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Urbanization of Aquatic Systems--
Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation

Derek B. Booth[1] and C. Rhett Jackson[2]

[1]Professor and Director, Center for Urban Water Resources Management, Department of Civil Engineering, Box 352700, University of Washington, Seattle, WA 98195; 206-543-7923; email *dbooth@u.washington.edu*

[2]Senior Hydrologist, Pentec Environmental, Inc., 120 Third Avenue S, Suite 110, Edmonds, WA 98020; 206-775-4682; email *rhett@pentec.wa.com*

ABSTRACT: Urbanization of a watershed degrades both the form and the function of the downstream aquatic system, causing changes that can occur rapidly and are very difficult to avoid or correct. A variety of physical data from lowland streams in western Washington display the onset of readily observable aquatic-system degradation at a remarkably consistent level of development, typically about ten percent effective impervious area in a watershed. Even lower levels of urban development cause significant degradation in sensitive water bodies and a reduced, but less well quantified, level of function throughout the system as a whole. Unfortunately, established methods of mitigating the downstream impacts of urban development may have only limited effectiveness. Using continuous hydrologic modeling we have evaluated detention ponds designed by conventional event methodologies, and our findings demonstrate serious deficiencies in actual pond performance when compared to their design goals. Even with best efforts at mitigation, the sheer magnitude of development activities falling below a level of regulatory concern suggest that increased resource loss will invariably accompany development of a watershed. Without a better understanding of the critical processes that lead to degradation, some downstream aquatic-system damage is probably inevitable without limiting the extent of watershed development itself.

KEY TERMS: Stormwater Management; Urban Hydrology; Hydrograph Analysis and Modeling

INTRODUCTION

Urban development imposes a variety of watershed changes that profoundly affect runoff processes and the downstream surface-water aquatic system. Attention is generally given to *channel changes*: the stream channel itself is the object of interest and also, typically, the focus of any subsequent restoration or rehabilitation efforts. Yet that stream channel, commonly draining up to many square kilometers, is largely a product of its upland watershed. The net effect of *upland changes*, occurring across the land surface of the contributing headwater catchments, is at least as important in determining overall stream function, degradation, and rehabilitation potential (National Research Council, 1992). To understand the potentially degrading effects of urban development and the potential for mitigation, both areas—upland and riparian—must be considered in turn.

Our approach to this problem draws on both field data and hydrologic simulation results from a variety of lowland watersheds in King County, Washington (Figure 1 and Table 1). We have relied on field data to display overall trends in stream-channel changes; hydrologic simulations have been no less invaluable to improve our understanding of the likely physical processes that underlie those observed changes. Although an analysis of urban-induced channel changes would be complete without any discussion of mitigation, we have elected to include here an investigation into the most common of mitigation efforts, stormwater detention. Stormwater detention is a particularly widespread application that promises substantive improvements, but all-too-often it fails to achieve even the most limited of objectives.

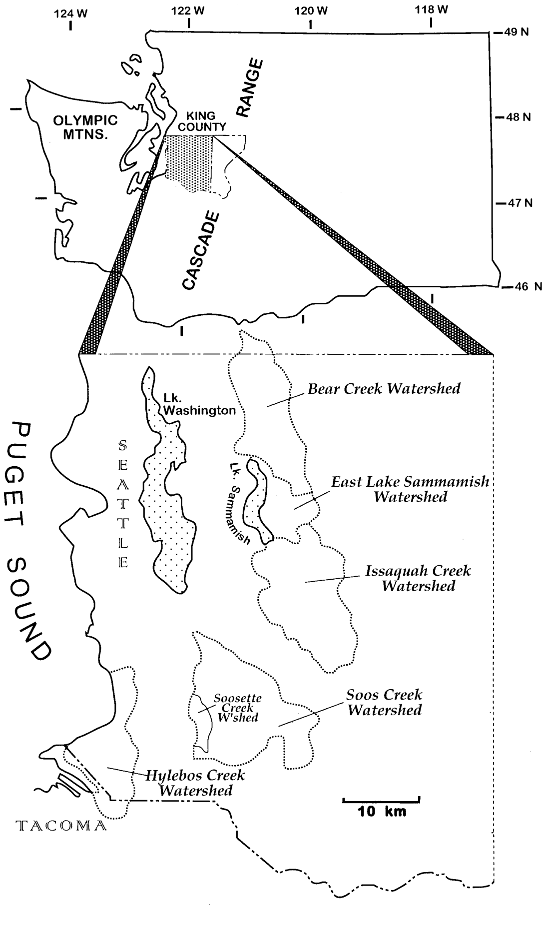

Figure 1. Map of watersheds used as sources of field data and in analyses. Physical and simulation characteristics are summarized in Table 1.

Table 1
Physical Characteristics of Watersheds Used as Data Sources and in Analyses

Watershed Name	Soos	Bear	Hylebos	East Lake Sammamish	Issaquah
Reference	King County, 1990a	King County, 1989	King County, 1990b	King County, 1990c	King County, 1991
Size	181 km^2	132 km^2	93 km^2	38 km^2	158 km^2
Range of watershed elevations	305 m—25 m	185 m—9 m	158 m—0 m	168 m—10 m	905 m—10 m
Avg. annual rainfall	1190 mm	1100 mm	1040 mm	1220 mm	1450 mm
Number of HSPF-modeled subcatchments	57	66	61	22	65
Subcatchment size—average and range	3.18 km^2 (avg.) 1.53—10.62 km^2 (range)	2.00 km^2 (avg.) 0.56—8.65 km^2 (range)	1.52 km^2 (avg.) 0.21—2.36 km^2 (range)	1.73 km^2 (avg.) 0.33—4.86 km^2 (range)	2.43 km^2 (avg.) 0.31—6.97 km^2 (range)
Watershed impervious area (EIA)	4.9 %	3.0 %	20.0 % (median of 8 independent sub-watersheds)	5.0 % (median of 3 independent sub-watersheds)	1.4 %
Impervious areas (EIA)—range by subcatchments	0.7—23.1 %	0.0—12 %	0.2—54 %	0.0—13.1 %	0.0—18.3 %
Forest cover	69 %	76 %	27 % (median of 8 sub-watersheds)	60 % (median of 3 sub-watersheds)	78 %
Forest cover—range by subcatchments	35.3—88.8%	41—100 %	0.1—100 %	29.0—68.4 %	25.6—100 %
Unit-area discharges (2-yr)— at watershed outlet and range within subcatchments	0.13 m^3/km^2 (at outlet; =12.1 cfs/mi^2) 0.08—0.41 m^3/km^2 (range)	0.14 m^3/km^2 (at outlet; =12.4 cfs/mi^2) 0.09—0.42 m^3/km^2 (range)	0.60 m^3/km^2 (median of 8 independent sub-watersheds at outlets; =55.0 cfs/mi^2) 0.01—0.98 m^3/km^2 (range)	0.19 m^3/km^2 (median of 3 independent sub-watersheds at outlets; =51.2 cfs/mi^2) 0.02—0.56 m^3/km^2 (range)	0.32 m^3/km^2 (at outlet; =28.9 cfs/mi^2) 0.10—0.66 m^3/km^2 (range)
Unit-area discharge (100-yr) —outlet and range	0.28 m^3/km^2 (at outlet; =25.9 cfs/mi^2) 0.13—0.97 m^3/km^2 (range)	0.31 m^3/km^2 (at outlet; =15.2 cfs/mi^2) 0.17—0.80 m^3/km^2 (range)	1.20 m^3/km^2 (median, at outlets; =110 cfs/mi^2) 0.03—1.94 m^3/km^2 (range)	0.41 m^3/km^2 (median, at outlets; =37.2 cfs/mi^2) 0.06—1.20 m^3/km^2 (range)	0.79 m^3/km^2 (at outlet; =72.5 cfs/mi^2) [range data not available]

Development-Induced Upland Changes—Runoff and Sediment Processes

Modifications of the land surface during urbanization produce changes in both the type and the magnitude of runoff processes. These changes result from vegetation clearing, soil compaction, ditching and draining, and finally covering the land surface with impervious roofs and roads. The infiltration capacity of these covered areas is lowered to zero, and much of the remaining soil-covered area is trampled to a near-impervious state. Compacted, stripped, or paved-over soil also has lower storage volumes, and so even if precipitation can infiltrate, the soil reaches surface saturation more rapidly and more frequently. Thus *Horton overland flow* or *saturation overland flow* (Dunne and Leopold, 1978) is introduced into areas that formerly may have generated runoff only by subsurface flow processes, particularly in humid areas of generally low-intensity rainfall such as the Pacific Northwest.

Besides changing the hydrologic flow regime, urbanization affects other elements of the drainage system. Gutters, drains, and storm sewers are laid in the urbanized area to convey runoff rapidly to stream channels. Natural channels are often straightened, deepened, or lined with concrete to make them hydraulically smoother. Each of these changes increases the efficiency of the channel, transmitting the flood wave downstream faster and with less retardation by the channel. In total, direct measurements and hydrologic simulation models demonstrate several related consequences: for any given intensity and duration of rainfall the peak discharge is greater (by factors of 2 to 5; Hollis, 1975), the duration of any given flow magnitude is longer (by factors of 5 to 10; Barker and others, 1991), and the frequency with which sediment-transporting and habitat-disturbing flows move down the channel network is increased dramatically (by factors of 10 or more; Booth, 1991, Booth and Fuerstenberg, 1994) (Figure 2).

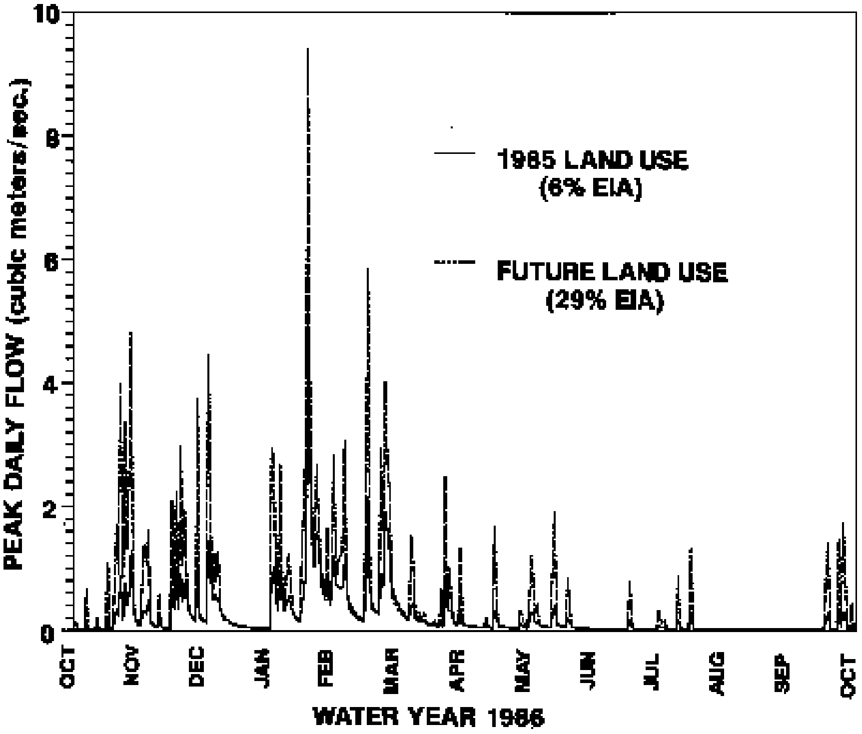

Figure 2. One year of simulated streamflow from a 14.2-km^2 watershed (Soosette Creek), under identical rainfall but differing land uses, using the continuous numerical model HSPF (USEPA, 1984). Parameters characterize the present-day (1985) land cover (6 percent effective impervious area

[EIA], the impervious surfaces with direct hydraulic connection to the stream system) and projected future land cover (29 percent EIA).

Changes in upland runoff processes, particularly from a predominantly *subsurface* flow regime to a predominantly *surface* flow regime, alter not only the magnitude of discharges but also the delivery of sediment to the stream network. With overland flow fine sediment is moved into channels throughout the year; when coupled with land-cover changes the sediment load can increase by many orders of magnitude (Wolman and Schick, 1967) and the predominant grain-size distribution can shift to much finer fractions. Such increases in the delivery of fine sediments significantly alters the sediment size distribution of gravel bed streams (*e.g.,* Carling, 1984; Jobson and Carey, 1989), with attendant changes in stream ecology (recognized as early as Ellis, 1936; also Hawkins and others, 1982; Culp and others, 1986; Chapman, 1988; Naiman and others, 1992; Weaver and Garman, 1994).

Development-Induced Riparian Changes

Urban development not only increases rates of water and sediment delivery but also encroaches on the riparian corridor. From clearing of streamside vegetation less wood enters the channel, depriving the stream of stabilizing elements that help dissipate flow energy and usually (although not always) help protect the bed and banks from erosion (Booth and others, 1996). Deep-rooted bank vegetation is replaced, if at all, by shallow-rooted grasses or ornamental plants that provide little resistance to channel widening (Booth and Jackson, 1994). Furthermore, the overhead canopy of a stream is lost, eliminating the shade that controls temperature and supplies leaf litter that enters the aquatic food chain.

Channel Response to Development-Induced Watershed Changes

As a result of these factors, channel widths and depths increase throughout urban areas (Hammer, 1972; Leopold, 1973) and heterogeneous channel morphology becomes more simplified and uniform. Most commonly, channels expand gradually in response to progressive increases in the flow regime (Figure 3). However, they can also experience rapid and nearly uncontrolled incision of the stream bed, usually in response to an increase in the flow rate combined with specific combinations of gradient, substrate, and reduced in-channel vegetation (Heede, 1985; Booth, 1990).

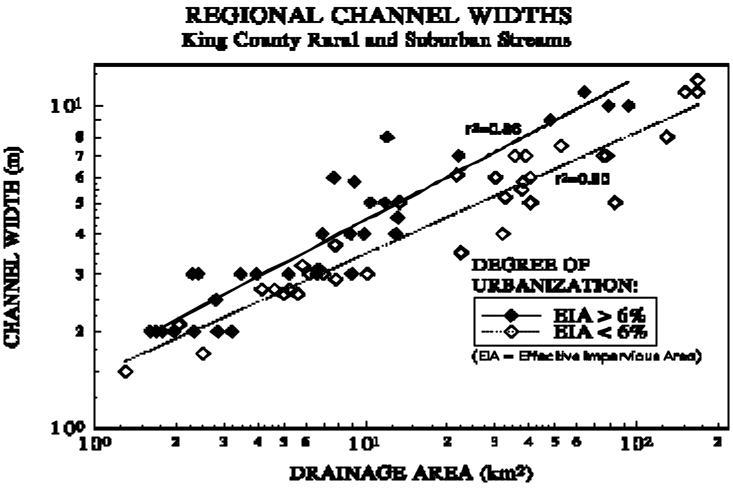

Figure 3. Channel widths as a function of contributing drainage area, measured by the senior author using the methods for bankfull channel identification in Williams (1978). Regression lines plotted for each data set independently. "Urban" channels have at least 6 percent effective impervious area in their contributing watershed.

At the end of this causal chain of upland, riparian, and channel changes lies the degradation of in-stream biological function that so often motivates rehabilitation efforts (Karr, 1996). In the Pacific Northwest, many of these efforts are focused on enhancing populations of anadromous salmon in lowland streams. These fish depend on a particular combination of water and sediment fluxes to maintain favorable channel conditions. Because land-use change in a watershed alters those fluxes, the resulting flow regime and channel configuration no longer tend to favor salmonids (Booth and Fuerstenburg, 1994), and thus most rehabilitation efforts that address only the in-stream symptoms of these watershed changes are unlikely to succeed (Roper and others, 1997). This study addresses only the *flow*-related consequences of upland watershed changes, and so it does not offer a comprehensive analysis of, or solution to, the loss of salmonids in urban streams of the Pacific Northwest. However, the work has been motivated in large measure by these concerns, and it demonstrates the tremendous ecological significance of those upland changes occurring in the urban environment.

THE RELATIONSHIP BETWEEN URBANIZATION AND AQUATIC-SYSTEM DEGRADATION

Study Approach

With this conceptual model of altered watershed processes as our context, we wish to better characterize the magnitude of urban development and to identify any consistent trends or thresholds of aquatic-system degradation associated with that development. Our approach has been to collect data rapidly from a large number and wide variety of urbanizing watersheds, acknowledging the extreme variability in our sample population but anticipating that the overriding influence of urban development will impose consistent trends in our measurements. Two types of data are required: those that characterize the *magnitude* of urban development, and those that characterize the *effects* of urban development.

Characterizing the Magnitude of Urban Development

Rationale. There is great appeal to identifying a single "index" variable that characterizes the magnitude of urban development in a watershed. Patterns can be readily displayed, correlations are simplified, and communication between scientists and planners is enhanced. Yet urban development comes in many styles, occurs on many different types of landscapes, and is accompanied by a variety of mitigation measures designed to reduce its negative consequences on downstream watercourses. So any simple correlation between urbanization and aquatic-system condition appears unlikely, and it is with this expectation that many of the data reported below were first collected.

TIA and EIA. Past efforts to quantify the degree of urban development have not been consistent. Recent and historical use of the most widely accepted parameter, percent impervious area in the contributing watershed, has been carefully documented in a recent review article (Schueler, 1995) but several issues remain ambiguous. Most significant of these is the distinction between ***total*** impervious area (TIA) and ***effective*** impervious area (EIA). TIA is the "intuitive" definition of imperviousness: that fraction of the watershed covered by constructed, non-infiltrating surfaces such as concrete, asphalt, and buildings. Hydrologically this definition is incomplete for two reasons. First, it ignores nominally "pervious" surfaces that are sufficiently compacted or otherwise so low in permeability that the rate of runoff from them are similar or indistinguishable from pavement. For example, Wigmosta and others (1994) found that the impervious unit-area runoff was only 20 percent greater than that from pervious areas, primarily thin sodded lawns over glacial till, in a western Washington residential subdivision. Clearly, this hydrologic contribution cannot be ignored entirely.

The second limitation of TIA is that it includes some paved surfaces that may contribute nothing to the storm-runoff response of the downstream channel. A gazebo in the middle of parkland, for example, probably will impose no hydrologic changes into the catchment except a very localized elevation of soil moisture at the edge of its roof. Less obvious, but still relevant, will be the different downstream consequences of rooftops that drain alternatively into a piped storm-drain system with direct discharge into a natural stream or onto splashblocks that disperse the runoff onto the garden or lawn at each corner of the building.

The first of these TIA limitations, the production of significant runoff from nominally pervious surfaces, is typically ignored in the characterization of urban development. The reason for such an approach lies in the difficulty in identifying such areas and estimating their contribution, although site-specific studies demonstrate that these tasks can be accomplished with simple field methods and the resulting hydrologic insights are often valuable (Burges and others, 1989). Furthermore, the degree to which pervious areas shed water as overland flow should be related, albeit imperfectly, with the amount of *impervious* area: where construction and development is more intense and covers progressively greater fractions of the watershed, the more likely that the intervening green spaces have been stripped and compacted during construction and only imperfectly rehabilitated for their hydrologic functions during subsequent "landscaping."

The second of these TIA limitations, inclusion of non-contributing impervious areas, is formally addressed through the concept of *effective impervious areas*, defined as the impervious surfaces with direct hydraulic connection to the downstream drainage (or stream) system. Thus any part of the TIA that drains onto pervious (*i.e.* "green") ground is excluded from the measurement of EIA. This parameter, at least conceptually, captures the hydrologic significance of imperviousness. EIA is the parameter normally used to characterize urban development in hydrologic models.

Yet the direct measurement of EIA is complicated. Studies designed specifically to quantify this parameter must make direct, independent measurements of both TIA and EIA (Alley and Veenhuis, 1983; Laenen, 1983; Prysch and Ebbert, 1986). The results can then be generalized either as either a correlation between the two parameters or as a "typical" value for a given land use. For example, Alley and Veenhuis found that $[EIA] = 0.15\ [TIA]^{1.41}$ in their highly urbanized watersheds in Denver, Colorado ($r^2 = 0.98$). Using the alternative approach, Dinicola (1989) compiled the findings of these earlier studies to recommend a single set of impervious-area values based on five land-use categories for use in studies of western Washington watersheds (Table 2). These values are the basis for the impervious-area assignments for our present study as well.

Table 2
Presumed Relationship between Imperviousness and Land Use
(from Dinicola, 1989)

LAND USE	TIA (%)	EIA (%)
Low density residential (1 unit per 2-5 acres)	10	4
Medium density residential (1 unit per acre)	20	10
"Suburban" density (4 units per acre)	35	24
High density (multi-family or 8+ units per acre)	60	48
Commercial and industrial	90	86

Characterizing the Effects of Urban Development

Previous Studies. Correlations between development and aquatic-system conditions have been investigated for nearly two decades with remarkably consistent results. Klein (1979) published the first such study, where he reported a rapid decline in biotic diversity where watershed imperviousness much exceeded 10 percent. A variety of more recent studies, mainly unpublished but covering a large number of study methods and researchers, has been compiled by Schueler (1995). Two aspects of his exhaustive compendium, however, limit the ability to draw overly precise conclusions:

1. The geographic scope of this body of work is largely restricted to streams of the mid-Atlantic seaboard and Pacific Northwest. A few reports from other humid regions are included, and they do not suggest radical differences. However, arid and semi-arid regions are entirely *un*represented by this set of studies.
2. The definition and determination of "imperviousness," by far the most common characterization of urban development in use, is not well described in most of the studies (including the preliminary report of this study—Booth and Jackson, 1994). Commonly, not even the use of TIA or EIA is specified, nor is the measurement method used (*e.g.*, direct measurement from aerial photographs, interpretation of LANDSAT imagery, or characteristic values assigned to different land uses). In the typical range of imperviousness for which "degradation thresholds"

have been investigated, this uncertainty in the choice of imperviousness measure introduces a potential factor-of-two error (Table 2) in comparing the results of one study with another.

Flow Increases. The data sets in our current investigation focus on measures of flow quantity, channel size, and condition of the riparian corridor. They were collected during a series of watershed assessments in the east-central Puget Lowland and are compiled in a series of associated planning documents (see Table 1). The absence of chemical measurements reflects our judgment of the voluminous, but inconclusive, body of water-quality data that shows only poor correlation between development intensity and water quality across the range of (mainly suburban) land uses that we are investigating (Horner and others, 1996). In contrast, the dramatic evidence of physical degradation that is so readily seen in these watersheds (Booth, 1991) suggests the overriding significance of urban-induced flow increases, characterized by both peak discharges and the aggregate duration of sediment-transporting events.

To identify rapidly the potential effects of flow increases in field observations, we discriminate between ***stable*** channels, with little or no erosion of their bed and banks, and ***unstable*** channels, which display long continuous reaches with bare and destabilized banks indicative of severe downcutting and widening (Galli, 1996). To quantify the increase in flows imposed by urbanization, we have used the output of a continuous hydrologic model (Hydrologic Simulation Program-FORTRAN [HSPF]; USEPA, 1984) to simulate discharges in a variety of local watersheds under identical rainfall regimes but differing land uses. We have indexed the magnitude of modeled flow changes in terms of the *post*development frequency of the discharge that had a *pre*development (*i.e.* forested) recurrence of 10 years ($Q_{10\text{-for}}$). Note, however, that other measures of hydrologic change would produce a similar result; there is nothing unique about this particular index discharge.

Model simulations on the watersheds of Figure 1, matched with corresponding field observations, are summarized by Figure 4. This plot discriminates the degree of observed channel stability at each station (indicated by the "X"s and "O"s of Figure 4), and it positions each observation with respect to the contributing watershed’s EIA (horizontal axis) and the now-increased frequency of $Q_{10\text{-for}}$ under current urbanized conditions (vertical axis). The simulations assumed no onsite detention of stormwater runoff under current conditions, because almost no development in this region had yet been constructed with hydrologically significant detention volumes when these observations were made (1988-1992) The forested land-use simulations assumed a rainfall regime and channel network identical to the present, focusing solely on the land-use changes from pre- to post-development conditions.

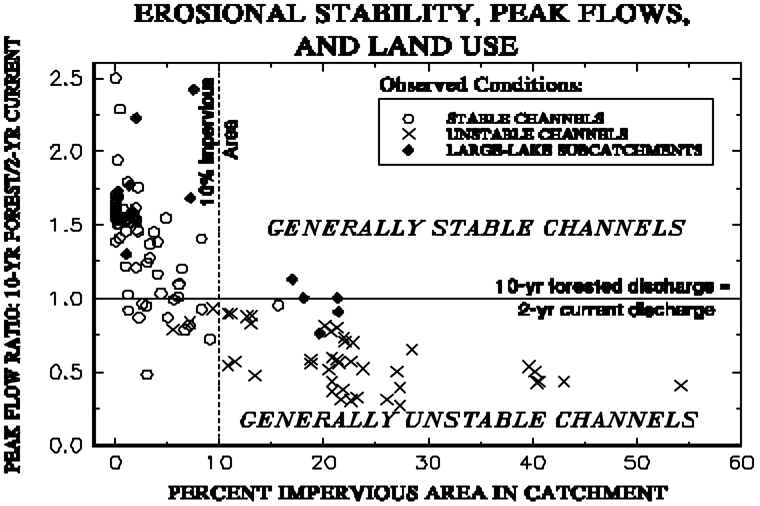

Figure 4. Observed stable ("O") and unstable ("X") channels, plotted by percent effective impervious area (EIA) in the upstream watershed (horizontal scale) and ratio of modeled 10-year forested and 2-year current (*i.e.* urbanized) discharges (vertical scale). Apparent thresholds relating channel stability with either 10-percent EIA or $Q_{2\text{-cur}}= Q_{10\text{-for}}$ are consistently met except for the few catchments containing large lakes.

A surprisingly good correlation emerges between observed channel stability and watershed urbanization, be it characterized by percent effective impervious area or by the magnitude of simulated flow increases. The observations here show that observed instability is all-but ubiquitous where the contributing effective impervious area percentage exceeds a rather low level: a value of about 10 percent (dashed vertical line in Figure 4) discriminates between observed stable and unstable reaches almost perfectly. The magnitude of simulated hydrologic change also discriminates between these observations: in any basin where the discharge equal to $Q_{10\text{-for}}$ now has a recurrence of 2 years or less (shown by the solid horizontal line in Figure 4), instability is assured. We see anomalously low flow increases with increasing EIA only where large lakes (surface area equals or exceeds 10 percent of the watershed area) are present upstream of the observation point. We emphasize that the good relationship between “instability” and “imperviousness” is not a simple causal relationship, because we recognize that EIA is but an *index* of the variety of hydrologic changes imposed by urban development. However, it is clearly a robust and easily estimated one.

Integrated Effects of Urban Development. Urbanization yields not only measurable changes in specific elements of aquatic systems but also a decline in the overall function of those systems. This fact is evident to any resident of such a watershed; similarly intuitive is the observation that degradation increases as development progresses. To understand the range of such effects we have made more complete surveys of the physical habitat along 140 km of stream channel in two of the King County watersheds (Figure 1), classifying each reach as excellent, fair, or poor, defined on the basis of not only channel stability but also pool:riffle ratio, channel roughness and diversity, and observed fish use. The effective impervious-area percentage of the watershed above each channel reach was measured, with EIA’s ranging from 2 to 50 percent in watersheds ranging from 2 to 110 km^2. As with all of our data, significant onsite detention is absent in these watersheds. The level of degradation changes markedly at about 8-10 percent EIA (Figure 5), excepting only a few sites with areas of significant upstream impoundments. A similar relations between habitat quality and effective impervious area has also been seen in wetlands of this region (Booth and Reinelt, 1993).

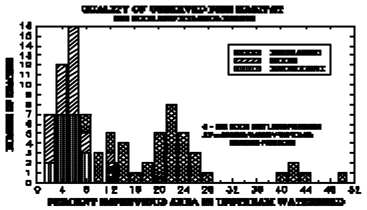

Figure 5. Observed fish-habitat quality as a function of effective impervious area in the contributing watershed, based on over 80 individually inventoried channel segments in south King County (Figure 1). "EXCELLENT" reaches show little or no habitat degradation; "GOOD" reaches show some damage to habitat 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. Three identified reaches with large wetland-to-watershed-area ratios disturb an otherwise consistent pattern of degradation across the gradient of urban development.

At very low levels of watershed urbanization, individual differences between watersheds produce greater variability in relative habitat quality. Patterns become evident only through more detailed evaluations of stream reaches, using not only physical but also biological criteria, which have been conducted through the watershed plans that now cover over 750 km^2 in the lightly (but rapidly) urbanizing areas of the region (Figure 1; *e.g.*, King County, 1990a, 1992, 1993). Each such plan has identified "Regionally Significant Resource Areas" (RSRA's), where the aquatic system is observed to function at a very high level "by virtue of exceptional species and habitat diversity and abundance, when compared to aquatic and terrestrial systems of similar size and structure elsewhere in the region" (King County, 1993). Across the region, 12 such RSRA stream reaches or subbasins have been identified out of a potential population of several hundred. With one exception, located in a uniquely infiltrative subbasin with extremely permeable soils, none are found where the contributing EIA exceeds 3.6 percent. Indeed, the three RSRA's with the greatest contributing impervious area are in basins with unusually widespread and rapid infiltration. *Every other* RSRA has 3 percent or less EIA in its watershed.

Conclusions—Urbanization and Aquatic-System Degradation

These results show remarkably clear and consistent 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, and probably irreversible, loss of aquatic-system function. Even lower levels of urban development cause significant degradation in sensitive water bodies and a reduced, but less well quantified, degree of loss throughout the system as a whole. These results do not indicate a "threshold" *per se*: degradation begins at very low levels of urban development and continues well beyond the range of imperviousness emphasized in this study. But we find a noteworthy accumulation of physical and biological effects, particularly those that can be consistently observed and measured by even rather crude (but also rapid and so inexpensive) methods, once EIA's reach about 10 percent. The *changes* imposed on the natural system are a continuum, and so defining a strict "threshold" in this context would be naive; but our *perception of* and our *tolerance for* those changes appears to undergo a far more abrupt transition, one which suggests a basis for discrete levels of both impact evaluation and management response.

ONSITE DETENTION AS MITIGATION FOR URBAN DEVELOPMENT

Design Issues

The value of storing stormwater runoff in large water bodies has been recognized for decades (Dunne and Leopold, 1978; Whipple, 1979) and is in widespread practice nationwide. In general, all such impoundments function similarly: water is collected from developed areas and is released by infiltration (retention facilities) or surface discharge (detention facilities) at a slower rate than it enters; the excess of inflow over outflow is temporarily stored in a pond or vault. In principle, adequate performance of these "R/D ponds" might change the level of or even eliminate the impervious-area thresholds that produce recognizable aquatic-system degradation.

The *actual* performance of R/D ponds, however, depends on the answer to two questions. The first is one of design ***policy***: how completely do we want the facility to mimic predevelopment runoff conditions? The second is one of design ***analysis***: how accurately does our hydrologic model predict true performance, so that the constructed facility actually achieves the intended management policy?

Policy: Design Performance. R/D ponds can achieve either of two levels of design performance, depending on the desired balance between achieving downstream protection and the cost of that protection. A ***peak standard***, the classic (and least costly) goal of R/D 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 sediment-transporting discharges at predevelopment levels. Duration standards are motivated by a desire to avoid potential disruption to the conveying channel itself by not allowing increased sediment transport. Without infiltration of runoff, however, the total volume of runoff increases in the postdevelopment condition, and so durations cannot be matched for all discharges—at some level 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, in press) or can be applied as a "generic" standard based on predevelopment discharges. Differences between stream channels ensure that no single threshold can possibly work equally well on all channels; nevertheless, a single criterion has substantial advantages in ease of analysis and implementation. A presumed threshold discharge of about one-half of the 2-year flow ($Q_{pre-2}/2$), at least for gravel-bed streams, appears to have reasonable substantiation in the scientific literature (*e.g.*, Pickup and Warner, 1976; Andrews, 1984; Carling, 1988; Sidle, 1988).

Faced with determining the threshold discharge for sediment transport by using either (1) a site-specific method that will likely prove somewhat ambiguous and cumbersome to use, or (2) a rapid, universally applicable method that almost certainly generates incorrect results in a fraction of circumstances, the choice of method may not appear obvious. However, public regulations are replete with examples of uniform (and predictable) standards that may be inappropriate in a minority of cases, because the benefits of such a uniform approach are judged to outweigh the disadvantages. That approach is recommended for this issue as well.

Analysis: Choice of Model. Having determined a design standard, a particular hydrologic model must be used during the design analysis. The choice is critical, because model predictions of pre- and post-development runoff determine the size and configuration of the detention facility. Use of a 24-hour Soil Conservation Service (SCS) Curve-Number method, typically the Santa Barbara Urban Hydrograph method, or SBUH, has been standard practice across much of the Pacific Northwest since 1990 despite its poor correlation between assigned and calibrated curve numbers (Hawkins, 1984) and the inability of any event-based model to predict accurately a continuous process such as runoff (Barker and others, 1991). Alternatives to the SCS method have produced promising results, particularly the King County Runoff Time Series program (KCRTS; King County, 1995). It is a relatively simple hydrologic analysis tool with nearly all of the accuracy and versatility of the continuous rainfall/runoff model, Hydrologic Simulation Program-FORTRAN (HSPF), on which it is based. KCRTS provides the user with a database (the runoff files) of unit-area runoff rates pre-simulated using HSPF for a range of land cover and soil conditions, and for different precipitation regions. Hydrograph analysis and design of detention facilities is then accomplished by directly manipulating the runoff-file and land-cover data with the supporting interface software.

Characterizing Pond Volumes. The volume of a detention pond is its single most important design characteristic. From a hydrologic perspective, that volume determines the time-integrated difference between inflow and outflow and so imposes an absolute limit on net hydrologic performance. It is also the single most expensive element of pond design and construction, because pond volume is directly related to pond area and thus cost, incurred in both construction and lost developable land. Once a development is complete, pond volume is also the most inflexible parameter. Orifices may be resized with only trivial effort, but the total pond area or the maximum depth of live storage generally cannot be changed without tremendous expense.

To facilitate comparisons, all detention-pond designs here are expressed in terms of a live-storage volume per unit area of developed land draining to the facility. This normalized measure of volume is thus, paradoxically, in units of *depth* and is equal to the volume of the pond as though it were evenly spread out over the area of the development. Typical unit-area volumes are expressed in cm-hectares per hectare (metric) or inch-acres per acre (English), and so the simplified units are simply “centimeters” or “inches” of net pond volume.

Performance of Ponds

Peak Standards. HSPF simulation of runoff originating from an SCS-designed detention pond was analyzed by Barker and others (1991). Ponds were initially designed using SBUH to match pre- and post-development 2- and 10-year peak discharges (a "2-10 standard”). Where the simulated land-use conversion was from forest land cover to urban land use, performance within the design range (*i.e.* up to the 10-year event) was near-perfect: in other words, pre- and post-development peak discharges for any given recurrence within this frequency range were equivalent. The volume of these ponds, a rough surrogate for facility cost, can be as much as 4 cm (*i.e.* 4 cm-hectares of volume per hectare of developed land). Where the land-use conversion was from *grassland* to urban uses, however, even 10-

year flows discharged from the SCS ponds increased up to 3-fold. Beyond the design range of discharges both land-cover conversions result in more extreme postdevelopment flooding; in particular, the predevelopment $Q_{100\text{-yr}}$ discharge for a grass-to-urban conversion recurs about 10 times as often. Even this relatively poor performance is an historic improvement; ponds constructed prior to 1990 using a design based on the rational method (Yrjanainen and Warren, 1973) typically provided one-quarter or less of this volume.

Using KCRTS for pond design, performance is uniform and successful across all types of land conversion following development. Indeed, because of a 20-percent safety factor added to the volume of all pond designs by this program, KCRTS ponds designed under the "2-10 standard" actually match postdevelopment and predevelopment peak discharges up to the *100*-year events. To achieve this performance, however, requires pond volumes as much as 50 percent greater than under the SCS design.

Duration Standards. Matching pre- and post-development flow durations is a far more challenging task than simply matching flow peaks, because the total *volume* of runoff arising from a given storm is greater and so must be released or disposed of in some fashion. We have considered two modeling approaches for attaining this enhanced performance in the absence of infiltration: using an apparent "over-performance" of the SCS 24-hour method (Table 3), or using KCRTS with this performance as an explicit goal. In either case, any R/D design that meets a flow-duration standard will easily meet a peak standard as well.

Table 3

Design Standard for Use with SCS Curve-Number Method to Control Postdevelopment Runoff Durations ("Overperformance")

Postdevelopment Recurrence	Target Postdevelopment Discharge
2 yr	$0.5 \times Q_{\text{predevelopment 2-yr}}$
10 yr	$Q_{\text{predevelopment 2-year}}$
100 yr	$Q_{\text{predevelopment 10-year}}$

A detailed comparison of duration-control ponds designed with these two models is instructive, using the 14.2-km^2 Soosette Creek watershed (Figure 1). The watershed's land use, currently 25 percent suburban, 25 percent grassland, and 50 percent forest, is typical of conditions across the region,. About 6 percent of the basin is covered by effective impervious area. HSPF simulations, which provide the "truest" picture of detention-pond performance, were generated by a model calibrated to this basin using 2 years of gauged rainfall-runoff data (King County, 1990a; see Figure 2 for sample simulation outputs from this watershed).

Pond performance depends strongly on the predevelopment vegetation cover. Conversion of the 50-percent forested land in the watershed results in little dependence on modeling method; ponds associated with such development meet their stated goals (*i.e.* matching of flow durations) regardless of which model is used for design. Pond volumes may be as much as 14 cm, depending on the details of the local soil and topography. Conversion of the 25-percent grassed areas, however, results in substantial differences between design methods. The "overperformance" SCS ponds result in extended postdevelopment flow durations, with discharges greater than $Q_{pre\text{-}2}$ occurring 15 to 40 percent more often than they did prior to this (limited) development. In contrast, the KCRTS ponds achieve durations that are less than or equal to the predevelopment durations for all discharges above one-half of the 2-year flow ($Q_{pre\text{-}2}/2$).

Describing the physical *consequences* of flow-duration changes is a vexing, but critical, task. Management decisions involving high-cost facilities will not be made on the basis of fractional flow-duration increases but on anticipated, tangible changes in downstream channels. We have estimated these consequences by comparison to other actual basins in the region where stream-channel conditions can be readily observed. The magnitude of flow-duration increase seen in the SCS-pond grassland simulation, 25 percent of the watershed area converted with a resultant 15-40 percent increase in flow durations, is of a magnitude seen once development achieves 1.7 to 4.6 percent effective impervious area in a watershed, based on calibrated HSPF simulation of such land-use conversions region-wide. Thus for a watershed that began as half forested and half grassland, for example, total urban development under an SCS-based "duration-control" standard would *in fact* allow duration increases about double to those seen in the Soosette example, and so similar to those already experienced by a watershed that now has approximately three to nine percent *undetained* EIA. Referring to our previous discussion, this level of equivalent watershed imperviousness is associated, at minimum, with loss of the highest degree of resource value and aquatic-system function in virtually any catchment in which it is applied. If yet more than 50 percent of the watershed is in grass cover prior to development the equivalent impervious-area increase will likely exceed 10 percent, ensuring substantial channel instability and the near-complete loss of significant aquatic resources despite a highly restrictive detention design.

Conclusion—Mitigation Using On-Site Detention

These results demonstrate fundamental elements of urban runoff mitigation. From the standpoint of *peak discharge,* even relatively modest detention volumes can achieve notable (though commonly imperfect) flow reductions, reducing the consequences of a given impervious-area increase on flow maxima by two-thirds or more. Reducing *flow durations,* in contrast, not only reduces or entirely solves downstream conveyance problems but also helps control development-induced channel erosion (Figure 6). This improved performance, however, comes with a cost, because the necessary detention volumes are dramatically larger. It also requires the use of an adequate hydrologic model, or the anticipated performance may never be achieved.

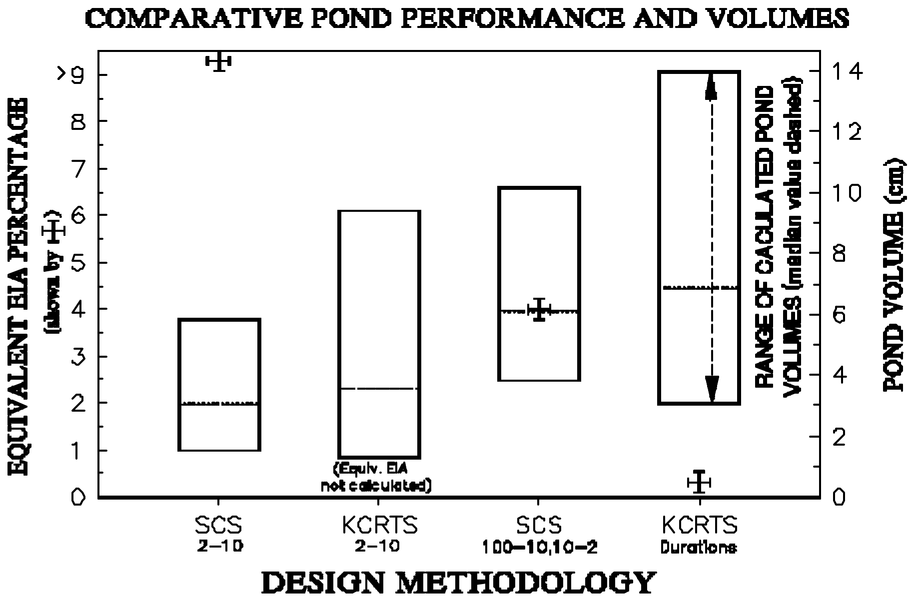

Figure 6. Comparative pond performance using different design methodologies—SCS and KCRTS hydrologic models, each under peak (labeled "2-10") and duration (labeled "100-10,10-2" or "Durations") standards. Evaluations are based on HSPF simulations of different developments within the fully built-out Soosette Creek watershed (29 % impervious; see Figure 1). Overall performance (crosses) is represented by the equivalent flow increases allowed by a watershed having the indicated impervious-area percentage (as EIA) *without* detention; only KCRTS with a duration standard achieves "full" mitigation. The range of pond sizes (boxes) is expressed in cm-ha of volume per developed ha, with the range imposed by variability of soils and pre-development vegetation and the median value for all simulations shown by the dotted line.

THE LIMITS OF MITIGATION

Despite the promise of successfully mitigating the effects of urban development through detention ponds, hydrologic modeling and empirical data suggest the elusivity of this goal. Along with the use of imperfect hydrologic models, several additional factors, both social and physical, are responsible for this shortcoming.

Regulatory Thresholds. There are practical limits to applying drainage regulations to individual small-scale land developments. Jurisdictions typically set a minimum "threshold of concern" to nearly all development activities: above this threshold the drainage regulations apply, but below this level regulations are minimal or absent (*e.g.*, local King County regulations stipulate a minimum 0.50-cfs [0.014-m^3/sec] increase in runoff, equivalent to about 0.5 acre [0.2 ha] impervious surface, before mitigation is required). Based on six years of King County permit activity (1987-1992), about one quarter of the impervious area added to the local watersheds there fell below this threshold and so are constructed without any detention facilities at all. Thus at full build-out (25-50 percent EIA, depending on zoning), a watershed will contain six to more than ten percent EIA that lacks any drainage control whatever. So under current regulatory thresholds, debates over the relative merits of alternative R/D design standards are largely moot—even the most restrictive design standard is unlikely to maintain future aquatic-system function at any but a recognizably degraded level.

Cost of Mitigation. Effective runoff mitigation in the Pacific Northwest appears to require pond volumes from 3 to as much as 14 centimeters (Figure 6). With associated berms, control structures, and maintenance access roads such a facility may occupy over ten percent of the gross area of a development (Figure 7). These are "lakes," not stormwater ponds, and although fully justifiable from a hydrologic standpoint they are unlikely to be built except in the most unusual of economic and social climates.

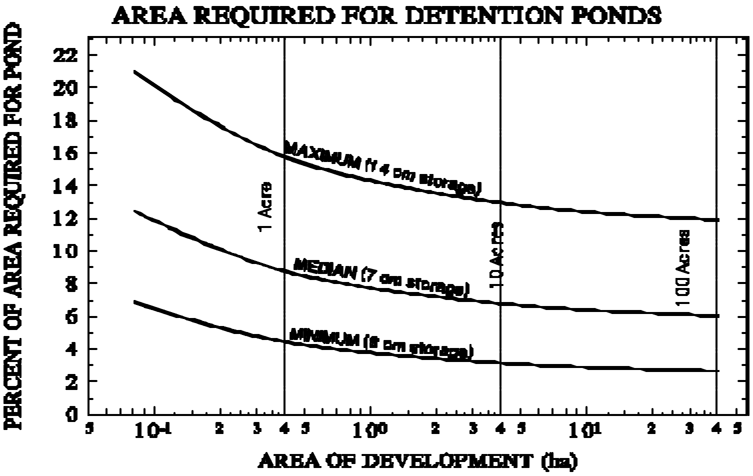

Figure 7. Relative gross area required for detention ponds, depending on the development area and the desired volume of stored runoff (expressed as cm-ha per ha of developed land). Pond layout and design is in accord with local regulations and assumes a 1.3-m (4-ft) maximum water depth and 3:1 sideslopes on all confining berms. Range of pond volumes correspond to the likely values determined with a "KCRTS duration" standard (Figure 6).

Thresholds of Sediment Movement. The concept of a "duration standard" implies the existence of a discharge below which no sediment transport occurs, allowing non-erosive release of urban-increased runoff volumes. For gravel-bed stream channels this threshold discharge is real and can be determined on a site-specific or generic basis. In sand-bedded channels, however, the threshold of sediment motion occurs at impractically low discharges, and so increases in the net transport of bed material is virtually unavoidable is such systems. We have not investigated the consequences of such a condition in small sand-bedded urban streams but speculate that they may be locally severe.

Point Discharges. Hydrologic models make the near-universal presumption that surface water exits a watershed at a point discharge. In the postdevelopment case this is invariably true: a constructed channel or a culvert outfall is generally quite identifiable. In the predeveloped case, however, watersheds up to several tens of hectares in size may have no discrete surface-water discharge point at all. Even if flow durations are matched precisely in pre- and post-developed cases, the change from a subsurface to a surface flow regime renders the entire design analysis irrelevant and can lead to severe, but entirely unanticipated, channel incision (Booth, 1990).

CONCLUSIONS—URBANIZATION, DEGRADATION, AND THE LIMITS OF MITIGATION

In western Washington, and likely in other humid regions as well, approximately 10 percent effective impervious area in a watershed typically yields demonstrable, and probably irreversible, loss of aquatic-system function. The data do not require a discrete “threshold” of effects, but they do display a noteworthy accumulation of physical and biological effects once this fraction of a watershed is covered by EIA. Onsite detention is an appealing and widespread strategy for mitigating these effects, but very restrictive and so costly standards may need to be met to protect aquatic systems in urbanizing areas. Even though this study has considered only this one mitigation strategy, substantial difficulties are revealed. The common hydrologic methods used to size detention facilities give a false sense of accomplishment, and regulatory thresholds designed to avoid economic hardship for small projects may nevertheless allow substantial cumulative impacts to accrue. Many of the changes to the landscape imposed by urbanization are probably beyond our best efforts to fully correct them, and so some downstream loss of aquatic-system function is probably inevitable at our present level of understanding. Unless we can develop a more precise, process-based understanding of how altered landscapes produced degraded stream channels we probably will not achieve genuine protection without limiting the extent of development itself, a strategy that is being used with increasing frequency in this region's remaining resource-rich watersheds.

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