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FOREST COVER, IMPERVIOUS-SURFACE AREA, AND THE MITIGATION OF STORMWATER IMPACTS[1]

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ABSTRACT: For 20 years, King County, Washington, has implemented progressively more demanding structural and nonstructural strategies in an attempt to protect aquatic resources and declining salmon populations from the cumulative effects of urbanization. This history holds lessons for planners, engineers, and resource managers throughout other urbanizing regions. Detention ponds, even with increasingly restrictive designs, have still proven inadequate to prevent channel erosion. Costly structural retrofits of urbanized watersheds can mitigate certain problems, such as flooding or erosion, but cannot restore the predevelopment flow regime or habitat conditions. Widespread conversion of forest to pasture or grass in rural areas, generally unregulated by most jurisdictions, degrades aquatic systems even when watershed imperviousness remains low. Preservation of aquatic resources in developing areas will require integrated mitigation, which must including impervious-surface limits, forest-retention policies, stormwater detention, riparian-buffer maintenance, and protection of wetlands and unstable slopes. New management goals are needed for those watersheds whose existing development precludes significant ecosystem recovery; the same goals cannot be achieved in both developed and undeveloped watersheds.

(KEY TERMS: urbanization; stormwater; BMP; land use planning; watershed management; urban water management.)

INTRODUCTION

For decades, watershed urbanization has been known to harm aquatic systems. Although the problem has been long articulated, solutions have been elusive because of the complexity of the problem, the evolution of still-imperfect analytical tools, and socioeconomic 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 toward aquatic resource protection has been marked by well-intentioned but ultimately mistaken approaches, compromises with other agency goals that thwart complete success, and imperfect implementation of adopted policies and plans. This experience demonstrates the difficulty of meeting urban and suburban water-quality and aquatic-resource protection goals in the face of competing social priorities and variable political resolve on environmental issues that require sustained, long-term strategies to achieve progress.

King County provides a useful case study for resource managers in urbanizing regions across the country. It covers about 5,600 square kilometers with a population of 1.7 million people, the twelfth most populous county in the United States. Its western boundary is Puget Sound and its eastern boundary is the crest of the Cascade Range. It contains all or most of three major river basins, two large natural lakes, and numerous small rivers and streams (Figure 1). The streams and lakes support all species of anadromous Pacific salmon and resident trout. Land uses include urban, industrial, suburban, agriculture, rural, commercial timber production, and National Forest. Cities include Seattle, Bellevue, Renton, and Redmond; population growth has been explosive over the last 20 years.

Recent Endangered Species Act (ESA) listings of Puget Sound chinook and bull trout, and the potential for more salmonid listings, have brought new scrutiny to all aspects of watershed protection and urbanization-mitigation efforts in King County and

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the surrounding region. Such increased attention is forcing improved articulation of the goals, the means, and the justification for mitigating the effects of urban development. It also has highlighted the failure of most stormwater mitigation efforts, not only in the Pacific Northwest but also across the country, where well-publicized successes are overshadowed by progressive degradation of once-healthy stream systems. This degradation has continued, despite sincere but ineffectual efforts via structural "Best Management Practices" (BMPs), particularly detention ponds, buffer regulations, and rural zoning.

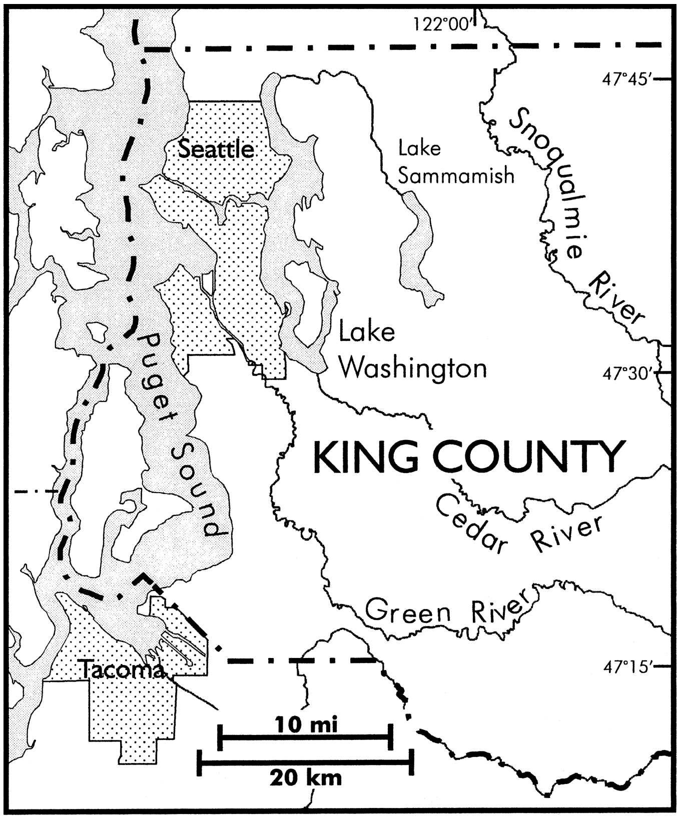

Figure 1. Location of King County, Washington. Most urban and suburban development here is occurring in the region between Puget Sound and the Snoqualmie River.

Our purpose here is to diagnose what has gone wrong with these structural and regulatory approaches, so that others can think more creatively and productively about potentially more successful strategies, and to suggest preliminary solutions of our own. Our approach has four elements: (1) to review some empirical relationships between watershed conditions and stream conditions; (2) to review the history of surface-water management in King County as it relates to the analysis and mitigation of urban development; (3) to evaluate the basis for regulating watershed land use, rather than building structural BMPs, to minimize the downstream consequences of urbanization; and (4) to recommend an integrated stormwater management strategy based on King County's experience of the past decade. We have no panaceas, however. If the problems were easily solved, they would have been so many years ago.

This paper focuses on changes in runoff and stream flow because they are ubiquitous in urbanizing basins and cause often dramatic changes in flooding, erosion, sediment transport, and ultimately channel morphology. Hydrologic change also influences the whole range of environmental features that affect aquatic biota – flow regime, aquatic habitat structure, water quality, biotic interactions, and food sources (Karr, 1991). Yet runoff and stream-flow regime, while important, are by no means the only drivers of aquatic health. Consequently, there should be no illusion that *just* addressing hydrologic conditions will necessarily "fix" or "protect" an urban stream.

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 dramatic chang in flow patterns 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).

EMPIRICAL RELATIONSHIPS BETWEEN WATERSHED CONDITIONS AND STREAM CONDITIONS

Correlations between watershed development and aquatic-system conditions have been investigated for over two decades. Klein (1979) published the first such study, where he reported a rapid decline in biotic diversity where watershed imperviousness exceeded 10 percent. Steedman (1988) believed that his data showed the consequences of both impervious cover and forest cover on instream biological conditions. Later studies, mainly unpublished but covering a large number of methods and researchers, were compiled by Schueler (1994). Since that time, additional work on this subject has been done by a variety of Pacific Northwest researchers, including May (1996), Booth and Jackson (1997), and Morley (2000) (Figures 3, 4, and 5).

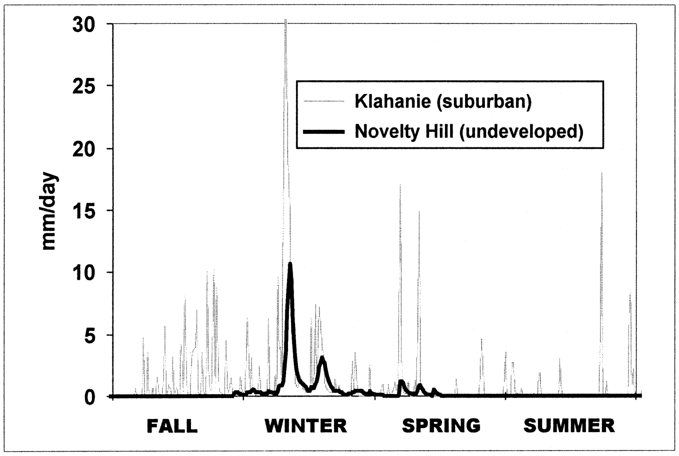

Figure 2. One year's measured discharges for a suburban (Klahanie) and an undeveloped (Novelty Hill) watershed, normalized by basin area (data from Burges *et al.,* 1998).

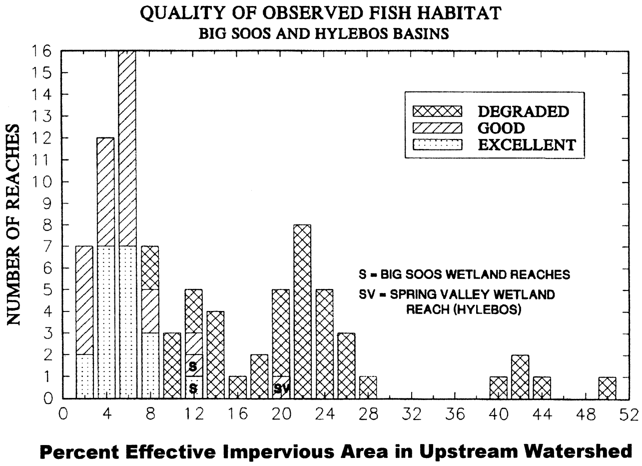

Figure 3. Observed fish habitat quality as a function of effective impervious area in the contributing watershed, based on more than 80 individually inventoried channel segments in south King County (from Booth and Jackson, 1997; data from King County, 1990a, 1990c). "EXCELLENT" reaches show little or 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.

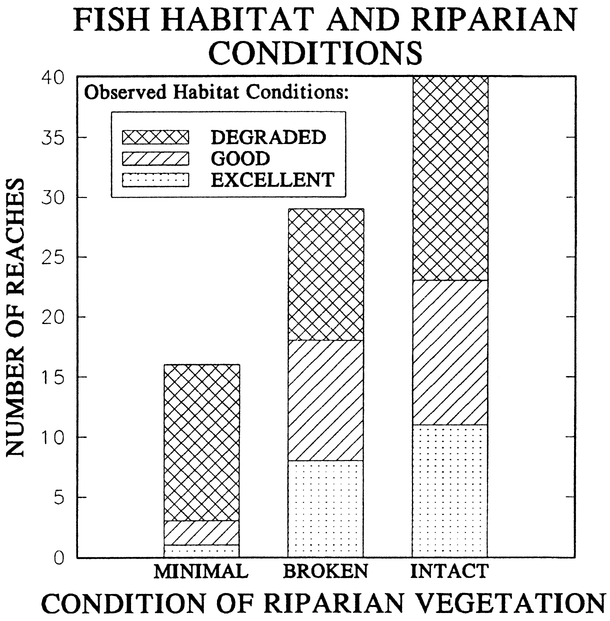

Figure 4. Relationship between riparian vegetation and instream conditions, using the same sites and criteria as for Figure 3. A relatively intact riparian corridor is clearly necessary, but not sufficient, for high quality habitat.

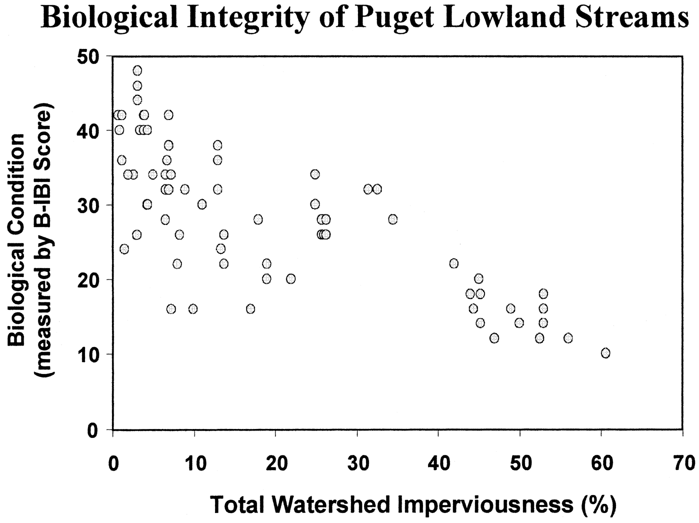

Figure 5. Compilation of biological data on Puget Lowland watersheds, reported by Kleindl (1995), May (1996), and Morley (2000). The pattern of progressive decline with increasing imperviousness in the upstream watershed is evident only in the upper bound of the data; significant degradation can occur 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 wide *range* of stream conditions, however, can be associated with any given level of imperviousness, particularly at lower levels of development.
- "Thresholds of effect," articulated in some of the earlier literature (e.g., Klein, 1979; Booth and Reinelt, 1993) exist largely as a function of measurement (im)precision, not an intrinsic characteristic 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 (e.g., Figure 5) demonstrate a continuum of effects, not a threshold response, resulting from human disturbance.

MITIGATION OF NEW DEVELOPMENT: THE KING COUNTY, WASHINGTON, EXPERIENCE

Hydrologic Mitigation Through Structural Means

As a consequence of the urban-induced runoff changes that cause flooding, erosion, and habitat damage, jurisdictions have long required some degree of stormwater mitigation for new developments. 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 post-development peak discharges at their predevelopment levels. Even if this goal is successfully achieved 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 post-development duration of a wide range of peak discharges at predevelopment levels. Yet unless runoff is infiltrated, the total *volume* of runoff must still increase in the post-development condition. Thus durations cannot be matched for all discharges because this "excess" water must also be released. Duration standards seek to avoid potential disruption to the downstream channels by choosing a "threshold discharge," below which sediment transport in the receiving channel is presumed not to occur and so post-development flow durations can be increased without concern. This choice 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.

The first efforts at runoff mitigation sought to reduce peak flows, reflecting the traditional focus on flood reduction. Well over 100 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. This formula was used by King County in the Pacific Northwest region's first surface-water design manual (King County, 1979). Unfortunately, it tended to overestimate predevelopment flows, which led to the construction of grossly undersized detention ponds that had little or no benefit in preventing downstream flooding (Booth and Jackson, 1997). Ponds designed with the Rational method had such high release rates that they rarely backed up water during storms.

The subsequent edition of King County's design manual (King County, 1990b) substituted the Soil Conservation Service's (SCS) 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 significant additional training in hydrologic-modeling skills for local engineers doing drainage-design work. Although it was an improvement over the Rational method, the SCS method still contained fundamental flaws that resulted in detention ponds that did not meet desired performance criteria. In this method, runoff from individual 24-hour design storm events was used to test and adjust pond designs, and ponds were assumed to be empty at the beginning of a storm. Yet this is rarely the case during (commonly sequential) wet-season storms. SCS curve-number hydrology also commonly overestimated predevelopment flows, a tendency sometimes exacerbated by design engineers who manipulated the time of concentration and curve number to reduce the size of the pond on their client's behalf. Furthermore, the SCS methodology was still a "peak standard" that ignored any problems associated with increased flow durations. Continuous flow modeling revealed that the ponds designed with the SCS method would not achieve the stated protection goals (Barker *et al.,* 1991). Although convincing the land developers and their engineers of these problems has proven difficult, the county's 1998 version of the Design Manual did incorporate a regionally calibrated continuous flow model for designing stormwater facilities (King County, 1998; Jackson *et al.,* 2001).

The practice of seeking duration control for new developments was introduced through King County's Basin Planning Program in the late 1980s. The goal of this standard 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 (Hydrologic Simulation Program-Fortran) (Bicknell *et al.,* 1997), could predict the detention needed to achieve this goal (Jackson *et al.,* 2001).

From the outset, this approach has been controversial for several reasons:

1. The required ponds are larger, often dramatically so, than required by previous design methods.
2. 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.
3. 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. For example, 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.
4. 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 1990s [and incorporated into more recent updates (1998) of the design manual]. Yet several issues remain unanswered, even with the current status of implementation:

"Threshold" Discharge. As noted above, there is a presumed threshold discharge below which there are "no effects" of flow-duration increase. This may be defensible, at best, 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 bed 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.

Point Discharge. 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 (e.g., Booth, 1990).

Ground Water. Any analysis of flow durations will not address changes to ground water 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 ground water.

Individual Storm Hydrographs. The flow-duration design, by definition, assures that the fractional time of a given discharge's exceedence remains unchanged over an extended climate record (nearly 50 years, in the case of King County), but there is no attempt (or ability) to construct detention ponds that match durations for specific storm events or even an entire storm season. Thus the *aggregate* flow-duration spectrum may be unchanged, but the timing and brevity of any single storm hydrograph may be quite different from the undisturbed condition.

Des Moines Creek, a small urban system, demonstrates these difficulties in accomplishing the hydrologic restoration in an urban stream. Since the 1940s, widespread conversion of forests and pastures has occurred to accommodate Seattle-Tacoma International Airport and other commercial and residential uses. Within the Creek's 14 km^2 watershed, total impervious area was raised approximately 50 percent, wetlands were filled, some of the stream headwaters were piped, and storm runoff to the remaining natural drainage system was discharged with minimal detention. As a result, increased magnitude, frequency, and duration of peak flows raised flow velocities, destabilized the stream channel, eroded spawning gravels, degraded fish habitat, and caused flooding of park facilities near the mouth of the stream. Additionally, summer base flows and water quality declined in the Creek.

By the 1990s, the public and local government resolved to develop and implement a basin plan to solve these problems and restore the creek. However, the challenges faced by the technical and policy teams were formidable (Des Moines Creek Basin Committee, 1997). Any solution to existing problems also needed to accommodate additional future development within the watershed that would raise total impervious area from approximately 50 percent to 65 percent of the total drainage area and to have a cost acceptable to the participating jurisdictions.

Hydrologic modeling was used to evaluate feasible combinations of on-site detention ponds, regional flow bypasses, and regional detention ponds to reduce storm-flow energy in the creek. For $6 million, covering a range of feasible options, very large reductions in flows and flow energy compared to 1990s conditions could be achieved. Yet none of these options could restore storm flows to pristine conditions. The preferred alternative combined peak control with on-site detention ponds, regional detention, and a preexisting pipeline to bypass peak stormwater flows. This alternative provides dramatic flow-duration improvement over current conditions (Figure 6a), but daily flows in the stream do not even begin to approximate pristine conditions, despite a capital cost of nearly $5,000 per watershed hectare (almost $2,000/acre) (Figure 6b).

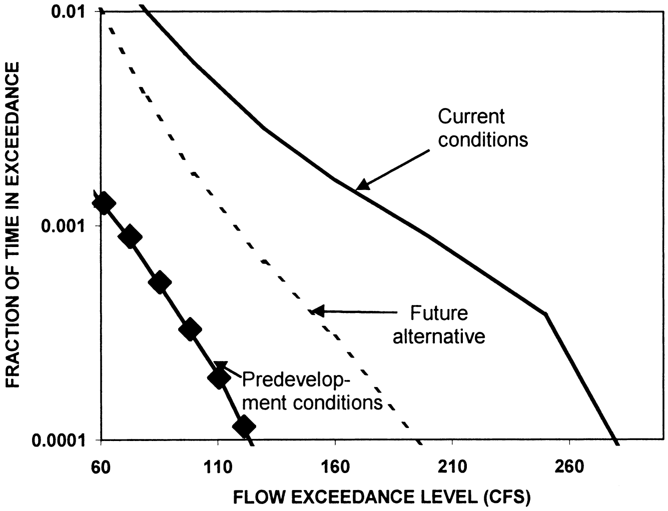

Figure 6a. HSPF-modeled flow-duration curve for Des Moines Creek, displaying dramatic improvement in future flow durations relative to current. Analysis assumes projected land-use changes and construction of proposed detention ponds and bypass pipeline (from Des Moines Basin Committee, 1997).

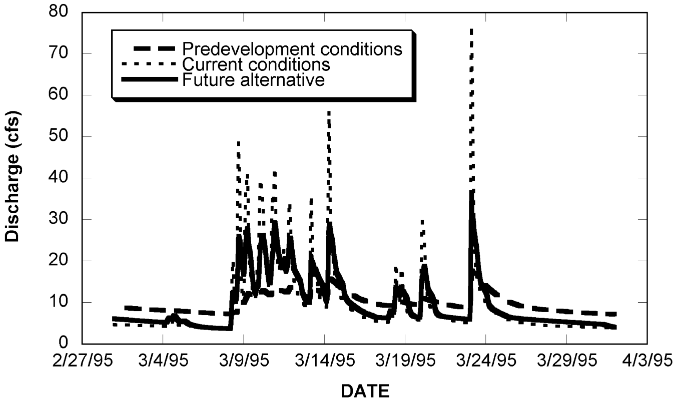

Figure 6b. One month's hydrographs for Des Moines Creek: current flows, predevelopment (i.e., forested) flows, and those under the anticipated future (mitigated) alternative. Note that although the flow-duration curves (Figure 6a) suggest that the future alternative is about mid-way between current and predevelopment conditions, the future hydrograph shows flashy discharge and low base flows much more like current (urban) conditions than those of predevelopment time.

Hydrologic Restoration Through Watershed Planning

Realizing that on-site drainage controls alone were insufficient to achieve the goals of either stormwater management or resource protection, King County initiated an interdisciplinary watershed planning program in the mid 1980s, with the goal of solving and preventing flooding, water-quality, and habitat problems within the rapidly-urbanizing western part of the county. This "basin planning process" involved a two step approach:

1. A detailed assessment of basin conditions that included inventories of point and nonpoint pollution sources, characterization of channel habitat and fish communities, mapping existing and anticipated land uses, identifying and characterizing flooding and channel erosion problems, and modeling stream flows under various development scenarios using HSPF.
2. Development of solutions that combined constructed projects, drainage and zoning regulations, and public education programs.

One finding of the early plans was that aquatic resources had been degraded by low-density rural development (e.g., one dwelling unit per five acres) (King County, 1990a, 1990d). Although this density of development generally did not create much imperviousness, the amount of forest clearing to create large lawns, pastures, or hobby farms could easily reach 60 percent of the landscape, with significant effects on watershed flow regime. Furthermore, many rural landowners were inclined to "manage" the streams on their property. This might include riparian forest clearing, removing woody debris from the channel, and hardening stream banks to protect property. Rural zoning, in and of itself, does not necessarily protect aquatic resources.

The failure of simple land-use controls (i.e., zoning) to protect aquatic resources led to the need for 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 1980s and early 1990s while working on the past and current basin plans (and subsequently published in Booth and Jackson, 1997) (Figure 7). These data showed that two linked thresholds apparently marked a transition of the visible channel form from "stable" to "unstable" (see also Henshaw and Booth, 2000). 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 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 ten-year forested (i.e., predevelopment) discharge ($Q_{10\text{-for}}$) and the two-year current discharge ($Q_{2\text{-urban}}$). There was, and is, no theoretical basis for these particular outcomes – they are simply empirical results, remarkable in their consistency across western Washington and quite possibly recognizable in other regions of the country as well (Schueler, 1994).

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 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? Recent investigations by Maxted and Shaver (1999) suggest virtually no improvement in stream conditions from typical detention ponds. Even if they could be designed to be hydrologically effective, ponds cannot avoid other key problems such as disruption of storm flow patterns, increased winter storm volumes, or declining base flows.

Notwithstanding these limitations (i.e., potentially unrecognized degradation and potentially effective detention ponds), the Issaquah Creek Basin Plan (King County, 1994) used the "threshold" criteria for stream-channel stability suggested by Figure 7 to evaluate the likely consequences of model predictions of post-development runoff conditions. 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 hydrologic criterion for channel instability ($Q_{2\text{-urban}} > Q_{10\text{-for}}$) was exceeded pervasively throughout the watershed under all future development scenarios.

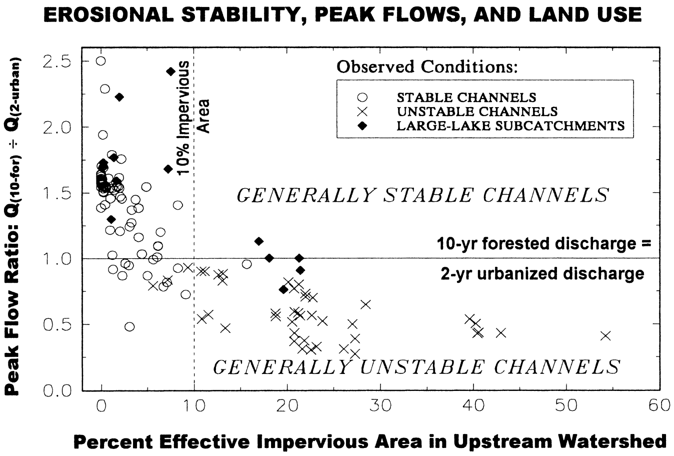

Figure 7. Observed stable ("O") and unstable ("X") channels, plotted by percent effective impervious area (EIA) in the upstream watershed (horizontal scale) and ratio of modeled ten-year forested and two-year urbanized (i.e., current) discharges (vertical scale). "Stable channels" consistently meet the apparent thresholds of either {EIA ≤ 10 percent} or {$Q_{2\text{-urban}} \leq Q_{10\text{-for}}$}, except for the few catchments containing large lakes (from Booth and Jackson, 1997).

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 five-acre zone (i.e., 20 houses per 100 acres, but clustered on the nonforested 35 percent of the land area), the criterion of keeping the two-year developed discharge below the ten-year forested discharge could be just met on glacial till soils (the most common type in King County). Greater amounts of cleared land resulted in two-year developed discharges that exceeded ten-year forested discharges, even though the amount of effective impervious area was well under 10 percent. The analysis noted that development on highly pervious glacial 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 in rural areas, forest clearing and conversion to suburban vegetation (mainly lawns) was far more significant in determining peak discharge increases than the small increases in impervious area typical of low-density development (Figure 8). As a result, forest retention has been adopted as an alternative to detention for rural plats and short plats in the latest update to the Stormwater Design Manual.

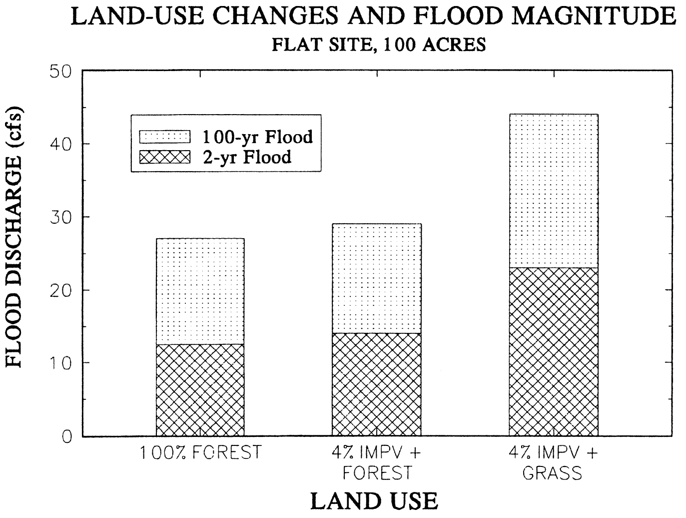

Figure 8. HSPF-modeled increases in two-year and 100-year discharges that result from forest conversion on moderately sloping till soils. Four percent (effective) imperviousness, a typical value for five-acre residential densities, shows particularly significant hydrologic changes only when accompanied by forest clearing.

THE BASIS FOR REGULATING 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 this region, approximately 10 percent effective impervious area in a watershed typically yields demonstrable degradation, some aspects of which are surely irreversible. Although early observations were not sensitive enough to show significant degradation at even lower levels of urban development, the basin plans of the early 1990s recognized that such damage was almost certainly occurring. More recently, biological data (e.g., Morley, 2000) 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 $Q_{2\text{-urban}}$ greater than $Q_{10\text{-for}}$, coupled with hydrologic analyses that have explored the relationship between forest-cover reduction and peak-flow increases. 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 $Q_{2\text{-urban}} = Q_{10\text{-for}}$. Using more generalized model parameters and a range of effective impervious areas typical of rural areas, 65 percent forest cover is a plausible, but by no means definitive, value for meeting the presumed "stability criterion" of $Q_{2\text{-urban}}$ less than $Q_{10\text{-for}}$ in rural-zoned watersheds on moderately (5 to 15 percent) sloping till soils (Figure 9). The analysis summarized in Figure 9 assumes no on-site detention facilities are present because they are often technically (and politically) infeasible in low-density rural areas. Other soils (particularly more infiltrative ones) may yield much greater hydrologic response with even lesser amounts of clearing.

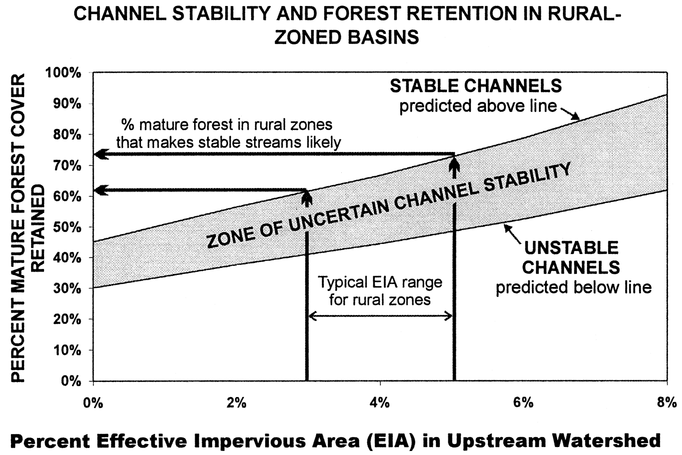

Figure 9. Conditions of forest cover and impervious area in an HSPF-modeled watershed, with moderate slopes and till soils, relative to the channel-stability criterion $Q_{2\text{-urban}} = Q_{10\text{-for}}$. The range of effective impervious areas (EIA = 3 to 5 percent) reflects variation in rural land cover conditions; the "zone of uncertain channel stability" reflects uncertainty in the hydrologic parameters.

Hydrological analyses suggest that maintaining forest cover is more important than limiting impervious-area percentages, at least at rural residential densities where zoning effectively limits the range of EIA between 2 and 6 percent of the gross development area. Absent clearing limitations, however, forest cover will range between 5 and about 85 percent. Consequently, even if both types of land cover control (i.e., forest retention and EIA limitation) are critical to protect stream conditions, current land-use practices suggest that mandating retention of forest cover is the more pressing regulatory need in rural areas. Degraded watersheds, with less than 10 percent EIA and less than 65 percent forest cover, are common ("cleared rural"); in contrast, we have found *no* watersheds with more than 10 percent EIA that have also retained at least 65 percent forest cover ("forested urban") (Figure 10).

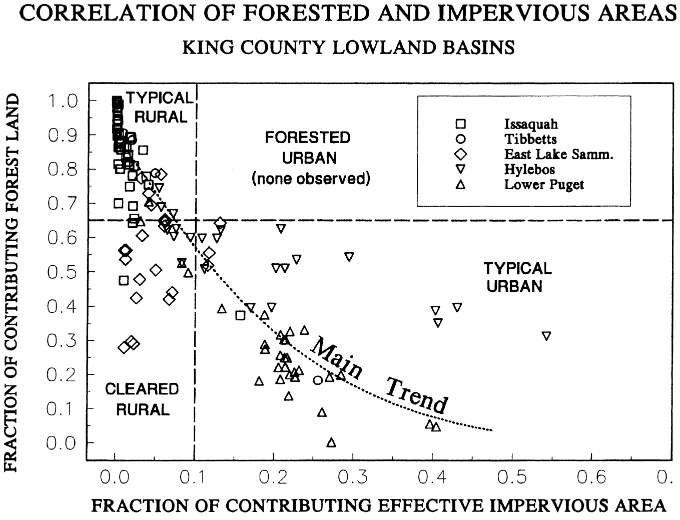

Figure 10. Land cover data from individual subcatchments within five King County watersheds, compiled from Basin Plan land-cover data (King County, 1990c, 1990e, 1991). At 65-percent forest retention, EIA ≤ 10 percent in all cases, yet with EIA < 10 percent, substantial clearing is still commonly observed.

The apparent correlations between stream stability and both impervious-area and forest-cover percentages present a 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 (Morley, 2000), 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.

These conditions also emphasize the need to develop new approaches to mitigate the consequences of watershed urbanization on streams. If urban and suburban watersheds cannot hydrologically mimic forested ones, no matter how large their associated detention ponds, then reducing the coverage of effective impervious area or the extent of urban development itself is an inescapable consequence of the present desire to "restore" urban watercourses. If those necessary reductions run counter to other, even more pressing social goals, most notably those to accommodate additional population growth, then our goals for aquatic-resource conservation need to be modified in urban areas. By not acknowledging the need for such tradeoffs, opportunities to discover the most rational and effective strategy for protecting the condition of once-natural aquatic systems continue to be lost.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Land development that eliminates hydrologically mature forest cover and undisturbed soil can result in significant changes to urban stream flow regimes and, in turn, to the physical stability of stream channels. These changes are manifested in altered stream flow patterns with higher volumes of storm flow, leading to accelerated channel erosion and habitat simplification. Even with stormwater detention ponds, seasonal and stormflow patterns are substantially different from those to which native biota have adapted. These hydrologic changes cannot be completely mitigated with structural measures. Although factors other than hydrologic change (e.g., water chemistry, riparian buffers) can undoubtedly affect the magnitude of urban impacts, the breadth of the existing data suggest that improvements in these other factors can never fully mitigate the hydrologic consequences of overly intense urban development. Under typical rural land uses, the magnitude of observed forest-cover losses affects watershed flow regime as much as, or more than, associated increases in impervious area.

The goals of stormwater detention have become progressively more ambitious as the consequences of urban-altered flow regime have become better recognized and understood. Even the largest detention ponds, however, are 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 flow regime 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 (EIA) of about ten percent.

Field observations and hydrologic modeling showed that the watershed plans of the early- to mid-1990s could only hope to meet plan-stipulated goals for resource protection by imposing clearing and impervious-area restrictions. The most commonly chosen thresholds, maximum 10 percent EIA and minimum 65 percent forest cover, mark an observed transition in the downstream channels from minimally 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; for any given watershed, additional development tends to produce additional aquatic-system degradation. However, these impervious and forest-retention percentages have proven to be attractive regulatory thresholds and are being advocated by the National Marine Fisheries Service as necessary conditions for mandated protection of rural areas under the Endangered Species Act.

Development that minimizes the damage to aquatic resources cannot rely on structural BMP's, because there is no evidence that they can mitigate any but the most egregious consequences of urbanization. Instead, control of watershed land-cover changes, including limits to both imperviousness and clearing, must be incorporated (see also Horner and May, 1999). We anticipate needing all of the following elements to maintain the possibility of effective protection:

- clustered developments that protect half or more of the forest cover, preferentially in headwater areas and around streams and wetlands to maintain intact riparian buffers;

- a maximum of 20 percent total impervious area, and substantially less effective impervious area through the widespread reinfiltration of stormwater (Konrad and Burges, 2001);

- on-site detention, realistically designed to control flow durations (not just peaks);

- riparian buffer and wetland protection zones that minimize road and utility crossings as well as overall clearing; and

- no construction on steep or unstable slopes.

Past experience suggests that each of these factors are important. However, we still lack empirical data on the response of aquatic resources to such "well-designed" developments. Therefore, these recommendations are based only on extrapolations, model results, and judgment; they are tentative at best. Where development has already occurred, these conditions clearly cannot be met and different management objectives are inescapable: many, perhaps all, streams in already-urban areas cannot be truly protected or restored, and a significant degree of probably irreversible stream degradation is unavoidable in these settings.

We can recognize why streams nominally protected under past drainage regulations have experienced severe degradation, we can articulate the kinds of development styles and strategies that should minimize new examples of degraded streams, and we can recognize the role of watershed land-cover regulation in minimizing the consequences of new development, but we cannot find any basis to expect that the full range of hydrological and ecological conditions can be replaced in a now-degraded urban channel. The key tasks facing watershed managers, and the public that can support or impede their efforts, are therefore: (1) to identify those watersheds where existing low urbanization and associated high-quality stream conditions that warrant the kinds of development conditions that may protect much of the existing quality of these systems; and (2) to develop a new set of management goals for those watersheds whose surrounding development precludes significant ecosystem recovery. Following the same strategy in *all* watersheds, developed and undeveloped alike, simply makes no sense.

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