LEAVITT 80

Watershed Determinants of Ecosystem Functioning

Richard R. Horner[1,2], M. ASCE; Derek B. Booth[2]; Amanda Azous[3]; and Christopher W. May[2]

Abstract

By the mid-1980s it was clear that urban stormwater runoff was strongly implicated in the alteration of streams and freshwater wetlands in the Puget Sound Basin of Washington state to ecosystems lower in biologically diversity and productivity of the species most valued by society. It was also apparent that the causes of these modifications were rooted in watershed hydrology and sediment transport as well as reduced water quality. Recognition of these connections and the rapid pace of development in the region stimulated research to define the linkages among stream and wetland habitat structure, conditions in the surrounding landscapes, and the associated biological responses. One project monitored watershed and riparian zone conditions, flow, physical habitat characteristics, water quality, benthic macroinvertebrates, and fish in 31 reaches on 19 low-order streams, representing a gradient of urbanization, over a three-year period. A second project followed 19 palustrine wetlands during an eight-year period when urbanization began or increased in the watersheds of about half, while the remainder were essentially unchanged. Overall, the findings of these projects agree that the effects of modified hydrology accompanying urbanization exert the earliest and, at least initially, the strongest deleterious influences on the freshwater ecosystems studied. Furthermore, the results agree that the steepest rates of decline in biological functioning of both streams and wetlands, and the conditions necessary to support that functioning, occur as urbanization increases total impervious land cover from 0 to about 6 percent, unless mitigated by extensive riparian protection, management efforts, or both. Thereafter, the decline proceeds at a slower rate as impervious cover increases further. Functioning at the highest level (e. g., stream benthic index of biotic integrity, B-IBI, > 35) with very low imperviousness drops by roughly half

[1]230 NW 55th Street, Seattle, WA 98107; [2]Center for Urban Water Resources Management, University of Washington, Box 352700, Seattle, WA 98195-2700; [3]P. O. Box 530, Olga, WA 98279.

(e. g., B-IBI < 20) as urbanization progresses to about 45 percent impervious cover. The results suggest that management concentrate on preservation through land use controls where resource values are high, and on prevention of further degradation and enhancement, especially directed at riparian zones, where functioning is impaired but not lost.

Introduction

Ecological Functions and Problems of Pacific Northwest Streams and Wetlands

In the Puget Sound region of the Pacific Northwest, in common with many areas in North America, urban development is rapidly extending into areas containing much of the remaining aquatic resource base. In this region the aquatic ecosystems most directly affected by the prevailing pattern of watershed development are relatively small streams and wetlands in the lowlands surrounding Puget Sound. These streams are critical spawning and rearing locations for seven species of native anadromous and resident salmonid fish of great ecological, cultural, social, and economic importance. Despite its value, this resource is in considerable jeopardy of being lost. More than 100 native salmon and anadromous trout runs in the region are already extinct, and approximately 200 more are seriously threatened (Nehlsen et al. 1991). Wetlands frequently form the headwaters of lowland spawning and rearing streams and comprise substantial portions of their riparian zones. Wetlands also supply other crucial ecological functions and social values, including diverse vegetation; habitat for amphibians, birds, and small mammals; open space; and recreational and educational opportunities.

Ten years ago environmental scientists and managers in the region lacked a foundation to formulate strategies for arresting the decline of these key freshwater resources. Many of them contributed to several research projects over the intervening years to narrow the gaps in knowledge of ecosystem functioning and improve management ability. As the first stage of these efforts is nearing completion, this paper was prepared to summarize the overall approach, key representative results, and implications for managing the region's lowland watersheds to accomplish stream and wetland resource protection goals.

Watershed urbanization effects on streams, in particular, have been fairly well documented and include numerous and extensive changes in the hydrologic regime, channel morphology, riparian corridor, and water quality. These alterations in sum produce a very different habitat structure than the one in which aquatic organisms have evolved, usually resulting in decline or complete loss of at least some populations and substantial modification of biological communities. A full account of the many individual changes is beyond the scope of this paper and may be found elsewhere (e. g., Booth 1990, 1991; Booth and Jackson 1994; Horner et al. 1994).

In analyses of aquatic ecosystem impacts, watershed urbanization has been expressed most commonly in terms of the proportion of watershed area covered by impervious surface. Some past work has identified impervious cover of 10 +/- several percent as the level at which stream ecosystem impairment becomes evident. For example, Klein (1979) used a variety of hydrologic, water quality, biological information to conclude that serious stream quality impairment can be prevented if watershed imperviousness does not exceed 15 percent, or 10 percent for more sensitive ecosystems with self-sustaining trout populations. Booth and Reinelt (1993) found a very similar relationship for Puget Sound Basin lowland streams. Shaver et al. (1995) found decline in macroinvertebrate community indices in Delaware creeks with 8 percent watershed imperviousness and substantially more decrease above 15 percent. They demonstrated that the impact was linked more to physical habitat than water quality degradation.

Toward a Systematic Approach to Managing Watershed and Aquatic Ecosystem Change

With recognition of the web tying together landscapes and aquatic habitats and their inhabitants has come an interest in defining the functional relationships between discharges from watersheds and aquatic resources well enough to avoid or minimize resource losses through management intervention. In this scenario there would be reasonable confidence that a goal to maintain a given organism or community at a specified level could be met by sustaining a certain set of habitat measures, which in turn depend on established values of particular watershed measures. To realize the promise of this approach, of course, it will be necessary to set well conceived goals that set the direction and parameters of the entire management thrust.

Needed for progress in systematically managing watersheds and their aquatic resources are meaningful and convenient measures of watershed conditions, biological "health," and the habitat conditions on which biota depend. Moreover, these measures must be suitable for defining the linkages among these ecosystem components. For expressing watershed conditions, the traditional use of impervious cover must be supplemented by measures that express other facets of the landscape (e. g., riparian zone and drainage system characteristics). Perhaps most critical to progress in describing habitat structure is to identify on an ecoregional scale the variables with the most utility for assessing habitat relationships with watershed circumstances on the one hand and biological responses on the other. The work reported here makes an attempt to advance the measurement and interpretation of both watershed and habitat conditions.

The last 15 years have seen substantial progress in expressing biological community attributes in useful forms for comprehensive watershed studies. Major developments include the index of biotic integrity (IBI; Karr 1981; Karr and Dudley 1981; Karr et al. 1986; Karr 1991; Kerans and Karr 1994; Fore et al. in review), the

U. S. Environmental Protection Agency's (USEPA) Rapid Bioassessment Protocols (Plafkin et al. 1989), and the state of Ohio's biological criteria (Yoder 1991). Further IBI development was performed as part of the study discussed in this paper (Kleindl 1995).

RESEARCH PROGRAM FORMAT

Research Scope

Several research projects have been performed over the last 10 years to identify watershed determinants of freshwater ecosystem character and functioning in the Puget Sound region. These projects have applied the systematic approach outlined in the previous section in which watershed, physical and chemical habitat, and biological variables have been measured and linked with the goal of understanding and learning better how to manage watershed and aquatic ecosystem change. The projects providing most of the data base for this paper are:

- A study of the attributes of lowland streams across a gradient of urbanization, again with an underlying interest in better managing streams, their resources, and the discharges to them from diffuse sources on the landscape (1994-1996). This research is being performed by the University of Washington with a grant from the Washington Department of Ecology's Centennial Clean Water Program and in-kind support from several local governments.

- An investigation of the effects of urbanization, especially urban stormwater discharge, on freshwater wetlands and how to manage wetlands and stormwater for optimal aquatic resource protection (1986-1996). This research is being performed by a cooperative unit involving the King County Natural Resources Department and its predecessor agencies and the University of Washington, with major funding from the Centennial Program, USEPA Region X, and a variety of support from several local governments.

The paper also takes advantage of a series of studies of the habitat and fish resources in lowland streams in the urban and urbanizing area of King County, Washington, performed by King County Surface Water Management Division. This agency has been a participant and contributor of material support and data to both research efforts and has shared and utilized the findings produced by those projects.

Experimental Designs

Stream Research

The design of the stream study was to establish attributes of the watersheds contributing to selected stream reaches and then to make a number of measurements of the riparian, habitat, and biological conditions within those reaches. The concept underlying the study, simply illustrated as follows, was that watershed and riparian characteristics determine habitat conditions, which, in relation to evolved organism preferences and tolerances, set the composition of the biological communities:

Watershed and riparian characteristics → Habitat conditions → Biota

Data analysis was directed at establishing the linkages represented by the arrows, as well as the less direct connections between watershed characteristics and biota.

Researchers and governmental participants in the research selected streams and study reaches from over 100 candidates that best met 15 criteria expressing such factors as representativeness of Puget Sound lowland stream conditions and resources, ability to cover a range of watershed urbanization from near zero to more than 50 percent imperviousness, and data availability. All study reaches are of the same general scale, being of first, second, or third order. They have mean annual discharges in the approximate range 0.1-1.7 m^3/s (3.5-60 ft^3/second); lie at altitudes of less than 150 meters above sea level; and have average stream gradients under 5 percent.

Site selection emphasized contributing catchments in the early stages of urbanization, when it was hypothesized that the most rapid change in ecological conditions occurs, or with very little to no urbanization. These latter catchments represent what is considered to be the maximum attainable ecological function in Puget Sound lowland streams. Until recently, these "reference" sites have experienced relatively little human activity after being logged approximately 100 years ago. Watersheds contributing to the 31 study reaches monitored since 1994 exhibit the following distributions of TIA: 0-5%--8 sites, 5-10%--7 sites, 10-20%--3 sites, 20-30%--3 sites, 30-50% 6 sites, and > 50%--4 sites.

The study watersheds cover two distinctly different geologic conditions. All but two are underlain by glacial till, in which continental glaciation (15,000 years b. p.) deposited a dense hardpan, now approximately 1 meter beneath the surface and overlain by a loamy soil. The other watersheds are underlain by glacial outwash, with surface coarse material providing direct hydraulic communication between the surface and the regional aquifer. In the undisturbed forested condition glacial till catchments are capable of providing precipitation storage on the order of 15 cm in the overlying soil, and the outwash areas much more (Wigmosta et al. 1994).

Suburban development of routine density and style with the stormwater management standards prevailing in King County between 1979 and 1990 reduced storage by roughly 90 percent. New standards taking effect in 1990 in that county and elsewhere in the study area would recover more storage but still provide no more than 25 percent of the original amount (Barker et al. 1991; Booth and Jackson 1994). Because the new standards affected little new development between 1990 and 1994, conditions in this study more reflect the pre-1990 situation; i. e., little effective stormwater management.

Monitoring occurred over three years in 31 reaches on 19 streams and consisted of determination of watershed land cover and other attributes, riparian zone dimensions and characteristics, a host of physical habitat measurements, flow and water quality under storm and base flow conditions, bed sediment quality, benthic macroinvertebrate community composition, and salmonid fish usage. Habitat and riparian zone assessments were conducted on 120 segments, representative of local physiographic and land use conditions and approximately 1 km in length, extending between study reaches and headwaters. Additional details on study design and the specific monitoring methods are given by Olthof (1994), Bryant (1995), Kleindl (1995), and May (1996).

Wetlands Research

The wetland and stream study designs were similar, with one exception. While the stream research was confined within a fairly short stretch of time, during which little land use change occurred, the wetland study extended long enough to observe the effects of land use changes in some of the contributing watersheds. Those that did not change were regarded as references. As with the stream study, wetland research sites were chosen according to specific criteria, in this case from approximately 150 candidates. The complete set of activities over all years of monitoring involves 19 wetlands. An additional seven wetlands served for special studies. All lie at altitudes of less than 150 meters above sea level. Wetland areas range from 0.61 to 12.55 ha. Contributing watersheds of the 19 principal study sites exhibited the following TIA distributions at the beginning and end of the project: 0-5%--8 sites in 1989, 6 in 1995; 5-10%--3 sites in 1989, 2 in 1995; 10-20%--4 sites in 1989, 5 in 1995; 20-30%--2 sites in 1989, 3 in 1995; 30-50%--1 site in 1989, 2 in 1995; and > 50%--1 site in 1989, 1 in 1995.

Monitoring encompassed determination of watershed land cover and other attributes; wetland morphology; water level fluctuation patterns; water and sediment quality; and insect, amphibian, bird, and small mammal community characteristics during 5 years over the period 1986-1995. Like the stream research, the wetlands project investigated associations among those system components. Additional details on study design and the specific monitoring methods are given by King County Resource Planning Section (1987, 1988), Reinelt and Horner (1990, 1991), Cooke (1991), Taylor (1993), and Richter and Azous (1995).

Research Results and Interpretations

Stream Research

Stream Biology in Relation to Watershed and Riparian Characteristics

This discussion considers observed linkages between the source and response components of the system, letting aside for the moment the intermediate habitat component:

Watershed and riparian characteristics	→	Habitat conditions	→	**Biota**

Throughout this paper watershed condition is characterized by impervious cover. Analyses demonstrated that the relationships discussed are very similar if watershed condition is alternatively expressed by road density (km/km^2 of watershed area, May 1996).

The ecological condition and functioning of the benthic macroinvertebrate community was expressed in terms of a Benthic Index of Biotic Integrity (B-IBI), which accounts for the relative presence in the respective reaches of certain taxa and trophic groups with varying tolerances to stress (Kleindl 1995). Figure 1 portrays the relationship between B-IBI values computed in 1994 and 1995 and urbanization level, expressed by total impervious area as a percentage of the total watershed (% TIA). Only reaches with TIA < 3.9 percent exhibited an index of 35 or greater. All B-IBI values of at least 25 were associated with watersheds having no more than 11 percent impervious, with eight notable exceptions. These eight points (B-IBI = 25-31) were computed for reaches on two streams having contributing catchments with 25-34 percent TIA. Despite the moderately high level of urbanization in these cases, these streams have more of their riparian areas in intact wetlands (17.2-21.5 percent) than all but one of the 19 streams and have overall wider riparian zones (~ 60 percent > 30 meters wide) than most cases of similar urbanization level. These observations give an indication that maintenance of the adjacent stream buffer zone may help ameliorate the effects of more distant urbanization.

Setting aside these eight points, the general shape of the curve in Figure 1 indicates a relatively rapid rate of decline in biological function as impervious area increases to about 8 percent, following which the rate of decline appears to slow as urbanization increases further. It appears from these data to be probable that Puget Sound lowland streams would have a B-IBI of 15 or less with more than 45 percent imperviousness.

Among the salmonid fish, the research concentrated on the coho salmon (*Oncorhynchus kisutch*), the species arguably most vulnerable to urban runoff effects. Coho especially rely on small lowland creeks and is the only Northwest salmon species that over-winters in fresh water as a juvenile (Nickelson et al. 1992), dwelling primarily in pools (Bisson et al. 1988). In urban streams coho suffer from loss of pools through increased sedimentation and less large woody debris (LWD). On the community level, urbanization seems to alter the relationship between coho salmon and cutthroat trout (*Oncorhynchus clarki*), another salmonid species with far less social and economic recognition. These two species are often in competition for food and habitat space, and adult cutthroat prey on juvenile coho. Coho tend to dominate in less urbanized watersheds, while the advantage shifts to cutthroat with increasing development (Perkins 1982, Richey 1982, Steward 1983, Scott et al. 1986).

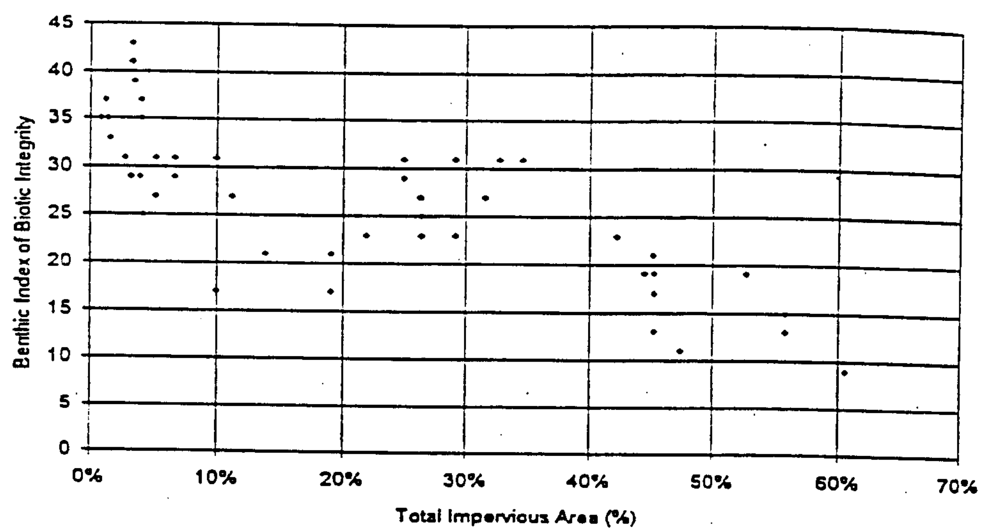

Figure 1. — Benthic Index of Biotic Integrity in Puget Sound Lowland Streams Over a Gradient of Watershed Impervious Land Cover

Figure 2 shows salmonid fish data available for a subset of the study streams, expressed in terms of the ratio of coho salmon to cutthroat trout abundance. The less tolerant coho dominate only with a small amount of urbanization, the level of which can not be fixed because of a gap in the data between 4 and 10 percent TIA. They appear to have a slight dominance in the 10-15 percent TIA range, following which dominance switches to the trout. Lucchetti and Fuerstenberg (1993) earlier found a similar trend of decreasing coho abundance with increasing imperviousness in a partially overlapping set of King County creeks.

Habitat Conditions in Relation to Watershed and Riparian Characteristics

This discussion considers the direct linkages between the source and physical and chemical habitat components of the system:

Watershed and riparian characteristics – **Habitat conditions** – Biota

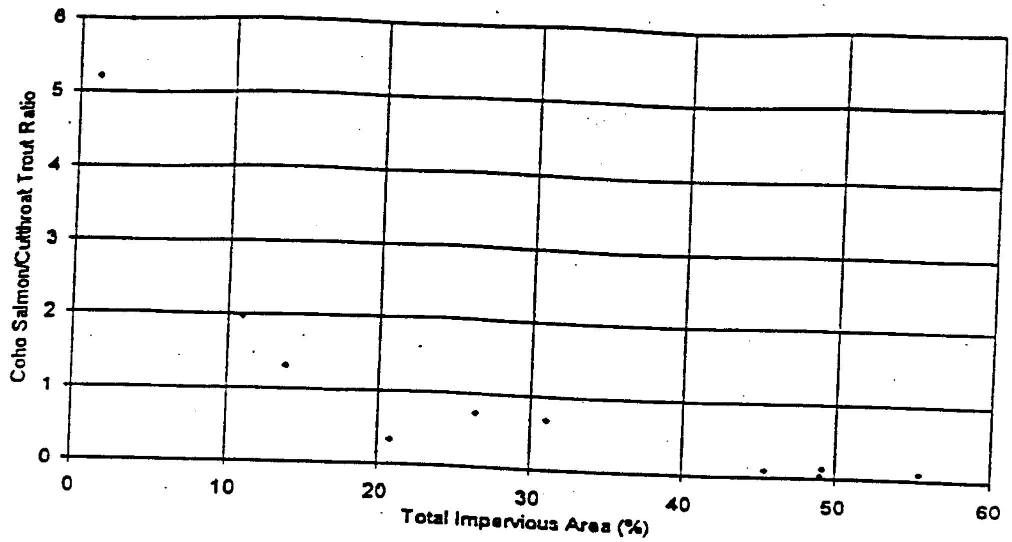

Figure 2. — Ratio of Coho Salmon to Cutthroat Trout in Puget Sound Lowland Streams Over a Gradient of Watershed Impervious Land Cover

Water quality was examined in wet and dry season base flow and during runoff from small (0.6-1.2 cm precipitation), medium (1.2-1.8 cm), and large (> 1.8 cm) rain storms. Figure 3 illustrates a representative result, showing total zinc concentrations versus TIA for all three storm sizes. Also shown are acute and chronic criteria for protection of aquatic life for the hardness prevailing in these streams. The concentration was well below both criteria under all conditions until TIA rose above 40 percent. The gaps between measured concentrations and regulatory criteria were even greater for other metals. The distributions of storm flow concentrations were similar for total suspended solids and other contaminants. Base flow concentrations were generally lower. It does not appear that measured water quality effects are strongly associated with the biological responses seen with rather small impervious proportions in Figures 1 and 2.

Figure 4 plots sediment zinc concentrations over the % TIA gradient. All were below the "lowest effect threshold" of the Washington Department of Ecology (1991) freshwater sediment criteria and far below the "severe effect threshold." The low measured concentrations relative to advisory or regulatory criteria were found with other metals as well. As with water quality, it appears that sediment quality does not change appreciably until urbanization reaches the vicinity of 50 percent impervious. Again, there is no sign of a strong association between sediment quality and the biological changes that occur much earlier during the onset of urbanization.

See rd paper for question.

In contrast to the absence of associations between water and sediment quality with relatively low and moderate levels of urbanization, increasing hydrologic fluctuation seems to be an early harbinger of rising impervious cover. Discharge

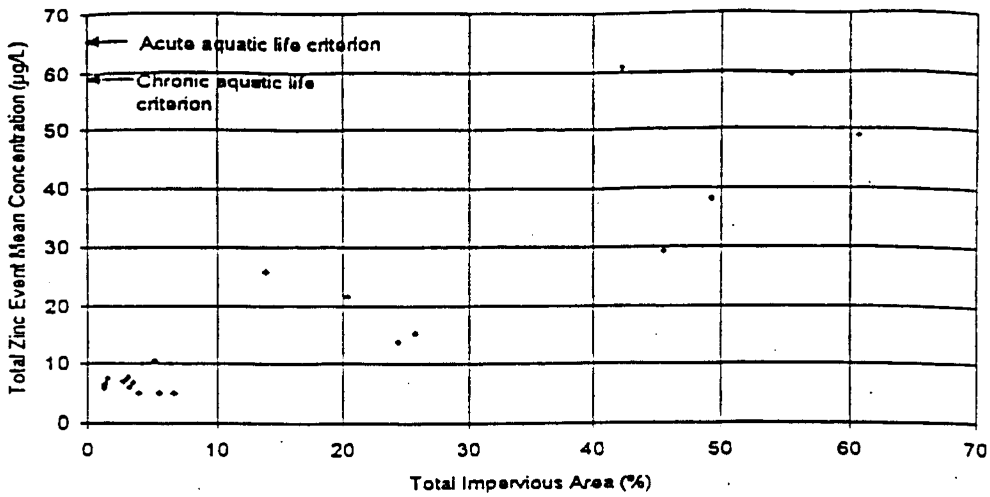

Figure 3. — Total Zinc Event Mean Concentrations in Puget Sound Lowland Streams During Storm Runoff Over a Gradient of Watershed Impervious Land Cover

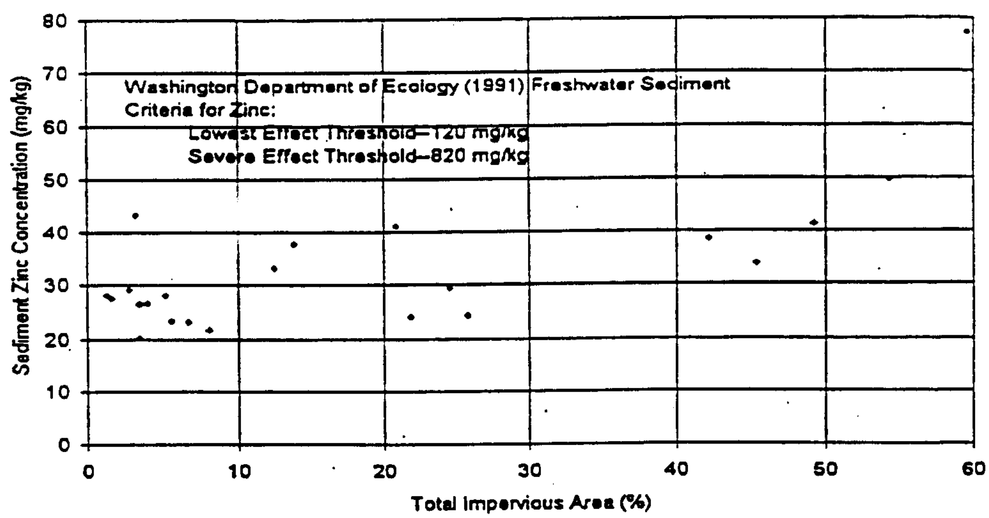

Figure 4. — Zinc Concentrations in Puget Sound Lowland Stream Sediments Over a Gradient of Watershed Impervious Land Cover

records were modeled using either: (1) the Hydrologic Simulation Program-FORTRAN (HSPF) continuous simulation computer program; (2) "runoff files" generated from regional data and HSPF runs (King County Surface Water Management Division 1995); or (3) multiple regression analyses to determine an unknown discharge from a known one in terms of relative catchment areas, % TIA, mean annual precipitation, and proportion of catchment with till soils (Cooper 1996). Modeling results were compared to values from stream gauge records where available. Figure 5 illustrates the available results in the form of a plot of the ratio of the 2-year frequency peak to the winter (wet season) base flow versus % TIA.

The ratio expresses the relative stream power, and thus physical stress on habitats and biota, exerted by storm runoff in relation to interevent conditions. The ratio is consistently < 20 with TIA < 15 percent, mostly 20-30 with TIA = 20-40 percent, and usually above 40 thereafter.

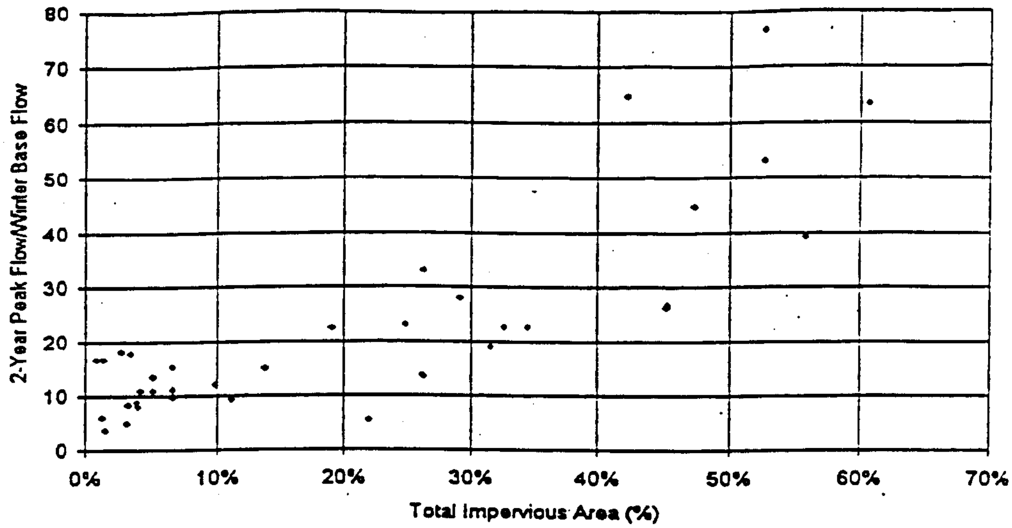

Figure 5. — Ratio of 2-Year Peak Flow to Winter Base Flow in Puget Sound Lowland Stream Sediments Over a Gradient of Watershed Impervious Land Cover

Several other habitat features have been related to urbanization as expressed by impervious cover. Figure 6 shows, for example, the results for large woody debris quantity. This feature is particularly important in Northwest streams, providing roughness that regulates velocities, cover to fish, and aid in forming pools in which fish feed and rest (McMahon and Hartman 1989). LWD more numerous than 300 pieces/km never occurred when TIA was more than 9 percent, with two exceptions where, respectively, wood was added to the channel in a habitat improvement project and a culvert prevents wood movement downstream. Numbers were alway: below 100/km with TIA > 40 percent. As a second example, not illustrated, the proportion of fines (< 0.85 mm) in the stream bed surface (top 10 cm) did not exceed 16 percent until TIA went above 20 percent. Values were in the range 22-27 percent fines with TIA at 45 percent or above, except where flushed by high flows.

A major reason, probably the leading one, for the death of salmonid embryos in the egg is ineffective dissolved oxygen (DO) interchange through fines that cover the spawning grounds. Measurement of both water column and intragravel DO gave the opportunity to assess this risk in relation to urbanization, as pictured in Figure 7. The ratio of intragravel to water column DO was above 90 percent in about hal of the cases where TIA was 5 percent or less and above 80 percent for all but one c the remainder. Values generally fell below 70 percent above 10 percent TIA, but some reaches with more riparian protection exhibited more effective DO interchange. At TIA above 40 percent all ratios were below 70 and fell as low as 30 percent.

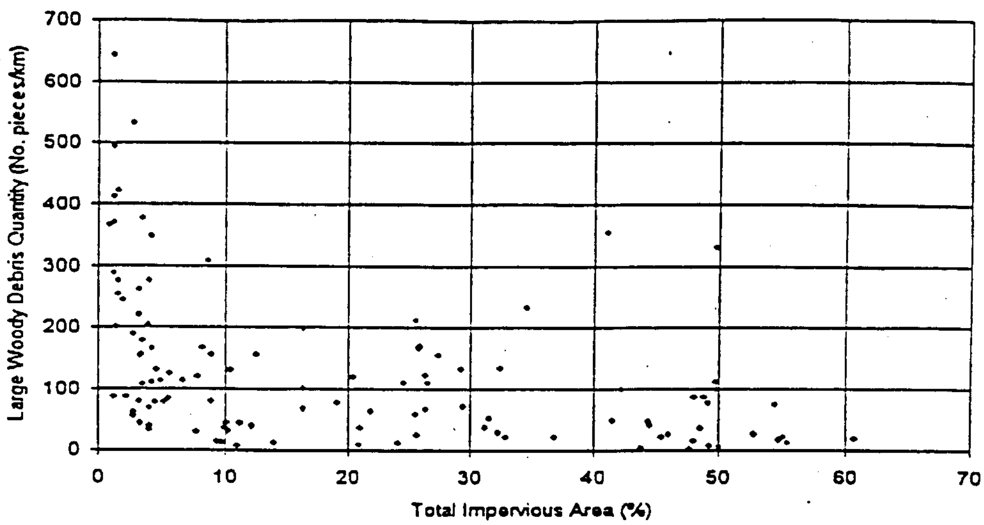

Figure 6. — Large Woody Debris Quantity in Puget Sound Lowland Stream Sediments Over a Gradient of Watershed Impervious Land Cover

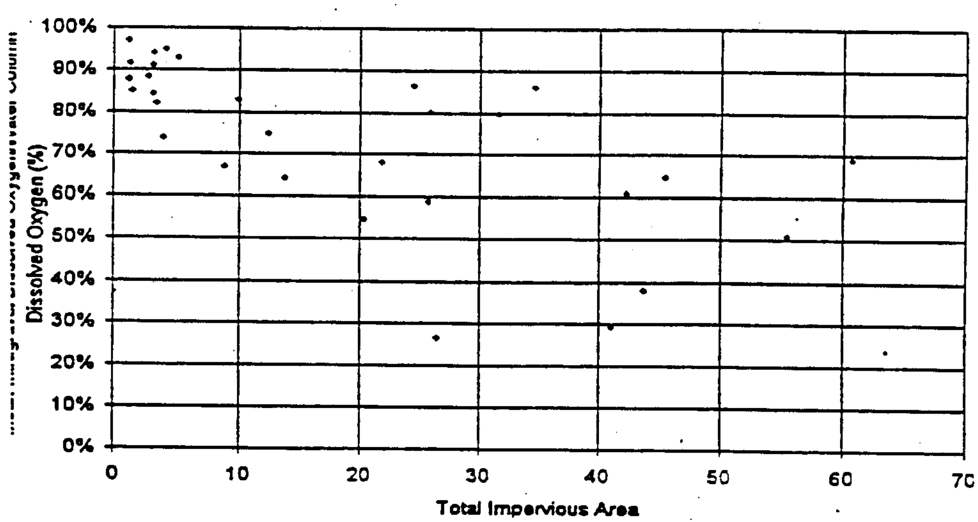

Figure 7. — Ratio of Intragravel to Water Column Dissolved Oxygen in Puget Sound Lowland Stream Sediments Over a Gradient of Watershed Impervious Land Cover

Stream Biology in Relation to Habitat Conditions

Given that relationships were identified between biological communities and contributing catchment conditions and between those conditions and habitat attributes, it is reasonable to suppose that associations of similar form exist between habitat conditions and biology. This discussion explores those linkages:

Watershed and riparian characteristics — **Habitat conditions** — **Biota**

Figure 8 illustrates how B-IBI varies in relation to the ratio of 2-year peak flow to winter base flow. All indices of 35 or above were found in reaches where the hydrologic ratio was below 20. With ratios of 39 and above all but one B-IBI value was less than 20.

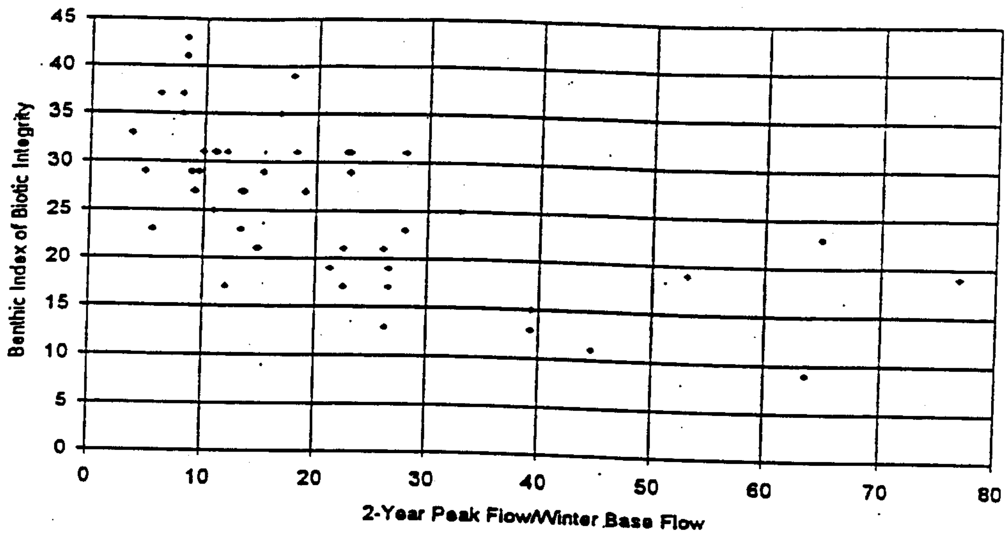

Figure 8. — Benthic Index of Biotic Integrity in Relation to Ratio of 2-Year Peak Flow to Winter Base Flow in Puget Sound Lowland Streams

Figure 9 shows the influence of the riparian zone on the biotic index. The highest indices (>/= 35) were all found where at least 60 percent of the riparian buffer zone upstream of the sampling point was at least 30 meters wide, and the lowest (< 20) where less than 50 percent of the buffer was that wide.

Also investigated, but not shown, was B-IBI versus percent fines (< 0.85 mm) in the bed substratum. All indices >/= 35 were consistent with no more than 15 percent fines, whereas reaches with 22 percent or more fines all had B-IBI < 20. The benthos thus appear to be quite sensitive to a relatively small alteration of the substratum.

Finally, Figure 10 shows B-IBI and coho salmon/cutthroat trout ratio in relation to a Qualitative Habitat Index. This index was derived by assigning scores of 1-4 to 15 attributes and summing (May 1996). Coho salmon dominance is consistent with B-IBI > 35 and a habitat index > 50. At the other extreme, cutthroat trout dominance is absolute with B-IBI under 20 and habitat index less than 40.

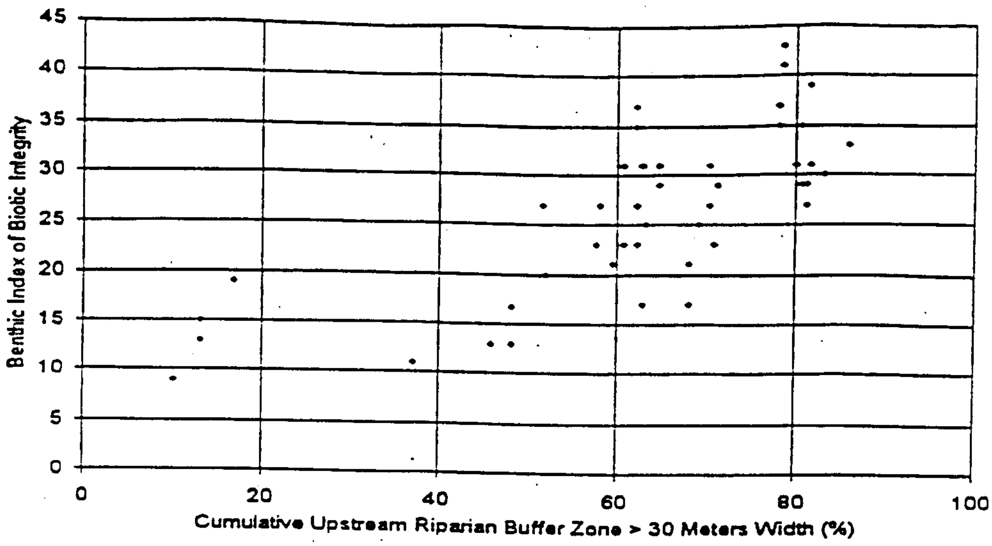

Figure 9. — Benthic Index of Biotic Integrity in Relation to Cumulative Upstream Riparian Zone Width in Puget Sound Lowland Streams

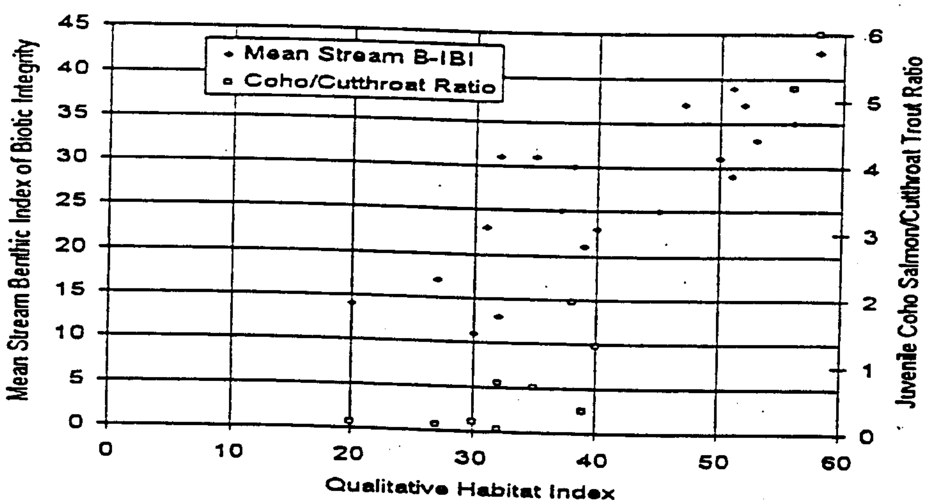

Figure 10. — Benthic Index of Biotic Integrity and Coho/Cutthroat Trout Ratio in Relation to Qualitative Habitat Index in Puget Sound Lowland Streams

WETLANDS RESEARCH

Wetland Biology in Relation to Habitat Conditions

This discussion considers observed linkages between WLF and key elements of wetland biological communities:

Watershed and riparian characteristics – **Habitat conditions** – **Biota**

As in the stream study, water pollutant concentrations were generally well below levels known to have direct biological effects, thus raising the relative significance of hydrology further (Reinelt and Horner 1990). The widely recognized primacy of hydroperiod (inundation pattern, specifically its depth, frequency, and duration) as a determinant of wetland ecosystem character (Mitsch and Gosselink 1993) produced an interest in finding a convenient means of measuring and expressing hydroperiod and investigating its relationship to biological communities on the one hand and attributes of contributing watersheds on the other. Instantaneous and crest (maximum since preceding measurement) water level readings were taken and used in computing water level fluctuation (WLF) as the difference between the crest and the average instantaneous depth in a time period (Azous 1990, Taylor 1993).

Plant species richness (number of species represented) was found to decline with increased mean annual WLF in the emergent (Figure 11) and scrub-shrub zones (not shown). Richness differed significantly (Mann-Whitney test, $p < 0.002$) between areas with mean annual WLF above and below 22 cm in both zones. No emergent areas had more than 14 species if WLF exceeded 22 cm, whereas 30 percent of the areas with WLF < 22 cm had at least 16 species. In the higher WLF group 33 percent had five or less species, in contrast to only 8 percent in the group subject to less fluctuation. Very similar distinctions pertained to scrub-shrub zones.

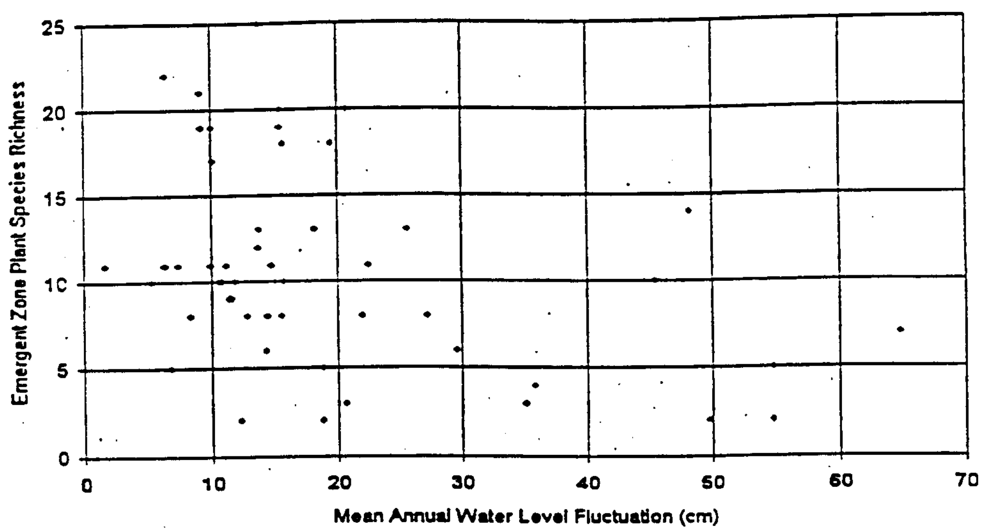

Figure 11. — Emergent Zone Plant Species Richness in Relation to Mean Annual Water Level Fluctuation in Puget Sound Lowland Wetlands

Being restricted to wetlands for reproduction, amphibians represent a biological indicator useful in assessing wetland condition. Figure 12 graphs richness in this community during the baseline years of the study versus mean annual WLF and presents a picture similar to the plant community. Of the wetlands with WLF < 22 cm, 62 percent had five or more species, and all had at least three. Of the wetlands in the group with WLF >/= 22 cm, 83 percent had four or less species. In later years amphibians declined in all wetlands, whether affected by urbanization or not. The reason for this decline is not known but may be the result of natural variation, meteorological effects, or human-induced stress other than urbanization. Over all years, 83 percent of wetlands with mean annual WLF < 22 cm averaged three or more species, while 73 percent with WLF at or above this level had two or fewe species.

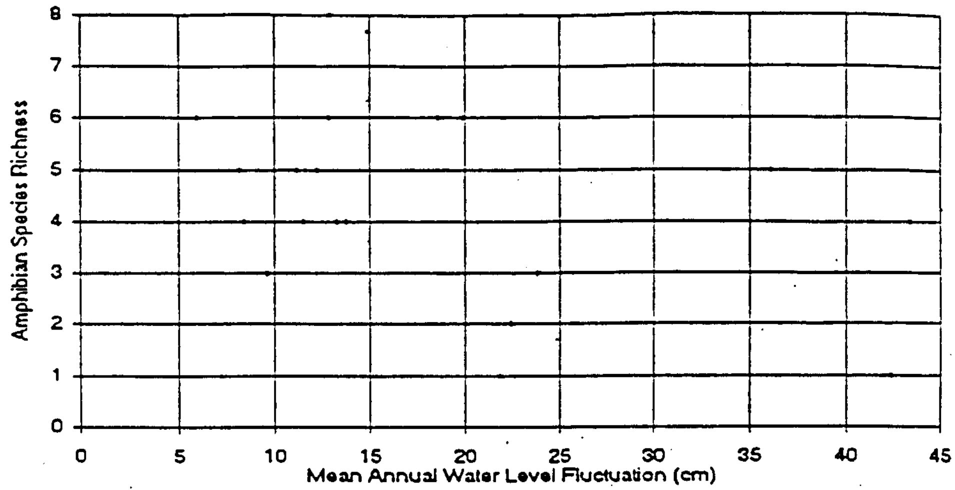

Figure 12. — Amphibian Species Richness in Relation to Mean Annual Water Level Fluctuation in Puget Sound Lowland Wetlands

The patterns of decline of species richness for both plants and amphibians exhibi continuous rather than threshold response to water level fluctuation. Still, the po... at about WLF = 22 cm seems to represent a boundary of tolerance in both communities, above which substantially fewer species tolerate the more dynamically fluctuating environment.

Wetland Habitat Conditions and Biology in Relation to Watershed Conditions

With respect to linkages between habitat and watershed conditions:

Watershed characteristics	**–**	**Habitat conditions**	**–**	Biota

WLF was found to have a relationship to urbanization. All watersheds with < 5.5 percent TIA had mean WLF in the two periods 1988-1990 and 1993-1995 no higher than 21 cm. With TIA > 21 percent, WLF exceeded this level in 89 percent of the cases.

Not surprisingly in light of these results and those reported earlier, watershed and biological connections were also established:

Watershed characteristics	**–**	Habitat conditions	**–**	**Biota**

Amphibians responded negatively to urbanization in a pattern similar to the variation of WLF with imperviousness (Figure 13). Of the instances of highest amphibian richness (5 or more species), all were in watersheds with 22 percent or less impervious area, and 78 percent had watersheds with TIA < 6 percent. Another observation for this group of wetlands, although not graphed, was that watershed forest cover was at least 35 percent in 88 percent of the cases.

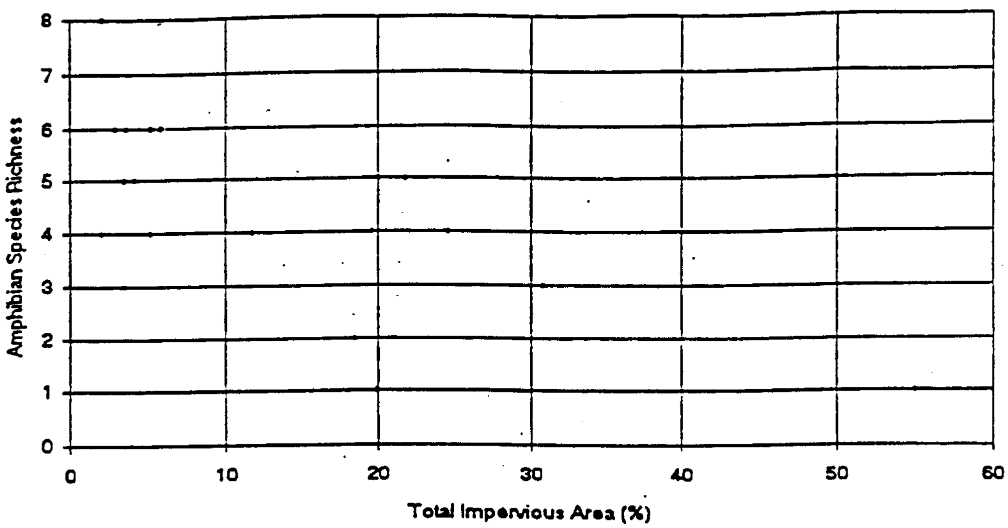

Figure 13. — Amphibian Species Richness in Puget Sound Lowland Wetlands Over a Gradient of Watershed Impervious Land Cover

Conclusions and Implications for Watershed Management

Research in representative sets of Puget Sound lowland streams and wetlands has shown that a host of physical habitat and biological characteristics change with increasing urbanization in a continuous rather than threshold fashion. Although the patterns of change differ among the attributes studied and are more strongly evidenced for some than for others, physical and biological measures generally were seen to change most rapidly from levels lightly affected by urbanization as total impervious area increased to 5-8 percent. With greater urbanization, the rate of alteration of habitat and biology usually slowed. There was direct evidence in both stream and wetland cases that altered watershed hydrology was at the source o the overall changes observed.

Water quality measures and concentrations of metals in sediments did not follow this pattern. They did not change much over the urbanization gradient until imperviousness approached 50 percent. Even then water column concentrations di not surpass aquatic life criteria, and sediment concentrations remained far below freshwater sediment criteria.

Thus, physical and biological change were seen to start early, almost immediately, in the urbanization process. Chemical pollutants did not exhibit a role in these early stages. They may not even have a large role at the intermediate levels represented in these studies, still being below regulatory criteria. Of course, for various reasons these criteria may not provide a realistic basis for judgment in t dynamic urban runoff environment. As urbanization increases above the 60 perc. impervious level, with pollutant concentrations rising rapidly at that point, it is likely that the role of water and sediment chemistry will become more important biologically.

It is clear that biological community alterations in urban streams and wetlands are functions of many variables representing conditions in the immediate and more remote surroundings. In addition to urbanization level, a key determinant of biological condition appears to be the integrity of the riparian area available to buffer the aquatic community, in some measure, from negative influences in the watershed. The involvement of these numerous variables throughout the wider system shows the wisdom of moving to the watershed level to consider how to manage aquatic systems.

From the research results there appears to be a set of necessary, though not by themselves sufficient, conditions for the highest level of biological functioning. If maintenance of that level is an adopted goal, then this set of conditions constitutes standards that must be achieved if the goal is to be met. Using Puget Sound area lowland streams as an example, if that level is taken to be a B-IBI of at least 35, TIA must be < 5 percent, unless mitigated by extensive riparian protection, management efforts, or both. Some of the specific conditions that must be met would be:

- 2-year peak flow/winter baseflow < 20;
- > 60 percent of upstream buffer > 30 meters wide; and
- < 15 percent of surface bed material < 0.85 mm.

This set will be enlarged and refined as data analysis proceeds. Other sets of conditions could, and will, be similarly established for other biological goals.

To assess what these observations mean for watershed management, it may be useful to generalize the observed pattern of physical habitat and biological change with urbanization and consider what management objectives and challenges would most likely apply in different situations (Figure 14). In the broad region on the right side of the graph, some of the original resource base has been lost. Attempting to recover it, even if possible, would require large reductions in or compensations for urban land use. Thus, dramatic ecological restoration would be extremely challenging. The principal management objective in this situation should properly be stemming decline. Fortunately, with the relatively slow rate of change here, the system is likely to be more "forgiving" of change than in the region to left. Holding the line can be successful if changes with negative tendencies are compensated by actions that maintain the overall status in about the same position. Another management objective should be to use any available opportunities to enhance the ecosystem structure and functioning. One of the leading strategies, on the basis of both its feasibility and probably effectiveness, should be to protect the riparian zone and, whenever possible, acquire riparian property and return it to a natural condition.

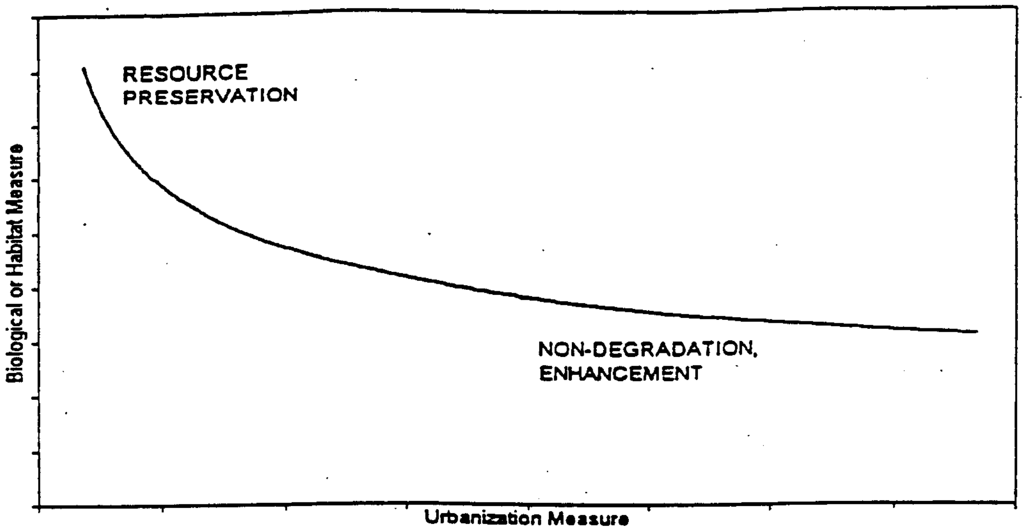

Figure 14. — General Pattern of Physical Habitat Characteristics in Puget Sound Lowland Streams and Wetlands Over a Gradient of Urbanization, with Regions Representing Different Watershed Management Objectives and Challenges

In the region on the left of the graph, resources have not been substantially affected and are likely to be highly valued. Here, a relatively small modification outside of the aquatic system is likely to create a proportionately bigger change within. The management objective would probably be to preserve the resources. Accomplishing this objective would require intense management to control the amount and location of impervious surfaces, maintain existing runoff storage capacity, prevent disruption of riparian areas, and the like, a very difficult challenge technically, and perhaps even more so, politically. The only way to meet such an objective is through strong preservation and regulation that allows very little and only certain types of watershed alteration. Implementing this program may be possible only with extensive property-owner incentives, government purchase of a large portion of the contributing catchment, transfer of development rights to an already highly degraded watershed, or some combination. Obviously, government could not movi in such a fashion, nor justify the political and economic costs, without a strong casi for the value of the resource thereby saved.

References

Alley, W. A. and Veenhuis, J. E., "Effective Impervious Area in Urban Runoff Modeling," *Journal of Hydrological Engineering, ASCE* 109(2):313-319, 1983.

Barker, B. L., Nelson, R. D., and Wigmosta, M. S., "Performance of Detention Ponds Designed According to Current Standards," *Proceedings of the Puget Sound Research '91 Conference*, Puget Sound Water Quality Authority, held at Seattle, WA, 1991, pp. 64-72.

Bisson, P. A., Sullivan, K., and Nielsen, J. L., "Channel Hydraulics, Habitat Use, and Body Form of Juvenile Coho Salmon Steelhead, and Cutthroat Trout in Streams," *Transactions of the American Fisheries Society* 117:262-273, 1988.

Booth, D. B., "Stream Channel Incision Following Drainage Basin Urbanization," *Water Resources Bulletin* 26(3):407-417, 1990.

Booth, D. B., "Urbanization and the Natural Drainage System--Impacts, Solutions, and Prognosis," *Northwest Environmental Journal* 7:93-118, 1991.

Booth, D. B. and Jackson, C. R., "Urbanization of Aquatic Systems--Thresholds and the Limits of Mitigation," *Proceedings of the Symposium on Effects of Human-Induced Changes in Hydrologic Systems*, held at Jackson Hole, WY, 1994, pp. 425-434.

Booth, D. B. and Reinelt, L. E., "Consequences of Urbanization on Aquatic Systems--Measured Effects, Degradation Thresholds, and Corrective Strategies," *Proceedings of the Watersheds '93 Conference*, U. S. Environmental Protection Agency, held at Alexandria, VA, 1994, pp. 545-550.

Bryant, J., "The Effects of Urbanization on Water Quality in Puget Sound Lowland Streams," thesis presented to the University of Washington, at Seattle, WA, in 1995, in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering.

Cooke, S. S., "The Effects of Urban Stormwater on Wetland Vegetation and Soils," *Proceedings of the Puget Sound Research '91 Conference*, Puget Sound Water Quality Authority, held at Seattle, WA, 1991, pp. 43-51.

Cooper, C., Untitled thesis to be presented to the University of Washington, Seattle, WA, in 1996, in partial fulfillment of the requirements for the degree of Masters of Science.

Fore, L. S., Karr, J. R. and Wisseman, R., "A Benthic Index of Biotic Integrity for Streams in the Pacific Northwest," *Journal of the North American Benthological Society*, in review.

Horner, R. R., Skupien, J. J., Livingston, E. H., and Shaver, H. E., *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, Terrene Institute, Washington, D. C., 1994.

Karr, J. R., "Assessment of Biotic Integrity Using Fish Communities," *Fisheries* 6(6), 1981.

Karr, J. R., "Biological Integrity: A Long Neglected Aspect of Water Resources Management," *Ecological Applications* 1(1):66-84, 1991.

Karr, J. R. and Dudley, D. R., "Ecological Perspective on Water Quality Goals," *Environmental Management* 5:55-68, 1981.

Karr, J. R., Fausch, K. D., Angermier, P. L., Yant, P. R., and Schlosser, I. J., "Assessing Biological Integrity in Running Waters: A Method and Its Rationale," Special Publication 5, Illinois Natural History Survey, Urbana, IL, 1986.

Kerans, B. L. and Karr, J. R., "A Benthic Index of Biotic Integrity (B-IBI) for Rivers of the Tennessee Valley," *Ecological Applications* 4(4):768-785, 1994.

King County Resource Planning Section, "Detailed Planning of the Puget Sound Wetlands and Stormwater Management Research Program," King County Resource Planning Section, Seattle, WA, 1987.

King County Resource Planning Section, "Puget Sound Wetlands and Stormwater Management Research Program: Initial Year of Comprehensive Research," King County Resource Planning Section, Seattle, WA, 1988.

King County Surface Water Management Division, "King County Runoff Time Series (KCRTS), Version 3.0, Computer Software Reference Manual," King County Department of Public Works, Seattle, WA, 1995.

Klein, R. D., "Urbanization and Stream Quality Impairment," *Water Resources Bulletin* 15:948-963, 1979.

Kleindl, W., "A Benthic Index of Biotic Integrity for Puget Sound Lowland Streams," thesis presented to the University of Washington, Seattle, WA, in 1995, in partial fulfillment of the requirements for the degree of Masters of Science.

Lucchetti, G. and Fuerstenberg, R., "Relative Fish Use in Urban and Non-urban Streams," *Proceedings of the Conference on Wild Salmon*, Vancouver, B. C., Canada, 1993.

May, C., "Assessment of Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion: Implications for Salmonid Resource Management," dissertation to be presented to the University of Washington, Seattle, WA, in 1996, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

McMahon, T. E. and Hartman, G. F., "Influence of Cover Complexity and Current Velocity on Winter Habitat Use by Juvenile Coho Salmon," *Canadian Journal of Fisheries and Aquatic Sciences* 46:1551-1557, 1989.

Mitsch, W. J. and Gosselink, J. G., *Wetlands*, 2nd Ed., Van Nostrand Reinhold, New York, NY, 722 pages.

Nehlsen, W., Williams, J., and Lichotowish, J., "Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho, and Washington," *Fisheries* 16(2):4-21, 1991.

Nickelson, T. E., Rodgers, J. D., Johnson, S. L., and Solazzi, M. L., "Seasonal Changes in Habitat Use by Coho Salmon in Oregon Coastal Streams," *Canadian Journal of Fisheries and Aquatic Sciences* 49:783-789, 1992.

Olthof, J. "Puget Sound Lowland Stream Habitat and Relations to Basin Urbanization," thesis presented to the University of Washington, Seattle, WA, in 1994, in partial fulfillment of the requirements for the degree of Masters of Science.

Perkins, M. A., "An Evaluation of Instream Ecological Effects Associated with Urban Runoff to a Lowland Stream in Western Washington, U. S. Environmental Protection Agency, Washington, D. C., 1982.

Plafkin, J. L., Barbour, M. T., Porter, K. D., Gross, S. K., and Hughes, R. M., "Rapid Bioassessment Protocols for Use in Streams and Rivers: Benthic Macroinvertebrates and Fish," EPA 440-4-89-001, U. S. Environmental Protection Agency, Washington, D. C., 1989.

Prych, E. A. and Ebbert, J. C., "Quantity and Quality of Storm Runoff from Three Urban Catchments in Bellevue, Washington," Water Resources Investigations Report 86-4000, U. S. Geological Survey, Tacoma, WA, 1986.

Reinelt, L. E. and Horner, R. R., "Characterization of the Hydrology and Water Quality of Palustrine Wetlands Affected by Urban Stormwater," King County Resource Planning Section, Seattle, WA, 1990.

Reinelt, L. E. and Horner, R. R., "Urban Stormwater Impacts on the Hydrology and Water Quality of Palustrine Wetlands in the Puget Sound Region," *Proceedings of the Puget Sound Research '91 Conference*, Puget Sound Water Quality Authority, held at Seattle, WA, 1991, pp. 33-42.

Richey, J. S., "Effects of Urbanization on a Lowland Stream in Western Washington," dissertation presented to the University of Washington, Seattle, WA, in 1982, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Richter, K. O. and Azous, A. L., "Amphibian Occurrence and Wetland Characteristics in the Puget Sound Basin, " *Wetlands* 15(3):305-312, 1995.

Scott, J. B., Steward, C. R., and Stober, Q. J., "Effects of Urban Development on Fish Population Dynamics in Kelsey Creek, Washington," *Transactions of the American Fisheries Society* 115:555-567, 1986.

Shaver, E. Maxted, J., Curtis, G., and Carter, D., "Watershed Protection Using and Integrated Approach," *Stormwater NPDES Related Monitoring Needs*, H. C. Torno, ed., American Society of Civil Engineers, New York, NY, 1995, pp. 435-459.

Steward, C. R., "Salmonid Populations in an Urban Stream Environment," thesis presented to the University of Washington, Seattle, WA, in 1983, in partial fulfillment of the requirements for the degree of Masters of Science.

Taylor, B. L., "The Influence of Wetland and Watershed Morphological Characteristics on Wetland Hydrology and Relationships to Wetland Vegetation Communities," thesis presented to the University of Washington, Seattle, WA, in 1993, in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering.

Washington Department of Ecology, "Summary of Criteria and Guidelines for Contaminated Freshwater Sediments," Washington Department of Ecology, Olympia, WA, 1991.

Wigmosta, M. S., Burges, S. J., and Meena, J. M., "Modeling and Monitoring to Predict Spatial and Temporal Hydrologic Characteristics in Small Catchments," U. S. Geological Survey Water Resources Technical Report Number 137, 1994 223 pp.

Yoder, C., "The Integrated Biosurvey as a Tool for Evaluation of Aquatic Life Us Attainment and Impairment in Ohio Surface Waters," *Biological Criteria: Research and Regulation*, U. S. Environmental Protection Agency, Washi - D. C., 1991, pp. 110-122.

EFFECTS OF WATERSHED DEVELOPMENT AND MANAGEMENT ON AQUATIC ECOSYSTEMS

Proceedings of an Engineering Foundation Conference

Edited by Larry A. Roesner

Conference Chairs

Earl Shaver
Delaware Department of Natural Resources and Environmental Control
and
Richard Horner, Ph.D.
University of Washington

and

Conference Co-Chairs

Michael E. Cook, Director, Office of Wastewater Management
U.S. Environmental Protection Agency

and

Christine Anderson
Director of Public Works, Eugene, Oregon

Conference Co-Sponsors

Urban Water Resources Research Council of Civil Engineers
American Public Works Association
U.S. Environmental Protection Agency

August 4-9, 1996
Snowbird Resort and Conference Center
Snowbird, Utah

Approved for publication by the ASCE Water Resources Planning and Management Division

Published by the
ASCE American Society of Civil Engineers
345 East 47th Street