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FOREST COVER, IMPERVIOUS-SURFACE AREA, AND THE MITIGATION OF URBANIZATION IMPACTS IN KING COUNTY, WASHINGTON

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INTRODUCTION

For decades, watershed urbanization has been known to have severe consequences on aquatic systems. Although the problem has been long articulated, solutions have proven elusive because of the complexity of the problem, the evolution of improving but still-imperfect analytical tools, and socio-economic forces with different and often incompatible interests. King County, Washington, has been a recognized leader in the effort to analyze and to reduce the consequences of urban development, but even in this jurisdiction the path has been marked by well-intentioned but ultimately mistaken approaches, compromises with other agency goals that thwart complete success, and imperfect implementation of the measures that ultimately have been adopted.

The designation of ESA-listed species within the urban and urbanizing parts of the Puget Sound region has brought new scrutiny to all aspects of these watershed-mitigation efforts. Such increased attention is forcing a better articulation of the goals, the means, and the justification for mitigating the effects of urban development. This paper is one manifestation of that attention. The purpose here is to remind readers of the scientific framework for evaluating the consequences of urban development on aquatic systems; to review the history of surface-water management in King County as it relates to the analysis and mitigation of those consequences; and to evaluate the basis for a specific proposal, first explored almost a decade ago, to limit effective impervious areas in high-quality watersheds at or below 10 percent and to maintain forest cover above 65 percent.

HYDROLOGIC FRAMEWORK

This paper cannot address every factor that affects urban stream systems. Instead, it focuses on changes in *hydrology*, because hydrologic processes dominate the formation and functioning of aquatic habitat, and because these changes are ubiquitous in urban settings. There should be no misunderstanding, however, that addressing only hydrologic conditions will necessarily “fix” or "protect" an urban stream. Nothing in the following discussion is intended to convey that impression (Figure 1).

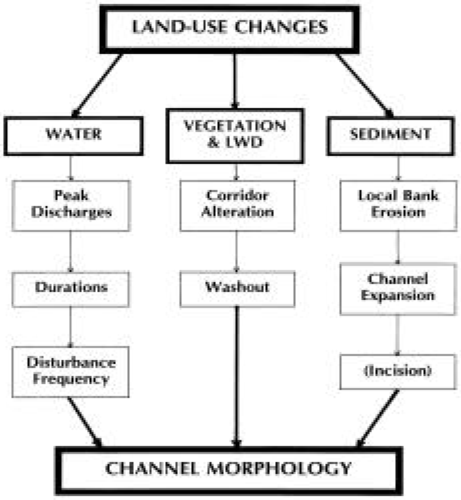

Figure 1. A conceptual framework for how land-use changes are manifested in the physical form of an urban stream channel. Additional elements that are *not* included here, such as biological interactions and water chemistry, may not influence channel morphology but are also critical in determining biological condition.

Of the hydrologic elements relevant to urbanization, the most important is storm runoff, that part of the rainfall that reaches a stream channel quickly. Typically, storm runoff is produced by either of two methods. The first occurs if the precipitation falls on the soil surface more rapidly than the soil can absorb it, causing the excess precipitation to run over the surface of the land. This process was first described by Horton (1945) and is now called "Horton overland flow" (HOF). It is most common in regions of periodically intense rainfall, limited vegetation, and thin soils, notably the arid and semiarid interior east of the Cascade Range. In these situations, water moves quickly from the hillslopes into the channel, and all parts of the drainage basin contribute to the storm runoff in the channel. Conversely, where rainfall intensities are generally lower than the rate at which the soil can absorb it, all of the precipitation is infiltrated where it first lands. Water still moves downslope, but it flows below the ground surface at substantially slower rates than HOF. This mechanism, known as the subsurface flow regime, predominates where rainfall is gentle and vegetation is lush; the coastal regions of the Pacific Northwest provide one of the best examples on the North American continent. Water moves very slowly off the hillslopes, and only those parts of the basin near the stream itself will contribute to the storm runoff.

As a storm continues, changes occur in the flow patterns, runoff quantities, and subsequent stream flow. Where HOF dominates, these changes are due to a rapid reduction in soil infiltration capacity as the ground first gets wet. The change typically occurs within the first hour after the onset of a storm, with the infiltration capacity then remaining constant (e.g., Strahler, 1975). Under the subsurface flow regime, this change is unimportant, as the soil always retains adequate infiltration ability to absorb water as rapidly as the rain can fall. Instead, a different process causes a change in runoff quantity. Water tables in the soil will rise as water is added to the subsurface. If those water tables lie at or near the surface, their progressive rise expands the area of saturated ground in the drainage basin. In these saturated areas, new precipitation cannot infiltrate because the soil has no space to absorb more rainfall. They are typically located towards the bottom of slopes, in seasonally wet valleys, and adjacent to streams and lakes. Therefore, the total area of saturated ground, and thus the area where overland flow will occur, expands as the water table rises. This expansion occurs over a period of days, and so the part of a drainage basin that is contributing rapid storm runoff to the channel steadily increases during the course of a single storm. Areas of saturated ground also tend to expand through an entire storm season, making any changes in stream flow more intense for similar-sized storms occurring later in the rainy periods (Hewlett and Hibbert, 1967).

Modifications of the land surface during urbanization produce changes in both the magnitude and the type of runoff processes. In the Pacific Northwest, the fundamental hydrologic effect of urban development is the loss of water storage in the soil column. This may occur because the soil is compacted or stripped during the course of development, or because impervious surfaces convert what was once subsurface runoff to Horton overland flow. In either situation, the precipitation over a small watershed reaches the stream channel with a typical delay of just a few minutes, instead of what had been a lag of hours, days, or even weeks. The result is a dramatically changed pattern of flows in the downstream channel, with the largest flood peaks doubled or more and more frequent storm discharges increased by as much as ten-fold (Figure 2).

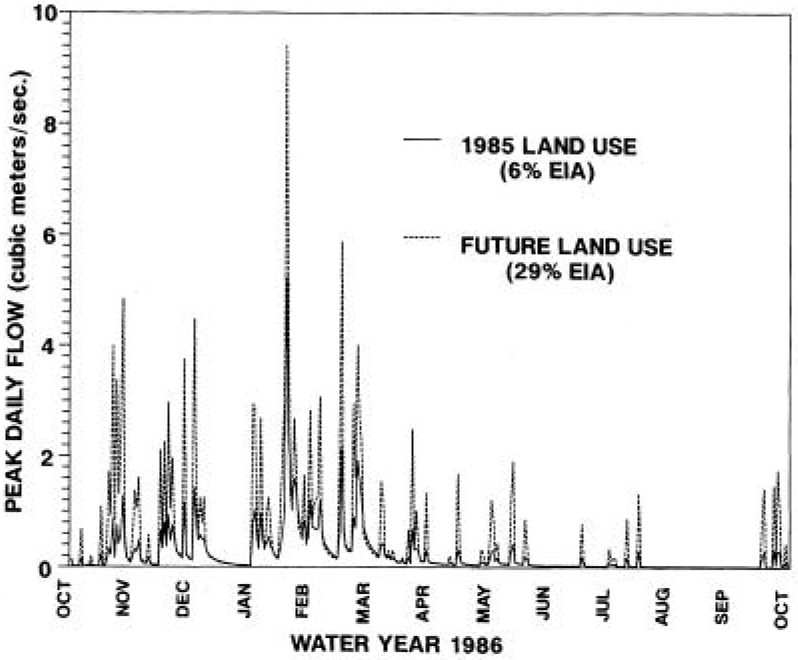

Figure 2. One year's modeled discharges for the 14-km^2 Soosette Creek watershed in south-central King County (King County, 1990a). Two land-use scenarios are modeled: the first, under existing 1985 land use, shows a typical low-development pattern of large wintertime peaks, and low and relatively constant discharge between mid-spring and early fall. The second, presuming full build-out under the 1985 zoning for the area, results in a final effective impervious-area coverage ("EIA") of 29 percent and dramatic increases in both winter and (especially) summer storm flows (from Booth, 1990).

HISTORIC BACKGROUND

Mitigation of Urban-Induced Flow Increases

As a consequence of urban-induced runoff changes, which in turn cause flooding, erosion, and habitat damage, jurisdictions have long required some degree of stormwater mitigation. The most common approach has been to reduce flows through the use of detention ponds, which are intended to capture and detain stormwater runoff from developed areas. These ponds can be designed to either of two levels of performance, depending on the desired balance between achieving downstream protection and the cost of providing that protection. A ***peak standard***, the classic (and least costly) goal of detention facilities, seeks to maintain postdevelopment peak discharges at their predevelopment levels. Even if this goal is achieved successfully, however, the aggregate duration that such flows occupy the channel must increase because the overall volume of runoff is greater.

In contrast, a ***duration standard*** seeks to maintain the postdevelopment *duration* of all discharges at predevelopment levels. Duration standards are motivated by a desire to avoid potential disruption to the downstream channels by not allowing any flow changes that might increase sediment transport beyond predevelopment levels. Without infiltration of runoff, however, the total *volume* of runoff must still increase in the postdevelopment condition, and so durations cannot be matched for all discharges—below some discharge rate, the “excess” water must be released. This is accomplished by determining a threshold discharge below which sediment transport in the receiving channel does not occur. This determination can be made by site-specific, but rather expensive, analysis based on stream hydraulics and sediment size (Buffington and Montgomery, 1997) or can be applied as a “generic” standard based on predevelopment discharges. A rate of about 50 percent of the predevelopment 2-year discharge is a credible generic value for the initiation of sediment transport in gravel-bedded streams, but there is no information on whether this “threshold” is equivalently benign or problematic for fish or other biota.

The first recognized hydrologic consequences of urbanization were those associated with peak-flow increases (i.e., “more flooding”). Careful analysis, culminating in a synthesis of many separate studies (Hollis, 1975), showed how the dual factors of percent impervious and percent of a watershed in storm sewers increased the peak discharges of floods (Figure 3; Hollis’s “Figure 2”). Large, infrequent floods were increased less than smaller, more common events; in general, Hollis found peak-flow increases of two- to three-fold are common for the moderate-sized floods in moderately urbanized watersheds. These general results have been replicated in both empirical and modeling studies, on many dozens of watersheds throughout the United States and in the Pacific Northwest.

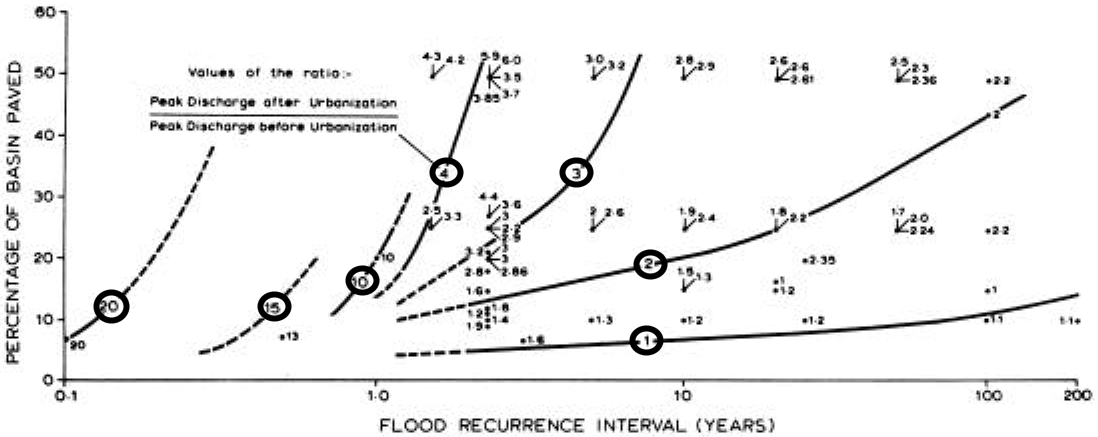

Fig. 2. Effect of urbanization on flood peaks. (Data taken from Table 1.)

Figure 3. Relationship between watershed imperviousness (vertical axis) and increases in peak flows for floods of various recurrence intervals. At the graph's extremes, the line labeled "1" marks the limit of observed flow increases; those labeled "15" and "20," marking very large increases in very frequent flows, are based on minimal data (from Hollis, 1975)

The first efforts at runoff mitigation were intended to reduce peak flows, reflecting the traditional focus on flood reduction. Well over one hundred years ago, the fundamental predicting equation of runoff used in these early mitigation efforts was developed (Mulvany, 1851). The Rational Runoff Formula related the runoff rate to the simple product of the rate of rainfall, the basin area, and the *runoff coefficient*, a number equal to the fraction of the rain falling on a basin that presumably contributes to the flood peak. The runoff coefficient is adjusted for different land uses and land covers. Thus, highly pervious, forested ground is typically assigned a value of near zero (i.e., almost no water reaches the channel); pavement is given values approaching 100 percent. This formula was used by King County in the region's first surface-water design manual (King County, 1979), but its fundamental shortcomings led to the construction of grossly undersized detention ponds having little or no benefit in preventing downstream flooding.

The subsequent edition of King County's design manual (King County, 1990b) substituted the Soil Conservation Service's curve-number methodology for the Rational equation. This was a dramatic, and costly, change on several fronts: 1) it nominally allowed for closer matching of watershed conditions by the modeling, 2) it generally yielded a requirement for larger detention ponds; and 3) it necessitated a significant upgrading of the hydrologic-modeling skills of much of the local professional design community. Yet it was still a "peak standard" that still failed to achieve complete mitigation of peak-flow increases, and it ignored any problems associated with increased flow durations.

The practice of seeking duration control for new developments was introduced through King County's Basin Planning Program in the late 1980's. Its goal is to match pre-and post-development flow durations for all discharges above a chosen threshold. Hydrologic analysis using a more advanced (albeit still imperfect) hydrologic model, HSPF, could predict the detention needed to achieve this goal. From the outset, however, this approach has been controversial for several reasons:

- The required ponds are larger, often dramatically so, than required by previous design methods.
- The method requires a threshold discharge, below which durations will increase dramatically, but how to choose that discharge is not immediately obvious or without dispute.
- The analytic tool (HSPF) used to establish the standard is not as widely used as the Rational or SCS method, and so appeared less transparently justifiable to many practitioners. As part of the Bear Creek Basin Plan (King County, 1990d), a surrogate approach that involved an intentional "misapplication" of the SCS method was proposed to achieve the same objective without requiring the ability to run HSPF.
- Few (and initially, no) ponds were actually constructed under this standard, and so empirical evidence for their effectiveness (or lack thereof) is sparse.

Despite these shortcomings, these standards reflected the best understanding of hydrologic conditions in urban streams and so have been part of Basin Plan-recommended detention standards in King County since the early 1990's (and incorporated into more recent updates [1998] of the design manual). Yet several issues remain unanswered, even with the current status of implementation:

- As noted above, there is a presumed threshold discharge below which there are "no effects" of flow-duration increase. This is defensible only with regard to sediment transport in gravel-bed streams. A true "threshold of no effects" is certainly *not* correct for sediment transport in sand-bedded streams (uncommon but not unknown in the region); some material moves at almost any discharge. In addition, there has been no evaluation of any other effects (either physical or biological) of extended low-flow durations.
- These analyses ignore the consequences of converting what was once spatially distributed subsurface runoff into a point discharge at a surface-water outfall, because there are no analytic tools to assess those consequences. Field examples, however, demonstrate that the consequences of point discharges can include locally severe erosion and disruption of riparian vegetation and instream habitat.
- Any analysis of flow durations will not address changes to groundwater recharge or discharge, because no constructed detention ponds, even the largest designed under this standard, can delay wintertime rainfall sufficiently for it to become summertime runoff. Yet exactly this magnitude of delay *does* occur under predevelopment conditions, because far more of the precipitation is stored as groundwater.
- The flow-duration analysis, by definition, uses discharge values from the entire period of hydrologic simulation (over 40 years, in the case of King County), but there is no attempt (or ability) to construct detention ponds that match durations on the scale of a single storm (or even a single storm season). Thus the aggregate flow-duration spectrum may be unchanged, but the timing, frequency, and brevity of any single storm hydrograph may be quite different from the undisturbed condition.

An example illustrates the difference between "aggregate" and "true" duration matching. Des Moines Creek drains a 14-km^2 watershed that includes the south end of Seattle-Tacoma

International Airport and has been the focus of intensive hydrologic analysis (Des Moines Creek Basin Committee, 1997). Several mitigation scenarios for the projected increases in effective impervious area (from 35 to >47 percent), which include large detention ponds and a bypass pipeline, have been modeled and compared to current and past (i.e. fully forested) conditions. Although flow durations for the proposed mitigation represent dramatic improvement over current conditions (Figure 4a), daily flow conditions in the stream do not return to preexisting conditions (Figure 4b).

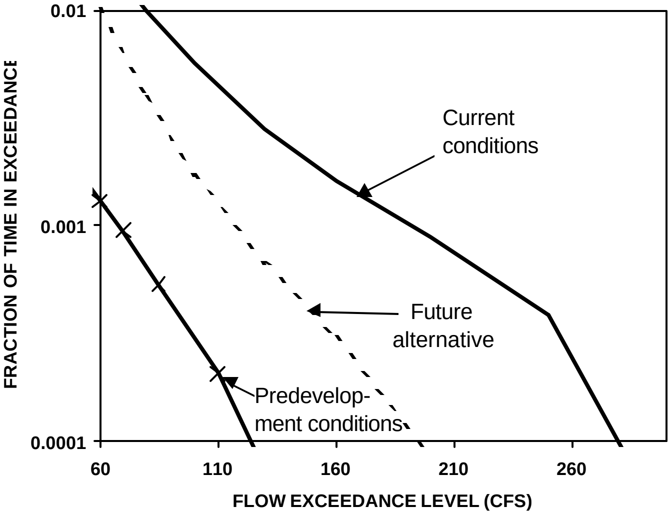

Figure 4a. HSPF-modeled flow-duration curve for Des Moines creek, displaying dramatic improvement in future flow durations relative to current. Analysis assumes projected land-use changes and construction of proposed detention ponds and bypass pipeline (from Des Moines Basin Committee, 1997).

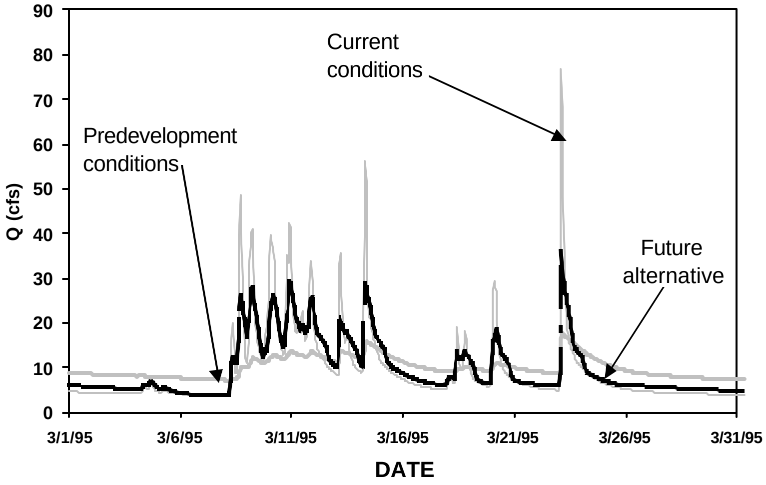

Figure 4b. One month’s hydrographs for Des Moines Creek: current flows, predevelopment (i.e. forested) flows, and those under anticipated future conditions. Note that although the flow-duration curves (Figure 4a) suggest that the future alternative is mid-way between current and predevelopment conditions, the future hydrograph shows flashy discharge and low base flows much more like current conditions than those of predevelopment time.

Empirical Relationships between Watershed Conditions and Stream Conditions

Originally independent of mitigation and regulatory efforts, investigations into the correlation between development and aquatic-system conditions have been pursued for over two decades. Klein (1979) published the first such study, where he reported a rapid decline in biotic diversity where watershed imperviousness much exceeded 10 percent. Steedman (1988) believed that his data showed the consequences of both impervious cover and forest cover on instream biological conditions (Figure 5). Later studies, mainly unpublished but covering a large number of study methods and researchers, was compiled by Schueler (1994). Since that time, additional work on this subject has been made by a variety of Pacific Northwest researchers, including May (1996), Booth and Jackson (1997), and Morley (2000) (figures 6, 7, and 8).

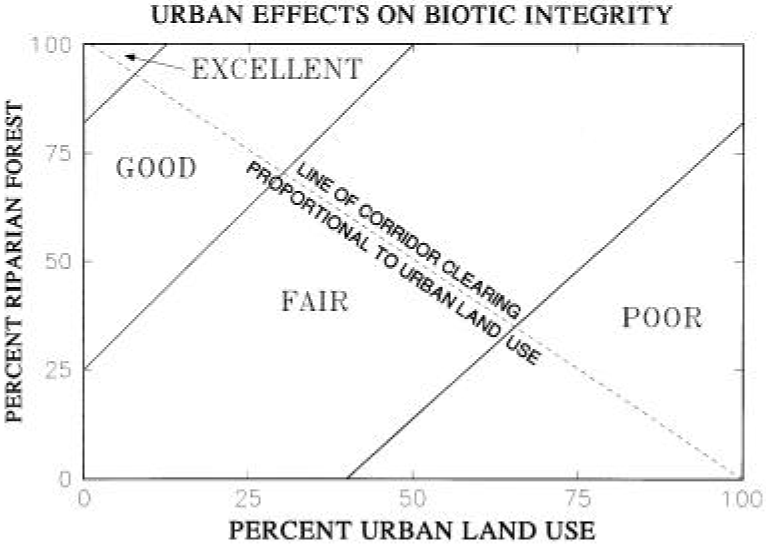

Figure 5. Conceptual relationship between urban land use, forest cover, and biological conditions. The specific values and descriptors ("GOOD," "POOR," etc.) were designated by Steedman (1988).

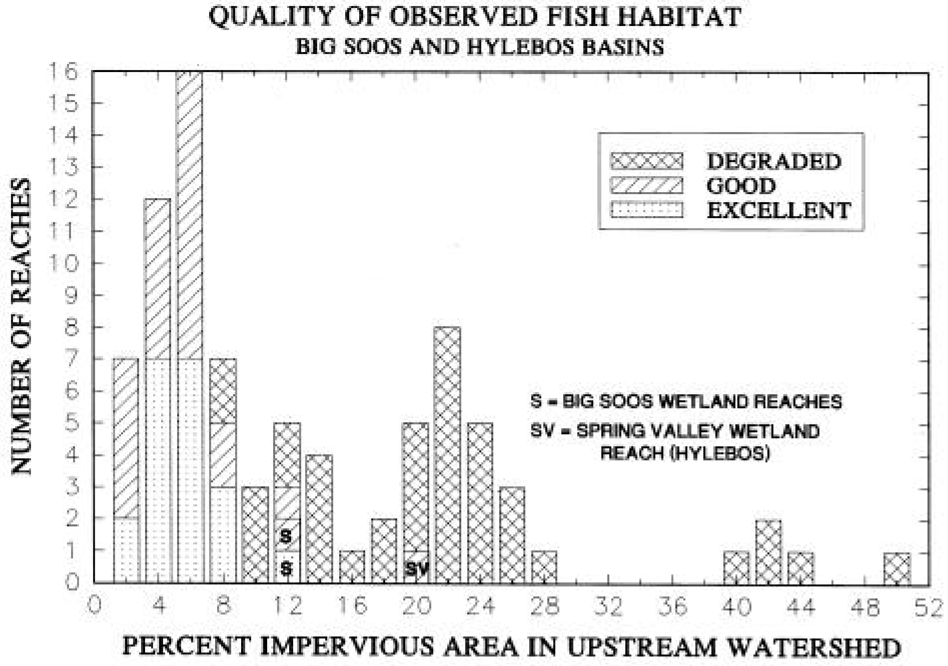

Figure 6. Observed fish habitat quality as a function of effective impervious area in the contributing watershed, based on more than 80 individually inventoried channel segments in south King County (From Booth and Jackson, 1997; data from King County 1990a,c). "EXCELLENT" reaches show little or no habitat degradation; "GOOD" reaches show some damage to habitat but still maintain good biological function; and "DEGRADED" reaches contain aquatic habitat that has been clearly and extensively damaged, typically from bank erosion, channel incision, and sedimentation.

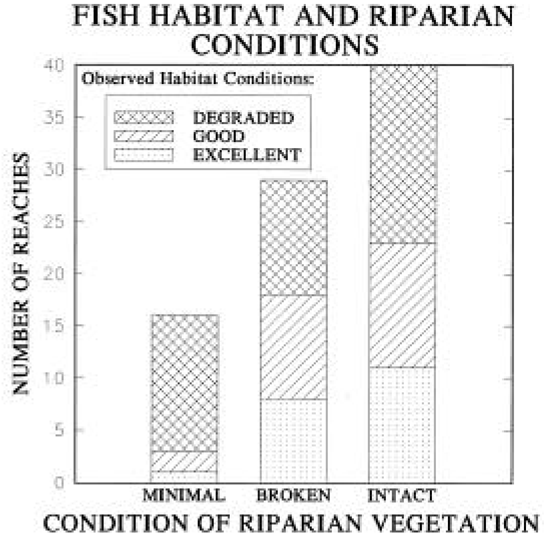

Figure 7. Relationship between riparian vegetation and instream conditions, using the same sites and criteria as for Figure 6. A relatively intact riparian corridor is clearly *necessary*, but not *sufficient*, for high quality habitat.

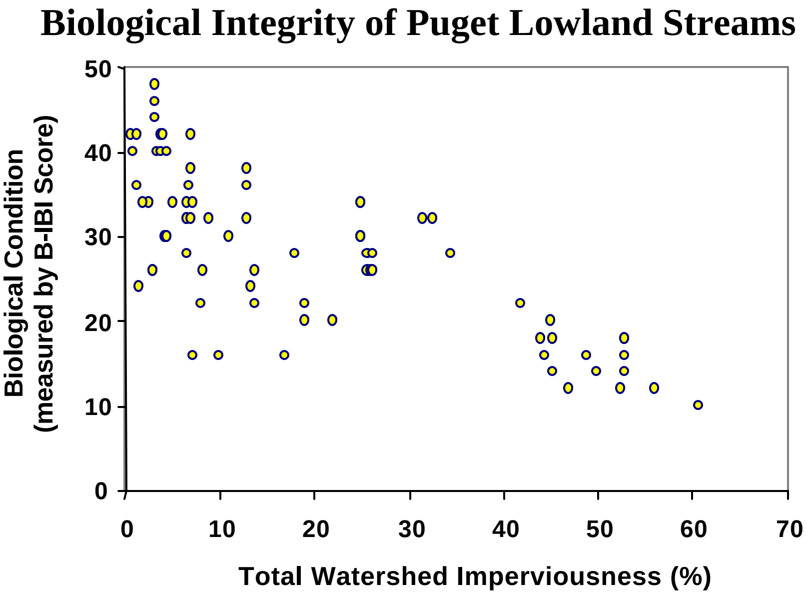

Figure 8. Compilation of biological data on Puget Lowland watersheds, reported by Kleindl (1995), May (1996), and Morley (2000). The pattern of progressive decline with increasing imperviousness is evident only in the upper bound of the data; significant degradation can occur at *any* level of human disturbance (at least as measured by impervious cover).

These data have several overall implications:

- "Imperviousness," although an imperfect measure of human influence, is clearly associated with stream-system decline. A *range* of stream conditions, however, can be associated with any given level of imperviousness.
- "Thresholds of effect," identified in some of the earlier literature (e.g., Klein, 1979; Booth and Reinelt, 1993) exist largely as a function of measurement precision, not necessarily as intrinsic characteristics of the system being measured. Crude evaluation tools require that large changes accrue before they can be detected, but lower levels of development may still have consequences that can be revealed by other, more sensitive methods. In particular, biological indicators demonstrate a continuum of effects resulting from human disturbance.
- Hydrology is not the *sole* determinant of stream conditions, but its effects are ubiquitous in urban systems.

Basin Planning in King County

Recommendations that were incorporated into King County's basin plans reflected the evolution of hydrologic understanding in the late 1980's and early 1990's. The first plans prepared under the Basin Planning Program, those for Soos, Bear, and Hylebos creeks (King County, 1990a, d, 1991a), took similar approaches: detention standards for new development were based on the then-new 1990 drainage manual with its "peak" standard, supplementing a duration standard in selected subbasins with a history of problems or with high-quality aquatic resources. The Bear Creek plan recommended relatively severe clearing restrictions, based on the amount of land per residential parcel needed for a home site. However, it permitted outright waiver of the clearing limitations if detention at the specified flow-duration standard was provided. The Hylebos plan advocated revegetation, but in acknowledgement of the existing level of deforestation as a result of preexisting conversion to urban development, it made no recommendations for clearing limitations on new development. A subsequent, unpublished review of alternative designs for clustered residential development showed that a wide range of rural and suburban densities could be achieved on one-third to one-half of a large parcel, with the balance maintained in an undisturbed state.

The Issaquah Creek Basin Plan (King County, 1994) was the first study of a King County watershed that was overwhelmingly forest-covered, and where flooding problems were already causing substantial economic and resource damages. It was the first plan where the limitations of King County drainage regulations, particularly the regulatory thresholds for drainage review that excluded nearly all rural residential development from any drainage controls, were fully acknowledged. It was also the first plan that defined an objective criterion for “acceptable” hydrologic performance that might protect stream channels.

This “stream-protection” criterion was taken directly from previous empirical assessments of channel stability and bank erosion, which in turn had been generated from observations made in the late 1980’s and early 1990’s while working on the past and current basin plans (and subsequently published in Booth and Jackson, 1997) (Figure 9). These data showed that two linked thresholds apparently marked a transition of channels from “stable” to “unstable.” One was the measure discussed previously: where effective impervious area in the contributing watershed had exceeded 10 percent, readily observed physical degradation of the channel was virtually ubiquitous. The other was based on hydrologic analyses of those same contributing watersheds: almost without exception, the same observed transition from “stable” to “unstable” channels was marked by the equality of the 10-year forested (i.e. predevelopment) discharge ($Q_{10\text{-for}}$) and the 2-year current discharge ($Q_{2\text{-cur}}$). There was, and is, no theoretical basis for these particular outcomes—they are simply empirical results. Yet they have been observed across enough different watersheds that one would be foolish to presume that future development in an as-yet pristine watershed could proceed past these levels without similar consequences.

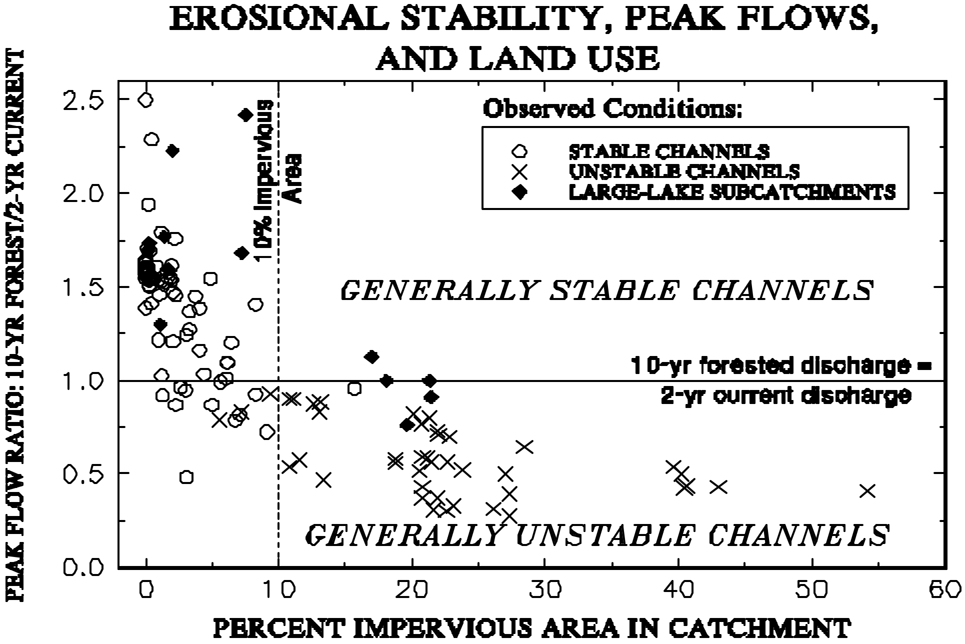

Figure 9. Observed stable ("O") and unstable ("X") channels, plotted by percent effective impervious area (EIA) in the upstream watershed (horizontal scale) and ratio of modeled 10-year forested and 2-year current (i.e. urbanized) discharges (vertical scale). "Stable channels" consistently meet the apparent thresholds of either {EIA ≤ 10 percent} or {$Q_{2\text{-cur}} \leq Q_{10\text{-for}}$}, except for the few catchments containing large lakes.

Although these data compose a robust set of observations, spanning a wide variety of streams with remarkably consistent results, they also carry two limitations. First, the absence of observed instability does not guarantee an absence of any effects. The converse, however, is more likely true: if there *is* instability, other conditions (particularly biological) are almost certainly degraded as well. The second limitation is more vexing: these data were collected on watersheds without much, if any, effective stormwater detention. Had larger and more effective ponds been present, would the observed impacts been reduced? Such a possibility certainly exists, but there are as yet no equivalent data from a "well-detained" watershed to demonstrate that success. Insofar as detention ponds can mitigate for only some of the aspects of urban-altered hydrology (see above), complete success is quite unlikely.

Guided by these "threshold" criteria (Figure 9) for stream-channel stability, the Issaquah Creek Basin Plan developed model predictions of postdevelopment runoff conditions and their likely consequences on channel erosion and bank stability. These initial assessments, presuming basinwide application of the mitigation tools that were then "accepted practice" (*i.e.* exemption of rural-zoned developments from detention requirements, and SCS-based hydrologic designs for the rest), produced results that were inconsistent with the goals of the basin plan—to protect aquatic habitat and to resolve existing and potential future flooding problems. The empirical criterion for channel instability ($Q_{2\text{-cur}} > Q_{10\text{-for}}$) was exceeded pervasively throughout the watershed under most if not all future development scenarios.

As a consequence of these results, the Issaquah plan evaluated a variety of alternative rural development scenarios (Appendix G of King County, 1994). The analyses found that with 65-percent forest retention in a nominal 5-acre zone (*i.e.* 20 houses per 100 acres, clustered on 35 percent of the land area), the criterion of keeping the 2-year developed discharge below the 10-year forested discharge could be just met on till soils (the most common type in King County). Greater amounts of cleared land resulted in 2-year developed discharges that exceeded 10-year forested discharges, even though the amount of effective impervious area was well under 10 percent. The analysis noted that development on outwash soils (the other, but much less common, soil type used for hydrologic modeling) failed the criterion at virtually any level of forest retention, because so little runoff occurs there naturally that almost *any* amount of imperviousness produces proportionally large peak-flow increases. The analysis also found that with additional forest retention (on till soils), additional density could by accommodated on the remaining developed land, and it observed that the retention of forest cover was far more significant in determining discharge increases at rural densities than typical increases in impervious area (Figure 10).

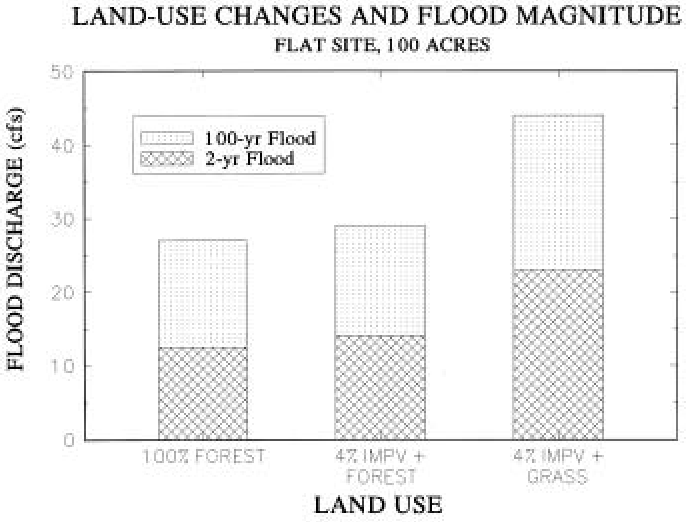

Figure 10. HSPF-modeled increases in 2-year and 100-year discharges that result from forest conversion on moderately sloping till soils. Four percent (effective) imperviousness, a typical value for 5-acre residential densities, shows particularly significant hydrologic changes only when accompanied by clearing on the remaining 96 percent of the watershed.

HYDROLOGIC AND REGULATORY CRITERIA FOR RESTRICTING IMPERVIOUS AREA AND CLEARING

In the realm of physical channel conditions, the data collected from field observations have consistently shown remarkably clear trends in aquatic-system degradation. In western Washington, and likely in other humid regions as well, approximately 10 percent effective impervious area in a watershed typically yields demonstrable degradation, some aspects of which are surely irreversible. Although early observations were overly *in*sensitive to show significant degradation at even lower levels of urban development, the basin plans of the early 1990's recognized that such damage was almost certainly occurring. More recently, biological data have demonstrated the anticipated consequences at these lower levels of human disturbances.

Less empirical data have been collected on the direct correlation between forest cover and stream conditions than for watershed imperviousness and stream conditions. In general, the "evidence" has been based on the observed correlation of channel instability to the modeled hydrologic condition of $Q_{2\text{-cur}} > Q_{10\text{-for}}$, coupled with hydrologic analyses that have explored the relationship between such peak-flow increases and forest-cover reduction. The first such analyses, for the Issaquah Creek Basin Plan, made a variety of assumptions about "typical" watershed characteristics in that basin and found that 65 percent forest cover with 4 percent effective impervious area closely approached the condition of $Q_{2\text{-cur}} = Q_{10\text{-for}}$. More recently, David Hartley (King County, written comm., 2000) has explored a broader set of likely hydrologic responses, using more generalized model parameters and a range of effective impervious areas typical of rural areas. His results (Figure 11) suggest that 65 percent forest cover is a plausible, but by no means definitive, value for meeting the presumed "stability criterion" of $Q_{2\text{-cur}} < Q_{10\text{-for}}$ in rural-zoned watersheds on moderately (5%-15%) sloping till soils. As noted in earlier analyses, other soils (particularly more infiltrative ones) yield much greater hydrologic response, even with lesser amounts of clearing.

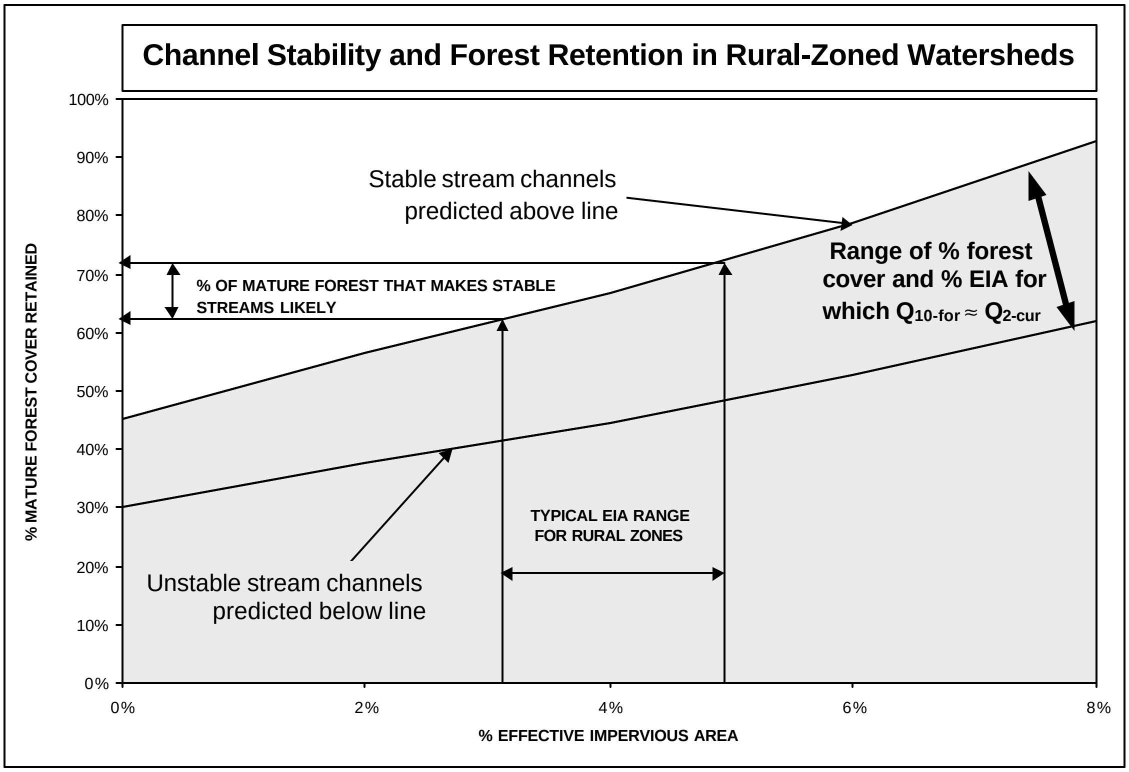

Figure 11. Conditions of forest cover and impervious area in an HSPF-modeled watershed with moderate slopes and till soils relative to the channel-stability criterion $Q_{2\text{-cur}} = Q_{10\text{-for}}$. The range of forest-retention values reflects uncertainty in the hydrologic parameters; the range of effective impervious areas reflects variation in rural land cover conditions (D. Hartley, writ. comm., 2000).

Hydrological analyses suggest that forest cover is more important than impervious-area percentages, at least at rural densities. Even if both are critical to protect stream conditions, current land-use practices suggest that mandating retention of forest cover is the more pressing regulatory need. Watersheds with less than 10 percent EIA and less than 65 percent forest cover are common ("cleared rural"); in contrast, *none* have more than 65 percent forest cover and also more than 10 percent EIA ("forested urban") (Figure 12).

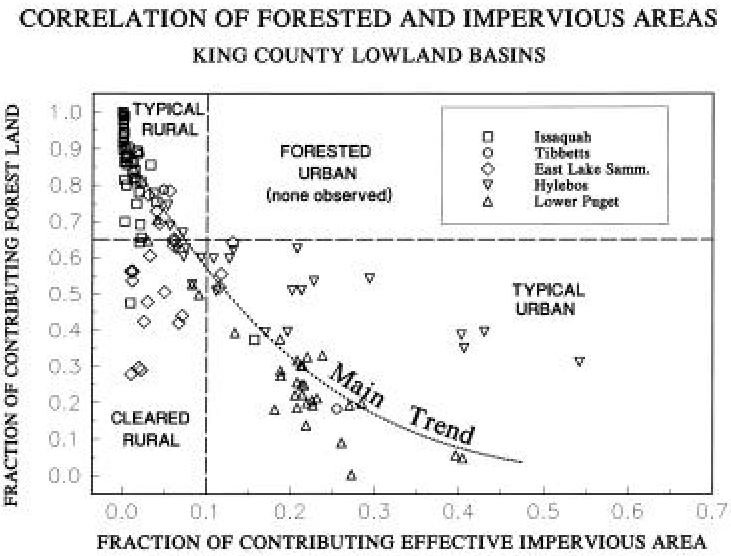

Figure 12. Land cover data from individual subcatchments within five King County watersheds, compiled from basin plan land-cover data (King County, 1990c,e, 1991b). At 65-percent forest retention, EIA ≤ 10% in all cases, yet with EIA < 10%, substantial clearing is still commonly observed.

The apparent correlations between stream stability and both impervious-area and forest-cover percentages present a vexing quandary for watershed managers. On the one hand, these correlations point to a tangible, defensible criteria for achieving a specific management objective, namely "stable stream channels." On the other hand, this objective, however worthy, *still* allows the possibility of serious and significant aquatic-system degradation—and as development is allowed to approach these clearing and imperviousness criteria, degradation is virtually guaranteed. The thresholds implied by these data are simply the "wrong" type on which to base genuine resource protection. They do not separate a condition of "no impact" from that of "some impact;" instead, they separate the condition of "some impact" from that of "gross and easily perceived impact." Hydrologically and biologically, there are no truly negligible amounts of clearing or watershed imperviousness, even though our perception of, and our tolerance for, many of the associated changes in downstream channels appear to undergo a relatively abrupt transition. Almost every increment of cleared land, and of constructed pavement, is likely to result in some degree of resource degradation of loss. The decision of how much is "acceptable" is thus as much a social decision as a hydrologic one.

CONCLUSIONS

Hydrologic Framework

- Land development that eliminates hydrologically mature forest cover and undisturbed soil can result in significant changes to urban stream hydrology and, in turn, to the physical stability of stream channels.
- Land development modifies streamflow patterns; even with stormwater detention ponds, it can produce seasonal and stormflow patterns that are substantially different from those to which native biota have adapted.
- Although factors other than hydrologic change can undoubtedly affect the magnitude of urban impacts, the breadth of the existing data suggest that improvements in these other factors (e.g., riparian buffers) cannot fully mitigate the hydrologic consequences of overly intense urban development.
- Under typical rural land uses, the magnitude of observed forest-cover losses affects watershed hydrology as much as or more than associated increases in impervious area.

Historic Background

- The goals of stormwater detention have become progressively more ambitious as the consequences of urban-altered hydrology have become better recognized and understood. Even the largest detention ponds, however, have been recognized as limited in their ability to mitigate all aspects of hydrologic change.
- Twenty years of empirical data display a good correlation between readily observed damage to channels and modeled changes in hydrology that correspond to loss of about one-third of the forest cover in a “typical” western Washington watershed. A similar degree of observed damage also correlates to a level of watershed effective imperviousness of about ten percent.

The Basis for Restricting Watershed Imperviousness and Clearing

- Field observations and hydrologic modeling showed that the watershed plans of the early- to mid-1990’s could only hope to meet plan-stipulated goals for resource protection by imposing clearing and impervious-area restrictions. The most commonly chosen thresholds, 10 % EIA and 65 % forest cover, marked an observed transition to severely degraded stream conditions.
- At lower levels of human disturbance, aquatic-system damage may range from slight to severe but is nearly everywhere recognizable with appropriate monitoring tools. Not every watershed responds equally to a given level of human disturbance, but some degree of measurable resource degradation can be seen at virtually any level of urban development.
- The apparent “threshold” of observed stream-channel stability has no correlative in measured biological conditions.

REFERENCES

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

Booth, D. B., and Jackson, C. J., 1997, Urbanization of aquatic systems—degradation thresholds, stormwater detention, and the limits of mitigation: Water Resources Bulletin, v. 33, p. 1077-1090.

Booth, D. B., and Reinelt, L. E., 1993, Consequences of urbanization on aquatic systems--Measured effects, degradation thresholds, and corrective strategies: Watersheds '93, Conference sponsored by U. S. Environmental Protection Agency, Alexandria, VA, March 21-24, p. 545-550.

Buffington, J. M., and Montgomery, D. R., 1997, A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research, v. 33, no. 8, p. 1993-2029.

Des Moines Creek Basin Committee, 1997, Des Moines Creek Basin Plan: Seattle, King County Department of Public Works, Surface Water Management Division, 6 chapters.

Hewlett, J. D., and Hibbert, A. R., 1967, Factors affecting the response of small watersheds to precipitation in humid areas: in Sopper, W. E., and Lull, H. W., eds., Forest Hydrology: Oxford, Pergamon Press, p. 2752-2790.

Hollis, G. E., 1975, The effects of urbanization on floods of different recurrence intervals: Water Resources Research, v. 11, p. 431-435.

Horton, R. E., 1945, Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology: Geological Society of America Bulletin, v. 56, p. 275-370.

King County, 1979, Storm Drainage Control--Requirements and Guidelines: Seattle, Department of Public Works, Division of Hydraulics, 55 p.

King County, 1990a, Soos Creek Basin Plan and Final Environmental Impact Statement: Seattle, Department of Public Works, Surface Water Management Division, 330 p.

___________1990b, Surface Water Design Manual: Seattle, Department of Public Works, Surface Water Management Division, 5 chapters.

___________1990c, Hylebos Creek and Lower Puget Sound Basins Current and Future Conditions Report: Seattle, Department of Public Works, Surface Water Management Division, 4 sections.

___________1990d, Bear Creek Basin Plan: Seattle, Department of Public Works, Surface Water Management Division, 119 p.

___________1990e, East Lake Sammamish Conditions Report--Preliminary Analysis: Seattle, Department of Public Works, Surface Water Management Division, Seattle, Washington, 148 p.

___________1991a, Hylebos Creek and Lower Puget Sound Basin Plan: Seattle, Department of Public Works, Surface Water Management Division, 5 sections.

___________1991b, Issaquah Creek Current/Future Conditions and Source Identification Report: Seattle, Department of Public Works, Surface Water Management Division, 12 chapters.

___________1994, Issaquah Creek Basin and Nonpoint Action Plan: Seattle, Department of Public Works, Surface Water Management Division, 6 chapters.

Klein, R., 1979, Urbanization and stream quality impairment: Water Resources Bulletin, v. 15, p. 948-963.

Kleindl, W., 1995, A Benthic Index of Biotic Integrity for Puget Sound Lowland Streams, Washington, USA: Seattle, University of Washington, Masters Thesis.

May, C. W., 1996, Assessment of cumulative effects of urbanization on small streams in the Puget Sound Lowland ecoregion: implications for salmonid resource management: Seattle, University of Washington, Department of Civil Engineering, Ph.D. dissertation, 383 p.

Morley, S. A., 2000, Effects of urbanization on the biological integrity of Puget Sound lowland streams: restoration with a biological focus: Seattle, University of Washington, M.S. Thesis.

Mulvany, T. J., 1851, On the use of self-registering rain and flood gauges, in making observations of the relations of rain fall and flood discharges in a given catchment: Transactions and Minutes of the Proceedings of the Institute of Civil Engineers of Ireland, Session 1850-1, v. IV, pt. II, Dublin, Ireland.

Schueler, T. R., 1994, The importance of imperviousness: Watershed Protection Techniques 1(3), p. 100-111.

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, v. 45, p. 492-501.

Strahler, A. N., 1975, Physical Geography: New York, Wiley, 4th edition, 643 p.