Consequences of Urbanization on Aquatic Systems—Measured Effects, Degradation Thresholds, and Corrective Strategies

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Urbanization imposes a variety of watershed changes that profoundly affect runoff processes and the downstream surface-water drainage system. These changes include not only the most obvious manifestation of urban development, namely impervious surfaces that cover the land, but also the associated vegetation clearing, soil compaction, water-conveyance modifications, riparian-corridor alterations, human intrusion, and import of chemical contaminants that invariably accompany such development. These pervasive, landscape-level changes commonly affect virtually all areas of an urban watershed.

Downstream channels reflect these watershed changes in a variety of ways. Increases in peak flows have been best documented, with the discharge of floods of a given recurrence interval typically increasing by factors of about 2 to 5. Recent, more sophisticated monitoring and numerical modeling of urbanizing drainage basins show that the duration of any given flood discharge, summed over the time period of gage record or simulation, may increase by an order of magnitude. Such modeling also shows that the frequency of "large" flows, recognized by the discharge necessary to accomplish significant erosive work on the channel form, may increase by nearly two orders of magnitude—from once or twice per decade to several times per year (Booth, 1991).

Physical conditions in channels also change as a result of urbanization. Some of those changes are a direct consequence of development and human habitation—riparian corridors are cleared, channels are straightened, and logs are removed from channels in the name of tidiness or for firewood. Other changes result from the increase in flows delivered from the upstream basin. These flows transport more sediment as a result of increased flow durations and accomplish more channel erosion as a result of the increased frequency of large floods. Geomorphic work on the channel is increased even as the resistance of the channel to that work, typically derived from the roughness and armoring properties of bank vegetation and large woody debris, is reduced. Urban channels are therefore deeper, wider, and commonly incised; they are also more homogenous with little of the morphological variability, such as alternating pools and riffles, that characterizes channels in more undisturbed settings.

The chemical composition of urban storm water also differs, sometimes dramatically, from predevelopment conditions. Although measured data vary widely between systems, increases of up to one order of magnitude are typical for most pollutant classes, including solids, nutrients, metals, and bacteria. Construction-phase impacts can be particularly severe on stream systems and wetlands with small drainage areas.

In summary, landscape alteration affects aquatic system function, primarily

by the physical processes of reduced soil-moisture storage by compaction and paving, direct human intrusion into streams and wetlands, and import of pollutants. In recognition of these dominant processes, we have collected sets of physical, chemical, and biological data from a wide variety of lowland streams and wetlands in King County, western Washington State. We seek both a threshold of significant aquatic system degradation, which appears from our data to occur at a rather well-defined level of urbanization, and insight into the processes by which that degradation occurs. Only with such insight are subsequent efforts at mitigation or protection likely to be successful.

Choice of Parameters and Methods of Data Collection

We have chosen to consider data from both streams and wetlands because these two classes of aquatic features are intimately interconnected in the watersheds of western Washington. The *structure* of these features is evaluated through measurement of physical parameters, such as bankfull width and depth for channels, or fluctuations in water level and water chemistry for wetlands. The *function* of these aquatic systems is measured by biological utilization, which is judged to integrate the suite of urban induced effects and to provide the best aggregate measures of "quality" or "degradation." We have evaluated biological parameters quantitatively by species and population counts, and more qualitatively by rapid field assessment of habitat quality.

Urbanization is similarly diverse in characterization. Several parameters have been used by past workers (e.g., percentage of area urbanized, percentage of area served by storm sewers); all are strongly cross-correlated, and so to some extent the choice is a matter of personal preference. We have elected to cast all data in terms of the percentage impervious area in a watershed, using typical impervious-area ratios for individual land uses; this parameter can be unequivocally measured and is particularly well correlated with the runoff processes that we judge are most significant. We also have independently measured conditions of the riparian corridor because these areas are directly connected to aquatic systems and because many jurisdictions are actively regulating these zones independent of broader, watershed-level controls.

Correlations Between Urbanization and Aquatic System Function

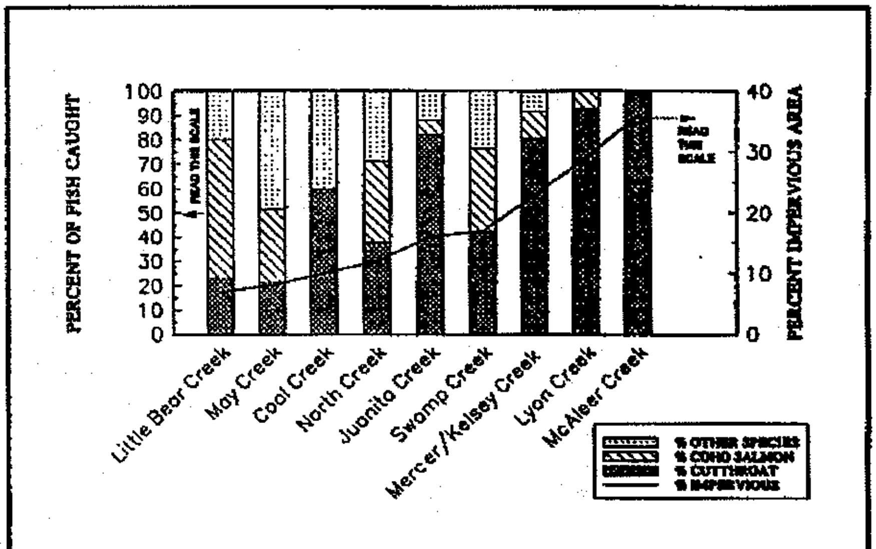
In aggregate, the physical changes imposed by urban development on the landscape result in a decline in function of aquatic systems. This fact is evident to any resident of such a watershed; similarly intuitive is the observation that degradation increases as development progresses. However, it is much more difficult to quantify decline in function and identify its relationship with upstream urbanization.

We have sought such a relationship by use of both new and existing data, relying heavily on biological indicators of stream and wetland function. Fish use in streams has been investigated directly by Lucchetti and Fuerstenberg (1993), who considered the differences in relative abundance between two species of salmon, cutthroat trout (*Onchorynchus clarki*) and coho salmon (*O. kisutch*), that have significantly different life cycles and habitat requirements. Cutthroat trout are tolerant of small-sized and relatively homogenous habitat; coho salmon, in contrast, require a varied physical environment that includes large pools and a stable substrate. Figure 1 shows the relationship between populations and watershed impervious-area percentages for eight similarly sized drainage basins in western Washington (ranging in drainage area from 10 to 30 km^2). The data show little in the way of a discrete "threshold" but indicate that population changes may be measurable at rather low levels of urban development and become quite significant much beyond 10-15 percent.

Similarly, the relationship between fish habitat and urban development was evaluated by rapid field assessment along 140 km of stream channel in two drainage basins (Soos and Hylebos Creeks) in King County. Habitat was classified as excellent, fair, or poor on the basis of pool:riffle ratio, channel roughness and diversity, and observed fish use. The total contributing area and impervious-area percentage of the watershed above each channel reach was measured, with total areas ranging from 2 to 110 km^2 and impervious areas ranging from 2 to 50 percent. The results are graphed in Figure 2; marked degradation occurs at about 8-10 percent impervious area with almost no exceptions on either side of that value.

Data collected from 19 wetlands throughout King County (Reinelt and Horner, 1991; Richter et al., 1991) suggest a similar pattern. Wetland function was characterized by measurement of hydrology, water quality, soils, plants, and animals in these wetlands from 1988 to 1990. Water-level fluctuation (WLF) was chosen as the primary measure of hydrology because it integrates numerous factors governing wetland hydrology, including wetland-to-watershed area ratios, level of watershed development, wetland morphometry, outlet conditions, and soils. Mean WLF was used in this analysis because it is less influenced by evaporation and summer drying. Water quality analyses examined 21 variables, including nutrients, metals, and bacteria, with a majority of samples collected during the wet (November-February) and dry (July-September) seasons; conductivity, total suspended solids (TSS), and fecal coliforms (FC) showed the greatest systematic variation (Reinelt and Horner, 1991). The diversity and abundance of amphibians, collected in pitfall traps and supplemented by egg-mass observations, were used to characterize animal use in wetlands (Richter et al., 1991).

The five variables noted above (WLF, conductivity, TSS, FC, and amphibian species) were used to compare wetland function with percentage impervious area in the wetland watersheds. Each variable was scored from 0 to 100, where 0 represented the least degraded value in the entire data set and 100 the most degraded value. Other scores were assigned proportionally between these two extremes. A "water quality" score was calculated as the mean of the three water quality variables; it was then averaged with WLF and amphibian scores (Figure 3). These data support the intuitive knowledge that increased levels of urban development yield increased degradation, although this particular data set is deficient in impervious-area percentages between 4 and 14 percent. With one exception (JC28, with only moderate water quality degradation and almost no WLF as a result of exceptionally permeable watershed soils and a very stable regional ground-water table), all wetlands with impervious-area



Source: Adapted from Lucchetti and Fuerstenberg, 1993.

Figure 1. Relative fish use, King County streams.

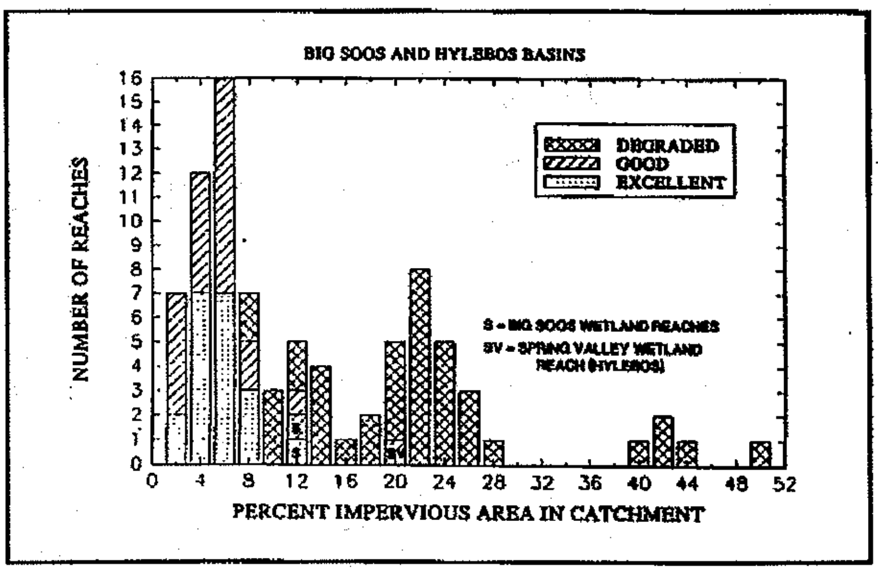


Figure 2. Quality of observed fish habitat.

percentages above 14 percent had scores greater than 50 percent, whereas those below 4 percent had scores below 40.

Causal Relationships Between Development and Function

Although the above examples clearly display a linkage between aquatic system function and urban development, they do not offer much insight into the causal relationship(s) between the likely vectors of urban impacts (e.g., flow, water quality, physical intrusion) and the resulting changes in function. To achieve such insight, we must seek data that successfully isolate the effects of one urban development parameter from all others. To date, our information is largely restricted to measures of flow quantity, channel size, and condition of the riparian corridor; but additional investigation of water chemistry changes is probably warranted as well.

The effects of changing the riparian corridor can be evaluated by measurement of channel characteristics along a stream reach with varying adjacent land use. Along one such western Washington stream (Leach Creek, with a drainage area of about 9 km^2), bankfull channel widths and adjacent bank conditions were measured at 20-m intervals along 2 km of channel (Figure 4). An average 0.6 m of channel widening has occurred wherever the native bank vegetation had been altered or removed. This increase, about 17 percent, is trivial in comparison to the potential magnitude of catastrophic channel incision but a substantial fraction of the total "equilibrium" channel widening normally associated with urban-induced flow increases (Hammer, 1972; Booth, 1990). More generally, corridor condition and habitat quality were correlated in two other basins (Figure 5); note that good habitat quality is not guaranteed by corridor conditions, but an *absence* of significant riparian vegetation virtually assures degraded habitat.

Changes in flood discharge from urbanization are likely to affect aquatic systems most directly by an increase in streambank instability and channel erosion. We discriminate between *stable* channels, with little or no erosion of their bed and banks, and *unstable* channels that display long continuous reaches with bare and destabilized banks indicative of severe downcutting and widening. To characterize the increase in flows imposed by urbanization, we have used a continuous hydrologic model (HSPF; USEPA, 1984) to

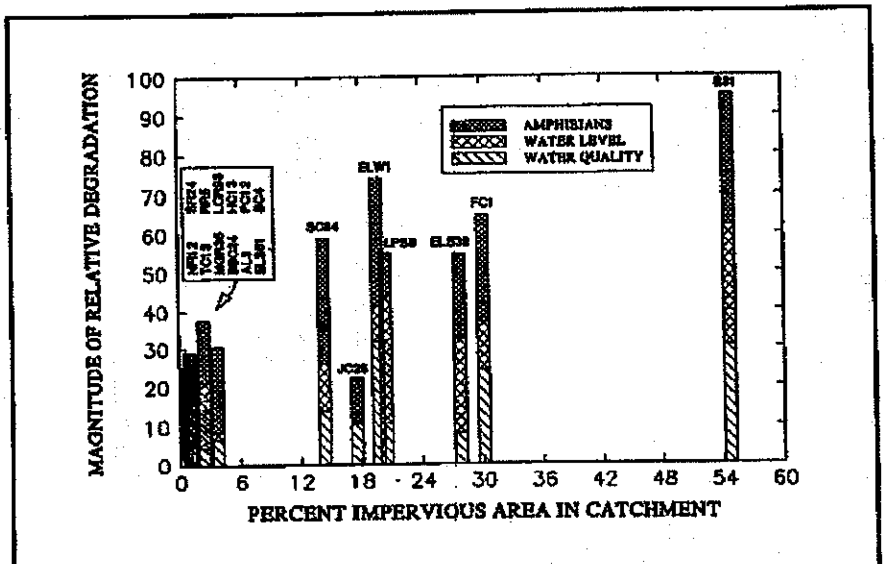


Figure 3. Relative wetland degradation.

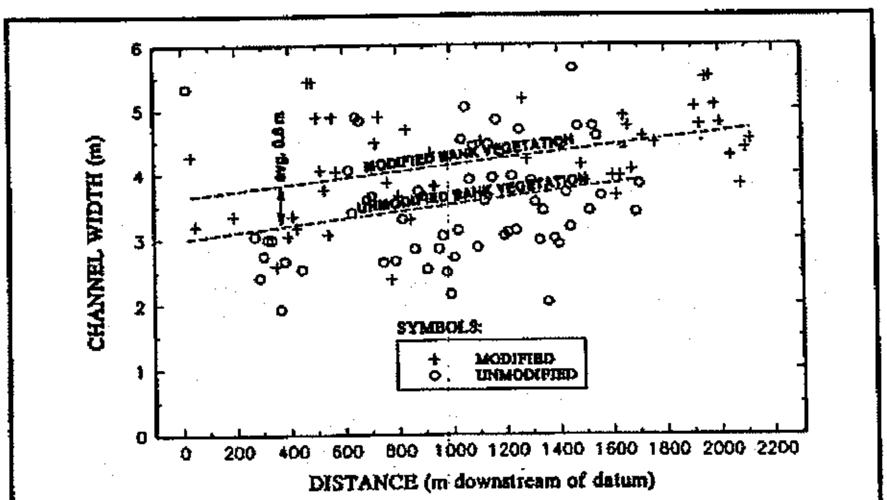


Figure 4. Correlation of channel width and bank vegetation, Leach Creek, Washington.

simulate the increased frequency of equaling or exceeding the discharge with a recurrence of 10 years under forested conditions ($Q_{10\text{-}for}$). This discharge was chosen as an index value of the total hydrograph because moderately large storm flows are commonly observed to affect stream-channel form and to move large streambed material (e.g., Sidle, 1988). The correlation between observed channel stability (indicated by the X's and O's of Figure 6) and frequency of $Q_{10\text{-}for}$ under current conditions (vertical scale of Figure 6) was determined for four basins having HSPF simulation of both forested and current land cover. A consistent threshold of change is seen for those basins with a present-day recurrence of 2 years or less for the discharge equal to $Q_{10\text{-}for}$ (solid horizontal line in Figure 6, using the annual flood series). This threshold of instability also can be recognized simply by measuring impervious area percentage in the upstream basin; again, a value of about 10 percent (dashed vertical line in Figure 6) seems pivotal.

These two factors, decreased corridor integrity and increased flows from the upstream basin, are typically interdependent because urban development tends to affect both. Different management strategies apply to these two areas, however, and so discriminating their respective effects on the stream system is valuable. Steedman (1988) correlated the biologic function at 209 stream sites in southern Ontario, Canada, with land use and riparian corridor (Figure 7). As with our data (Figures 2 and 5), both watershed and riparian land uses must be favorable (i.e., non-urban) for best conditions. If corridor clearing is proportional to basinwide urban land uses (the diagonal dashed line of Figure 7), stream conditions can be no better than "fair" once the basin achieves about 30 percent urban land use. At typical suburban densities, this corresponds to about 7-10 percent impervious area. Even with virtually complete retention of streamside buffers (i.e., "percentage riparian forest" equals 100 percent), impervious-area coverage much beyond this range will lead to nearly certain, measurable degradation.

Conclusions

These results suggest remarkably clear and consistent thresholds of aquatic system degradation. In this region, approximately 10 percent impervious area in a watershed typically yields demonstrable, and probably irreversible, loss of aquatic

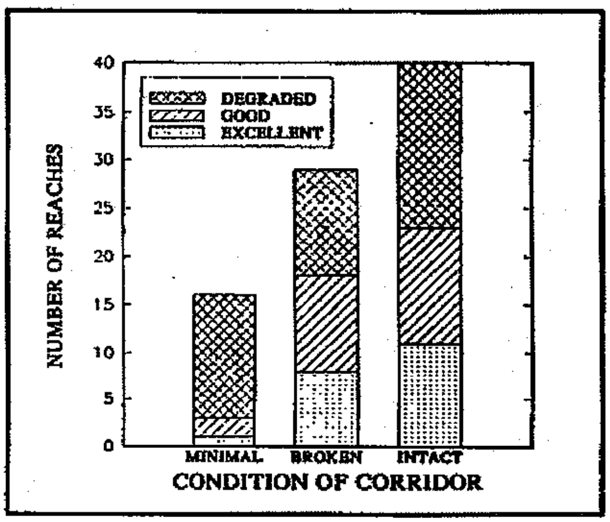


Figure 5. Quality of observed fish habitat, corridor conditions—Soos and Hylebos.

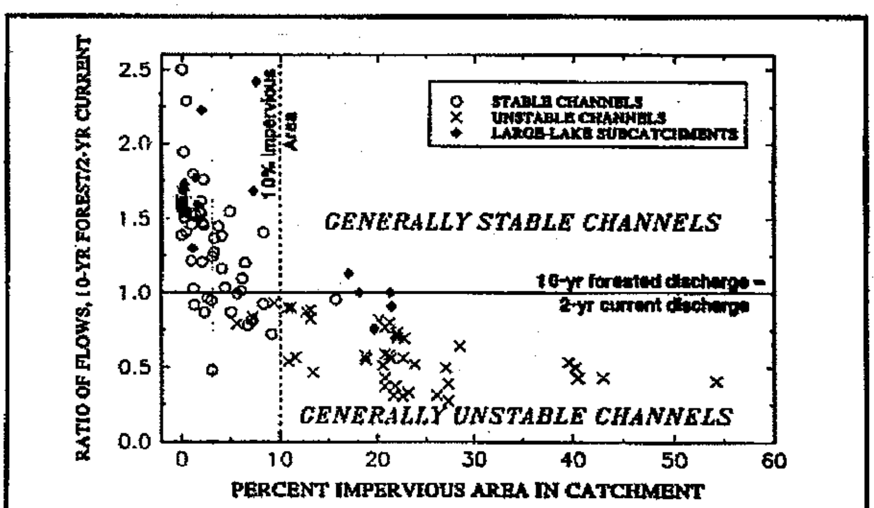
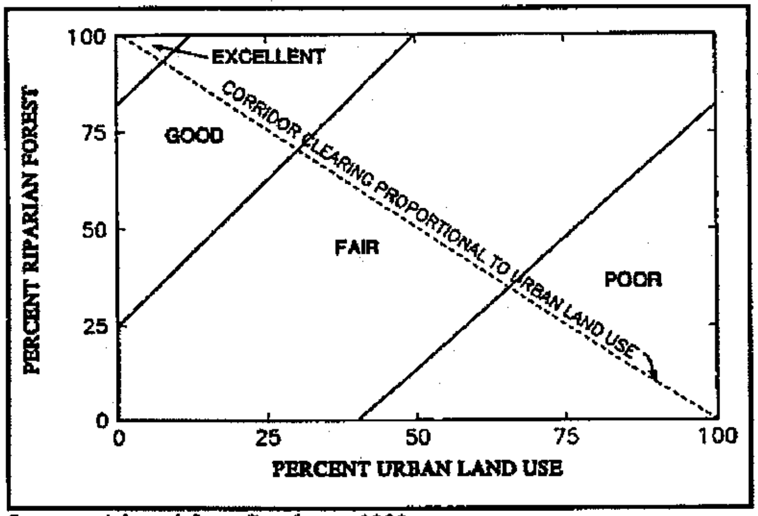


Figure 6. Channel stability and land use, Hylebos, East Lake Sammamish, Issaquah Basins.



Source: Adapted from Steedman, 1988.

Figure 7. Urban effects on biotic integrity.

system function. This loss is reflected by measured changes in channel morphology, fish and amphibian populations, vegetation succession, and water chemistry. Even lower levels of urban development cause significant degradation in sensitive waterbodies and a reduced, but less well quantified, degree of loss throughout the system as a whole. In the restricted context of western Washington aquatic systems, differences between watersheds are not apparently critical in determining this threshold; but those differences do determine the magnitude of the aquatic system response and what strategies might provide effective mitigation.

These findings suggest that successful corrective measures must not simply protect or restore the structure of individual stream or wetland elements. For example, buffers around waterbodies are necessary but must be combined with watershed-level restrictions on the rate and duration of storm water discharge; loss of instream fish habitat cannot be repaired by engineered structures alone. Yet the changes to the landscape imposed by urbanization are probably beyond our best efforts to fully correct them. Thus some downstream loss is probably inevitable without limiting the extent of development itself, a strategy that is being used with increasing frequency in this region's remaining resource-rich watersheds.

References

Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. *Water Resources Bulletin* 26:407-417.

———. 1991. Urbanization and the natural drainage system—impacts, solutions, and prognoses. *Northwest Environmental Journal* 7:93-118.

Hammer, T.R. 1972. Stream and channel enlargement due to urbanization. *Water Resources Research* 8:1530-1540.

Lucchetti, G., and R. Fuerstenberg. 1993. Relative fish use in urban and non-urban streams. Conference on Wild Salmon, Vancouver, Canada.

Reinelt, L.E., and R.R. Horner. 1991. Urban storm water impacts on the hydrology and water quality of palustrine wetlands in the Puget Sound region in *Puget Sound Research '91 Proceedings*, Puget Sound Water Quality Authority, vol. 1, pp. 33-42.

Richter, K.O., A. Azous, S.S. Cooke, R.W. Wisseman, and R.R Horner. 1991. *Effects of storm water runoff on wetland zoology and wetland soils characterization analysis.* Puget Sound Wetlands and Stormwater Management Research Program, King County, WA.

Sidle, R.C. 1988. Bed load transport regime of a small forest stream. *Water Resources Research* 24:207-218.

Steedman, R.J. 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in Southern Ontario. *Canadian Journal of Fisheries and Aquatic Sciences* 45:492-501.

USEPA. 1984. Hydrological simulation program—Fortran, Release 8.0. U.S. Environmental Protection Agency, Southeast Environmental Research Laboratory, Office of Research and Development, Athens, GA.