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NATURAL RESTABILIZATION OF STREAM CHANNELS IN URBAN WATERSHEDS[1]

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ABSTRACT: Stream channels are known to change their form as a result of watershed urbanization, but do they restabilize under subsequent conditions of constant urban land use? Streams in seven developed and developing watersheds (drainage areas 5-35 km^2) in the Puget Sound lowlands were evaluated for their channel stability and degree of urbanization, using field and historical data. Protocols for determining channel stability by visual assessment, calculated bed mobility at bankfull flows, and resurveyed cross-sections were compared and yielded nearly identical results. We found that channel restabilization generally does occur within one or two decades of constant watershed land use, but it is not universal. When (or if) an individual stream will restabilize depends on specific hydrologic and geomorphic characteristics of the channel and its watershed; observed stability is not well predicted by simply the magnitude of urban development or the rate of ongoing land-use change. The tendency for channel restabilization suggests that management efforts focused primarily on maintaining stability, particularly in a still-urbanizing watershed, may not always be necessary. Yet physical stability alone is not a sufficient condition for a biologically healthy stream, and additional rehabilitation measures will almost certainly be required to restore biological conditions in urban systems.
(KEY TERMS: channel stability; urban channels; channel response; geomorphology; stability assessment; watershed urbanization; urban hydrology.)

INTRODUCTION

Concern over the status of native salmon runs has brought renewed attention to the quality of urban streams in the Pacific Northwest. With fewer salmon returning to the local streams to spawn, land managers have begun extensive programs to rehabilitate appropriate habitat that has been lost or degraded due to urban development. Urbanization can have profound impacts on the physical, chemical, and biological character of streams, often resulting in degraded water quality, loss or removal of stream habitat, and physical alteration to the channel. The latter, which is the focus of this study, is commonly expressed by rapid erosion or deposition and changing channel form. Although rebuilt habitat in a stabilized urban stream may not provide the level of ecological integrity required to maintain endangered salmon and other stream biota, physical stability is likely one necessary component of a healthy stream.

The purpose of this study was to determine whether eroding channels in urban watersheds are capable of restabilizing over a period of years to decades. Based on a variety of field and historical data from a range of streams draining urban and urbanizing watersheds in the Puget Sound lowlands of western Washington, we investigated the relationships between channel stability, watershed urbanization, and other factors that may also affect the timing or extent of geomorphic response.

BACKGROUND

The deleterious influences of urbanization on the hydrology and geomorphology of small streams have been extensively explored and documented (Hammer, 1972; Leopold, 1973; Arnold *et al.*, 1982; Booth, 1990). The transition of a watershed from the natural, forested state characteristic of humid regions to a predominantly urban condition encompasses removal of vegetation and canopy, compaction of soils, creation of impervious surfaces, and alteration of natural

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drainage networks. These actions result in increased surface runoff and changes to sediment budgets which in turn commonly induce a geomorphic response that alters the cross-sectional geometry, channel morphology, profile, and planform of the stream. The emphasis of this work is on the specific response of channel cross-sectional form to watershed urbanization over time. Cross sections adjust rapidly and are more directly influenced by discharge and sediment supply than are most other components of channel form and morphology, and they are also among the most commonly collected data on stream channels of any size and watershed setting (MacDonald *et al.,* 1991).

Channel Stability

Although widely used in the scientific literature and in engineering practice, the concept of "channel stability" is somewhat ambiguous, with individual authors and disciplines offering different interpretations of what constitutes a stable channel. This is particularly true for urban streams, where perceptions of stability (and especially instability) from a human or engineering perspective may be in direct conflict with more traditional geomorphic views of a stable channel. While most geomorphic definitions of stability attempt to account for the inherent variability of channel systems, engineers and public works managers have preferred to seek channels that are "unchanging in shape, dimensions, and pattern" (Schumm, 1977:131). This preference provides the justification for the construction of channelized, concrete-lined floodways but is unrealistic for natural alluvial channels that are intended to support healthy biological communities.

The definition of a stable channel may best be summed up as one in which there is no progressive adjustment in channel form (Schumm, 1977; Montgomery, 1994). Thus "stability" implies that channel form (in this case, cross-sectional shape and dimensions) is essentially constant, but not static, over a defined time scale and under a typical range of flow and sediment conditions.

Channel Response to Urbanization

In response to urban-induced changes in flow and sediment regimes (Wolman, 1967; Leopold, 1968; Hollis, 1975), streams are forced to alter their channels. In smaller watersheds, most channels are observed to enlarge, implying that increases in flood peaks have a greater influence than increases in watershed sediment yield (Dunne and Leopold, 1978). Although sedimentation and channel contraction are sometimes observed, particularly early in urbanization (Leopold, 1973) or in very low-gradient systems (Odemerho, 1992), the predominant responses reported in the literature are channel erosion and enlargement.

Channel enlargement may occur through lateral erosion increasing channel width, bed erosion or (less commonly) overbank deposition increasing channel depth, or some combination of these mechanisms. It is important to distinguish these types of moderate channel expansion from catastrophic incision, wherein rapid bed degradation effectively separates the bed from the channel banks to create a nonalluvial, gully-like morphology. The latter process, described by Booth (1990) for western Washington streams, is less common and is beyond the scope of this study.

Channel expansion in response to watershed urbanization has been observed in a variety of climatic and physiographic regions. Hammer (1972) related increases in channel size to various land uses in urban and urbanizing watersheds in eastern Pennsylvania, finding enlargement ratios proportional to the increases in mean annual flood determined by Leopold (1968). Hollis and Luckett (1976) found similar, though less pronounced, responses in a number of small catchments in southeast England. Urban-induced channel enlargement has also been reported from New York and western Pennsylvania (Morisawa and LaFlure, 1979), north-central Texas (Allen and Narramore, 1985), New South Wales in Australia (Neller, 1988), and southwestern British Columbia (MacRae, 1997).

The magnitude and spatial extent of urban-induced channel enlargement is related to a number of factors that have been explored by individual authors. These include the type of development (Hammer, 1972) and its location in the watershed (Ebisemiju, 1989), the extent of stormwater drainage systems (Hammer, 1972), bank composition (Roberts, 1989), and the extent of bank vegetation (Allen and Narramore, 1985; Rowntree and Dollar, 1999).

Restabilization and Response Times

Although the initial effects of urbanization on cross-sectional geometry are well documented, longer term channel response is less well understood. Assuming that stream channels are in a stable state prior to watershed urbanization, the altered urban hydrologic regime should disrupt that stability. This leads to the formation, at least temporarily, of the sorts of unstable channels that have been widely reported in the literature (e.g. Leopold, 1973; Arnold *et al.,* 1982; Booth and Henshaw, in press). Existing models of geomorphic response to changes in hydrologic forcings (Graf, 1977; Wolman and Gerson, 1978; Bull, 1991; Simon, 1989) suggest that such disturbed channels should adjust and develop a new, stable form over time, yet no systematic data have demonstrated this restabilization process in urban stream systems.

Some prior studies have inferred that achievement of a stable, urban state occurs over a period of one to several decades of relatively constant land use in the watershed (Hammer, 1972; Ebisemiju, 1989; Roberts, 1989; Gregory *et al.,* 1992), but others predict that stream channels disturbed by urbanization will remain unstable indefinitely (Wolman, 1967; Arnold *et al.,* 1982). We have conducted this study to evaluate the generic prediction of restabilization, and to establish its timing in a particular geomorphic setting under a type of disturbance, urbanization, that is increasingly prevalent in the modern landscape.

STUDY AREA

Setting

The Puget Sound lowlands (PSL) of western Washington extend from the foothills of the Olympic Mountains east to the Cascade Range foothills, and from the south end of Puget Sound north to the Canadian border (Figure 1). The region is home to the majority of the state's population, including the cities of Seattle, Tacoma, Everett, and Olympia, and it is the center of rapid urban growth in the Pacific Northwest.

The PSL experience a cool maritime climate characterized by mild, wet winters and warm, drier summers. Seattle receives an annual average of 97 cm of precipitation, most of which falls as rain. The rainy season extends from October through May, with over 85 percent of annual precipitation falling during that period.

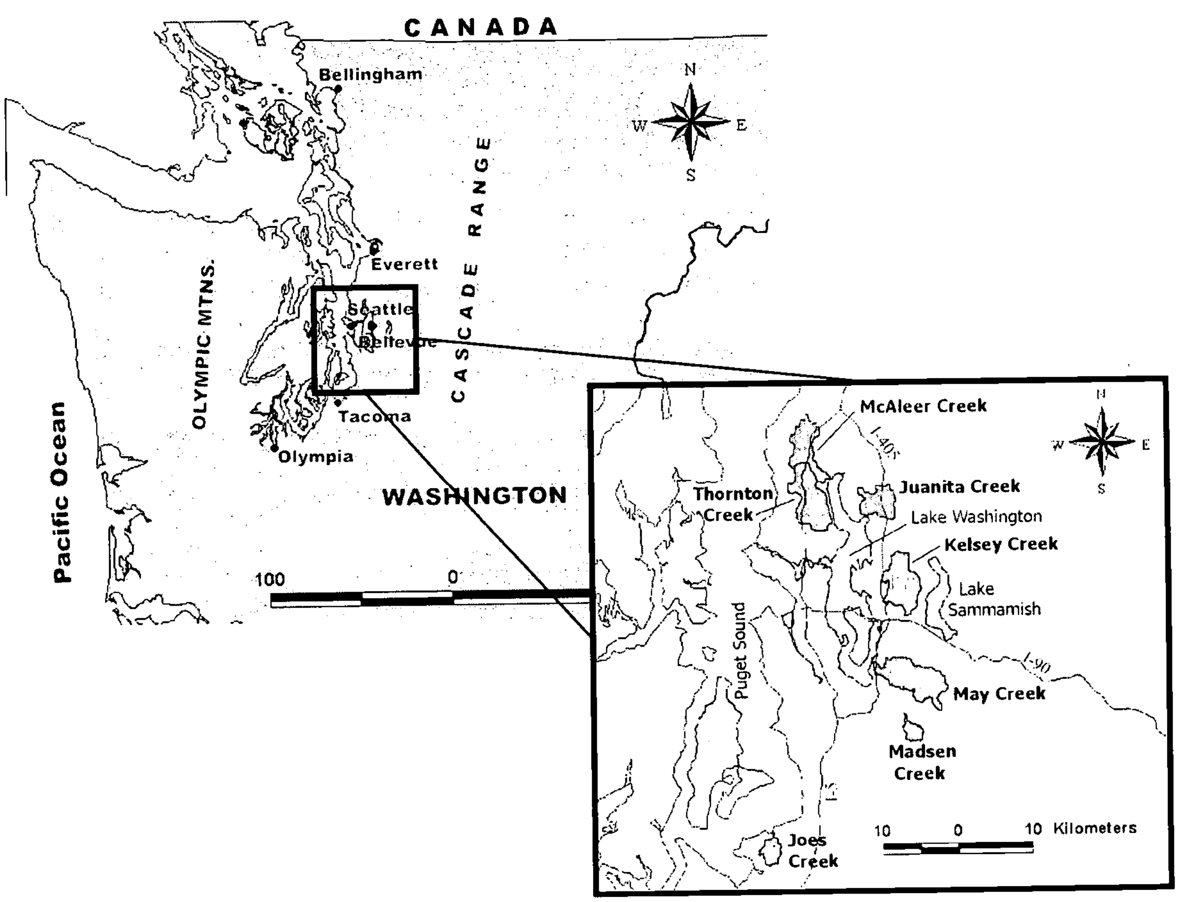

Figure 1. Puget Sound Vicinity and Watershed Location Map.

The geology and topography of the PSL reflect the influences of past glacial activity. Valleys are typically floored in moderately permeable outwash, deposited by rivers and streams draining from the last continental ice sheet about 15,000 years ago. These unconsolidated deposits provide an essentially limitless potential source of coarse sediment to modern streams. Upland plateaus are most commonly underlain by thin and relatively impermeable glacial till, a highly compacted and resistant substrate. Due to its consolidated structure, till has low infiltration rates, and where the overlying soil layer has been cleared for development, surface runoff is generated with even low-intensity rainfall.

In addition to large rivers that drain the flanking mountains, the region's rolling topography supports an abundance of smaller streams. Typical PSL streams drain small watersheds (up to a few tens of km^2) at moderate gradients (0.5-3 percent slope). These small streams have historically provided important anadromous salmonid habitat and consequently have become a focal point in the response to the recent Endangered Species Act listing of several dwindling Puget Sound salmon runs.

At the present time, local stormwater regulations have focused on controlling runoff to these streams primarily via retention/detention facilities to limit peak flow magnitudes. Booth and Jackson (1997) found that the existing regulations have been largely ineffective in protecting stream channels during the period of watershed urbanization, suggesting that new approaches to stream and watershed management are necessary.

Stream Descriptions

The study streams (Figure 1) were chosen to represent typical low-order PSL streams. Their watersheds encompass a range of development intensities (50 to > 90 percent developed area) and representative topographic and geologic characteristics. Four primary streams (May, Juanita, Kelsey, and Thornton Creeks) were the subject of detailed field study, consisting of current stability assessment at two or three alluvial sites along each channel. Field sites on three additional streams (Madsen, Joes, and McAleer Creeks) provided a supplemental record of long-term channel monitoring. These three secondary streams were selected from a group of about 30 PSL streams that have been surveyed on an annual to biannual basis over the past decade (Booth and Henshaw, in press), because they correspond most closely in gradient and watershed area to the primary streams.

The level of urban development in each of these seven watersheds was used to define the basins as either "transitional," where development is ongoing or has only recently stopped, or "post-development," meaning that land cover has been essentially constant for at least the past decade. Watershed characteristics are summarized in Table 1.

In addition to these seven streams, the stability of channels in five less developed PSL basins – Bear, Jenkins, Upper Little Bear, Rock and Soos Creeks – was evaluated to broaden the range of urbanization levels covered by the seven study streams. Developed area in these watersheds ranges between about 40 to 70 percent, with much of the land cover change having occurred within the last ten years. Data from multiple surveys of cross-sections on Boeing Creek, reported by Booth and Henshaw (in press), provided additional information about restabilization response in a post-development watershed following a major disturbance.

TABLE 1. Watershed Characteristics.

Creek	Drainage Area (km^2)	Basin Slope	Development Level	Dominant Surface Geology	Study Emphasis
May	33	0.008	Transitional	Till, Bedrock	Primary
Madsen	5	0.030	Transitional	Till	Secondary
Joes	8	0.028	Transitional	Outwash, Till	Secondary
Juanita	16	0.012	Transitional	Outwash, Till	Primary
Kelsey	26	0.010	Post-Development	Till, Outwash	Primary
McAleer	20	0.013	Post-Development	Till	Secondary
Thornton	31	0.013	Post-Development	Till	Primary

METHODS

Approach

Channel stability and levels of watershed urbanization for each study stream were assessed to examine the relationship between channel stability and the magnitude and rate of development in the watershed. Channel stability at each of the study sites was analyzed using a combination of current observations and measurements and available historical records of channel dimensions, gathered from USGS cross-section surveys, rating curves and inspection reports from nearby stream gages and bridges, and previous studies. However, given the general lack of historical data, only current stability could be directly determined in most cases. Comparison with decade-long records of channel form for the four secondary streams provided an opportunity to assess the utility of these short-term measurements as indicators of long-term channel stability.

Hydrologic Data

Precipitation and discharge data were obtained to establish a hydrologic context within which the watershed and channel changes were occurring. Daily precipitation records for 1949-1997 were obtained from the National Weather Service rain gage at the Seattle-Tacoma International Airport (Sea-Tac). Using these data, the maximum five-day precipitation event was determined for each water year to assess changes in precipitation over the period of record and over the ten-year period of observation for the secondary streams. The five-day maximum event was used because in the PSL region, under natural conditions, the largest flows are generated by rain on already saturated surfaces.

Daily discharge and annual maximum flow data were obtained from USGS and King County stream gage stations on May (USGS 12119600/King County 37A), Juanita (USGS 12120500/King County 27A), Mercer (USGS 12120000), and Thornton (USGS 12128000) Creeks to examine changes in streamflow and hydrologic regime over the past few decades of urbanization. Mercer Creek flow data were used as a surrogate for Kelsey Creek; the Kelsey Creek watershed accounts for roughly 70 percent of the contributing area at the Mercer Creek gage. Recent USGS records from Thornton Creek were not used due to the influence of a high-flow diversion constructed just upstream of the gage location. Additional ten-minute data from a Seattle Public Utilities gage farther upstream on Thornton Creek (SPU 42) were substituted for 1998.

In addition to trend analysis on mean annual and annual maximum flows, discharge records were used to determine a measure of the "flashiness" of the contributing watershed (Konrad, 2000). Flashiness was defined as the percent of flows (daily or ten-minute average, as available) that exceeded the mean flow for the year. Low values for this metric indicate a flashy hydrograph with short-duration peaks, whereas higher values would occur in watersheds that produce more sustained peaks. Comparisons of flashiness between basins reflect differences in geology and land cover, both of which affect runoff generation and flow routing.

Field Data

Field data were collected in the fall of 1998 and spring of 1999. Cross sections and sediment sizes were measured at 10 sites on May, Juanita, Kelsey, and Thornton creeks (Table 2), where qualitative stability indicators were also observed. Only observational data were collected for Joes, Madsen, and McAleer Creeks, supplementing the existing multi-year record of cross-sectional measurements. Qualitative observations were also made on Boeing Creek to supplement a two-year monitoring record of cross-sectional response to a catastrophic sediment inflow (Booth and Henshaw, in press).

Site Selection. Sites on the four primary channels were chosen on the basis of their capacity for alluvial response and their location relative to other available data to establish a context of historical channel change. Field sites were located in straight, plane-bed reaches (Montgomery and Buffington, 1997) to limit the effects of local geomorphic influences (such as meander bends or riffle-pool sequences) on observed channel stability. Observations were made in straight reaches to avoid confusing urban-induced instability with natural processes of erosion and channel migration in bends. Although this approach will miss low levels of increased channel erosion occurring only at the outside of bends, the great range of observed channel instability suggests that this limitation is not particularly significant. Channelized and confined (i.e., riprapped) reaches were not considered because of the imposed restrictions on cross-sectional response, which limited the number of potential study sites, particularly on the more urbanized streams. Sites below tributary junctions, pipe inflows, or wetland reaches were also eliminated because of the added complexity at these locations.

TABLE 2. Site Measurements.

Site	Drainage Area (km^2)	Median Bed Particle (mm)	Water Surface Slope	Bankfull Width at Cross Section (m)	Bankfull Flow Cross-Sectional Area (m^2)
			May Creek		
M1	33	33	0.008	6.1	2.5
M2	32	47	0.007	6.0	1.4
M3	22	27	0.002	8.6	5.4
			Juanita Creek		
J1	16	12	0.0007	4.2	3.7
J2	15	11	0.002	5.7	3.5
J3	14	13	0.002	5.4	2.3
			Kelsey Creek		
K1	20	43	0.002	5.8	2.1
K2	8	14	0.001	2.3	1.0
			Thornton Creek		
T1	31	24	0.010	5.2	2.5
T2	3	< 2	0.0004	5.3	1.7

Although grade adjustment is also a component of alluvial response, slope typically adjusts more slowly than channel dimensions and can be considered an independent variable in geomorphic response over shorter time scales (Ferguson, 1986). Consequently, sites affected by downstream grade controls were not summarily eliminated from consideration. Of the selected sites, the Joes Creek and Lower Juanita Creek (J1) sites are affected by rigid downstream grade controls. The Lower Kelsey Creek (K1) and May Creek sites (M1) are within 100 m of downstream bridges but are believed to be beyond the hydraulic influence of the structures.

Bank Conditions. On the four primary streams, a representative cross section at each site was surveyed to determine current channel dimensions. The bankfull channel boundaries were estimated by noting the lower edge of perennial vegetation and transition in bank slope from near-vertical to near-horizontal (Williams, 1978; Olsen *et al.,* 1997).

To supplement quantitative field measurements, sites were grouped into four stability categories by visual observation of indicators such as bank erosion and vegetation extent (Table 3 and Figure 2). The categories were modeled after the bank stability portion of Galli's (1996) rapid stream assessment technique (RSAT). Bank stability categories at several of the sites were determined independently by two field observers, and the assessments proved to be both rapid and reproducible. Ratings were determined for the five less urban streams (Konrad *et al.,* 1998) in addition to the seven study channels.

The bank stability ratings for sites on Madsen, Joes, and McAleer Creeks were compared with multiple cross-sections previously surveyed by Booth and others over the past decade (Booth and Henshaw, in press) to test the observational technique as an indicator of long-term channel instability.

Bed Conditions. Pebble counts were conducted to determine the bed particle size distribution at each site. The pebble count procedure (after Wolman, 1954) consisted of random selection and measurement of the intermediate diameter of 100 bed surface particles from evenly distributed locations across the reach. Particle sizes were used to classify the bed material and to calculate bed shear stresses for evaluating bed mobility.

The relative bed stability (RBS) index, described by Olsen *et al.* (1997), defines bed stability as a ratio of the critical bed shear stress required to mobilize the D_{84}-size particle (τ_{c84}) to bed shear stress at bankfull flow (τ_{bf}). The critical bed shear stress is calculated using the form of the Shields equation in Olsen *et al.* (1997):

$$\tau_{c84} = \tau_c^* (\rho_s - \rho) g D_{84} \quad (1)$$

TABLE 3. Streambank Stability Classification Criteria.

Class	Description
IV	STABLE • Perennial vegetation to waterline • No raw or undercut banks (some erosion on outside of meander bends OK) • No recently exposed roots • No recent tree falls
III	SLIGHTLY UNSTABLE • Perennial vegetation to waterline in most places • Some scalloping of banks • Minor erosion and/or bank undercutting • Recently exposed tree roots rare but present
II	MODERATELY UNSTABLE • Perennial vegetation to waterline sparse (mainly scoured or stripped by lateral erosion) • Bank held by hard points (trees, boulders) and eroded back elsewhere • Extensive erosion and bank undercutting • Recently exposed tree roots and fine root hairs common
I	COMPLETELY UNSTABLE • No perennial vegetation at waterline • Banks held only by hard points • Severe erosion of both banks • Recently exposed tree roots common • Tree falls and/or severely undercut trees common

where ρ_s and ρ represent sediment and water densities, respectively, and g is the acceleration of gravity. The dimensionless shear stress, τ_c^*, is related to the bed particle size distribution by:

$$\tau_c^* = \theta(D_{84}/D_{50})^{-x} \tag{2}$$

where θ and x are empirical values. Values of 0.045 (θ) and 0.7 (x) were used in this study after Olsen *et al.* (1997), who based these on data from Komar (1989). The bed shear stress at bankfull flow is determined as:

$$\tau_{bf} = \rho g R S \tag{3}$$

where R is the hydraulic radius and S is the water surface slope. The relative bed stability index is then defined as:

$$RBS = \tau_{c84} / \tau_{bf} \tag{4}$$

If the RBS is greater than 1, the bed is presumed to be fully mobilized only for events larger than bankfull and the channel is relatively stable. Conversely, if RBS is less than 1, the bed is mobilized at subbankfull flows and the channel is presumably unstable.

Historical Data

Historical channel information was collected to help establish patterns of change over time and to assess long-term channel stability. Unfortunately, the historical records documenting stream channel conditions or changes were limited and generally of little value for analysis or comparison. The most useful historical data consisted of previously measured cross sections, USGS rating curves, and bridge inspection records.

Land Cover

Changes in developed area were characterized from aerial photographs (1970, 1971, 1980, and 1988) and previously classified 25-meter resolution Landsat Thematic Mapper images (1991 and 1995) for each watershed. For the Landsat images, training sites of relatively uniform land cover were selected from around the region to determine the reflectance for different types of vegetative and urban ground cover. The Signature Editor module in ERDAS's "Imagine" software (version 8.4) was then used to extract spectral signatures for each training site, which in turn

Figure 2a. Stable Reach (IV). Vegetation extends to the waterline along the entire bank, and there is no evidence of erosion (Kelsey Creek, Site K2).

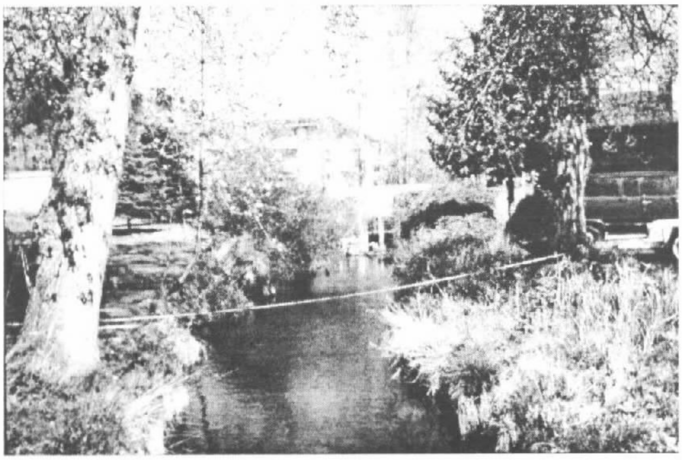

Figure 2b. Slightly Unstable Reach (III). Vegetation extends to waterline, but banks are slightly scalloped and grass roots indicate recent erosion (Juanita Creek, Site J1).

Figure 2c. Moderately Unstable Reach (II). Minimal vegetation at the waterline and the left bank (right in picture) is scalloped back except at hard points (Juanita Creek, Site J3).

Figure 2d. Completely Unstable Reach (I). Minimal bank vegetation and nearly vertical, severely eroded banks. The right bank (left in picture) has been eroded back far enough to almost undermine the large tree (Thornton Creek, Site T1).

were used to classify the entire Landsat image (Botsford *et al.,* 1999). Using the 1991 classified image, we selected random classified pixels to compare with low-elevation 1991 orthophotos for validation of the classified image. The categories, and their corresponding average land cover percentages, are given in Table 4. While these results generally support the use of this method for our broad categorization of developed and undeveloped areas, the variability within the classified land-cover categories suggests that the classification scheme may not be reliable for more specific distinctions between individual land covers.

Percent developed area consisted of residential, commercial, and industrial land uses and included all grassy areas, which Wigmosta and Burges (1997) and Burges *et al.* (1998) found to contribute a large portion of runoff in developed catchments. Results of the land-cover analyses are shown in Table 5, along with the percent change in developed area between 1991 and 1995 and between 1988 and 1995. Changes in developed area are shown for each watershed and for the drainage area above each study site on the primary streams. We estimate that differences of one or two percent are not significant because of minor differences in the definition of land-cover categories between the classification schemes for the 1991 and 1995 land-cover data.

TABLE 4. Land-Cover Percentages of Developed and Undeveloped Watershed Areas.

Categories From the Classified Landsat Image	Actual Land Cover From Orthophotos (percent)			
	Open Water	Trees	Shrubs/ Grass	Pavement or Bare Earth
UNDEVELOPED				
Open Water	100	0	0	0
Coniferous Vegetation	–	91	8	1
Deciduous Vegetation	–	47	49	4
DEVELOPED				
Grassy/Shrubby Vegetation	–	8	63	29
Forested Urban	7	39	31	23
Grassy Urban	–	8	61	31
Intense Urban	9	8	21	62

TABLE 5. Percent Developed Area Over Time.

Creek/Site	Percent Developed						Percent Change	
	1970	1971	1980	1988	1991	1995	1991-1995	1988-1995
May	23	–	36	37	42	50	19.0	35.1
M1	–	–	–	–	42	50	19.0	
M2	–	–	–	–	41	49	19.5	
M3	–	–	–	–	32	41	28.1	
Juanita	52	–	79	83	88	89	1.1	7.2
J1	–	–	–	–	88	89	1.1	
J2	–	–	–	–	89	90	1.1	
J3	–	–	–	–	89	90	1.1	
Kelsey	–	79	83	82	84	85	1.2	3.7
K1	–	–	–	–	85	86	1.2	
K2	–	–	–	–	86	87	1.2	
Thornton	–	98	98	98	97	97	0.0	-1.0
T1	–	–	–	–	97	97	0.0	
T2	–	–	–	–	96	97	1.0	
Joes	–	–	–	80	87	90	3.4	12.5
Madsen	–	–	–	67	67	70	4.5	4.5
McAleer	–	–	–	92	92	92	0.0	0.0
Bear	–	–	–	–	54	58	7.7	–
Jenkins	–	–	–	–	56	69	24.3	–
Little Bear	–	–	–	–	46	66	43.4	–
Rock	–	–	–	–	37	39	5.1	–
Soos	–	–	–	–	60	73	21.9	–

RESULTS

Hydrology

Rank-sum analysis (Helsel and Hirsch, 1992) of the annual maximum flood series from the May, Juanita, and Mercer Creek stream gages showed significant increases in peak flows over the latter part of the record on Mercer and Juanita Creeks, at 99 percent and 95 percent levels, respectively. May Creek, the least developed of the study basins, did not show a significant change in annual maximum discharge. These results are consistent with those reported by Moscrip and Montgomery (1997) for the same streams. There were no accompanying changes in mean annual flow for any of the basins. Records from Thornton Creek were not used for this analysis due to insufficient record length.

Flashiness data (Figure 3) were analyzed for change over time using the Mann-Kendall test (Helsel and Hirsch, 1992). Both Mercer and Juanita Creeks experienced increasingly flashy discharges, as shown by decreasing trends in the value of the metric, significant at the 99 percent level. There was no significant change in flashiness of the May Creek discharge, and trends were not evaluated for Thornton Creek.

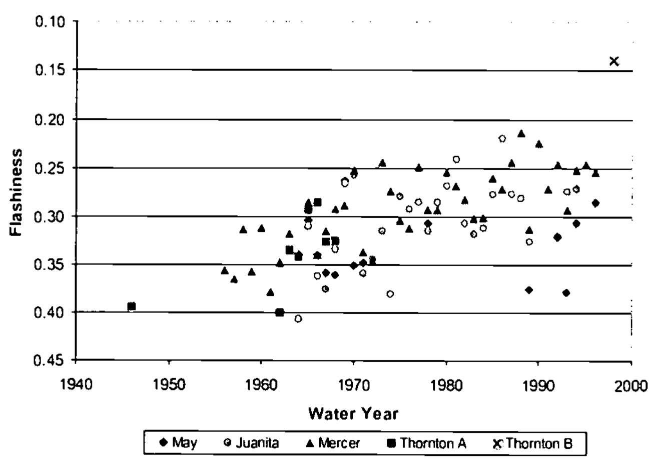

Figure 3. Percent of Gage Readings Above Mean Annual Flow. Lower values indicate flashier hydrographs. Thornton A is the USGS gage station and Thornton B is the Seattle Public Utilities gage (Sources: USGS, King County, Seattle Public Utilities).

The annual five-day maximum rainfall from the Sea-Tac precipitation record (Figure 4) was also analyzed for trends using the Mann-Kendall test. There was no significant change in the five-day maximum over the period of record nor over the decade spanned by the secondary stream monitoring, suggesting that increases in runoff or peak flow were not climate-driven.

Channel Stability

Overall stability was determined for each channel as an aggregate of its available stability measures; with one exception, all measures indicated the same relative stability in each watershed. Stability assessments for the four primary study streams were based solely on measures of current stability (the RBS index and bank stability class), whereas the secondary streams were assessed based on a combination of bank stability class and long-term channel behavior. Only bank stability data (Konrad *et al.,* 1998) were used for the five additional streams. In general, channel stability evaluations show no systematic pattern of channel stability with the magnitude, or the rate, of development in the watershed (Table 6 and Figure 5).

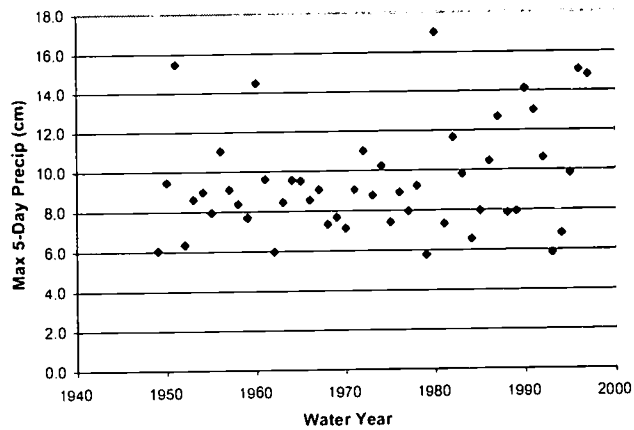

Figure 4. Maximum Five-Day Precipitation by Water Year (Source: National Weather Service, Sea-Tac station).

Kelsey Creek. Kelsey Creek offers an example of a highly developed watershed whose channel has presumably undergone a period of change and has now restabilized. Survey results and bridge inspection reports for a bridge about 50 m downstream of K1 suggest that both Kelsey Creek sites are currently stable, and that channel change has been minimal for at least the past three years. The level of development in the watershed has been essentially constant since 1980, following rapid development in the 1960s and 1970s.

Thornton Creek. Despite having experienced virtually no change in land cover in the past three decades, Thornton Creek is the least stable of the studied channels, with the two field sites classified as "completely unstable" and "moderately unstable." Both the bed and banks are unstable; the channel at the upstream site (T2, drainage area 3 km^2) is extremely overwidened with a bankfull width virtually the same as at site T1 (drainage area 31 km^2).

Juanita Creek. Juanita Creek represents a transitional basin where development has only recently slowed, so we speculate that the channel may still be adjusting to land-cover changes in the watershed. The channel displays recent instability, but there is

TABLE 6. Summary of Results.

	Land Cover		Channel Stability			
	Developed Area (percent) (1995)	Percent Change (1991-1995)	Current (average of stations) Bank (IV = stable)	Bed (> 1 = stable)		
Creek*					Long-Term	Overall
Thornton (1)	97	0	I-II	0.6	n/a	Completely Unstable
McAleer (2)	92	0	IV	n/a	Stable	Stable
Kelsey (1)	85	1.2	IV	5.1	n/a	Stable
Juanita (1)	89	1.1	II-III	1.8	n/a	Moderately Unstable
Joes (2)	90	3.4	III	n/a	Slightly Unstable	Slightly Unstable
Madsen (2)	70	4.5	IV	n/a	Slightly Unstable	Stable
Rock (3)	39	5.1	IV	n/a	n/a	Stable
Bear (3)	58	7.7	III	n/a	n/a	Slightly Unstable
May (1)	50	19	III-IV	2.6	n/a	Slightly Unstable
Soos (3)	73	22	III	n/a	n/a	Slightly Unstable
Jenkins (3)	70	24	IV	n/a	n/a	Stable
Little Bear (3)	66	43	IV	n/a	n/a	Stable

*Study emphasis for each creek indicated as (1) primary, (2) secondary, or (3) other.

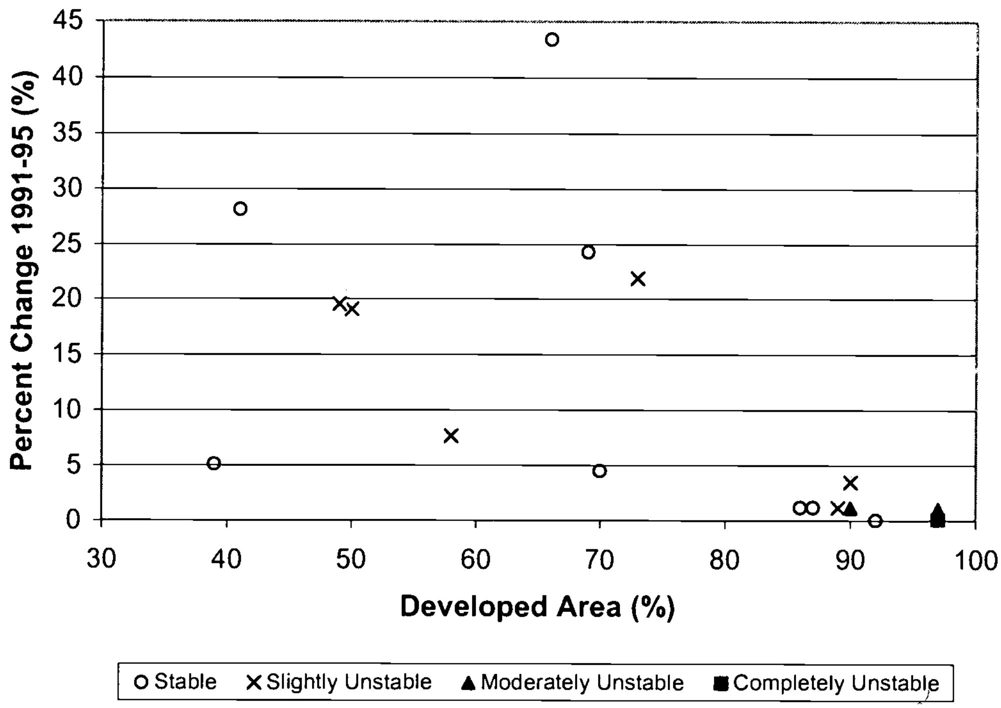

Figure 5. Stability as a Function of Developed Area and Change in Development. Results are shown for each field site on May, Juanita, Kelsey, and Thornton Creeks and for the full watershed for other streams.

no basis to predict whether instability will persist, as with Thornton Creek, or whether the channel will restabilize, as with Kelsey Creek.

USGS cross section surveys at the Juanita Creek gage site indicate an increase in width sometime in the 1960s, followed by consistent values through the end of the record in 1990 (Figure 6). Although the data gap precludes further analysis of the path of the channel adjustment (e.g., gradual linear increase versus step change), these data do provide confirmation of the expected response of channel enlargement following the onset of significant urbanization. The lack of change in channel width in the last 10 to 15 years of recorded cross sections is difficult to interpret, as the limited response of the confined lower banks at the gaging site may not accurately reflect conditions in the fully alluvial reaches.

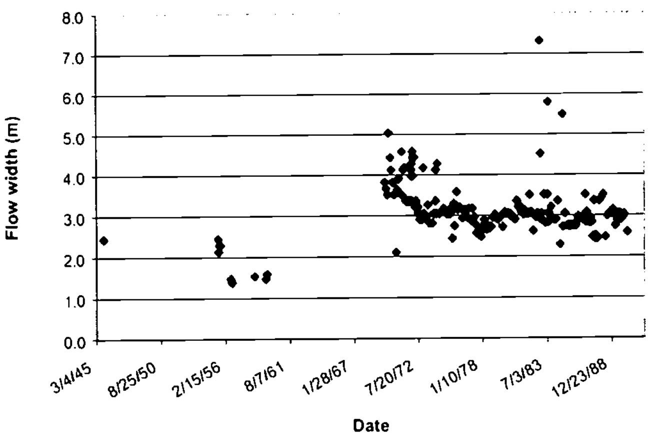

Figure 6. Flow Widths Measured at USGS Station 12120500 on Juanita Creek, 1945-1990 (Source: USGS).

May Creek. Despite rapid development of the watershed over the last decade, field observations and measurements indicate at most slight instability, and that only in the lower reaches, of May Creek. Cross section measurements made by the USGS in 1942 (near M1) and 1958 (near M2) showed flow widths less than those determined from the current surveys. In the absence of a reference width (such as bankfull) or stage-discharge relation for comparison, however, there are insufficient data to evaluate the magnitude of any channel enlargement over the last four decades.

Short-Term Versus Long-Term Channel Stability

The most accurate way to determine channel stability is through long-term monitoring of one or more cross sections selected specifically for this purpose. However, in nearly all cases where such data are needed for geomorphic assessment or for management action, this approach is infeasible. We therefore used our three secondary streams to determine whether short-term observations can accurately reflect long-term stability, by comparing current observed stability with the amount of cross-sectional adjustment over the past decade. Results were quite consistent for three of the four sites (the three secondary study streams plus an additional site on a tributary to McAleer Creek), with conditions of slight or no instability readily identified by both long-term and short-term methods. The only exception was Madsen Creek, which was classified as "stable" based on bank stability observations despite significant measured channel change over the past ten years (Figure 7). The source of this disparity is clear from the cross section: the site experienced significant aggradation between the 1989 and 1990 surveys, a result of massive erosion about 400 m upstream during a large storm in January 1990, and has since undergone bed degradation. The banks, however, restabilized more rapidly and have remained essentially unchanged for the last five years of the monitoring period. The channel adjustment in the long-term record is a result of a sediment inflow from a discrete upstream event, rather than instability intrinsic to the site itself.

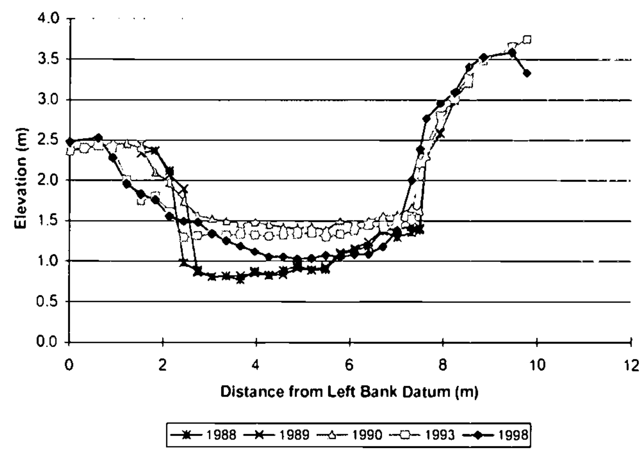

Figure 7. Cross Sections of Madsen Creek Upstream From SR 169, 1988-1998 (1998 survey provided courtesy of R. W. Beck).

A two-year record of cross-sectional surveys for seven cross sections on Boeing Creek (Booth and Henshaw, in press) shows that all but one of the cross-sections restabilized within a year following a catastrophic debris flow in late December 1996, with two of the sections achieving a new stable form within three months of the event. All seven cross-sections were categorized as "stable" or "slightly unstable" using the bank stability classification scheme.

DISCUSSION

Urbanization and Channel Stability

Urbanization acts as the impulse for the hydrologic changes that typically cause channel instability in developing watersheds. Once a watershed is developed, however, does the urban setting continue to play a dominant role in channel response, or do the hydrologic and geomorphic characteristics of the channel and watershed reassert control? Results of the current study suggest that the extent of channel instability and the likelihood of channel restabilization are not determined strictly by the magnitude of disturbance (i.e., the amount or rate of urbanization) but instead depend jointly on the degree of urbanization and the responsiveness of the channel and watershed to land-use change.

The level of urbanization in a watershed exerts at most a coarse effect on the likelihood that the stream channel will be stable, and the rate at which urban development is occurring shows no systematic influence at all (Figure 5). In this study, channels in the less developed watersheds were stable or only slightly unstable, and pronounced instability was observed only in the most developed watersheds. Yet PSL watersheds at even very low levels of development can display major channel adjustments (Booth, 1990; Booth and Henshaw, in press), indicating that the level of channel response is more likely controlled by conditions in the channel and watershed other than general levels of contributing urban land cover. Simple correlations will not be universally applicable, even within the same region.

The circumstances for observed channel stability are not uniform. Stable channels in developing basins (e.g., May, Bear, Jenkins, Upper Little Bear, Soos, and Rock Creeks) are not "restabilized," because there is no evidence or record of prior channel instability and because land cover is still in such active flux. Their stability is presumably a continued expression of only gradual divergence from pre-urbanization conditions. Conversely, the stable channels that have been affected by several decades of substantial watershed urbanization (e.g., McAleer, Kelsey, and Madsen) almost certainly reflect restabilization following urban disturbance, rather than mere persistence of the pre-development channel form.

Of our presently unstable channels, the prognosis for future restabilization is uncertain. Theoretical concepts of the "equilibrium channel" (Leopold *et al.*, 1964) and "graded stream" (Mackin, 1948), and multiple examples of stable urban channels, suggest that such an outcome might be expected. Those still experiencing changes in watershed land cover (e.g., Juanita and Joes Creeks) may restabilize in time. Yet Thornton Creek remains highly unstable despite an urbanization level that has been virtually unchanged for more than two decades, suggesting no reason to anticipate restabilization here in the near future. Again, a simple rule will not yield a universally correct prediction.

Other Factors Controlling the Restabilization Response

If channel stability in developed watersheds is determined only weakly, if at all, by the magnitude or rate of land-cover change, other factors must play significant roles in determining whether a channel will destabilize and/or restabilize over time. The potential for restabilization, in particular, depends on how changes in the watershed affect the channel's flow and sediment regimes, and to what extent the channel is capable of responding to these changes. Relevant factors must therefore exist at both the watershed and channel scales.

Watershed-Scale Factors. The hydrologic regime experienced by the channel is closely tied to the level of urbanization and impervious area in the watershed, particularly where the underlying geologic substrate does not have a large infiltration capacity, as is the case with the glacial till underlying parts of the study basins. Increased surface runoff in humid-climate urban watersheds alters the natural subsurface flow regime, leading to larger, shorter-duration hydrograph peaks. These changes affect streams by creating more frequent competent flows with greater capability for channel alteration. If the discharge pattern becomes too flashy, typical inter-storm flows cannot rework all of the sediment moved by the much larger storm discharges (Booth, 1991). Thus, channel form becomes dominated by the large events, and the channel loses its ability to develop a stable form adjusted to smaller, more frequent discharges (e.g., Leopold *et al.*, 1964).

Thornton Creek is the prototype for such conditions. Despite draining the most established and unchanging watershed, it was the least stable of the channels observed. With a 97 percent developed watershed with essentially no detention or runoff-attenuation capability, Thornton Creek produced the flashiest of the gaged discharges. Discharge exceeded mean annual flow less than 15 percent of the time, compared with 25 to 30 percent for Juanita, Mercer, and May Creeks.

In contrast, May Creek, which is stable to only slightly unstable, has not experienced the changes in peak flows or flashiness typically seen in largely urbanized basins. Compared to pre-development conditions, discharges for the two-year event have increased by relatively modest amounts, ranging from 15 to 50 percent along the mainstem to only 5 to 20 percent in the highland tributaries (King County, 1995). Runoff generation mechanisms here are also more consistent with the natural condition, with the largest peaks generated by multi-day storms rather than the one-day events that now generate the largest flows in the more urban Juanita and Mercer Creek basins.

In addition to the hydrologic regime, topographic gradients might also be expected to influence channel stability. Yet across the range of slopes in the study watersheds and streams, neither slope nor stream power showed any apparent relationship to observed channel stability. Booth and Henshaw (in press) reported a similar lack of correlation across an even wider range of channel gradients (from less than 0.01 to 0.5).

Channel-Scale Factors. Several site-specific conditions contribute to the responsiveness of channels to land-use change. Most fundamentally, the erosional characteristics of the geologic substrate surrounding the channel can influence the extent to which the channel form initially responds to watershed urbanization, which in turn will influence how much adjustment is necessary to establish a new stable form.

The dominant geological materials in the PSL have quite contrasting properties: glacial till is a highly resistant and relatively impermeable substrate, whereas glacial outwash is a less consolidated and much more erodible deposit. Outwash channels are particularly prone to channel enlargement and instability. Booth (1990) and Booth and Henshaw (in press) found that virtually all cases of extreme incision occurred in channels flowing over these deposits. Where less dramatic channel changes are evaluated, the pattern is less definitive but still consistent: slight to moderate instability is displayed by the outwash channels in the present study, Juanita and Joes creeks.

In contrast, if the natural channel substrate is highly resistant to erosion then the initial extent of channel response, and the difficulty of subsequent restabilization, should be limited. The best example among the study streams is found in the lower reaches of McAleer Creek, which flow over extremely resistant fossilized peat beds. Even highly erosive, sediment-poor flows can produce only modest changes in this substrate, which helps to account for the extremely stable conditions observed on McAleer Creek despite its highly urbanized watershed.

Yet human actions at the channel scale can alter natural tendencies. On Thornton Creek, bank armoring and upland development have eliminated most sources of coarse sediment (Trimble, 1997; Nelson, 1999), resulting in a finer bed particle size distribution than the other study streams despite high flows. The disruption of coarse sediment supply presumably yields a sediment imbalance, forcing the stream to continue eroding any still-exposed banks and preventing restabilization in the relict alluvial reaches.

Although channel gradient itself has no apparent relation to channel stability, the extent of local controls on the gradient does appear to have some influence. This condition is particularly relevant to urban streams, with their typically high densities of road and utility crossings. Gradients just downstream of the study sites on Joes Creek and Lower Juanita Creek (J1) are rigidly controlled, limiting the ability of the channels to incise. Both sites are only slightly unstable, whereas the two upstream sites on Juanita Creek, which are subject to less rigid and more widely spaced grade controls, are both moderately unstable. Gradients on McAleer Creek, the most stable of the streams despite a 92 percent developed watershed, are tightly controlled by a series of culverts along the length of the channel, along with numerous points of highly resistant substrate.

In addition to the localized effects of substrate and grade control on stability response, the extent of the riparian corridor may also influence responsiveness at the channel scale. Although this factor was not explored in detail, the most stable channels in this study are generally associated with reaches with relatively intact natural riparian vegetation. Preservation of a natural riparian corridor reduces the area of land-cover modification and so lessens the degree of hydrologic change; it also discourages direct disturbance of the channel and stabilizes (or allows more rapid restabilization of) potentially erodible banks. May, McAleer, and Madsen Creeks have the most extensive natural riparian corridors and were either stable or only slightly unstable, whereas the moderately to completely unstable channels (Juanita and Thornton Creeks) have limited, if any, natural streamside vegetation.

Time Scale of Restabilization

The observed stability of many established urban watersheds indicates that channels can restabilize without intervention. Results from these study streams suggest that this restabilization occurs over one to two decades. Development in the McAleer Creek basin ceased around the late 1960s, and long-term monitoring results show that the channel has been stable for at least the last ten years; land use in the Kelsey Creek watershed has been roughly constant since the late 1970s, and both stream sites appear to be quite stable. Yet no single generality applies to all urban channels: Thornton Creek has not restabilized at all, even after more than 20 years of virtually unchanging land cover.

Under fortuitous stream and watershed conditions, channel restabilization following a major disturbance can occur very quickly. Booth and Henshaw (in press) reported on the reestablishment of a stable channel on Boeing Creek within months of a major debris flow. On Madsen Creek, the banks were found to have restabilized within three years of a major storm in 1990 (Figure 7). Thus restabilization can occur in far less than a decade, even while land cover continues to change.

As a general guideline, we judge that PSL streams will tend to restabilize within one or two decades following urbanization. Despite differences in hydrology, geology, and the extent and patterns of development in our study watersheds, the consistency of results suggests broad relevance to the variety of urban channel conditions in the region. Yet no single period of adjustment applies universally to restabilizing PSL streams because of important differences in the determining hydrologic and geomorphic characteristics. Only a case-by-case evaluation of watershed and stream conditions can show whether a 10-year to 20-year interval is appropriate for a given site, and any simple prediction of channel response based on watershed urbanization is guaranteed to yield spurious results.

Utility of Alternative Stability Assessment Techniques

We used two alternative techniques, based on field data and observations, to assess the current state of channel stability: (1) we classified bank stability based purely on observational data in order to rapidly group streams into several categories, and (2) we used Olsen *et al.*'s (1997) relative bed stability (RBS) index to characterize channel stability based on sediment transport at bankfull flows. Both methods produced similar results (Figure 8), and although higher bank stability classes did not uniformly yield greater RBS values, both measures clearly increased in consort. Thus, either one of these metrics is probably a sufficient indicator of relative stability in most cases, although the two in combination offer some increasing degree of discrimination.

Although useful as an indicator of relative stability between sites, the RBS index tended to overpredict absolute stability. Only two sites (both on Thornton Creek) had RBS values less than the defined stability threshold of 1, even though two other sites were classified as moderately unstable and seven of the ten sites showed at least slight instabilities. This suggests either that motion of bed surface particles smaller than the D_{84} may be better associated with instability for channels in this setting, or that the coarse particles are more mobile than the critical shear stresses determined from Olsen *et al.*'s (1997) chosen dimensionless shear stress parameters would indicate. Studies of bed motion in gravel-bedded channels have yielded a wide range of plausible values for the constants in the dimensionless shear stress function (Buffington and Montgomery, 1997); assumption of a more equally mobile bed would give lower critical shear stresses and consequently lower RBS values. Using the bankfull discharge as the index for sediment transport may also be unwarranted, as there is no certainty that these urban channels are adjusted to a typical 1.5-year to two-year recurrence bankfull discharge (e.g. Wolman and Miller, 1960; Carling, 1988).

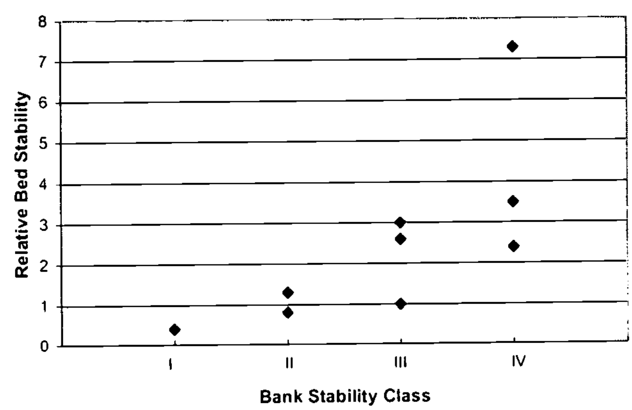

Figure 8. Comparison of Stability Assessment Techniques.

CONCLUSIONS

Channel Restabilization

Hydrologic, field, and historical data were used to classify the stability of channel cross sections in seven watersheds and, where sufficient data existed, to determine the rate and extent of change in channel form over time. The results indicate:

1. Restabilization of urban stream channels in the PSL can, and commonly does, occur even in highly

urbanized watersheds. However, the degree of stability is not well predicted by either the magnitude of developed area or the rate of recent development.

2. There is no generalizable formula for channel restabilization. When, and if, an individual channel will restabilize depends on a combination of hydrologic and geomorphic characteristics of the channel and its watershed, beyond simply the magnitude or rate of urban development. The hydrologic regime and geologic setting appear to be important controlling factors; extent of grade control and condition of the riparian corridor likely play noteworthy, but less influential, roles.

Management Implications

Although slight instability was observed in channels whose watersheds were as little as 50 percent urbanized, and previous work has documented the potential for rapid changes at even lower levels of urbanization, significant channel instability was observed in this study only in the most urban (greater than 90 percent developed) watersheds. Thus, the overall physical form of many PSL streams can withstand high levels of urbanization pressure, even at rapid development rates, and will also tend to restabilize even if morphologic changes have occurred. From the perspective of basin stewardship, this suggests that management response to watershed urbanization should not emphasize the immediate imposition of channel stabilization measures, particularly if urbanization levels are low or the watershed is still developing. In many of these cases, restabilization is likely to occur even without direct intervention, and bank protection can actually accelerate bed degradation in an unstable channel (Simon and Downs, 1995). Resources may be better utilized during this period to protect local habitat and mitigate increased flows and downstream sediment load, rather than for intensive bank stabilization. So-called "remedial" measures may result in permanent riparian alteration with potentially greater long-term biological consequences. Maintaining the channel and its riparian corridor in as natural a state as possible should be emphasized, because sites with better-preserved natural riparian corridors appear to have a greater tendency toward stability.

Yet some channels will not restabilize quickly, if at all. Channels in extremely urban basins are at progressively higher risk, and those bedded in intrinsically erodible sediment, in particular, are prone to channel enlargement or even incision. The presence of rigid grade controls has some positive influence on channel stability, although such in-channel measures are likely to reduce the quality of other desirable channel functions (such as biological habitat or aesthetics).

Restabilization does not imply a return of the channel to its natural state, and restabilization alone is not a sufficient goal for protecting aquatic communities. A restabilized cross section will typically be larger and less geomorphically complex than the pre-urbanization channel form. This change affects aquatic biology through loss of habitat and altered flow patterns, water velocities, temperatures, and organic inputs (Booth *et al.,* 1997; Horner *et al.,* 1997; Karr and Chu, 1999). Changes in short-term sediment flux and scour, which are not well described by the stability indicators used here, are also biologically important (Montgomery *et al.,* 1996). Further assessment and subsequent rehabilitation will be required to restore the biological integrity of the stream even after geomorphic stability is achieved, and the success of such additional efforts is by no means assured.

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