface drainage system. Total and effective basin impervious fractions are typically proportional to each other (Alley and Veenhuis 1983; Beyerlein 1996). In previous studies, an impervious level (%TIA) of about 10% has been identified as the level at which stream ecosystem impairment begins (Klein 1979; Steedman 1988; Schueler 1992; Booth and Reinelt 1993). Recent studies also suggest that this potential threshold may apply to wetlands as well (Reinelt and Horner 1991; Taylor 1993; Horner et al. 1996).

STUDY DESIGN

A key objective of the Puget Sound lowland (PSL) stream study was to identify the linkages between landscape-level 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 minimizing resource degradation due to development pressures. In this scenario, there would be a reasonable expectation that a goal of maintaining given populations or communities of organisms (native salmonids) at a specified level could be met by 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 sub-set (22) of small-stream watersheds was chosen to represent a range of development levels from relatively undeveloped (reference) to highly urbanized (Figure 2). 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 ten 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.

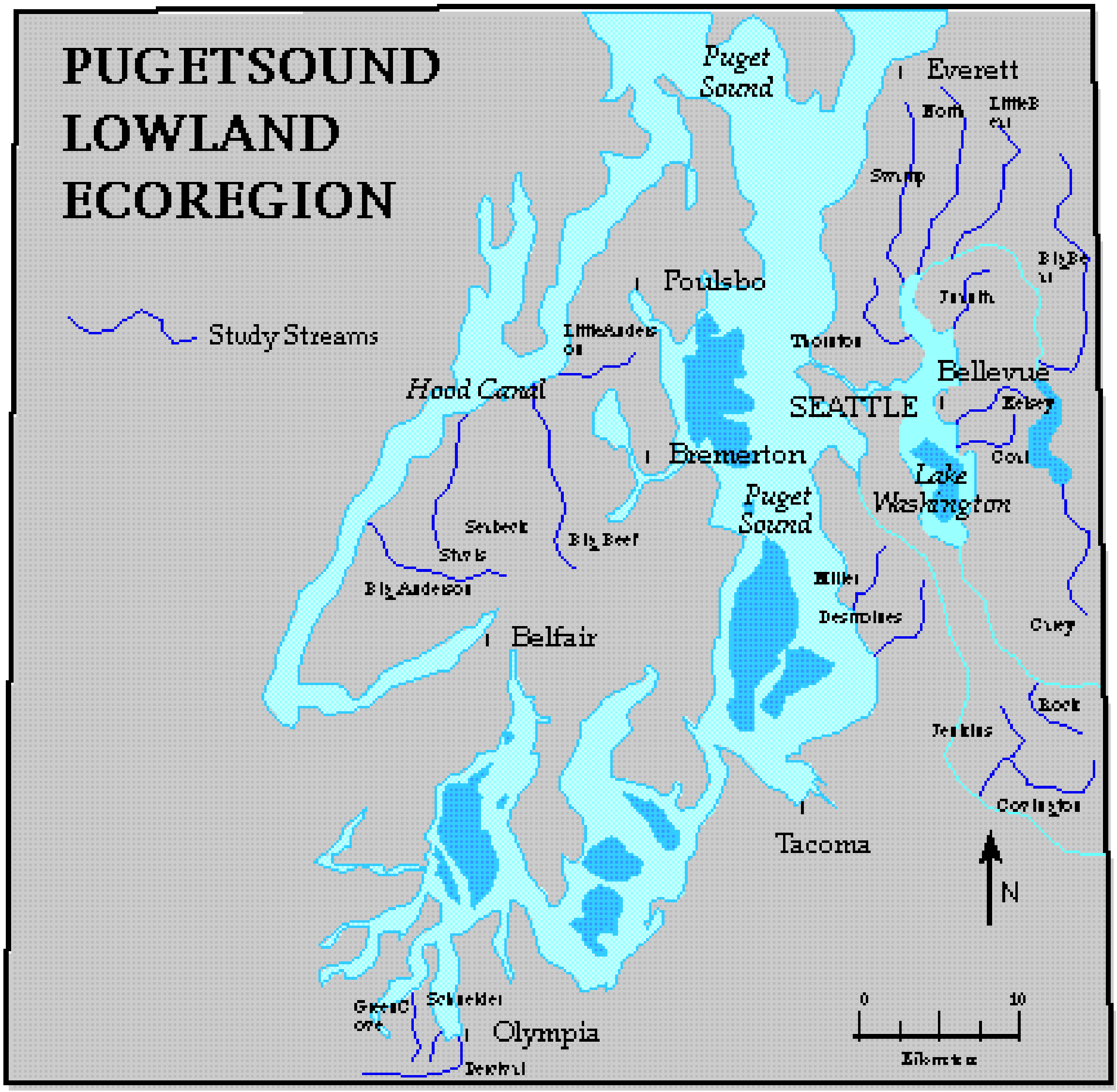

Figure 2: Puget Sound Lowland (PSL) Ecoregion

All streams were third-order or smaller, ranging in basin area from 3 to 90 km2, 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. Therefore, in natural PSL watersheds a subsurface flow hydrologic regime dominates. Development typically strips away this absorbent forest soil layer and compacts the underlying soil and exposes the underlying till layer. Also lost is a significant amount of interception storage as well as evapo-transpiration potential provided by the regionally dominant coniferous forest. The typical suburban development in the PNW 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 (BMPs) 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 (BMPs) and regulations during this research.

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 3). 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 typical 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 2-year stormflow to mean winter baseflow (Cooper 1996), was used as an indicator of development-induced hydrologic fluctuation (Figure 4). 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 km2 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. The ratio of urban to natural DD was used as an indicator of urban impact (Figure 5).

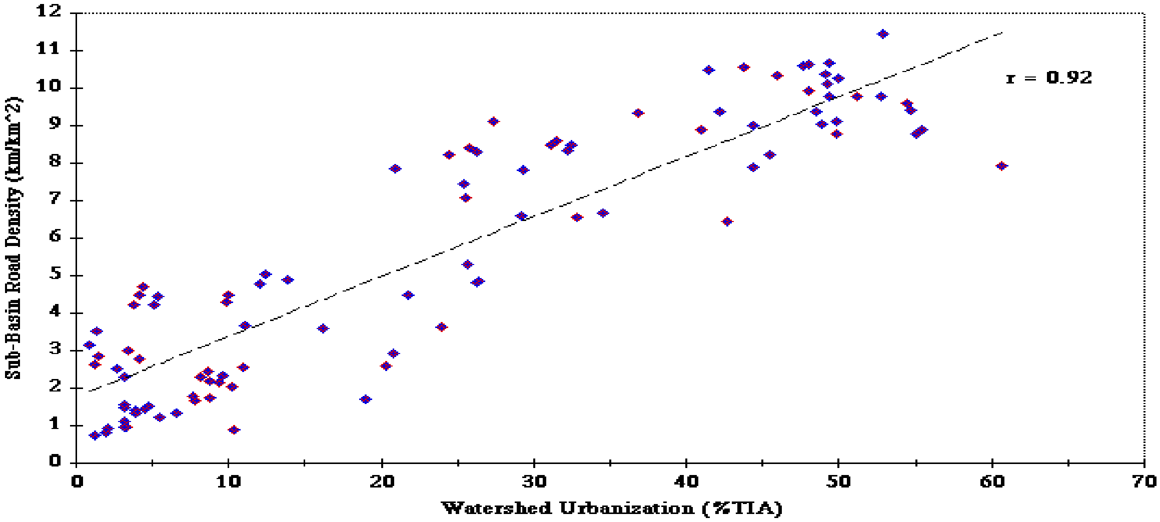

Figure 3: Relationship between urbanization (%TIA) and sub-basin road-density in Puget So**und lowland (PSL) streams.**

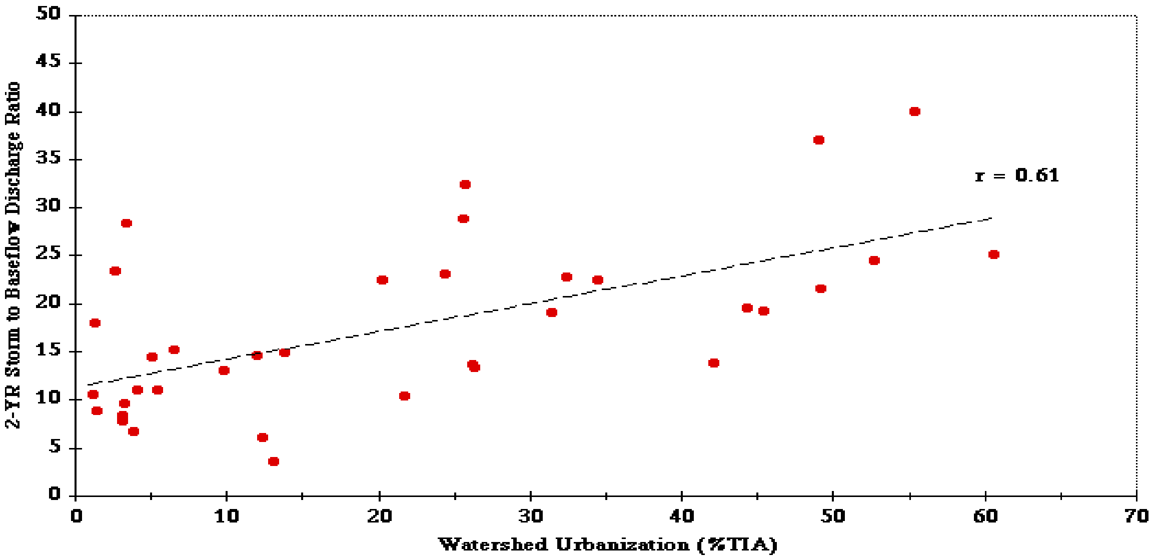

Figure 4: Change in basin hydrologic regime with urbanization in Puget Sound lowland (PSL) streams as indicated by the ratio of 2**- year stormflow to winter baseflow.**

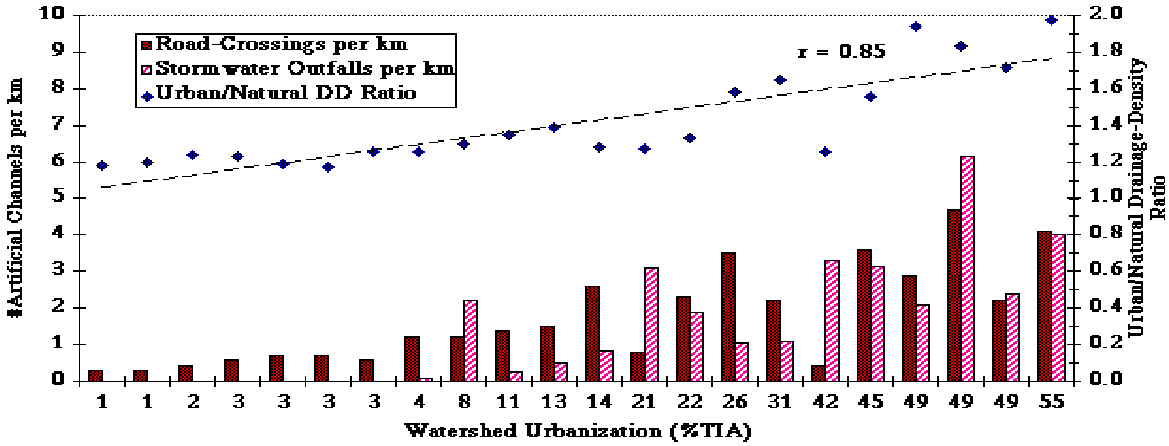

Figure 5: Change in watershed drainage-density (DD) due to the effects of urbanization on the stream channel network.

Riparian Conditions

The natural riparian corridors along PNW streams are among the most diverse, dynamic, and complex ecosystems in the region. Natural riparian integrity in the PNW is characterized by wide buffers, a near-continuous corridor, and mature, coniferous forest as the dominant vegetation. Riparian corridors are key landscape features with significant regulatory control on environmental conditions in stream ecosystems (Naiman 1992). The extent of the riparian zone, the level of control that the riparian forest exerts on the stream environment, and the diversity of functional attributes are mainly determined by the size of the stream and the longitudinal position within the drainage network (Naiman et al. 1993). Well developed, morphologically complex floodplains are often an integral part of riparian corridors in PNW streams and rivers (Naiman 1992). The riparian corridor is frequently disturbed by flooding events, creating a naturally complex landscape. Ecological diversity in riparian zones is maintained by the natural disturbance regime (Naiman et al. 1993).

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 depending on the type and intensity of land-use, the degree of disturbance to streamside vegetation, and the residual integrity of the riparian zone. Under past land-use practices, increased development has led to a loss of riparian buffer width, a fragmentation of the riparian corridor, and an overall degradation in riparian quality. In general, until recently (1993), development regulations in the PNW did not specifically address riparian buffer requirements. Sensitive area ordinances, now in effect in most local municipalities, typically require riparian buffers of 30-50 meters (100-150 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 6). 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).

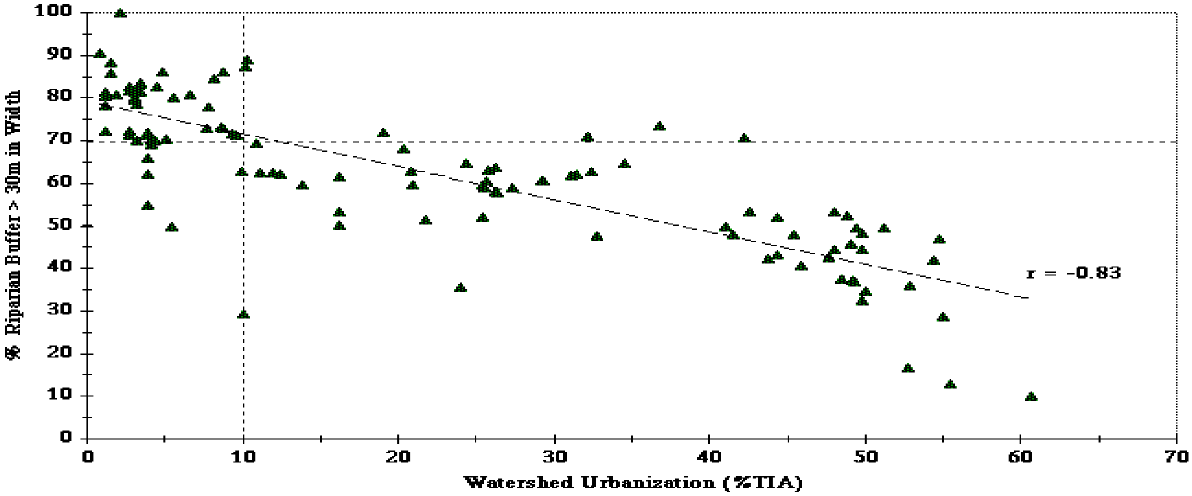

Figure 6: Relationship between riparian buffer width and basin **urbanization (%TIA) in Puget Sound lowland (PSL) streams.**

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 in width 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 non-functional 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 non-functional 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 PNW (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).

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 PNW (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 7). In addition, none of the urbanized PSL streams retained more than 25% of their natural floodplain area.

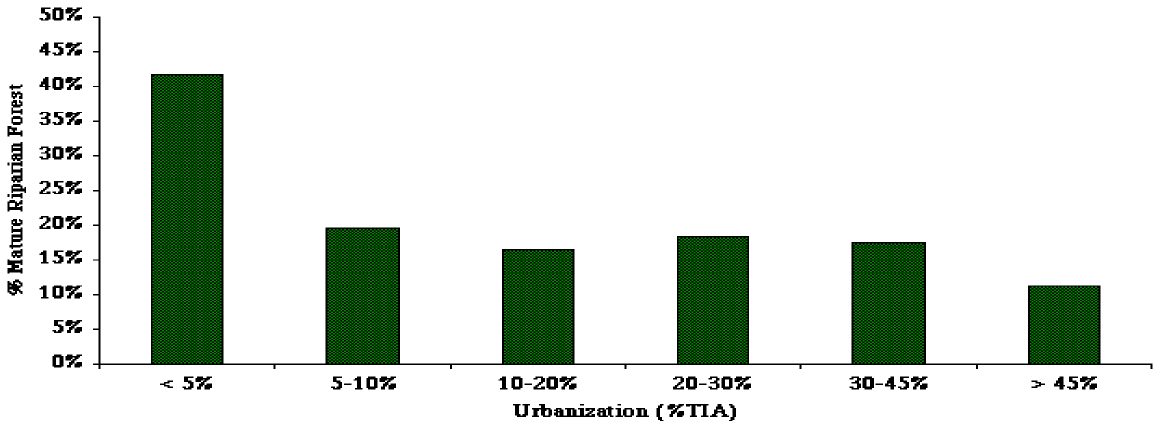

Figure 7 : Relationship between watershed urbanization (%TIA) and riparian quality (maturity) in Puget Sound lowland (PSL) streams.

Chemical Water Quality

Chemical water quality constituents were monitored under baseflow and stormflow conditions. Baseflow conductivity (µS/cm) was found to be strongly related to the level of basin development (Figure 8). Coal Creek was a confirmed outlier due to the residual effects of historic coal-mining in its headwaters. While conductivity is a non-specific chemical parameter, it is a surrogate for total dissolved solids and alkalinity, and an excellent indicator of the cumulative effects of urbanization (Olthof 1994). Storm event mean concentrations (EMC) of several chemical constituents were found to be related to both storm size (magnitude and intensity) and basin imperviousness (Bryant 1995). However, water quality criteria were rarely violated except in the most highly urbanized watersheds (%TIA > 45%). Figure 8 shows total zinc (TZn) as a representative storm EMC. 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.

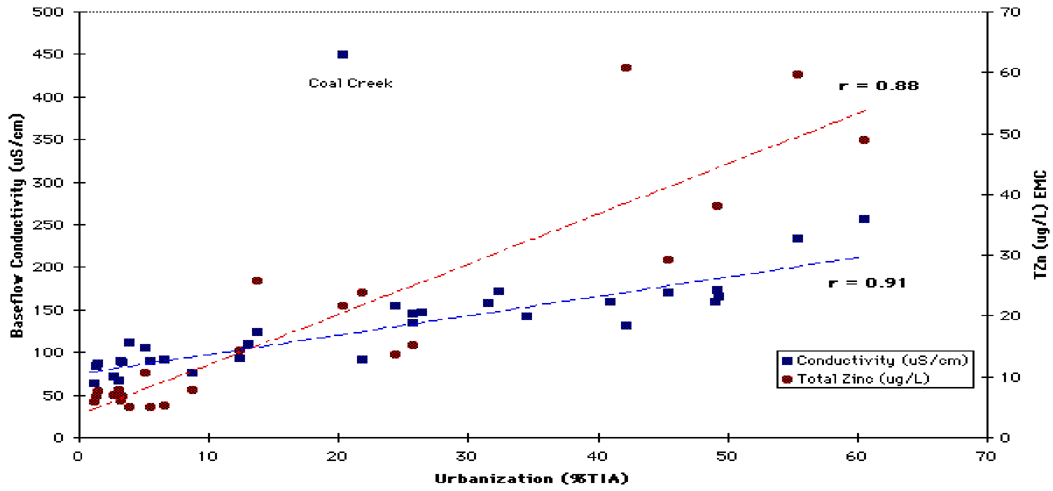

Figure 8: Baseflow conductivity and storm event mean concentration (EMC) total zinc (T**Z**n) in comparison to watershed urbanization **(%TIA) in Puget Sound lowland (PSL) streams.**

Instream Salmonid Habitat Characteristics

Large woody debris (LWD) is a ubiquitous component in streams of the PNW. 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 prvalence and quantity of LWD declined with increasing basin urbanization (Figure 9). At the same time, measures of salmonid rearing habitat, including % 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 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 10). In general, except for restoration sites, higher quantities of LWD were found only in stream-segments with intact upstream 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. This natural LWD historically provided stable, long-lasting instream structure for salmonid habitat and flow mitigation (Masser et al. 1988).

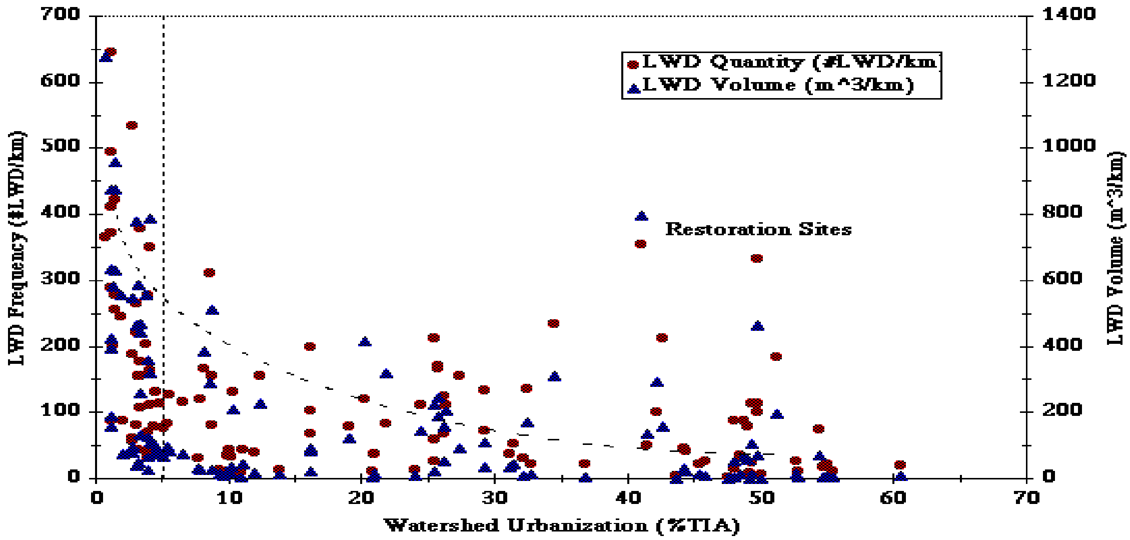

Figure 9: LWD quantity and watershed urbanization (%TIA) in Puget Sound lowland (PSL) streams.

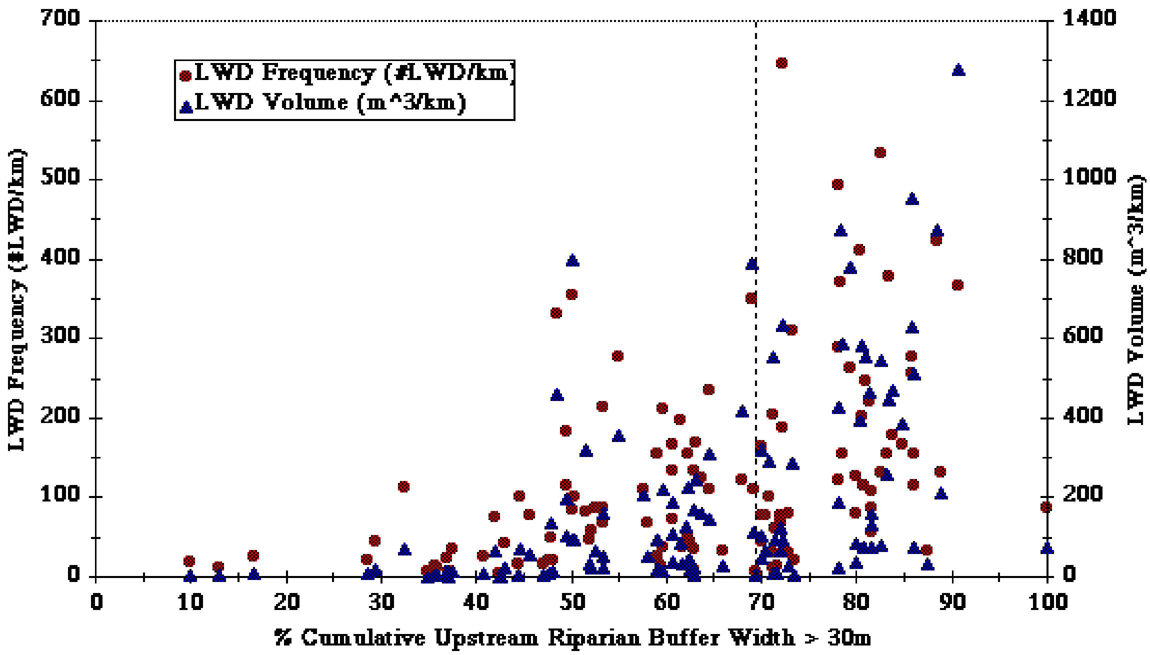

Figure 10: LWD quantity and riparian integrity in Puget Sound lowland (PSL) streams.

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). Figures 11a and 11b illustrate these devices. As would be expected, larger scour and/or fill events normally resulted from larger storms and the resultant higher flows. The available stream power and basal shear stress may be the most significant factors with regard to the potential for streambed instability. Stream power is proportional to discharge and slope. Since flows tend to increase with urbanization, it would generally be expected that stream power would increase as urbanization does, all else being equal. Cooper (1996) found this to be the case for the PSL study streams. Shear stress is dependent on slope, flow velocity, and bed-roughness. It is the critical basal shear stress that determines the onset of streambed particle motion and the magnitude of scour and/or aggradation. In that local slope and streambed roughness are highly variable, it is not surprising that scour and fill are also variable and that no significant relationship was noted between the 2-Year stormflow to winter-baseflow ratio and any of the scour monitor measurements. This tends to emphasize the local nature of scour and aggradation events. Nevertheless, 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.

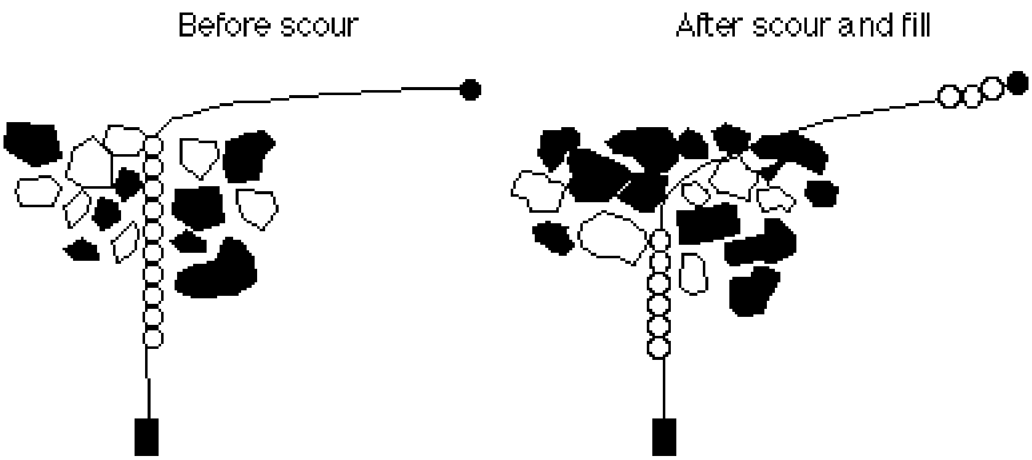

Figure 11a: Sliding-bead type scour monitors.

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 4. Between 50% and 75% stable banks were scored as a 3, 25-50% as a 2, and <25% as a 1. Artificial streambank protection (rip-rap) was considered a sign of bank instability and graded accordingly (1). Only two undeveloped, reference (%TIA < 5%) stream-segments had a stability rating less than 3. In the 5-10% basin imperviousness (%TIA) range, the streambank ratings were generally 3 or 4. Between 10-30% sub-basin impervious area (%TIA), there was a fairly even mixture of streambank conditions from stable and natural to highly eroded or artificially "protected". Above a sub-basin %TIA of 30%, there were no segments with a streambank stability rating of 4 and very few with a rating of 3. These outliers were found only in segments with intact and wide riparian corridors. Artificial streambank protection (rip-rap) was a common feature of all highly-urbanized (%TIA > 45%) 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 rating was strongly 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. Besides vegetative cover, other stream corridor characteristics, such as soil-type and valley hillslope gradient, also contribute to the stability potential and current condition of the banks.

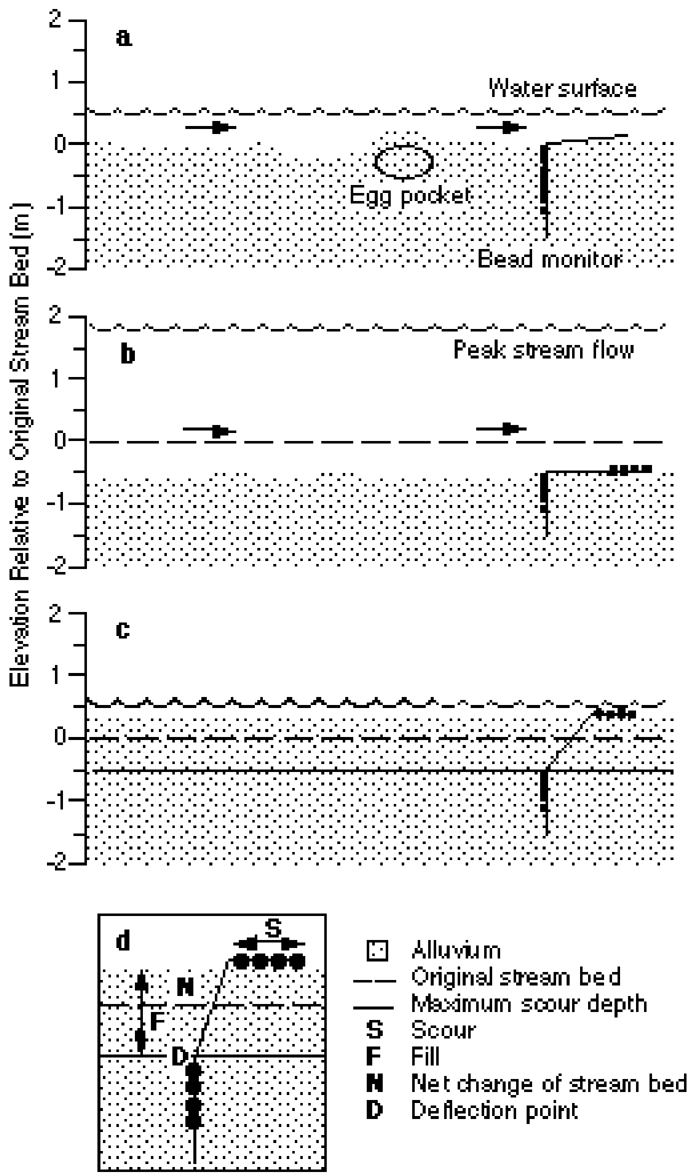

Figure 10b: Streambed scour and fill as measured by a sliding-bead scour monitor.
(a) Scour monitor installed in streambed near salmonid redd
(b) Maximum streambed scour at peak flow during a large storm
* Scoured beads slide down to the end of the wire
* Deep enough scour may wash out salmonid redd
(c) Post-storm sediment aggradation buries scour monitor wire
(d) Measurement of scour and fill (aggradation)
(modified from Nawa and Frissell, 1993)

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, % fines did not exceed 15% until %TIA exceeded 20%. In the highly urbanized basins (% TIA > 45%), the % fines were consistently > 20% except in higher gradient reaches where the 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. IGDO monitors were installed in artificial salmonid redds and monitored throughout the coho incubation period (Figures 12). 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. The typical mortality during this period in natural streams can be quite high (> 75%). 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. In extreme situations, sediment can form a barrier to alevin emergence, resulting in entombment and death. Elevated fine sediment levels can also have various sublethal 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 (Chapman 1988). Spawning salmonids themselves can also reduce the fine sediment content of the substrata, at least temporarily. Measurement of instream DO coincident with IGDO allowed for the calculation of a IGDO/DO interchange ratio (Figure 13). In all but one case, the mean interchange ratio was > 80% in the undeveloped reaches (%TIA < 5%). As basin development (% TIA) increased above 10%, there was a great majority of the reaches in which the mean interchange ratio was 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 12). 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 over-winter in the small streams of the PSL. Cutthroat trout are commonly found in almost all small streams in the PNW. Cutthroat and coho are sympatric in many small streams in the PNW 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 PNW 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.

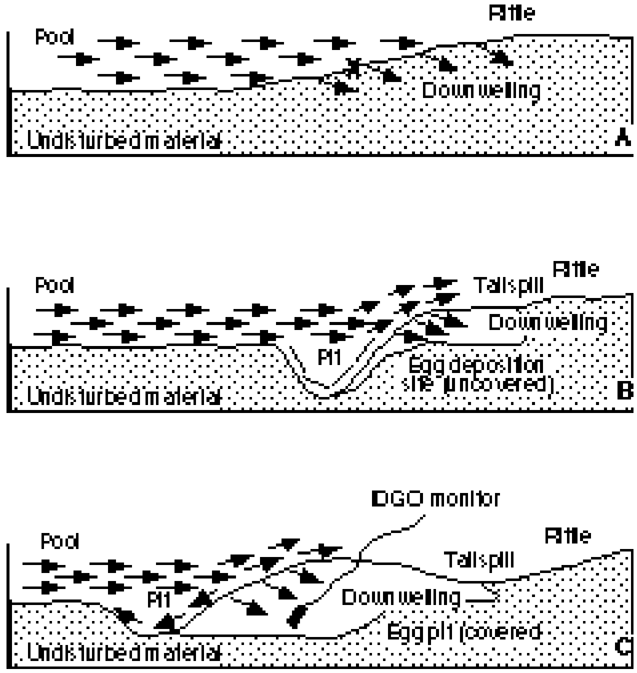

Figure 11: Architecture of a typical salmonid redd with intragravel dissolved oxygen (IGDO) monitor installed.
(A) Streambed topography near pool-tailout. Likely spawning area is marked with "X" (area of flow into gravel)
(B) Redd construction creates a low-flow zone, facilitating egg deposition and fertilization (fine sediment flushed from pocket)
(C) Egg-pocket covered by upstream digging activity and down-welling flow maximized by redd topography. Induced flow flushes fines, provided oxygenated surface water to developing embryos, and removes metabolic wastes.
(modified from Bjornn and Reiser, 1991)

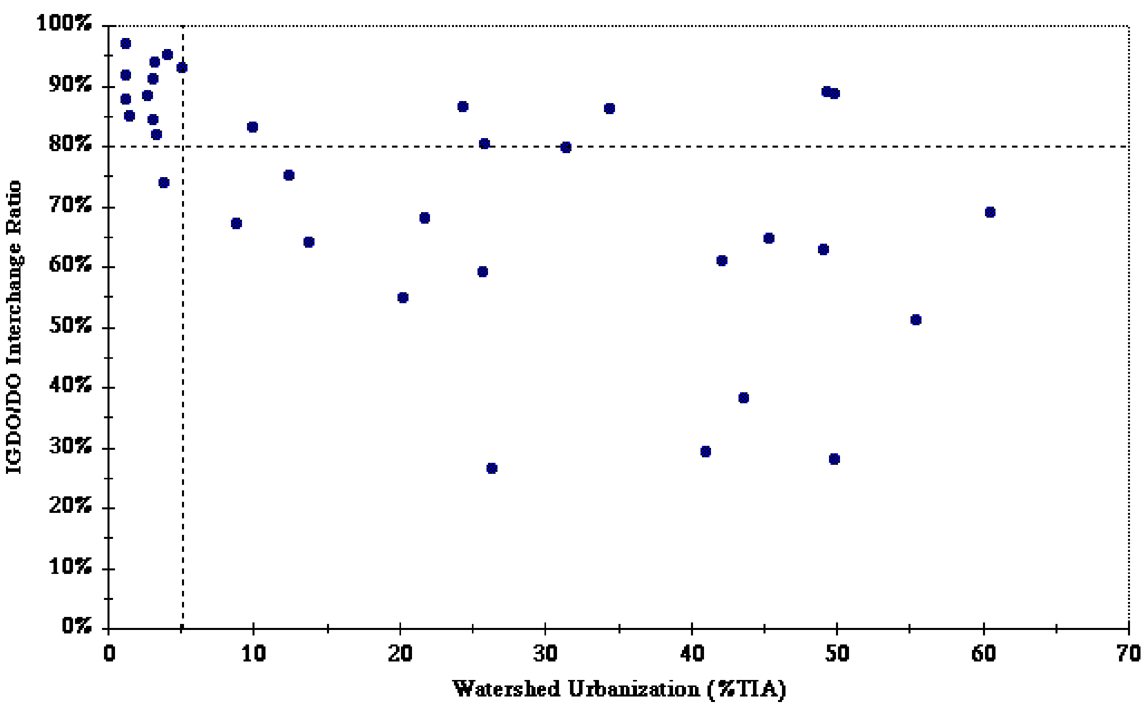

Figure 13: Relationship between urbanization (%TIA) and mean intragravel dissolved oxygen (IGDO) to instream dissolved oxygen **(DO) in Puget Sound lowland (PSL) streams.**

Biological Integrity

The biological condition of the benthic macroinvertebrate community was expressed in terms of a multi-metric 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 13 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 (%TIA < 10%). At the same time, it appears unlikely that streams draining highly urbanized sub-basins (%TIA > 45%) could maintain a B-IBI greater than 15 (minimum B-IBI is 9). B-IBI scores between 25 and 32 were associated with reaches having a %TIA < 10%, with eight notable exceptions (Figure 14). These eight reaches had sub-basin %TIA values in the 25-35% (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). 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. Figure 14 shows the ratio of coho to cutthroat abundance ratio in those PSL study streams (11) where data were available for the period of the study. Natural coho dominance (cutthroat:coho ratio > 2) was seen only at very low watershed development levels (%TIA < 5%). 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 (Perkins 1982; Steward 1983; Scott et al. 1986; Lucchetti and Fuerstenberg 1993).

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 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.

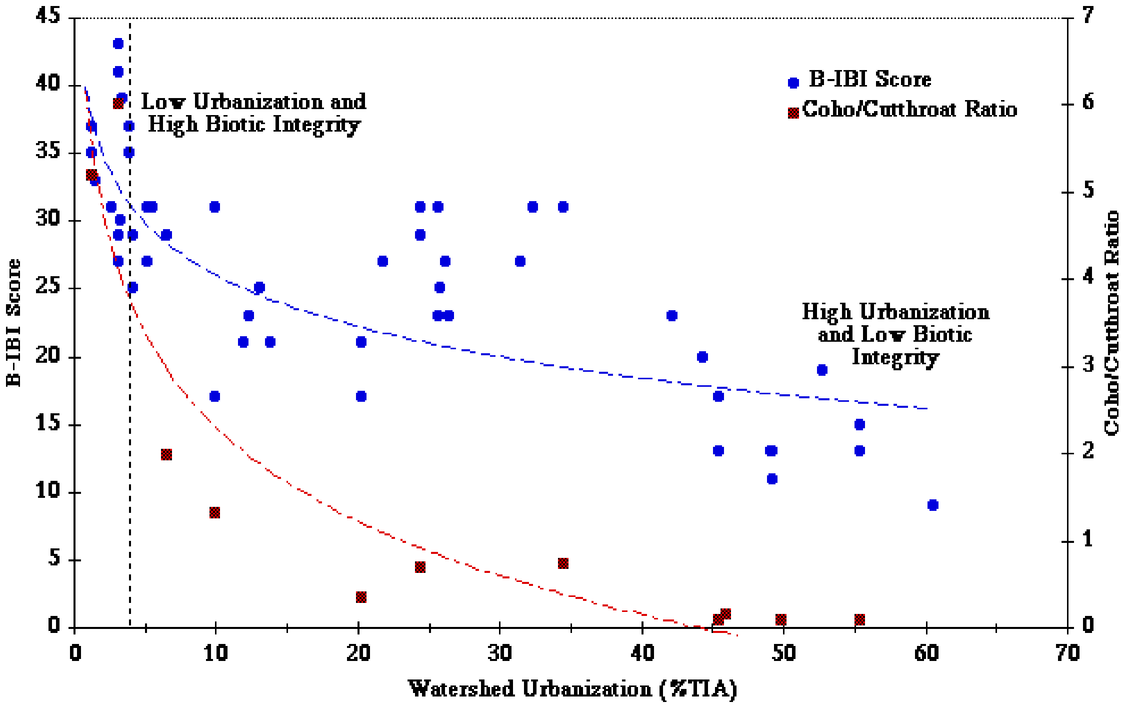

Figure 14: Relationship between watershed urbanization (%TIA) and biological integrity in Puget Sound lowland (PSL) streams. Benthic **index of biotic integrity (B-IBI) and the abundance ratio of juvenile** coho salmon to cutthroat trout used as indices of biological integrity.

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 US EPA Rapid Bioassessment Protocol (Plafkin et al. 1989). As was expected, biological integrity was directly proportional to instream habitat quality (Figure 15). Coho dominance is consistent with a B-IBI > 33 and a QHI > 47; conditions found only in natural (%TIA < 5%), 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 (quantitative) requirements of resource managers. However, as a screening tool, it certainly has merit.

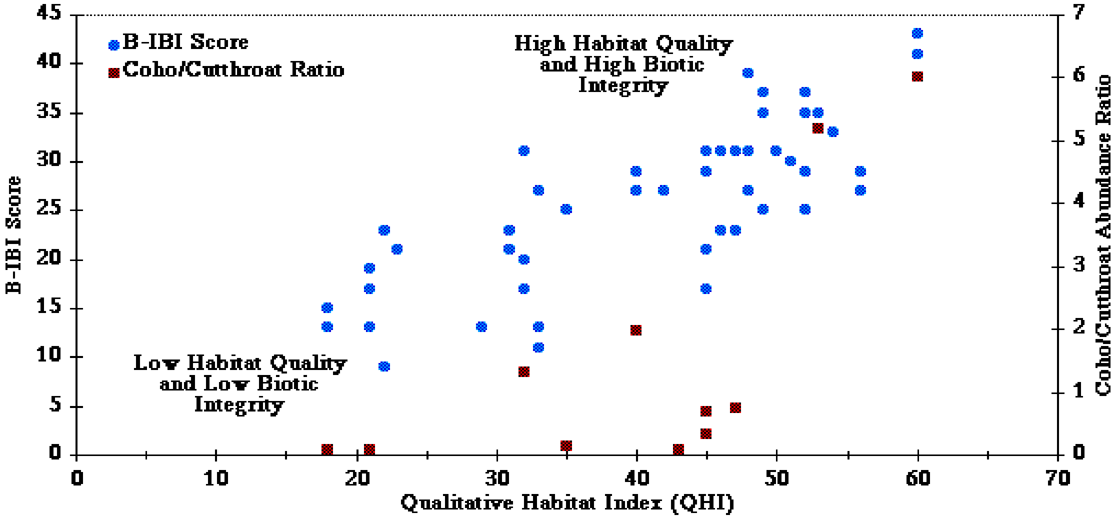

Figure 15: Relationship between instream habitat quality and biotic integrity. Benthic **index of biotic integrity (B-IBI) and the ratio of** juvenile coho salmon to cutthroat trout are **used as indices of** biological integrity in Puget Sound lowland (PSL) streams..

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 16 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.

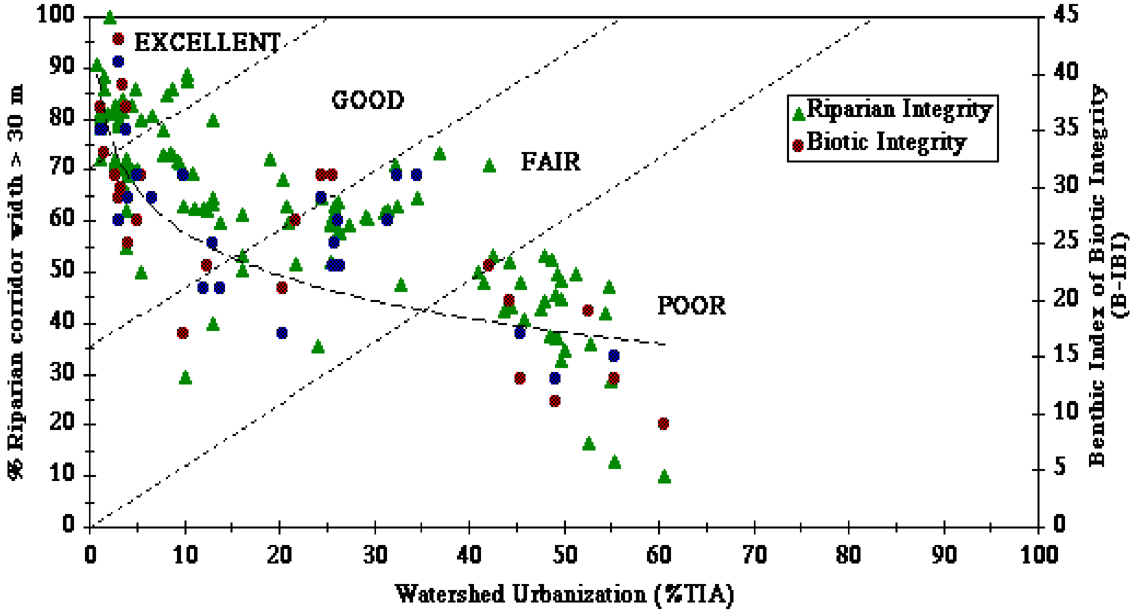

Figure 16: Relationship between basin development, riparian buffer width, and biological integrity in PSL streams

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 above the 5-10% 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.

Chemical water quality constituents and concentrations of metals in sediments 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. As urbanization (%TIA) increased above the 50% level, with most pollutant concentrations rising rapidly at that point, it is likely that the role of water and sediment chemical water quality constituents becomes 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 16). 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 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 (physical, chemical, and biological). 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 BMPs. 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 should be a priority. 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. In order to support natural levels of stream quality, the following recommendations are proposed:

- 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 (i.e. urban/natural DD ratio < 1.25).
- Continuously monitor streamflow and maintain 2-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.
- Replace culverted road-crossings with bridges or arched-culverts with natural streambed

material.

- Retrofit existing BMPs or replace with regional (sub-basin) stormwater control facilities with the goal of restoring the natural hydrologic regime.
- 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).
- Actively manage the riparian zone to ensure a long-range goal of at least 60% of the corridor as mature, coniferous forest.
- Allow no development in the active (100-year) floodplain area of streams. Allow the stream channel freedom of movement within the floodplain area.
- Protect and enhance headwater wetlands and off-channel riparian wetland areas as natural stormwater storage areas and valuable aquatic habitat resources (buffers).
- Adopt a set of regionally specific stream assessment protocols including standardized biological sampling (e.g., B-IBI).
- Under low-moderate basin development, chemical water quality monitoring should be used sparingly, if a chemical pollutant is suspected or in situations where biological monitoring indicates a problem. For highly urbanized streams, sampling should be more frequent, but should still be focused on specific constituents of concern.
- Monitoring of instream physical conditions should be tailored to the specific situation. Salmonid habitat surveys should include a measure of rearing habitat (LWD and/or pools) and a measure of spawning/incubating habitat (% fines and/or IGDO). In addition, standard channel morphological characteristics should be measured (BFW, BFD, pebble-count, and streambank condition). Scour monitoring should be used to evaluate local streambed stability in association with specific development activity.
- The complexity and diversity of salmonid life-cycles and stream communities, along with our limited understanding of them, should engender caution in proposing any simple solutions to reverse the cumulative effects of urbanization in streams of the PSL region as well as other regions.
- The following instream salmonid habitat target conditions are also proposed for urban, lowland streams in the PNW:

Instream Habitat Parameter	Salmonid Life-Phase Influenced	Indication of Poor Habitat Quality	Target for Fair Habitat Quality	Target for Good Habitat Quality
% Pool Habitat (Surface Area)	Rearing	< 30%	30-50%	> 50%

Pool Frequency (BFW-Spacing)	Rearing	> 4 BFWs	2-4 BFWs	< 2 BFWs
LWD Frequency (BFW-Spacing)	Rearing	< 1/BFW	1-2/BFW	> 2/BFW
% Key LWD (Dia. > 0.5 m)	Rearing	< 20%	20-40%	> 40%
Pool Cover (%)	Rearing	< 25%	25-50%	> 50%
IGDO/DO Interchange (%)	Spawning and Incubating	< 60%	60-80%	> 80%
Pebble-Count D10 (mm)	Spawning and Incubating	< 3 mm	3-5 mm	> 5 mm
Fine Sediment (% < 0.85 mm)	Spawning and Incubating	> 20%	15-20%	< 15%

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