URBANIZATION AND THE NATURAL DRAINAGE SYSTEM— IMPACTS, SOLUTIONS, AND PROGNOSES

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Urbanization and the Natural Drainage System — Impacts, Solutions, and Prognoses

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Introduction

Drainage systems consist of all of the elements of the landscape through which or over which water travels. These elements include the soil and the vegetation that grows on it, the geologic materials underlying that soil, the stream channels that carry water on the surface, and the zones where water is held in the soil and moves beneath the surface. Also included are any constructed elements, including pipes and culverts, cleared and compacted land surfaces, and pavement and other impervious surfaces that are not able to absorb water at all.

A landscape can be divided into individual drainage basins, each of which contains all the elements of a drainage system that contribute water to one particular stream channel. Conversely, each channel collects the rainfall from its own individual drainage basin, and that channel's form is a consequence of the runoff processes that are active in its basin.

The collection, movement, and storage of water through drainage basins characterize the hydrology of a region. Related systems, particularly the ever-changing shape of stream channels and the viability of plants and animals that live in those channels, can be very sensitive to the hydrologic processes occurring over these basins. Typically, these systems have evolved over hundreds or thousands of years under the prevailing hydrologic conditions; in turn, their stability often depends on the continued stability of those hydrologic conditions.

Alteration of a natural drainage basin, either by the impact of forestry, agriculture, or urbanization, can impose dramatic changes in the movement and storage of water. Some of these changes are intended, and they render the land more useful for the purpose for

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Plate 1. Ravine incision below suburban development in central King County, Washington. At this site, downcutting had proceeded at a rate of several feet per year since at least the mid-1960s, ultimately resulting in a multi-million dollar project to stabilize the surrounding area.

which it has been altered. Yet some of the changes are unintended and can have significant consequences. Flooding, channel erosion, landsliding, and destruction of aquatic habitat are some of the unanticipated changes that can also result from these alterations.

The alterations of a drainage basin accompanying urbanization

Robert Brittain

Plate 2. Overwhelmed drainage system in an area of rapid development. Flows that were once readily contained in culverts or roadside channels now expand well beyond the capacity of those facilities.

are among the most severe and potentially damaging. Their impacts have been inventoried by numerous studies (e.g., Wilson 1967; Seaburn 1969; Hammer 1972; Leopold 1973) because of the loss of both lives and property that sometimes result. With urbanization, stream channels expand catastrophically to consume adjacent land never before affected by either flooding or erosion; sediment inundates low-lying areas, seemingly far away from active channels; stormwater facilities are overwhelmed by frequent flows far beyond their design capabilities; and populations of aquatic organisms are decimated.

These changes have occurred far more rapidly than our understanding of *why* such impacts occur. Only since the 1980s have advances in the science of hydrology been applied to the conditions and needs of the urban environment. The result is a rapidly growing body of information on why certain impacts are occurring and on the measures that are necessary to effect genuine improvement.

What is lacking, however, is the development of parallel data on how well these measures actually succeed in reducing impacts: whether the undesired effects of urbanization on the hydrologic environment actually can be rolled back or avoided altogether. To date, measures have been taken that only partly address these impacts; even their limited performance has had insufficient time for a full evaluation. For example, most of the populous jurisdictions in the Northwest require some form of stormwater detention for urban developments, yet they require that only a *part* of the storm runoff be fully detained. The need for and nature of yet *more* stringent standards are only now being recognized in the technical community. Before the hydrologic performance of new methods can be demonstrated, however, their political and economic feasibility must be proven, as well.

This paper describes the causes and effects of urban-induced changes to the hydrology of a drainage basin. To understand the cause of change, the hydrologic behavior of the undisturbed basin first will be explained. The effects of development are then recognizable as the near-inevitable consequences of hydrologic changes. Therefore, effective solutions must not focus simply on the observed results (e.g., armoring an eroded stream bank), but rather on the underlying causes (e.g., replacing the amount of water storage capacity in the soil layer that was lost by paving over the ground surface).

Hydrologic Background

An Introduction to Storm Runoff

To understand the ultimate causes of urban impacts to the drainage system, the elements of the hydrologic systems must be described. First among these elements is *storm runoff*, that part of the rainfall that reaches a stream channel quickly—within a day or so of first falling on the ground. Typically, storm runoff is produced by any one of two methods. The first occurs if the precipitation falls on the soil surface more rapidly than the soil can absorb it, causing the excess precipitation to run over the surface of the land. This process was first described by Horton (1945) and is now called "Horton Overland Flow" (HOF). It is most common in regions of intense rainfall and shallow, vegetation-poor soils, notably the arid and semi-arid northwest interior east of the Cascade Range. Water moves quickly from the hillslopes into the channel, and all parts of the drainage basin contribute to the storm runoff in the channel.

Conversely, where rainfall intensities are generally lower than the rate at which the soil can absorb it, all of the precipitation can infiltrate where it first lands. Water still moves downslope, but it also flows below the surface. This mechanism, known as the *subsurface flow regime*, has been most thoroughly described by Dunne (e.g., Dunne, Moore, and Taylor 1975). It predominates where rainfall is gentle and vegetation is lush; the coastal regions of the Pacific

Northwest provide one of the best examples on the North American continent. Water moves very slowly off the hillslopes, and only those parts of the basin near the stream itself will contribute to the storm runoff.

As a storm continues, flow patterns and runoff quantities can change. Where overland flow dominates, the major change is a rapid reduction in soil infiltration capacity as the ground first gets wet. The change typically occurs within the first hour, with the infiltration capacity then remaining constant (e.g., Strahler 1975). Under the subsurface flow regime, this change is unimportant, as the soil still has adequate infiltration ability to absorb water as rapidly as the rain can fall.

Under the subsurface flow regime (where runoff moves predominantly *through*, not over, the soil), a different process causes a change in runoff quantity. Water tables in the soil will rise as water is added to the subsurface. If those water tables lie at or near the surface, their progressive rise expands the area of saturated ground in the drainage basin. In these saturated areas, new precipitation cannot infiltrate because the soil has no space to absorb more rainfall. They are typically located towards the bottom of slopes, in seasonally wet valleys, and adjacent to streams and lakes. Therefore, the total area of saturated ground, and thus the area where overland flow will occur, expands as the water table rises. This expansion occurs over a period of days, and so the part of a drainage basin that is contributing rapid storm runoff to the channel steadily increases during the course of a single storm. Expansion also tends to intensify through an entire storm season (Hewlett and Hibbert 1967).

What Controls the Magnitude of Storm Runoff

Basin Size. A variety of factors influence the discharge (rate of runoff) from a specific site or an entire drainage basin. These factors must be recognized to understand, and correct, alterations to basin hydrology. Most fundamental of the factors influencing discharge is the sheer size of the basin; the amount of runoff from a "large" basin depends primarily on the total *volume* of water that is released, usually over a period of many days. In contrast, "small" basins will be most strongly affected by the *rate* at which water is introduced to the basin and transported to the outlet stream. The boundary between these two size categories is very broad, but it lies in the range of a few hundred square miles. Most of the concern for urban development and stream hydrology focuses on "small" basins.

The storm runoff from a small basin will respond rapidly to changes in the rate of precipitation or runoff. Any factor that affects either the amount of water that enters the channel or the speed with which water moves through the basin will alter the magnitude of the discharge. Land-use conditions are particularly significant in determining these factors. Thus, differences or changes in the land use, generally muted in the hydrologic response of a large basin, dominate the hydrologic response of a small basin.

Land-Use Factors. The character of the land surface exerts a profound effect on runoff processes, which in small basins are almost immediately expressed by the rate of storm runoff. Typically, only a fraction of the total precipitation falling on a basin actually reaches the stream channel. The remainder either: (1) never reaches the ground and is evaporated off the surfaces of vegetation; (2) enters the ground but is transpired by plants or evaporated from the soil; or (3) percolates deeply to the regional groundwater system and is lost to the stream (as storm flow, at least). Of the fraction that reaches the channel, its time of arrival is controlled by whether it flows primarily through the subsurface or over the surface (subsurface flow vs. HOF), how quickly it is collected into open channels on the hillside, and whether it is detained in reservoirs (either within the soil column or in surface lakes or ponds).

Changes in land use will affect basins in the two hydrologic regimes differently. Where overland flow predominates, much of the precipitation reaches the channel under all storm conditions, regardless of the level of urban development. Runoff moves at rapid, surface-flow rates; although those rates depend in part on the nature of the conduit (e.g., flow in a smooth pipe is faster than in a meandering channel), the variability in speed is not high. Thus, urbanization in regions of HOF (in which water runs over the land surface) may increase the net percentage of precipitation that reaches the channel, even though the underlying runoff processes have not changed significantly.

Where subsurface flow predominates, however, much of the precipitation normally never reaches the channel; it is instead lost to evaporation and transpiration. The remaining water moves towards the channel through the subsurface, generally quite slowly and with ample opportunity for long-term storage in the soil. If the land surface is paved or otherwise modified to intercept more of that water, transport rates will increase many-fold and intervening storage is vastly reduced. Thus, in areas where the subsurface flow regime once predominated, urbanization will have a particularly dramatic effect on the magnitude of runoff because the fundamental processes of runoff generation are being altered. It is this situation, ideally exemplified in the broad lowlands of the Pacific Northwest, that provides the information for the following discussion.

Identifying the Effects of Urbanization

Introduction

Human activities accompanying development can have irreversible effects on drainage-basin hydrology, particularly where subsurface flow once predominated. Vegetation is cleared and the soil is stripped and compacted. Roads are installed, collecting surface and shallow subsurface water in continuous channels. Regrading eliminates previously undrained depressions. Subsurface utilities intercept yet deeper subsurface water and rapidly pipe it out of the basin as surface flow. Building construction is the most visible impact, but merely the final link in a long chain of hydrologic changes. Construction adds impervious areas that intercept rainfall before it can reach the soil surface.

These changes produce measurable effects in the hydrologic response of a drainage basin. Most dramatic, and most often studied, is the increase in the maximum discharge associated with floods. Synopses of such studies (e.g., Hollis 1975; Saver et al. 1983) all report similar results. Depending on the percentage of urbanized area, peak flows can increase five-fold over natural conditions, with the greatest changes observed for the most frequent flood events.

Other related hydrologic changes also occur from urbanization, but they require more sophisticated methods for predicting resultant stormwater runoff. Therefore, it is necessary to understand the past and present methodologies of hydrologic modeling which are the numerical tools by which runoff can be studied. Modeling methodologies will allow us to understand the changes wrought by urbanization, and show why many of the efforts to control runoff problems have not been entirely successful.

Hydrologic Modeling to Predict Runoff

Event-Based Models. Well over one hundred years ago, the fundamental predicting equation of runoff 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 that expressed the fraction of the rain falling on a basin that actually contributed to the flood peak. The runoff coefficient is adjusted for different land uses and land covers. Thus, highly pervious, forested ground is typically assigned a value of near zero (i.e., almost no water reaches the channel); pavement is given values approaching 100 percent.

An improvement of the Rational Runoff formula is the Soil Conservation Service's *Curve-Number Method* (U.S. Soil Conservation Service 1975), which was developed to improve hydrologic prediction. Greater flexibility is allowed in the matching of basin conditions with runoff coefficients; the results have been more extensively calibrated with actual data.

Both models, however, suffer from fundamental shortcomings. First, the storm of interest is a single event, typically of a few hours or a day in duration. Second, these methods assume that all parts of the basin function hydrologically in the same way. Finally, the models poorly represent the paths that runoff actually follows in and through a drainage basin. Thus their applicability to a particular drainage basin, particularly one where subsurface flow is a dominant runoff process, is rather poor (e.g., Hawkins 1975; Burges et al. 1989).

Continuous Hydrologic Models. Recent computer modeling efforts seek to correct the shortcomings of these earlier attempts. One such model, in relatively widespread use in the Pacific Northwest, is the Hydrologic Simulation Program Fortran or "HSPF" (U.S. Environmental Protection Agency 1984), based on the Stanford Watershed Model IV (Crawford and Linsley 1966). HSPF is a continuous hydrologic model that uses hourly (or more frequent) precipitation data as input over the entire period of simulation, which may be many years in length. The model keeps a running account of the amount of water within various hydrologic storage zones, both surface and subsurface, and divides the rainfall into these zones as it falls. Individual storm "events" are not discriminated; the actual rainfall record, over time, determines how the hydrologic system responds.

To date, the most comprehensive modeling effort with this model in the Pacific Northwest used 21 gage sites in five basins in Washington State's King and Snohomish Counties (Dinicola 1989). This work, and its continuance and expansion in selected basins elsewhere in King County (King County 1989, 1990*a*, *b*), provide the basis for much of the hydrologic analysis and discussion that follows.

Runoff Changes from Urbanization

Continuous hydrologic models can display a long-term record of streamflow out of a basin. Therefore, they can reveal a variety of changes resulting from urbanization. Such changes are easily simulated on the computer by applying the same rainfall input to the same land area, but under different simulated land uses. In contrast, older work has emphasized only the increase in peak discharges that accompany urbanization. This emphasis primarily has reflected

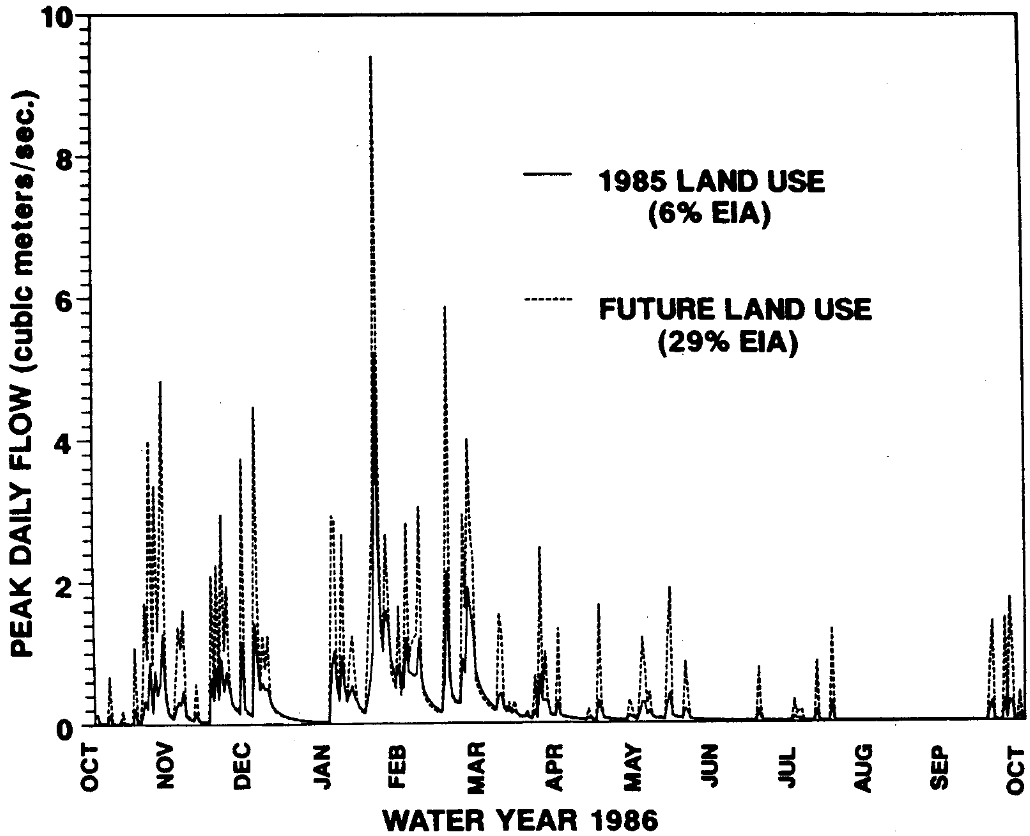

Fig. 1. One year of simulated streamflow for a 13-km² drainage basin under differing land uses, simulated with the Hydrologic Simulation Program Fortran (HSPF). Parameters characterize existing (1985) land cover (6 percent effective impervious area [EIA]) and projected future land cover (29 percent EIA).

the ease with which these particular data can be collected, not necessarily their overriding significance.

A sample simulation with a continuous hydrologic model is shown in Figure 1, displaying the differences in runoff between relatively low and high levels of urban development. In the highly urbanized case, the major flow peaks are amplified, and many new peaks also appear. These result from smaller storms, some of which produced no storm runoff at all before development, but which now can generate substantial flows.

Thus, urban development does more than simply *magnify* peak discharges; it also creates entirely *new* peak runoff events. As a result, floods of any given discharge will occur much more frequently after urbanization. For example, if the discharge of the 2-year flood doubles following urbanization, then clearly the (smaller) discharge must now be exceeded more frequently than every two years, on average. These changes in frequency can be quite dramatic; dis-

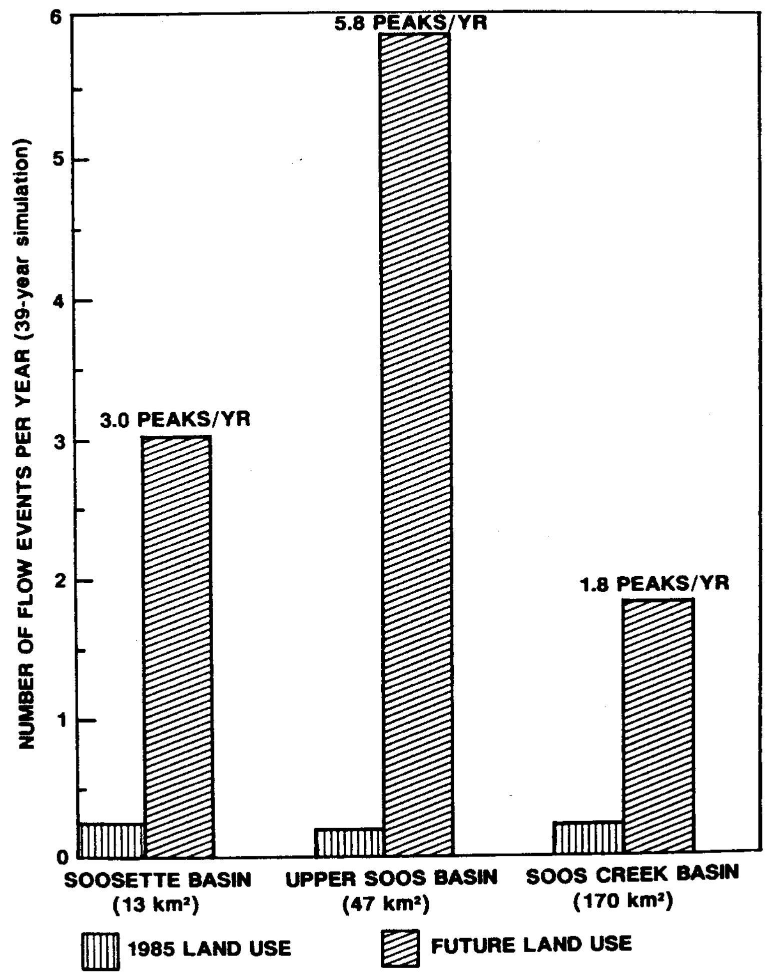

Fig. 2. Simulation of change in the frequency of "large" flood peaks at three points in the Soos Creek basin, as a result of future urbanization. The discharge of the present five-year flood peak is used as the threshold for defining "large" peaks; its future recurrence shows a nine- to 29-fold increase.

charges once associated with large, multi-year or multi-decade storm events now inundate the urban basin one or more times per year (Fig. 2).

Alteration of the Channel Corridor from Urbanization

Urban development not only increases flows, it also encroaches on the stream corridor—the zone surrounding the channel that influences the hydrology and biology of the flow. Frequently, this leads to the clearing of streamside vegetation, particularly trees. The consequences of this clearing are two-fold: first, less wood enters the channel, depriving the stream of stabilizing elements that help dissipate flow energy and usually help protect the bed and banks

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Plate 3. Complete obliteration of streamside corridor accompanying urban development. Reestablishment of channel diversity is no longer possible, because the necessary woody debris cannot be introduced from the adjacent land area.

from erosion. Second, the overhead canopy of a stream is lost, eliminating the shade that controls temperature and supplies leaf litter that enters the aquatic food chain.

These impacts are not unique to urban development; logging has generated a legacy of such impacts, with a number of studies assessing their effects (see, for example, Salo and Cundy 1987). But although logging imposes a dramatic change on a stream system, with proper management the ultimate result is only temporary (Fig. 3). With urban development, however, the changes are permanent. Their net effects were measured during the period 1982–1985 over a number of lowland streams in suburban King and Snohomish counties, Washington (Metro 1988) and show a consistent pattern; "rural" streams show many fewer impacts to the channel corridor than do their "urban" counterparts.

The Consequences of Runoff Changes and Corridor Alteration

Expansion of the Stream Channel

Background. In urban basins, stream channels are faced simultaneously with an increase in flow magnitudes and a decrease in

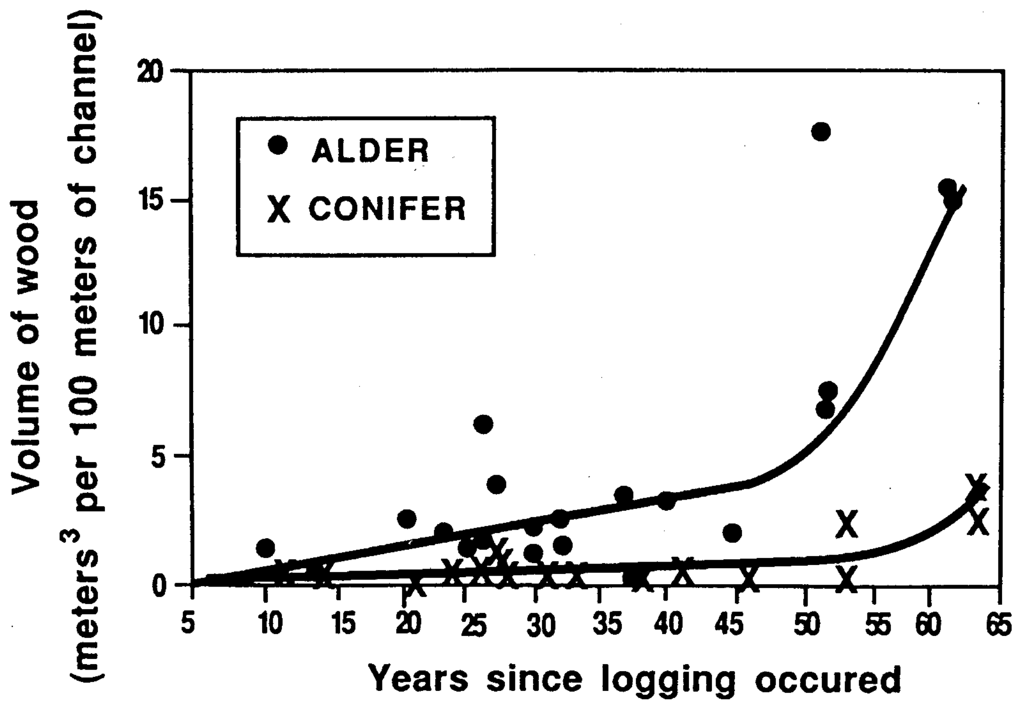

Fig. 3. Rate of recovery of woody debris in small stream channels following logging of second-growth forests in western Washington (from Grette 1985).

channel-stabilizing wood. Either factor alone would be sufficient to increase channel erosion, but in combination their consequences are magnified. Furthermore, the flow increases themselves can cause an increase in the wash-out of wood from the channel; even if the corridor remains intact, the rate of wood replacement back into the channel is ultimately limited by the rate of tree growth. Under the best of circumstances, accelerated wood removal will not be compensated by accelerated regrowth and replacement. More commonly, however, urbanization eliminates the corridor altogether, which means that wood is not replaced in the channel at all.

As a result of these factors, channel widths and depths increase throughout urban areas (e.g., Hammer 1972; Leopold 1973). But these increases do not always occur in the same fashion. Although channel dimensions can increase gradually in response to gradual increases in the flow regime, changes in channel dimensions are usually more sporadic and abrupt. Such events often happen during particular storms, where a single large flow can annul periods of stability that may have spanned many years (Fig. 4).

Channel Incision. More profound than channel expansion is channel incision, which is the nearly uncontrolled downcutting of a stream bed, usually in response to an increase in the flow rate (Booth 1990). Although expansion of a channel is damaging under any

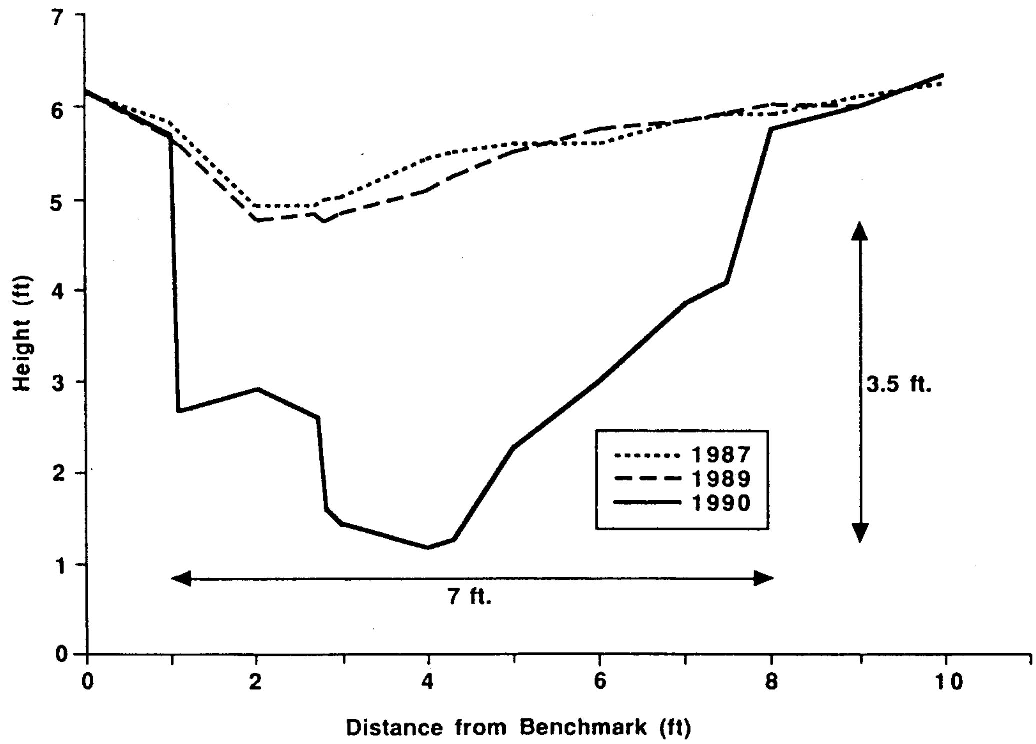

Fig. 4. Cross-sections measured in a three-year period in a small urban stream draining about one km². A large storm, with a recurrence of several decades, occurred in January of 1990 and resulted in significant downcutting at this site.

circumstance, true incision is particularly problematic because the resultant stream is generally devoid of habitat diversity and the eroded sediment can clog the downstream system. Based on studies of recently incised channels in King County, Washington, a number of conditions must be met for incision to occur in humid drainage basins in the Pacific Northwest. High flows in particular are necessary, but in addition we usually observe steep channel gradients; easily erodible substrate (typically sand); and few or only widely spaced controls on the *grade* (bed slope) of the channel—typically these are large logs lying on the channel bed that anchor the bed elevation.

Incision represents a loss of geomorphic balance between the forces of downcutting (the moving water) and the resistance of the stream bed to erosion (determined by sediment size, channel roughness, and the action of anchoring debris). Urban development influences two of these factors: the magnitude of flows and the persistence of wood in the channel. The other factors are intrinsic to the basin, so urbanization does not always cause incision. Where it does occur, however, the results can be truly spectacular and economically devastating (Booth 1989); the cost of rectifying the problems can be in the millions of dollars (e.g., King County 1987*a*, 1990*c*).

Disturbance Frequency

Disturbance and Watershed Dynamics. Disruption of a stream channel by very high flows is a natural process that occurs erratically but with characteristic time scales. During such events, the channel form itself is affected—stream banks erode, large cobbles and boulders are moved on the bed, woody debris is repositioned or washed out, pools are filled, and bars are scoured. Although the form of the channel is disrupted and the quality of the aquatic habitat is degraded, the effects are temporary. Lower flows, still sufficient to remobilize sediment within the affected channel reach, begin to "rebuild" the stream. New wood from the stream corridor enters the flow and is positioned anew. The "disturbance" ultimately results in a reformed, rejuvenated environment that continues for many years in a state of relative stability (Lisle 1986; Booth and Barker 1988).

In the Pacific Northwest, this process of episodic disturbance has always occurred on channels that have, historically, supported large anadromous fisheries. Under natural conditions, rates of disturbance and subsequent recovery varied widely, even between streams of the same watershed. Habitat elements were altered but had periods of stability that lasted from a decade to a century, or more. Salmonids in these lowland streams have evolved with this historic disturbance regime.

That which constitutes a "very large" flow, sufficient to alter the stream channel and the habitat within it, is largely empirical. Work done throughout the streams of the Pacific Northwest and in other humid environments suggests that large-scale channel disruption can be caused by flows larger than about the 5-year flood (e.g., Carling 1988; Sidle 1988).

The Effects of Urbanization. Hydrologic changes imposed by urban development profoundly affect the disturbance frequency in developing basins. This phenomenon can be investigated with the HSPF hydrologic computer model, using a sample drainage basin in southwest King County and northwest Pierce County, Washington (the Hylebos Creek basin; Booth, Fuerstenberg, and Barker 1990). Modeling of such a basin allows direct comparison between the flood events during a 40-year simulation period, using either fully forested or fully developed land uses as variables.

Using the historic rainfall record, modeling the Hylebos Creek basin with a simulated forest cover produces eight floods at or above

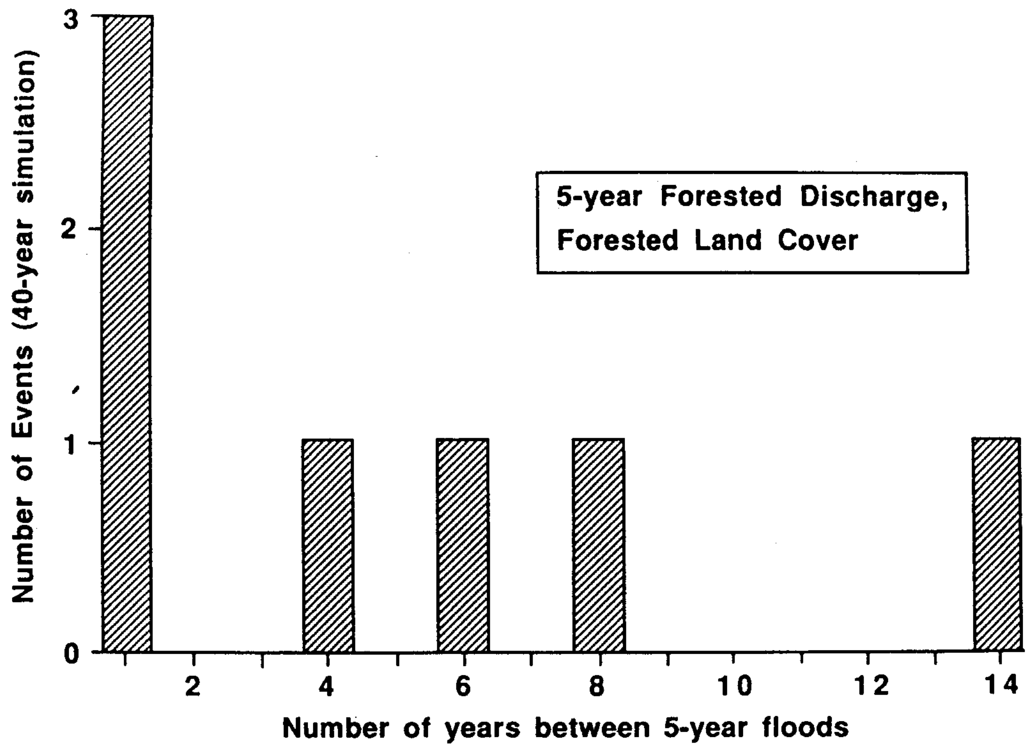

Fig. 5. HSPF simulation of the Hylebos Creek basin in southwest King County, Washington, under fully forested land cover. Bars show the number of years separating discharge events of 5-year recurrence or greater. The *average* separation is 5 years (40 years of simulation, 8 events), but the actual spacing varies from one year (i.e., successive years) to 14 years.

the 5-year discharge (Fig. 5). The intervals between such floods are quite variable, with as much as 14 years between two events, and others coming in successive (water) years.

In contrast, the same rainfall over the fully developed basin yields only one year *without* a flood of this discharge or greater (Fig. 6). Indeed, the average year has over five such flows, with a median interval between them of less than a month. If we consider only floods above the forested 10-year discharge, the results are virtually identical but even more severe—only three such events are seen in 40 years with fully forested land use, but in the developed basin they occur almost monthly.

A Summary of the Physical Effects on Channels

As a result of channel changes due to increased flows and altered corridors, urban streams have a characteristic "look" to them. Their beds are uniform, with few pools or developed riffles to break up the planar surface. Channel banks are raw and near-vertical, with

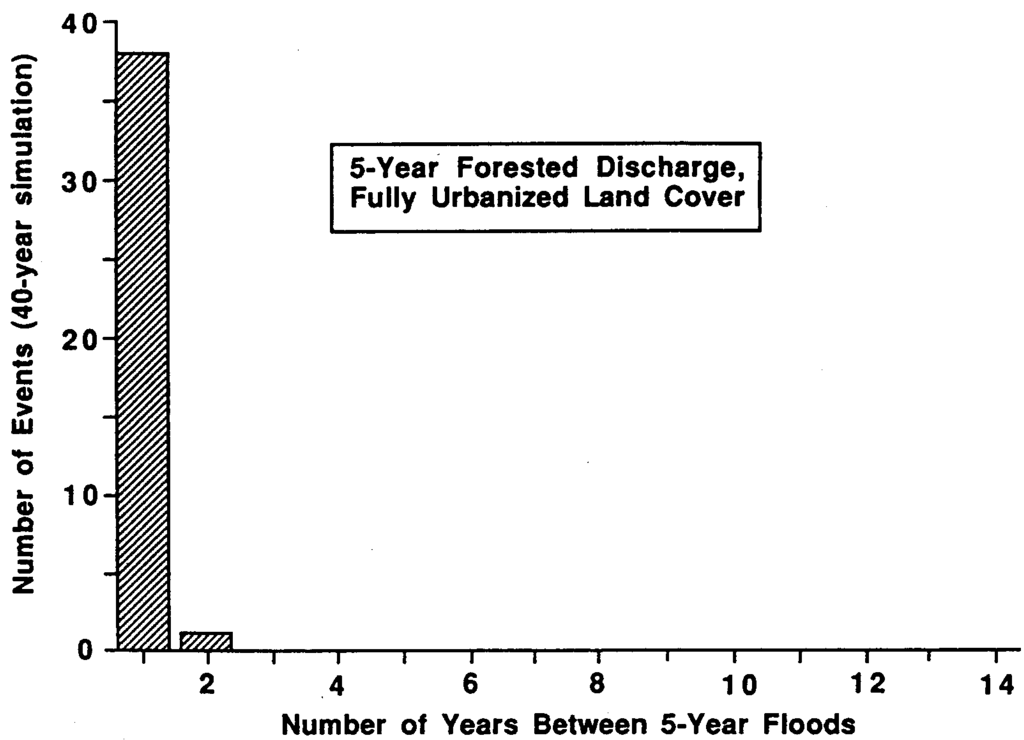

Fig. 6. Forty years of HSPF simulation of the Hylebos Creek basin under fully urbanized conditions (about 40 percent effective impervious area). Discharges at or greater than the 5-year forested event occur in every year except one (compare with Fig. 5).

incisions of one to many feet. The erosion of adjacent steep banks is constantly adding new sediment. Woody debris is small and sparse, and it is either suspended above the level of the flow or is only weakly anchored in the bed. Finally, the aquatic organisms that thickly populate equivalent drainages in undeveloped settings are nearly absent, reflecting the cumulative impact of physical and chemical changes to the stream and its substrate.

These characteristics occur throughout all the streams of an urban drainage basin. Almost no variability is observed, despite inevitable differences between drainage areas, and the channels have become homogeneous and sterile. These channels resemble the aftermath of a debris torrent, in which a flood of water and sediment moves catastrophically down a valley and leaves a nearly uniform, barren channel in its wake (e.g., Benda and Zhang 1989). But although such a channel can normally rebuild its long-term form, the urban channel has perhaps only days before another disturbance of nearly equivalent magnitude begins the process all over again. Thus hydraulic and biologic diversity is eliminated both within a stream and between streams. As urban development fills a watershed, its effects spread as well. These effects are so pervasive, affecting all

Plate 4. Boardman Creek in the North Cascades following the passage of a debris flow. Although the channel is presently homogeneous and rather sterile, abundant woody debris adjacent to the channel and a likely future of only moderate flood levels will allow rapid rebuilding of a diverse, productive stream.

aspects of the runoff processes, that only the most well-directed efforts at control have any hope of reversing the trend.

Correcting the Impacts of Urbanization

Principles

In the face of pervasive changes to basin hydrology, it is almost impossible to eliminate the impacts of urban development. In the Pacific Northwest, the major path by which water moves, namely subsurface flow, is almost wholly replaced by another. Travel times from hillslope to stream channel shorten by a factor of one hundred or more. Soil pores below the ground surface, which have sufficient volume to store a substantial fraction of the annual rainfall itself, are isolated from precipitation by paving. Stream channels are bridged, piped, or simply obliterated. Finally, the dissolved and suspended constituents carried into the channel are dramatically changed as bare soil is exposed through construction and the chemicals accompanying modern urban life are introduced into the watershed.

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Plate 5. A typical level of urban development in the Puget Sound region, where precipitation is largely denied access to the subsurface and minor stream channels are obliterated.

The underlying strategy for minimizing or avoiding the impacts of development is to reduce the amount of runoff and minimize the disturbance of the landscape, so some or all attributes of the predevelopment discharge and landscape are retained or mimicked. These impacts typically fall into three basic categories: (1) excessive runoff quantity, (2) lost channel and corridor integrity, and (3) degraded water quality (chemistry). Runoff quality, although a significant component of the net impact of urbanization, is presently the subject of intense regional study (e.g., Washington State Department of Ecology 1990) and will not be discussed here.

Mitigation Strategies

Water Quantity. For many decades, the classic method of runoff quantity control has been detention storage. With this method, stormwater runoff is temporarily impounded at the outlet of a development site, ostensibly to detain the (increased) peak runoff and let out the water to the channel at a controlled rate equivalent to the predevelopment state. But the volume of stormwater draining from impervious surfaces is greater than from undeveloped land surfaces; therefore, if pre- and post-development rates are the same, the *duration* of such controlled flows must increase. Only where detention storage is very long (weeks or more), or where some or all of the runoff can be re-infiltrated into the ground, can the duration, as well as the peak discharge, be controlled.

Detention as a mitigation strategy depends on accurate prediction of runoff, both before and after development. Traditionally, both predictions are made by hydrologic models. Modeling the predevelopment condition is done because it is more convenient than making on-site measurements; modeling postdevelopment conditions is needed to design the detention storage before the development occurs.

In general, existing detention ponds do not achieve the goal of protecting the downstream system (e.g., King County 1987*b*) for three reasons. First, such ponds have an explicit design limit; flows that exceed this limit will overtop or bypass the storage area and experience little to no detention. Thus the largest storms are least reduced. Second, the design criterion for most ponds specifies a match of peak discharge but not of flow durations. Thus a given flow will occur for longer; if that flow is erosive, it will do work on the downstream channel for many times longer than in the predevelopment case.

The final reason for the failure of ponds to protect the downstream system is a result of the hydrologic modeling that is used in the pond design. Historically, either the Rational or an SCS Curve-Number method are used. These typically over-predict runoff from undeveloped surfaces (Barker, Nelson, and Wigmosta 1991), and they consider only single storms of one day's duration or less. Thus, these models specify an excessive rate of release from the pond, and they underpredict the amount of storage that is needed to control sequential storms properly. If built, the actual pond is already part full when the one-day storm "event" begins.

These shortcomings in pond design can be analyzed quantitatively. An exhaustive review of detention standards and pond performance using the HSPF model (Barker and Nelson 1989; Barker, Nelson, and Wigmosta 1991) shows the magnitude of the problem. For example, the standards that applied to new development in King County from 1979 through 1989 (King County 1979) actually multiplied the 10-year peak discharges by a factor between 3 and 10, depending on land use. The current (1990) standard for new King County development (King County 1990*d*) significantly improves performance but still yields up to a doubling of 10-year flows under the most intense land uses. Despite these seemingly poor results, both detention standards were more restrictive, in their day, than those imposed by any other jurisdiction in the Pacific Northwest.

The cost of stormwater control is typically measured by the volume of storage pond required, because of the otherwise useable land that is occupied. For example the volumes of these mandated ponds, measured in inches of depth per unit area of development, is at most 0.5 inches for the 1979 standard and about 2 inches for the 1990 standard. For less intense land use (i.e., residential instead of commercial), pond volumes are about 50 percent smaller. Thus, a 50-acre development would need to provide at most 8 acre-feet of storage (i.e., a pond covering 8 acres with a maximum depth of 1 foot or, more likely, a 2-acre pond with about 4 feet of water-level fluctuation).

These present volumes are significantly smaller than what more stringent potential standards might require. For example, improving the methodology of the 1990 requirements, by modeling longer storm events and slower runoff rates, requires pond volumes 25 to 50 percent larger. The performance of these larger ponds is significantly better; 10-year peak discharges match, or actually are reduced slightly, from predevelopment levels. Controlling flows out to the 100-year flood further increases the storage needs by a factor of about one third. And finally, to achieve a matching of pre- and postdevelopment flow *durations,* as well as flow peaks, even greater volumes are required. At this final level of control, up to three inches of storage are needed for residential land uses and six inches for a fully impervious drainage area. This represents a tripling of what is currently required; e.g., a pond for the hypothetical 50-acre development would thus occupy six acres, inundating over 10 percent of the site.

These maximum detention volumes, necessary to achieve genuine flow control, are close to the active storage in the undisturbed soil column. This active storage is the difference between the *field capacity* of the soil (the amount of water held in the soil pores after it has been allowed to drain freely) and the *saturation* water content of the soil (the ratio of pore volume to total soil volume). During the winter, water storage in the soil will typically fluctuate between full saturation (i.e., completely soaked) and its field capacity (i.e., damp but fully drained). With undisturbed soil depths of a few feet beneath western Washington forests, saturation water contents of about 40–50 percent, and field capacities of 20–30 percent, the active water storage is typically about 20 percent of the soil thickness, or about 6 inches to a foot in depth. Therefore, it is not surprising that the runoff conditions prior to development can be recovered only by providing a like amount of surface storage once the subsurface reservoirs are paved over.

Channel and Corridor Integrity. Superficially, protection of the stream corridor appears to be a simple proposition. Boundaries are demarcated, clearing and construction within them are prohibited, and the stream proceeds with no "awareness" of the activities beyond its zone of influence. The width of that zone of influence has been debated at length (e.g., Murphy et al. 1986; Budd et al. 1987). In general, any measurable benefits of wood recruitment, aquatic food supply, and shading appear to decline much beyond 100 feet from the stream. As a result, 100-foot-wide buffers (or other near-equivalent distances) have been recently proposed or adopted by a number of jurisdictions in western Washington (e.g., King County, Snohomish County, Federal Way, and Tacoma, among others).

Several factors reduce the actual effectiveness of buffers. First, existing land use is typically unaffected, and so existing impacts remain. Second, stream crossings by roads and utilities may be reduced but are not eliminated. Third, human intrusion still occurs, albeit more diffusely. Fourth, a buffer regulated during land development may not persist unaltered over time, especially once individual property owners take on the "oversight" role from the original permitting authority. Finally, a number of the impacts to the stream system pass through the buffer unimpeded. Most direct are the flow increases experienced in the channel from upstream development. In addition, adjacent construction can release substantial amounts of fine sediment, which can move as channelized flow through almost any width of buffer zone with little attenuation, and thence into the stream channel.

Buffers provide only a partial solution to channel impacts. They reduce, but cannot eliminate, the impacts at their outer margins from reaching the stream system. Where that stream system is still judged valuable, even these reduced impacts of development may have a measurable effect. In such cases, only decreased development activity in the basin will be successful at maintaining the stream resources.

This final strategy of reduced development for stream protection is not widespread in the Pacific Northwest. It is achieved through reduced zoning of specified drainage areas. It has formed the basis of one permanent and two interim land-use actions since 1989, affecting in total over 20 square miles in northeastern and southeastern King County. This strategy is only effective, however, where existing development and land-use patterns are favorable for continued low density. Therefore, it has no remedial benefit on an already degraded system.

Prognosis: The Future of Urban Streams

State of Understanding

Recent improvements in the application of hydrology to humid, urbanized drainage basins offer hope that the impacts of development—long cataloged but little understood—can be addressed with adequate tools. Although hydrologic modeling will undoubtedly continue to evolve, the transition from unverified, physically implausible models to calibrated, physically reasonable ones has already occurred. Results will continue to be refined, but they are unlikely to change as radically in the future as they have in the past.

These improved hydrologic models explain much of the past failures to control urban runoff. The actual complexity of stormwater runoff is ill-represented by the single parameters, such as "peak discharge," that are generated by overly simplistic models. Past efforts to control flows through detention storage can be demonstrated to fail, even at their limited appointed task; in contrast, improved pond designs perform credibly in simulation and are of physically reasonable dimensions.

The role of less quantifiable factors, such as stream corridors and substrate materials, are also recognized; these factors are not "modeled" but they demonstrably affect the function and response of channel systems. Corridor vegetation, in-stream woody debris, and the intrinsic tendency of the channel bed to erode contribute directly to stream and habitat degradation in several areas of western Washington; the implications are clear for the rest of the region. Landscapes of particular concern for stream impacts can be identified, based on the local application of relatively universal criteria.

Applying Hydrologic Knowledge to Urban Planning

Although the present state of hydrologic knowledge is good and continually improving, the application of that knowledge to urban planning lags well behind. In part, delay is inevitable—information must be developed and then verified before it can become the foundation for widespread practical application. In the case of new methodologies, such as continuous hydrologic modeling, engineers and planners must first become educated as to its value and use.

However, the lag in application also reflects the practical implications of this new information. Because the mitigation measures that typically were applied over the last few decades are recognizably inadequate, any improvements in our understanding will unavoidably demonstrate the need for more extensive, and more expensive, mitigation. Larger detention ponds, broader undisturbed stream corridors, and lower-zoned densities all consume land otherwise judged "developable." Justifying the increased expense of additional mitigation is often difficult, because the tangible costs purchase only an intangible, often far-removed benefit—avoiding potential incremental damage to an off-site downstream system, perhaps at some time in the far-off future. Alternative strategies include building bypass pipelines for storm flows or more numerous, smaller detention facilities. However, these strategies add additional complexities that are only partly technical in nature, such as the need to acquire property beyond the development site or for long-term maintenance of multiple private facilities.

Most jurisdictions are unable to make the level of assessment and judgement needed to justify the high costs of effective mitigation. What are the values of the stream system in its predeveloped state? How effective will the mitigation be at protecting those values? Do the net benefits of mitigation justify their cost? Some of these questions do not involve quantifiable factors at all, and yet a consistent set of criteria, quantified as much as possible, would probably produce the most effective use of the mitigation effort that does occur.

Probably, a necessary first step is to develop studies on the scale of whole drainage basins, of the scope being prepared by King County (1990*c*, *e*; 1991) and only a few other jurisdictions nationwide. Through them, the resource values and problem conditions throughout a basin or a region can be assessed. Then efforts towards mitigation can be guided to greatest effectiveness, with the understanding that all parts of a drainage basin or a collection of drainage basins are not created equal. Measures that are appropriate to one part may be ineffective (or worse) in another (Moorehead et al. 1991).

Ultimately, however, such decisions are not made in the scientific arena but in the public one; there, calibrated hydrologic models are but one component of a debate in which due process, property rights, equal treatment, and economic hardship all share center stage. The last several years in western Washington suggest an overall trend towards greater mitigation of impacts and resource protection in the face of development, but the progress is by no means uniform or unidirectional.

Over the next decade, urban growth will force many more areas to address these questions, hopefully with better tools at their disposal. For other areas the development process will be largely complete. From those already developed areas, the consequences of past attention, or inattention, to the function of the natural drainage system provide an example for the rest of the region, where opportunities for mitigation or avoidance may still exist.

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