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STREAM-CHANNEL INCISION FOLLOWING DRAINAGE-BASIN URBANIZATION[1]

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ABSTRACT: Urbanization of a drainage basin results in pervasive hydrologic changes that in turn initiate long-term changes in stream channels. Increases in peak discharges and in durations of high flows result in either quasi-equilibrium channel expansion, where cross-section area increases in near-proportion to the discharge increase, or catastrophic channel incision, where changes occur far out of proportion to the discharge increases that initiated them. Field data and hydrologic modeling of rapidly urbanizing basins in King County, Washington, define conditions of flow, topography, geology, and channel roughness that identify streams susceptible to incision. Channel slope and geologic material are particularly critical; thus simple map overlays, nearly irrespective of contributing drainage area, provide a valuable planning tool for identification of susceptible terrain. Where such conditions exist, basal shear stress provides a quantifiable parameter for predicting likely problems, although knickpoints are typical in such settings and confound simple calculation of sediment-transport rates. Where urbanization proceeds in such areas, effective mitigation of the incision hazards requires a degree of stormwater control far in excess of standards typically applied to present development activity.

(KEY TERMS: urbanization; channel incision; runoff.)

INTRODUCTION

Changes in land use have long been known to increase the rate of stormwater runoff, which in turn can alter downstream river channels. The hydrologic effects of urbanization are particularly significant because such development typically engenders a radical and widespread disruption of existing runoff process and flow paths. Many previous studies (including Wilson, 1967; Seaburn, 1969; Hammer, 1972; Leopold, 1973; Arnold *et al.*, 1982; Neller, 1988) have documented the types of observed stream-channel changes, which include increases in channel width or depth, accelerated bank and side-hill mass failures, increased downstream sediment loading, and loss of fish habitat.

Enlargement of channels is a common basin response to headwater urbanization and occurs by either of two general modes. Channel enlargement includes both *incision,* defined as rapid channel deepening disproportional to the increase in water discharge, and quasi-equilibrium *expansion,* where increases in the discharge yield approximately proportional increases in channel width and depth. In the urban environment, channel expansion may pass unnoticed but incision can be distressingly obvious, by generating severe on-site and downstream consequences. Understanding and predicting the likely occurrence of incision in these settings is, therefore, critical.

RUNOFF CHANGES FOLLOWING URBANIZATION

The King County region in western Washington (Figure 1) typifies conditions under the subsurface flow regime, where surface runoff typically is absent or flows only near the base of slopes (Chorley, 1978). The region is underlain primarily by low-permeability till, lacustrine deposits, and bedrock, on which a more permeable soil has developed in the forest root zone during the 14,000 years since deglaciation. Because of generally low precipitation intensities, canopy interception figures significantly in the hydrologic balance and infiltration capacities of undisturbed soil are rarely exceeded. The largest runoff peaks are produced by multi-day storms, which continue for long

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enough to raise hillslope ground water tables and thereby expand the area of runoff-producing saturated ground surrounding streams and swales.

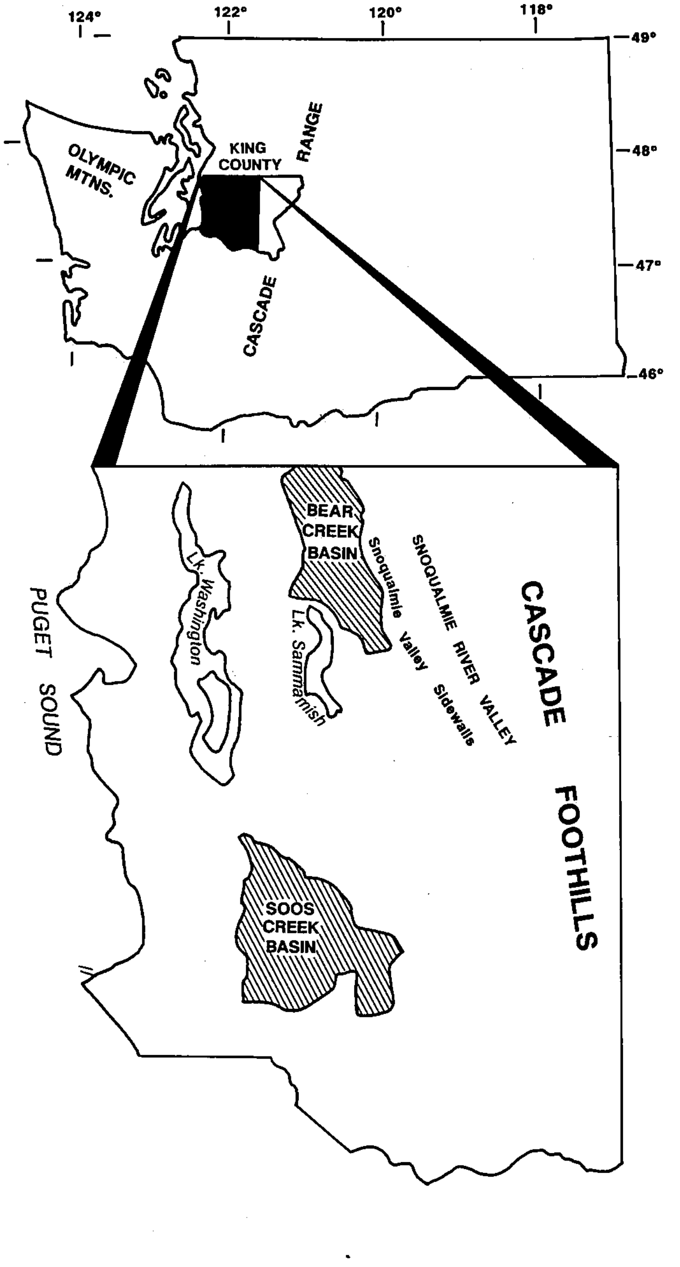

Figure 1. Location of King County and areas referenced in text.

In regions such as these, the entire process of runoff generation is altered by urban development (Booth, 1989), whose hydrologic consequences have been documented by various studies. Changes in peak discharge have typically been emphasized, because of their ease of measurement and relevance to flooding concerns. Hollis (1975) compiled such data from 15 previous studies, showing a pattern of increasing change in peak discharge with increasing percentage of impervious area and decreasing storm magnitude. Peak-flow increases of two- to three-fold typify the changes brought by low-level suburban development (10-20 percent impervious area) on flood peaks with 1-10 year recurrence intervals.

Although peak discharges are but one aspect of runoff, analysis of the entire stream hydrograph allows more complete investigation of the hydrologic changes wrought by urbanization. Numerical modeling is best suited to this task because of the detail of its output and its flexibility in defining land-use conditions. The analysis in this paper relies on the Hydrologic Simulation Program Fortran (HSPF; Environmental Protection Agency, 1984). HSPF is a deterministic, continuous hydrologic model that simulates runoff and streamflow by keeping a running account of the amount of water within various hydrologic storage zones, both surface and subsurface. At each time step of the simulation, overland flow, shallow subsurface flow, and deeper ground water flow are lagged and combined into a drainage network. The precipitation input is apportioned amongst the various soil and channel reservoirs based on specified parameters for evapotranspiration, infiltration, and storage volumes, based on the conceptual framework of the Stanford Watershed Model IV (Crawford and Linsley, 1966). Channel routing is simulated with a modified kinematic wave routine. Runoff from impervious surfaces is corrected for changes in surface storage and evaporation and then routed to the next drainage-network segment. Runoff from pervious surfaces is treated similarly but includes additional parameters for interception, transpiration, infiltration, and ground water discharge.

To calibrate the model, multiple streamflow and rainfall gages were installed in four basins throughout King County and two years of continuous data were collected (see also Dinicola, 1989, for a report on a concurrent simulation effort). Following calibration, flood-frequency and flow-duration distributions were generated for various land-use configurations by driving the model with the regional long-term rainfall record (1946-present, at 15-minute intervals).

Sample results display the hydrologic differences between relatively low and high levels of urbanization (Figure 2). In the highly urbanized case, not only are the major peaks amplified, but also many smaller storms, some which produced no predevelopment storm runoff at all, generate substantial flows. The duration of any given discharge also changes (Figure 3), with flows larger than the two-year (low urbanized) discharge occurring on average from 30 to over 100 times longer.

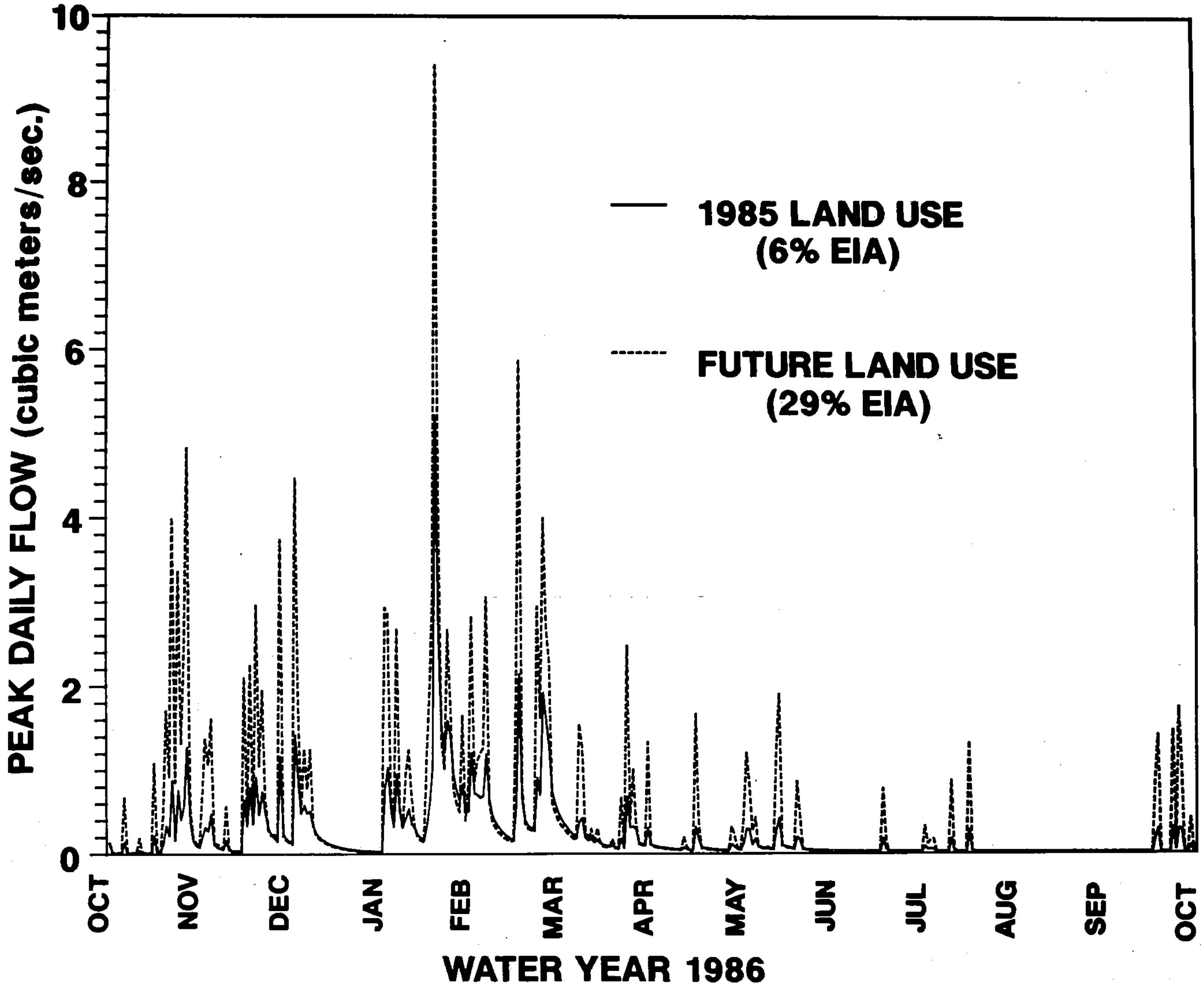

Figure 2. One year of HSPF-simulated streamflow for a 13-km^2 subcatchment in the Soos Creek basin under differing land-use conditions. Land-use parameters characterize existing (1985) land cover (6 percent effective impervious area, or EIA) and future land cover (29 percent EIA).

STREAM-CHANNEL ENLARGEMENT

Increases in channel width and depth commonly accompany headwater urbanization. A variety of previous studies infer or document many-fold increases in cross-sectional area (Hammer, 1972; Leopold, 1973; Morisawa and LaFlure, 1979; Allen and Narramore, 1985). Yet these changes do not occur in equivalent fashion. Whereas some channels expand gradually to accommodate a new, higher magnitude flow regime, other channels incise rapidly into their substrate, evacuating a proportionally much larger channel form whose capacity bears little relationship to the flows, either past or present, that have occurred.

Channel Expansion

Minimal attention is typically given to the urbanization-induced changes in bankfull width or depth because severe impacts rarely accompany the non-catastrophic expansion of a channel to accommodate even a two-fold or three-fold increase in flows. Hydraulic geometry relationships (Leopold and Maddock, 1953) suggest that only part of the flow increase need be accommodated by width and depth increases. In addition, perception of change is blunted by its occurrence over a period of many years or decades (Hammer, 1972).

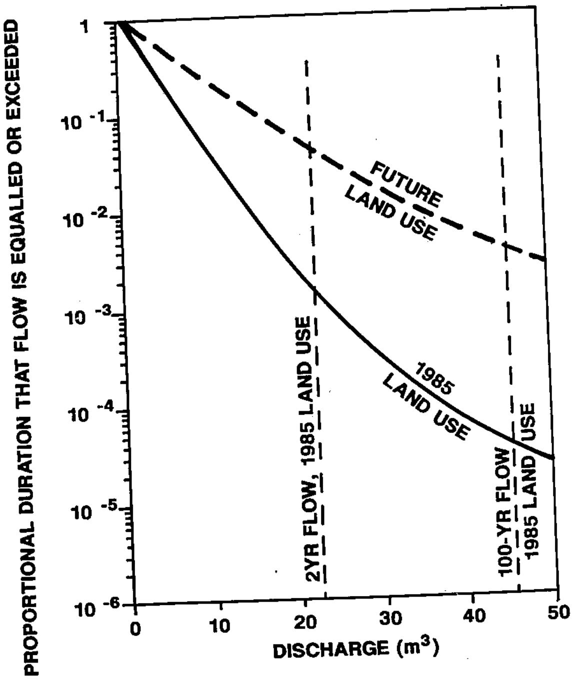

Figure 3. Flow durations under existing (1.7 percent EIA) and future (16 percent EIA) land uses for the 170-km^2 Soos Creek basin, which includes the subcatchment graphed in Figure 2.

The limited effects of quasi-equilibrium channel expansion were investigated using the technique of location-for-time substitution (e.g., Abrahams, 1972; Paine, 1985). I measured bankfull widths and depths at 40 separate stations in the Bear and Soos Creek drainage basins (Figure 1) using the height of newly vegetated bars, active floodplain levels, and historic flooding inundation to indicate the active (one- to two-year) channel dimension (Riley, 1972). Each of these sites have HSPF-modeled two-year discharges (Q_2) specified under existing land-use conditions, and thus a simple regression of channel area against two-year discharge (Figure 4) defines a relationship between these parameters:

$$\text{Channel Cross-Section } \alpha \; Q_2^{0.68} \tag{1}$$

Under future build-out conditions for these basins (i.e., urbanization to the maximum permitted by zoning), discharges are modeled to roughly double (King County, 1989a, b). Therefore, channels would be expected to increase in cross-sectional area by about three-quarters, yielding typical changes in depth of up to several tens of centimeters and in width of perhaps a meter or two. Presuming a period of at least a decade (and probably more) for both full build-out of the basin and for channel adjustment, annual changes will be small and probably within the range caused by variability in the annual flood (Pickup and Rieger, 1979).

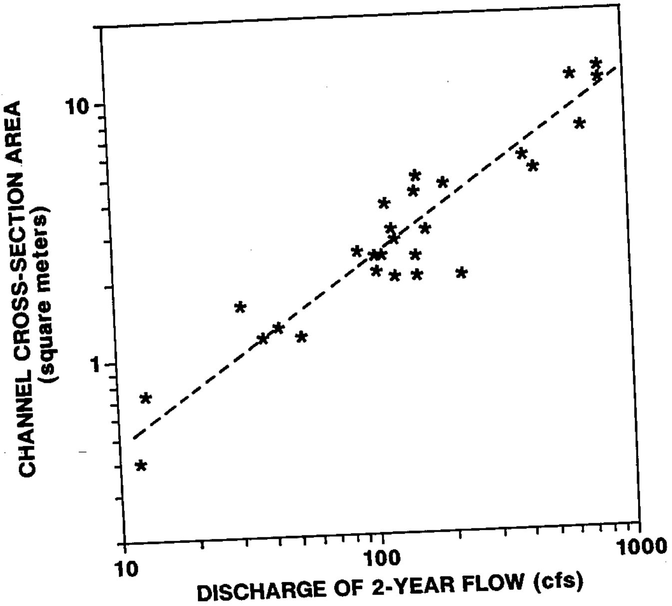

Figure 4. Variation of measured bankfull channel cross-sectional area with HSPF-predicted two-year discharges. Data from measurements in the Soos and Bear Creek basins, using only channels draining low-urbanized conditions (less than 5 percent EIA). Where adjacent measurements on the same tributary are included, tributary basin areas differ by at least 20 percent to improve independence of data points.

Two factors limit this method of predicting long-term channel changes. First, the hydrologic changes accompanying urbanization do not result in the simple, uniform magnification of all flows. High-frequency events are increased more than larger, less common flows; and thus simple analogy to a larger, undeveloped drainage basin with equivalent Q_2 (or any other chosen index discharge) may be misleading. Second, this method assumes that channels re-equilibrate in response to flow increases of any magnitude. Although the form of many urbanized channels affirm this assumption, others exhibit the crossing of a clear threshold, where the relatively slow expansion of channel width and depth is overtaken by catastrophic downcutting. A bankfull channel may still be defined, but its size and rate of growth is insignificant (and irrelevant) in comparison to the incised valley that now contains it.

Channel Incision

Rapid downcutting, many times in excess of the bankfull channel depth, is the response of certain streams to a variety of upstream disturbances (Schumm *et al.*, 1984). Urbanization produces many such examples, both because of the opportunities for ill-directed concentration of runoff and the accompanying increase in flows. Furthermore, the urban environment is particularly sensitive to such changes, with high values placed on sidestream property threatened by channel expansion and downstream property innundated by increased sediment loads.

Controls on Channel Incision – Flow and Sediment Parameters. Channel incision depends on the amount of sediment that the flow can transport relative to the sediment influx into the channel. These variables are not independent; an excess of transport over influx will yield downcutting, streambank steepening, and (eventually) increased influx. Most sediment input occurs in large measure by mass failures of the streambank material (Brunsden and Kesel, 1973), particularly when the upper watershed is now paved or its discharge emerges sediment-free from a pipe. The bank mass-failure rate can increase to balance transport only in response to changes in hillslope conditions. The sediment imbalance in the channel below provides that change, but only following channel-bed erosion, channel incision, and hillslope oversteepening (Harvey and Watson, 1986). Thus these streambank responses are not instantaneous, and so the initiation and early history of an incising channel can be justifiably addressed by considering only changes in sediment transport in the channel itself.

Sediment transport can be assessed by the transporting competence of the streamflow and the resistance of sediment to movement. Flow competence is best represented by its basal shear stress (τ_b):

$$\tau_b = \rho_w \, g \, d \, S, \qquad (2)$$

where ρ_w = water density, g = gravitational acceleration, d = flow depth, and S = energy gradient (approximately the water-surface slope). This equation ignores conditions of channel roughness that may decrease the effective shear stress available for moving sediment. The consequences of these conditions are discussed qualitatively in the next section.

By inspection of the above equation, the shear stress is a function of two easily measured parameters of the basin and the channel. Flow depth typically exhibits a fractional power-law correlation with discharge (Q); discharge similarly correlates with drainage area (A_{dr}). Thus shear stress is rather weakly proportional to drainage area (A_{dr}^b, with b between 0.2 and 0.4; Begin and Schumm, 1979). In contrast, the shear stress is directly proportional to the second parameter, namely the slope.

The resistance of sediment to transport is also simply approximated. It is typically defined by a minimum or "critical" shear stress, τ_{cr}, necessary to initiate motion. Most data sets show τ_{cr} directly proportional to the median sediment diameter in both well-sorted (Shields, 1936) and mixed-sized sediment (Andrews and Parker, 1987; Komar, 1987).

These relationships indicate the dominant controls on channel incision. Slope most directly affects the applied shear stress; grain size determines whether transport and erosion can then occur. A minimum discharge (or, by analogy, drainage area) is needed to initiate erosion, but any observed (or predicted) variability in incision across a region should be far less dependent on variations in drainage area than on variations in either the slope or the underlying geologic deposit. Thus simple map overlays identifying steep slopes and fine-grained noncohesive deposits are likely to easily yet accurately discriminate those areas susceptible to incision. In fact, threshold conditions of slope and substrate for incision commonly are recognizable from topography alone (Figure 5). The minimum drainage areas necessary for incision can be estimated from existing channel networks; for example, each of the defined channels in Figure 5 heads in drainage basins of about 0.1 km^2 (25 acres; see also Stoker, 1988). Following development, any given basin will increase its typical peak discharge by a factor of two or three; thus future incision may be initiated in basins down to about one-half or one-third of this size.

This approach to identifying incision-susceptible localities diverges in part from stream-power based formulations, such as the "Area-Gradient Index" (AGI) of Schumm *et al.* (1984). The differences are not fundamental; the gross relationship between stream power (proportional to discharge times slope) and sediment movement is well established. Yet equivalent values of the AGI on different channels may not yield equivalent responses, because the area over which that power is expended (i.e., proportional to the channel width) can vary greatly.

Improved correlation between flow parameters and observed erosion is achieved by either using the unit stream power (p), defined as the energy expended by the flow per unit time per unit bed *area* (i.e., $p = \rho_w g Q S / w = \tau_b v$), or the shear stress. In urbanizing channels, where a channel width already exists, the unit stream power is particularly easy to define and use. Where data are available, however, the shear stress should provide even better correlation between streamflow and any resulting erosion because flow velocity (and thus p) may be affected by channel roughness unrelated to transporting competence.

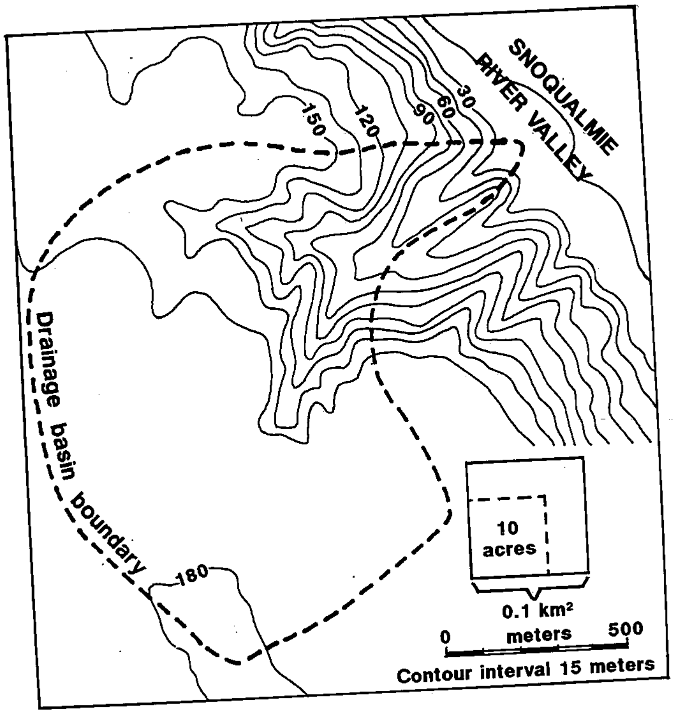

Figure 5. Characteristic topography of incised stream valleys, Snoqualmie valley sidewall region.

An example demonstrates these principles and suggests the value of such calculations, even where other conditions necessary for fully developed channel incision (see next section) are absent. I mapped "significant" bank erosion, defined as <1-yr-old bank cuts higher than the near-universally observed 10 to 30 cm, by walking 86 km of stream channel in the Bear and Soos Creek drainage basins (Figure 1). Discharges were taken from HSPF-simulated two-year flood peaks under current land use; slopes were measured from 1:1200 2-ft contour maps; bankfull widths and depths were measured in the field. Stream power, unit stream power, and shear stress for these channel reaches are plotted in Figure 6. Discrimination of eroding and noneroding reaches is not possible using stream power (compare Keller and Brookes, 1984) but is suggested for unit stream power and clearly shown for shear stress, with respective threshold values of about 80 watts/m^2 and 85 N/m^2. Interestingly, variability in substrate grain size does not appear to affect the occurrence of bank erosion, probably because bank deposits reflect the well-mixed sediment contributed from upbasin and upslope throughout this glaciated region. This independence, however, does not extend to occurrences of channel incision itself.

These flow parameters, which define a threshold for significant channel erosion, should be considered only index values (see also Begin and Schumm, 1979, for a related approach). They characterize the entire suite of flow-related variables by a single value, eliminating potentially relevant aspects of the discharge-frequency spectrum but vastly simplifying the discrimination between eroding and noneroding channels.

The use of index values also avoids another practical difficulty in modeling actual rates of sediment transport in incising channels, namely the presence of abrupt steps in the stream profile. The process of channel incision is not readily amenable to transport calculations because upstream migration of these steps, or knickpoints, rather than uniform channel lowering, is the observed mechanism by which these channels typically degrade their beds. Knickpoint formation is closely related to the magnitude of sediment transport and thus to the shear stress at a designated index discharge. Yet in these moderate- to high-gradient stream channels, local inhomogeneities in the bed lead to many small interruptions in the downstream sediment flux with intensified degradation just downstream. Logs, coarse lag deposits, or a silt-cemented bed then provide the vertical layering that is generally acknowledged to be a necessary condition for knickpoint growth and persistence over time (Brush and Wolman, 1960; Gardner, 1983).

Controls on Channel Incision – Channel Characteristics. In addition to these flow and sediment parameters, other characteristics of the channel and its adjacent hillslopes also influence the incision susceptibility of lowland streams. Although not generally quantifiable, these characteristics demonstrably affect the likelihood and magnitude of incision on a given stream channel. They provide an additional, site-specific measure of susceptibility for channels previously identified by simple virtue of slope and substrate.

The slope of a stream reach down to its local base level determines how effective a given degree of channel incision will be at reducing that bed slope. Reduction of bed slope in turn will limit the further transport of sediment and thus the magnitude of incision that can occur. The negative feedback on transporting capability will be much more pronounced where the channel slope is already low, because a given lowering of that bed level represents a greater percentage of the total channel gradient. Thus rapid

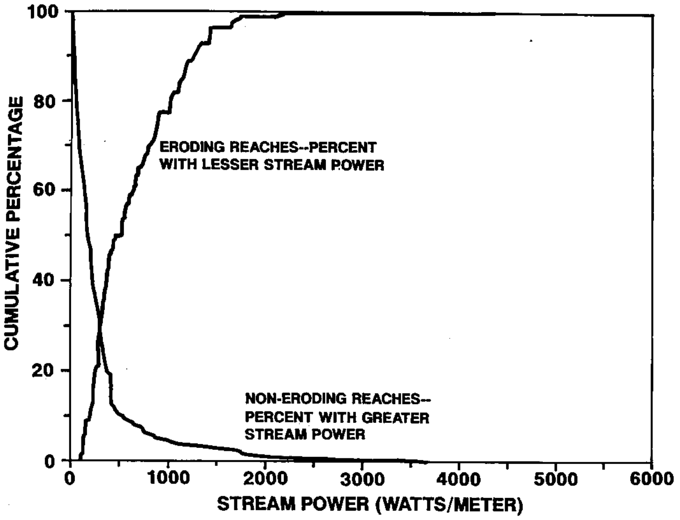

Figure 6a. Discrimination by stream power, calculated as $\rho_w g\ Q_{2\text{-year}}\ S$. No threshold value is evident, as large trunk streams have high total power that is typically dissipated over large bed areas.

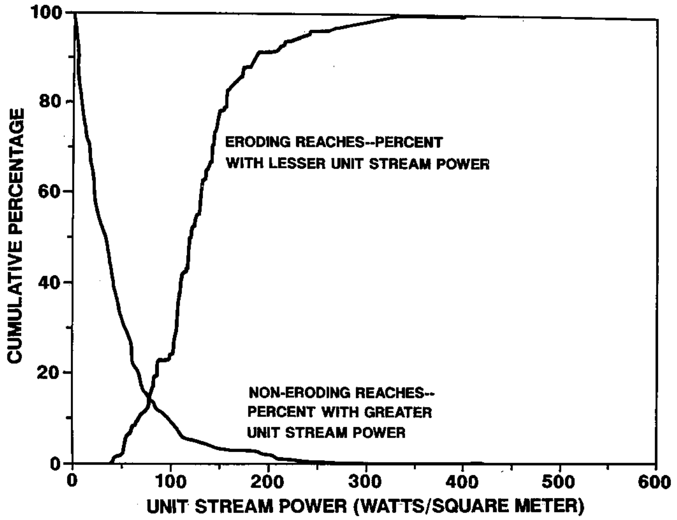

Figure 6b. Discrimination by unit stream power, calculated as stream power divided by bankfull width. A threshold value of about 80 watts/m^2 is only moderately well-defined here, because streams with low roughness can exhibit higher unit stream powers without any corresponding increase in erosivity.

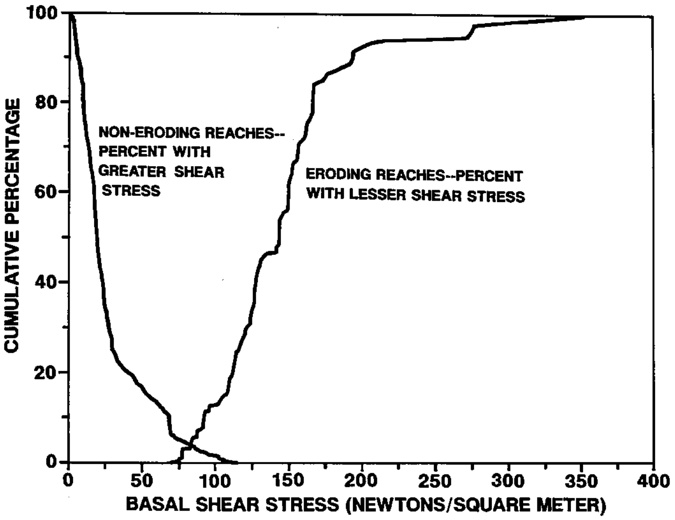

Figure 6c. Discrimination by basal shear stress, calculated as the product of $\rho_w gS$ and the bankfull depth. Near-threshold conditions are suggested by a value around 85 N/m^2, with less than 5 percent of the stream reaches misidentified by such a discrimination. Variability may be anticipated from region to region, reflecting differences in predominant sediment type, but within this region even the differences between basins yield no appreciable inconsistencies.

Figure 6. Correlation of bank erosion with various flow parameters for major tributaries in the Soos and Bear Creek basins. All reaches were walked and classified in the field; flow parameters were derived from topographic slope off 2-ft contour maps, HSPF-simulated two-year discharges (existing land use), and measured bankfull width and depth. About 77 km of channel length in the "non-eroding" category and 9 km in the "eroding" category are represented. Percentages indicate the proportional length of channels in each category that are found with a greater (in the noneroding case) or a lesser (in the eroding case) value of the specified flow parameter.

incision, once initiated, is far more likely to continue where channels are steep, notably in low-order headward tributaries rather than in high-order lowland trunk streams. This is well-illustrated by long-term discharge measurements in this area on low-gradient streams, where even shear stresses well in excess of those associated with headwater incision have produced only modest bed lowering (Figure 7).

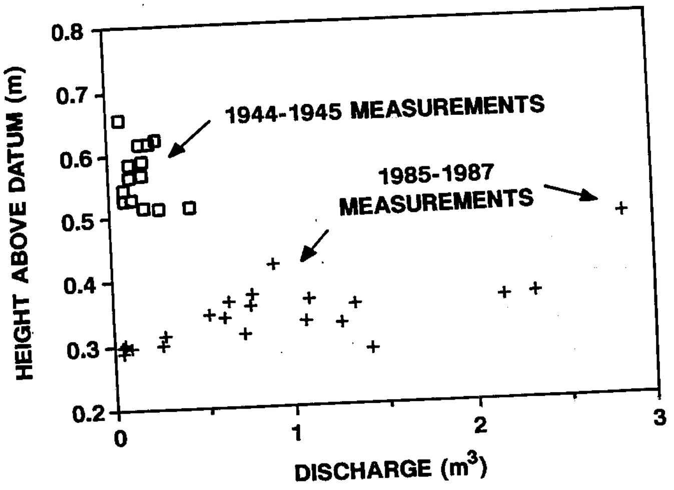

Figure 7. Long-term channel-bed lowering of 0.2-0.3 m shown by USGS file data collected at gage 12110000 in the Soos Creek basin with a tributary area of 49 km^2 and an average gradient of 0.025. Shear stresses, calculated from average channel slope and bankfull depth in this reach, vary from 110-160 N/m^2, which would be sufficient to initiate far more significant downcutting in steeper headwater channels.

Large organic debris (LOD) affects channel susceptibility to incision by adding an external, and potentially transitory, element of channel roughness. By increasing the roughness, LOD permits a stable channel gradient to evolve that is commonly far steeper than the sediment resistance to transport alone could support (Keller and Swanson, 1979). In such channels, incision brings an element of positive feedback because a rapid lowering of the channel bed "strands" logs, typically anchored in the banks, above the new depth of flow (Figure 8). Removal of logs, by either increased flows or human activity, has a similar effect. Where bed lowering does not significantly reduce the overall channel gradient, incision once initiated becomes far more difficult to stop, because less of the total shear stress is dissipated on nonerodable roughness elements.

Urbanization has an additional, pernicious impact on basin hydrology and channel form, by dramatically increasing the frequency of large flood flows. One such example is shown in Figure 9, indexing such "large" floods to the magnitude of the predevelopment five-year discharge. During these events, normally immobile objects are more likely to be washed out of the channel. In this region, logs and other LOD are the most common such objects, adding substantial flow roughness and channel structure (Arnold *et al.*, 1982; Lisle, 1986; Hogan, 1987; Booth and Barker, 1988). Equivalent relationships between the movement of other types of channel-defining elements and large floods have been demonstrated elsewhere (e.g., Sidle, 1988; Carling, 1988). The input rate of LOD, however, depends on rates of tree growth as well as on rates of discharge, channel incision, or mass failures. Thus accelerated washout cannot be fully compensated. A sediment transport imbalance can rapidly develop as channel roughness is irreplaceably lost, to be reequilibrated only as lower channel gradients and increased mass failures off the now-incised channel banks reduce flow competence and add new material. Where the strength of the bank material relies in part on transitory cohesion, such as is observed in vegetation-bound or glacially overconsolidated granular deposits, the frequent occurrence of sediment-transporting flows out of urban basins may create oversteepened, deeply incised ravines that balance sediment flux over the short term only by sideslope gradients steeper than long-term equilibrium angles will ultimately sustain. Later cycles of aggradation, and then perhaps reentrenchment, are thus precipitated from a single episode of downcutting (Schumm, 1977).

MITIGATION OF CHANNEL INCISION

Although a number of studies have discussed in detail some strategies for correcting channel incision (e.g., Schumm *et al.*, 1984), urbanization provides both unique limitations and opportunities. Rehabilitation of already-incised channels is almost always prohibitively expensive until channel widening has begun to slow or halt the rate of downcutting ("Type IV" of Harvey and Watson, 1986). Yet in some circumstances, the perceived value of sideslope or adjacent upland property may motivate such a solution before its optimal time. Grade controls (Heede, 1986) can limit the migration of knickpoints and increase the negative feedback of bed lowering on transport capability (by establishing a local base level and so shortening the length of the channel reach). Such control is provided naturally, and quite effectively, by partly buried logs or boulders; yet both natural and artificial structures can be overwhelmed by

Figure 8. Logs in the streambank, once providing substantial hydraulic roughness by intimate contact with the channel bed and water flow, now stranded by the recent upstream migration of a 1-m-high knickpoint.

undercutting, sidebank undermining, or high-flow washout. They also can impede fish migration and do not entirely eliminate channel alteration between such barriers.

Flow control from urbanizing basins potentially offers a more fundamental solution. Typical detention standards, however, only limit peak discharges and typically apply only to the low-frequency, high-magnitude events that cause flooding problems (e.g., the 10-year or 100-year flow). As a result, neither the flows that transport the most sediment, nor the duration of any flow, are maintained at predevelopment levels. In order to match both peaks and durations for pre- and post-development conditions down to at least a two-year event, however, detention volumes are required that average between 100 and 200 mm over the entire basin area (Barker and Nelson, 1989; King County, 1989a). These volumes compare quite well with the active soil-moisture volume available in forest soils (Trimble and Lull, 1956; Balci, 1964; Stoker, 1988). Yet they represent detention volumes about one order of magnitude larger than those typically required by municipalities for private (or public) development. The associated cost for facilities and land renders such space-intensive solutions unpopular; their implementation anywhere to date is quite limited.

Recognition of incision-susceptible terrain is clearly the most effective strategy for mitigation in urbanizing areas. The characteristics of such areas include low-order, high gradient streams; fine-grained, noncohesive geologic deposits; low infiltration capacities of upland soils, reducing opportunities for reinfiltration of development-concentrated flows; and channel form and gradient controlled by, and thus dependent on, large organic debris.

Development intensity correlates only weakly with incision. For a given basin, the intensity of development obviously will determine the degree of impacts, but equivalent levels of development in different basins will not yield equivalent channel impacts because of the physical differences between basins and streams channels. Thus mitigation simply determined by the intensity of development will either overprotect some channels or (more typically) underprotect others.

Where suspectible areas are identified and potential development impacts are anticipated, proactive strategies for avoidance can yield substantial long-range benefits. Flow diversion, piping, adequate detention, or extensive upland infiltrative buffers are all strategies that can lessen or eliminate channel impacts in this environment. Only limited experience, in this region or elsewhere, has been developed on the effectiveness and practicality of these measures. The public and private costs of our present ignorance, however, should motivate further effort to correct or avoid the conditions that make these costs otherwise inevitable.

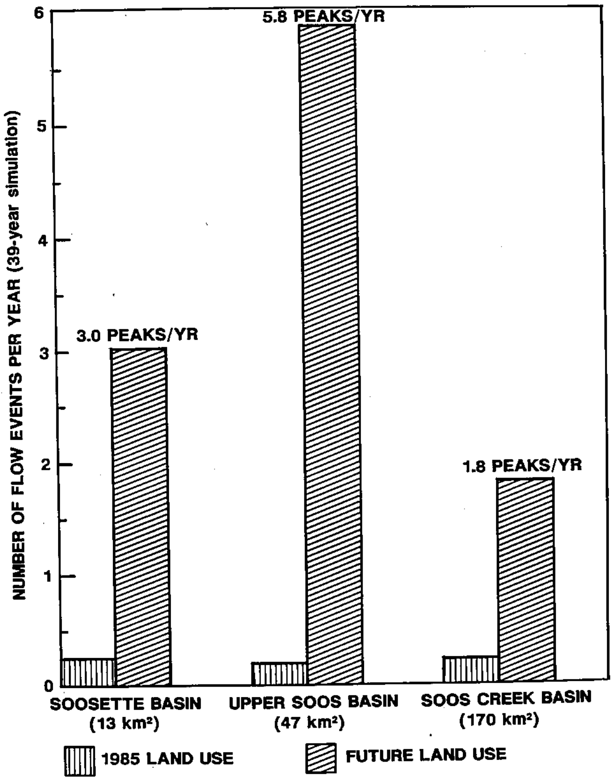

Figure 9. Model simulation of change in the frequency of "large" flood peaks at three points in the Soos Creek basin as a result of future urbanization. The discharge of the present five-year flood peak is used as the index value for such "large" peaks; its future recurrence, showing a 9- to 29-fold increase, indicates that flows of sufficient discharge to alter the roughness elements and structure of the stream channel itself will become far more commonplace as basin development occurs.

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