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EFFECTS OF URBANIZATION ON CHANNEL INSTABILITY[1]

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ABSTRACT: Channel instability and aquatic ecosystem degradation have been linked to watershed imperviousness in humid regions of the U.S. In an effort to provide a more process-based linkage between observed thresholds of aquatic ecosystem degradation and urbanization, standard single event approaches (U.S. Geological Survey Flood Regression Equations and rational) and continuous hydrologic models (HSPF and CASC2D) were used to examine potential changes in flow regime associated with varying levels of watershed imperviousness. The predicted changes in flow parameters were then interpreted in concert with risk-based models of channel form and instability. Although low levels of imperviousness (10 to 20 percent) clearly have the potential to destabilize streams, changes in discharge, and thus stream power, associated with increased impervious area are highly variable and dependent upon watershed-specific conditions. In addition to the storage characteristics of the pre-development watershed, the magnitude of change is sensitive to the connectivity and conveyance of impervious areas as well as the specific characteristics of the receiving channels. Different stream types are likely to exhibit varying degrees and types of instability, depending on entrenchment, relative erodibility of bed and banks, riparian condition, mode of sediment transport (bedload versus suspended load), and proximity to geomorphic thresholds. Nonetheless, simple risk-based analyses of the potential impacts of land use change on aquatic ecosystems have the potential to redirect and improve the effectiveness of watershed management strategies by facilitating the identification of channels that may be most sensitive to changes in stream power.

(KEY TERMS: stormwater management; erosion; sedimentation; land use planning; aquatic ecosystems; channel stability; modeling.)

INTRODUCTION

Urbanization can have many direct impacts on aquatic ecosystems as streams broaden or deepen to accommodate larger, more frequent, or longer duration flows of water. In the initial construction phase, a spate of sediment delivery to stream channels is accompanied by an increase in flow (Wolman, 1967). After exposed soil has been stabilized or covered with impervious surface, increased runoff coupled with a decline in watershed sediment yield typically results in channel enlargement through incision (Booth, 1990), widening (Arnold *et al.,* 1982) or both (Hammer, 1972; Roberts, 1989). Channel erosion due to urbanization can become the predominant source of excess sediment to downstream reaches (Trimble, 1995, 1997) and result in degradation of biotic integrity (Waters, 1995).

Investigators from various humid regions in the US have reported that channel instability and abrupt declines in indices of aquatic ecosystem integrity are observed at 10 to 20 percent watershed imperviousness (Morisawa and LaFlure, 1979; Booth, 1990, 1991; Booth and Reinelt, 1993; Schueler, 1994). The specific causative mechanisms behind this perceived threshold have yet to be identified. Numerous studies have linked watershed imperviousness with increased peak discharge magnitudes (Urbonas and Roesner, 1993). In a synthesis of several previous studies, Hollis (1975) suggested that flows less than bankfull may be increased by a factor of 10 or more depending on the degree of urbanization. At 10 to 20 percent watershed imperviousness, flows with recurrence intervals of 1.5 to two years in the annual maximum series may be doubled or tripled (Hammer, 1972; Hollis, 1975). In general, observations suggest that stream channels in smaller and more permeable watersheds exhibit a greater and more abrupt erosive response to urbanization.

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It is clear that increases in discharge and stream power associated with urbanization have the potential to severely destabilize streams in a variety of contexts. It seems unlikely, however, that there is a consistent relationship between imperviousness and the potential for channel response across watershed and stream types. The purpose of this paper is to examine linkages between imperviousness, increases in discharge and stream power, and the risk of channel instability in urbanizing watersheds. Because the disparate responses of stream channels are dependent upon flow regime, the following sections explore the variability in hydrologic response to urbanization before specifically addressing the risk of channel instability in subsequent sections.

RELATIONSHIPS BETWEEN IMPERVIOUSNESS AND FLOW CHARACTERISTICS

Measured data on the effects of urbanization on stream channel form are rare, and estimates are typically extrapolated from watershed models. In this analysis, the potential effects of watershed imperviousness were examined using hydrologic models that range from simple statistical relationships and the rational method (McCuen, 1989) to complex process-based models. Several USGS Flood Regression Equations, other USGS data, and National Urban Runoff Program (NURP) data were contrasted with continuous simulations based on the CASC2D (Julien *et al.*, 1995) and Hydrologic Simulation Program-Fortran (HSPF; Johanson *et al.*, 1980; USEPA, 1984) hydrologic models. Such a contrast provides insight into the usefulness of simple, single event approaches in projecting magnification of channel-forming flood events as well as cumulative effects across a broad range of flows occurring over an extended period of time.

Single Event Approaches

USGS Flood Regression Relationships. For many years, the USGS has been involved in the development of regional regression equations for estimating flood magnitude and frequency at ungaged sites. Regression equations for rural areas and, in some instances, urban areas are periodically compiled in a summary organized by state for the United States. The most recent compilation is provided in Jennings *et al.* (1993). These regression equations are used to transfer flood characteristics from gaged to ungaged sites through the use of watershed and climatic characteristics as predictor variables. The USGS-developed regression equations are generally unbiased, reproducible, and easy to apply.

For the purposes of this analysis, we are most concerned with some estimate of the dominant, channel forming discharge, which is often approximated as having a 1.5-year to two-year recurrence interval in the annual maximum series (approximately an annual flood). Estimates of the median annual flood event ($Q2$) derived from the USGS flood regression equations may be particularly useful in geomorphic assessment and hydraulic design and often provide an acceptable estimate of the dominant, channel-forming discharge. Six sets of USGS urban regression equations for $Q2$ provided in the 1993 summary were selected for this analysis based on range of applicability, data availability, and ease of application. The urban equations, the relationships used to estimate a rural $Q2$, and the sources for each are listed in Table 1. The number of region-specific relationships examined was limited to six since the other equations required site-specific information that rendered a general analysis infeasible. For example, several of the USGS flood regression equations for locations outside the six selected states utilize a "basin development factor" (BDF) developed by Sauer *et al.* (1983) for use in the USGS national flood regression equations for urban watersheds. The BDF is a function of channel improvements, channel linings, storm drains or sewers, and curb-and-gutter streets. It is intended to represent the efficiency of the drainage system. Subsequent testing of the BDF approach has yielded mixed results and the accuracy of the original data on specific drainage characteristics used in the regression analyses is uncertain (personal communication with Ben Urbonas, Chief of Planning, Urban Drainage and Flood Control District, Denver, Colorado, 1999).

Hypothetical watershed areas of 20, 50, and 100 km^2 were analyzed using the six USGS urban equations at levels of imperviousness ranging from 5 to 30 percent. The corresponding rural equations were used to approximate discharges for watersheds with minimal imperviousness. Since the Missouri and Wisconsin rural equations require channel slope as an independent variable (Jennings *et al.* 1993), the magnitude of rural $Q2$ in those states was estimated using the appropriate urban equation at a low level of imperviousness (Table 1). The Missouri data set included several watersheds at 1 percent imperviousness, and the estimated $Q2$ at 1 percent imperviousness was assumed to represent rural conditions. Similarly, the Wisconsin rural $Q2$ was assumed equal to the urban result at 5 percent imperviousness which was above the lower end of the range of data used in developing the regression equation. These analyses provide estimates of increased discharge for different

TABLE 1. USGS Flood Regression Equations for $Q2$ in Urban and Rural Areas Used in Analysis of Peak Flow Increases at Varying Levels of Imperviousness. Sample size (n) and standard error of the regression estimates (SE) are provided.

State	Urban Equation ($Q2$)		Rural Comparison ($Q2$)		Urban Equation Reference	Rural Equation Reference
Alabama	$150A^{0.70}IA^{0.36}$	($n = 23$, $SE = 24\text{-}26\%$)	$182A^{0.706}$	($n = 200$, $SE = 34\text{-}36\%$)	Olin and Bingham (1982)	Olin (1984)
Georgia	$4.93A^{0.29}IA^{0.28}(195A^{0.6})^{0.64}$	($n = 45$, $SE = 29\%$)	$182A^{0.622}$	($n = 436$, $SE = 26\text{-}38\%$)	Inman (1988); Price (1979)	Stamey and Hess (1993)
Missouri	$224A^{0.793}IA^{0.175}$	($n = 37$, $SE = 26\text{-}33\%$)	Urban result at 1%	–	Becker (1986)	–
North Carolina	$221A^{0.87}((0.49L/S^{0.5})^{0.5}IA^{-0.57})^{-0.6}$	($n = 127$, $SE = 30\text{-}35\%$)	$144A^{0.691}$	($SE = 44\%$)	Putnam (1972)	Gunter *et al.* (1987)
Tennessee	$1.76A^{0.74}IA^{0.48}P_{2yr}{}^{3.01}$	($n = 22$, $SE = 25\text{-}32\%$)	$118A^{0.753}$	($n = 304$, $SE = 32\text{-}48\%$)	Robbins (1984)	Weaver and Gamble (1993)
Wisconsin	$418A^{0.786}IA^{1.02}$	($n = 32$, $SE = 32\text{-}39\%$)	Urban result at 5%	–	Conger (1986)	–

Notes: $Q2$ is in cfs.
A is drainage area in square miles.
IA is percentage watershed impervious area.
$L/S^{0.5}$ assumed to equal to 0.5 in North Carolina (median of range specified by Putnam).
P_{2yr} is the two-year, 24-hour precipitation (assumed equal to 3.5 inches in Tennessee).
North Carolina equations are for the Piedmont Province.

regions as a function of imperviousness (Figure 1). Results from the urban regression equations for less than 5 percent imperviousness are not shown since some statistical models were not well calibrated at impervious levels of 0 to 5 percent.

At 10 percent imperviousness, the ratio of developed $Q2$ to rural $Q2$ ranges from 1.5 to 2.2. At 20 percent imperviousness, five out of six equations suggest that $Q2$ has increased by at least twofold with three states exceeding 2.5. Over the range of 8 to 30 percent imperviousness, the Alabama and Tennessee equations provide the median result, with peak discharge increasing by a factor of 1.9 and 2.5 at 10 percent and 20 percent imperviousness, respectively. Increasing basin area from 20 km^2 to 50 or 100 km^2 intensified the estimated increase in $Q2$ for some states since the estimated urban $Q2$s increase more rapidly than the rural $Q2$s with increasing basin area. Changes in basin area had little effect on the median results.

To further explore the potential effects of watershed imperviousness, the data of Sauer *et al.* (1983) were reanalyzed without BDF as an independent variable. Sauer *et al.* (1983) assembled a database of 269 sites from 31 states and 56 metropolitan areas. These data represent a broad spectrum of watershed conditions from several states outside those with urban equations as described above. Although many of the data were taken from the eastern U.S., several gages in semi-arid to arid regions of Arizona, California, and Colorado were also represented. As in the previous analysis, Sauer *et al.* (1983) used USGS regression equations developed for rural watersheds to provide an estimate of predevelopment discharges on a region-by-region basis.

A simple statistical analysis of the Sauer *et al.* (1983) data using categories of imperviousness from 0 to 30 percent indicates that the effects of total imperviousness on hydrologic response are extremely variable (Figure 2). The data also suggest that a twofold or greater increase in $Q2$ is frequent, even at very low levels of imperviousness. Of these 269 watersheds, 55 were reported to have "significant detention." Furthermore, 33 of the watersheds had estimates of rural $Q2$ that exceeded the estimated urban $Q2$. Only five of the sites identified as having "significant detention" had urban $Q2$ to rural $Q2$ ratios of less than one. All sites with "significant storage" and urban $Q2$ to rural $Q2$ ratios of less than one were included in the analysis. Including sites where urbanization has decreased $Q2$ in the absence of "significant storage" may be justified since unintentionally undersized culverts and storm sewers have been reported to significantly reduce peak discharges in some instances (Malcom, 1980).

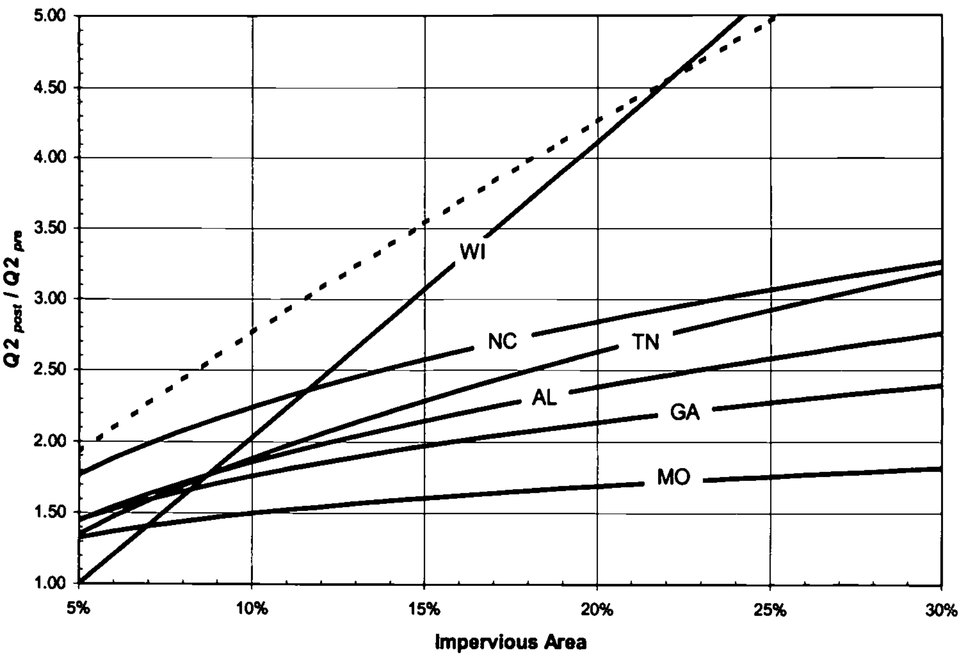


Figure 1. Ratio of Median Annual Flood in an Urbanizing Watershed to That of a Rural Watershed as a Function of Impervious Area Based on the USGS Flood Regression Equations for Six States. Watershed area is assumed to equal 20 km^2. The dashed line represents the relationship developed using NURP data.

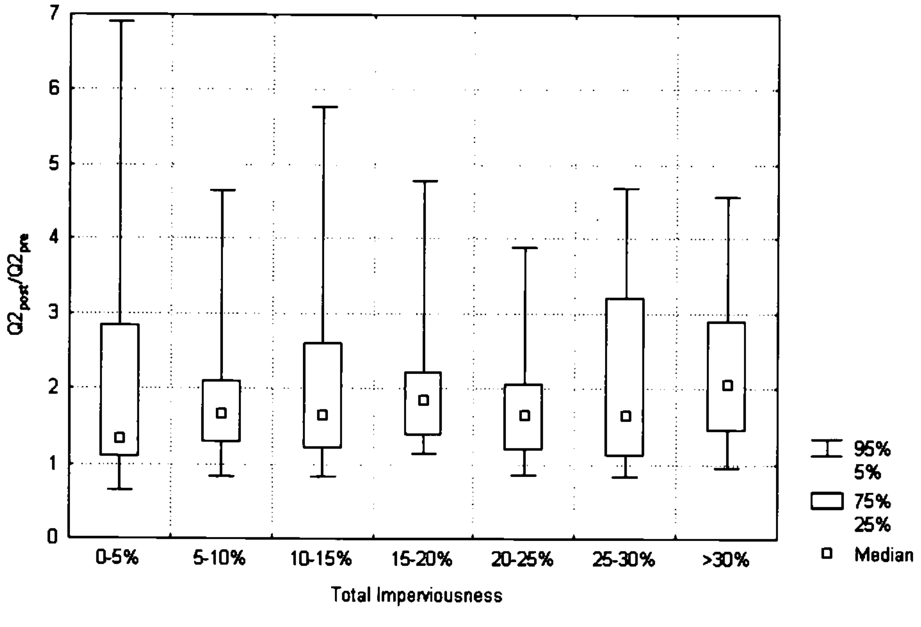


Figure 2. Box and Whisker Plots of Post-Development $Q2$ to Predevelopment $Q2$ Ratio of Different Levels of Imperviousness. (Data are from Sauer *et al.*, 1983.)

U.S. Nationwide Urban Runoff Program Data and the Rational Method. Data from the U.S. Nationwide Urban Runoff Program (NURP; USEPA, 1983) indicate that the runoff coefficient used in the rational method increases with the percentage of imperviousness in a watershed according to the following empirical equation:

$$C = (8.58 \times 10^{-7})I^3 - (7.8 \times 10^{-5})I^2 + 0.00774I + 0.04 \tag{1}$$

where I = percent watershed imperviousness. The rational method is a linear approach that relates the peak discharge, drainage area, rainfall intensity, and a runoff coefficient:

$$Q = CiA \tag{2}$$

where C = the runoff coefficient (typically 0.75-0.95 for impervious areas); A = the watershed area corresponding to the runoff coefficient; and i = rainfall intensity at a duration equal to the time of concentration.

The units employed for rainfall intensity and watershed area are typically in inches/hr and acres, respectively. This results in discharge units of acre-inches per hour which is approximately equivalent to ft^3/s. Although several limiting assumptions are implicit in the rational method (McCuen, 1989), it remains one of the most widely used approaches for basic hydrologic design in the United States. The rational method is generally applicable to basin areas less than about 0.8 km^2 (ASCE, 1992; Wanielista *et al.*, 1997).

Runoff coefficients represent the combined effects of land use, soils, geology, infiltration, and slope on runoff potential. The data used to develop Equation (1) were collected over a two-year period and are indicative of urban runoff from events less than or equal to a two-year storm. Multiple sites with less than 2 percent imperviousness were included in the study and resulted in a regression constant of 0.04 for zero imperviousness. Using Equation (1), an estimate of the relative increase in peak discharge was developed for varying levels of watershed imperviousness. This estimate is contrasted with increases in discharge predicted by the USGS regression relationships in Figure 1 and depicts the greater impact of imperviousness on events less than $Q2$. The comparison is based on the assumption that the pre- and post-development times of concentration are equal. In reality, time of concentration decreases as runoff is conveyed more rapidly by connected impervious areas and drainage facilities. As time of concentration decreases, the applicable precipitation intensity (i) increases. Therefore, differences in the NURP and USGS relationships depicted in Figure 1 would be magnified if the effects of reduced times of concentration were included. Conversely, a watershed with a greater predevelopment C would likely exhibit a smaller increase in peak flows. The data used to develop Equation (1) indicate that C can vary from 0.03-0.35 for levels of impervious of 10 to 20 percent. Runoff coefficients for undeveloped forest or grassland areas are typically less than 0.2 for moderate slopes with loamy soils but may range from virtually zero for small events to values approaching impervious areas when soils are compacted, clayey, or saturated by large events.

Continuous Simulations of Hydrology in Urbanizing Areas

The preceding analyses do not directly address the frequency characteristics of sediment transport events and flows less than a median annual flood. To improve interpretation of the effects of urbanization on the full range of channel-forming discharges, continuous simulation models were also used to examine changes in the magnitude, frequency, and duration of flow and sediment transport characteristics in three watersheds: over a 40-year period in the Hylebos and Des Moines Creek watersheds in King County, Washington, and over a growing season in Goodwin Creek watershed in Mississippi at imperviousness levels of 0 to 30 percent.

HSPF Simulations of Hylebos and Des Moines Creek Watersheds in King County, Washington. In a series of papers examining the impacts of urbanization on lowland watersheds in King County, Washington, Booth (1990, 1991) and Booth *et al.* (1993, 1997) have suggested that even low levels of imperviousness yield demonstrable, and probably irreversible, loss of aquatic ecosystem function. These papers evolved out of the innovative work of King County, Washington, in developing strategies to mitigate the adverse effects of land use change through watershed-scale planning. A key component of the King County approach is continuous hydrologic modeling of changing land use scenarios using detailed HSPF models.

To facilitate examination of the effects of imperviousness over the entire range of flows, HSPF continuous simulation models of watershed hydrology for varying levels of imperviousness in two watersheds were obtained from King County. The two watersheds, Hylebos Creek and Des Moines Creek, were selected because field data describing particle size distributions and discharges resulting in mobility of bedload were available. The watersheds are also very similar in size and both stream beds are composed of well-graded gravel with a sand matrix. King County developed continuous HSPF models that were calibrated to existing land use conditions in each watershed. Selected characteristics of the two watersheds at representative cross-sections are listed in Table 2. For a full description of watershed and stream characteristics, as well as calibration and validation procedures, see King County (1991, 1997, 1998a, 1998b).

The Hylebos and Des Moines Creek models were used in conjunction with 40-year records of meteorological data to simulate daily maximum flows in the watersheds with predevelopment forest conditions and existing land use over the entire 40-year period.

The results of these simulations were examined to determine: (1) the magnitude of an annual flood relative to pre-development conditions at various levels of imperviousness, and (2) the frequency of flows that result in a "significant scouring event" at various levels of imperviousness. In contrast to a simple incipient motion analysis, we defined a significant scouring event as pervasive and extensive movement of all particle sizes along with measurable scour as evidenced by field measurements. The discharge threshold for a significant souring event was based on field measurements of bedload movement using tagged rocks and scour pins over several large flow events (King County, 1997, 1998b). Based on these field measurements and values of "critical discharge" identified by King County, the site-specific flow magnitudes required for the occurrence of a significant scour event were set at 2.4 m^3/s and 1.4 m^3/s for Des Moines and Hylebos Creeks, respectively.

TABLE 2. Summary of Watershed and Representative Stream Characteristics for Forested and Existing Land Use Conditions in Des Moines and Hylebos Watersheds, King County, Washington.

	Des Moines	Hylebos
Watershed Area	14.7 km^2	15.1 km^2
Existing Percent Impervious	37%	18%
D_{50}	29 mm	20 mm
D_{84}	51 mm	56 mm
Slope	0.01	0.015
Forested $Q2$	1.1 cms	0.9 cms
Existing $Q2$	4.8 cms	2.2 cms
Average Number of Significant Scouring Events Per Year – Forested	< 1	< 1
Average Number of Significant Scouring Events Per Year – Existing Percent Impervious	11	5

The results of the 40-year simulations clearly indicate the drastic changes in flow regime that may arise from watershed imperviousness (Table 2). One of the most striking changes is the estimated fivefold increase in the frequency of significant scouring events at 18 percent impervious area. At 37 percent imperviousness, the frequencies of midbank to bankfull flows and significant scouring events have increased dramatically (Figure 3). In Hylebos watershed, the estimated $Q2$ at 18 percent impervious area is over 2.4 times the estimated predevelopment condition. At 37 percent imperviousness, the estimated Q2 in Des Moines Creek watershed is over four times larger than the estimated predevelopment annual flood.

Continuous Hydrologic Simulations of Goodwin Creek Watershed, Mississippi. Goodwin Creek is an experimental watershed located in the bluff hills region of north-central Mississippi. The watershed area is approximately 21.4 km^2, with elevations ranging between 66 and 129 m above sea level. The watershed is largely free of land management activities with only 13 percent of the total area being cultivated. The remainder of the land is idle, pasture, or forest land (Kuhnle *et al.,* 1996). Streams in the watershed have relatively cohesive banks and beds composed of sand and gravel. The watershed is divided into 14 nested subwatersheds with a flow-measuring flume constructed at each drainage outlet. Continuous streamflow and sediment load measurements are made at these gaging locations by an electronic data acquisition system. Twenty-nine standard recording rain gages are uniformly located within and just outside the watershed. Topographic surveys of channels and bed materials are conducted regularly to track morphometric changes in the basin. For a comprehensive description of Goodwin Creek Experimental Watershed, see Blackmarr (1995).

As one of the most highly instrumented watersheds in the world, Goodwin Creek has served as the primary watershed for developing the CASC2D watershed model (Julien *et al.,* 1995; Ogden, 2000). CASC2D is a fully-unsteady, physically-based, distributed-parameter, raster (square-grid), two-dimensional, infiltration-excess hydrologic model for simulating the hydrologic response of a watershed subject to an input rainfall field. Major components of the model include: continuous soil-moisture accounting, rainfall interception, infiltration, surface and channel runoff routing, soil erosion, and sediment transport. Continuous simulation capabilities have recently been added to CASC2D. Although the continuous version of CASC2D had not been released for public distribution at the time of the study, it had been exhaustively tested, calibrated, and validated for the growing season of 1987 in the Goodwin Creek watershed (Senarath *et al.,* 2000). Algorithms allowing application of the continuous version of CASC2D to winter months when freeze-thaw processes are important were not complete at the time of the study and only the 1987 growing season was modeled.

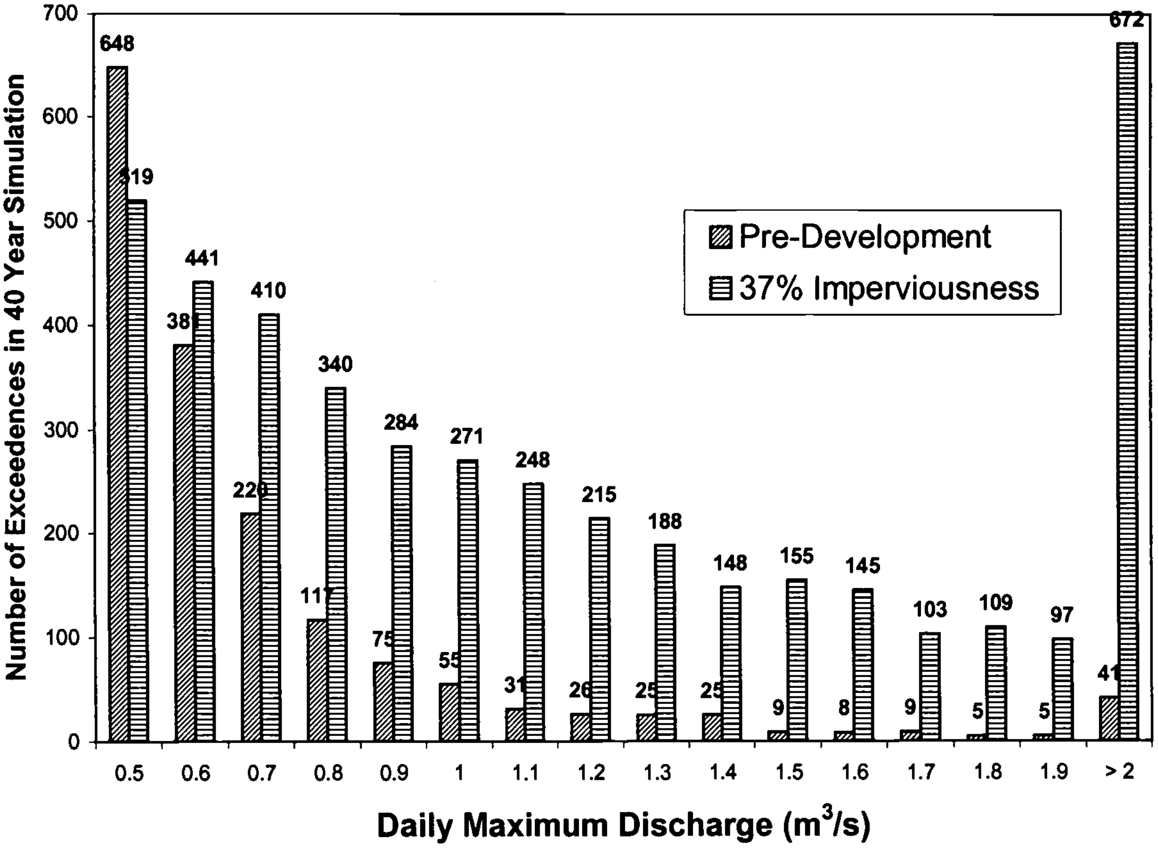


Figure 3. Frequency Distribution of High Flow Events Over 40-Year Simulation of Des Moines Creek Watershed With Two Land Use Scenarios.

TABLE 3. Characteristics of Goodwin Creek at the Experimental Watershed Outlet. (Sources: Blackmarr,1995; and Molnár and Ramírez, 1998.)

Bedslope	0.001
Depth-Discharge Relationship	$h = 0.294Q^{0.428}$
D_{50}	0.97 mm
D_{16}	0.41 mm
D_{84}	11.52 mm
Sand Concentration (ppm)	$C_{ppm} = 52.4\, e2^{.2146h}$; $h > 0.372$ m $C_{ppm} = 320.21\, h$; $h \leq 0.372$ m
$Q2$	78.2 cms

CASC2D models have been previously calibrated to the extensive monitoring network in the Goodwin Creek watershed by other investigators (e.g. Johnson, 1997; Senarath *et al.*, 2000). Pertinent hydraulic characteristics for the stream at the basin outlet are presented in Table 3. The equations for concentration of sand (bedload plus suspended load) were developed and used by Willis (1991) to calculate sand loads for the time period of 1985-1988 and have been independently verified. A calibrated model of the Goodwin Creek watershed with a 125 m grid size was used as a base case for examining the effects of increased imperviousness on the flow regime of a rural watershed. Existing watershed conditions were contrasted with multiple land use scenarios with impervious areas ranging between 5 and 30 percent. Eleven input maps representing infiltration, surface and subsurface water movement, and evapotranspiration parameters were modified for each scenario.

Both disconnected and connected imperviousness scenarios were modeled. In the disconnected imperviousness scenarios, selection of watershed areas for conversion to imperviousness was based on two criteria. Areas within the floodplain (defined as cells either containing a stream segment or directly adjacent to a cell containing a stream segment) and soils identified as having low suitability for development by the soil survey were excluded from conversion. Outside the excluded areas, imperviousness was randomly located throughout the watershed. This approach distributed the impervious areas in a largely disconnected pattern throughout the watershed (Figure 4a). In contrast, the connected imperviousness scenarios were developed by converting all cells in a central region of the watershed to impervious area (Figure 4b). Preliminary model runs revealed that the effect of increasing impervious area on peak discharge is very sensitive to the value of Manning's *n* selected for overland flow. Recommended values in the literature vary by an order of magnitude (Bedient and Huber, 1992; HEC, 1990). As a result, two scenarios of overland flow roughness were examined for each spatial configuration with Manning's *n* for overland flow equal to 0.1 and 0.013.

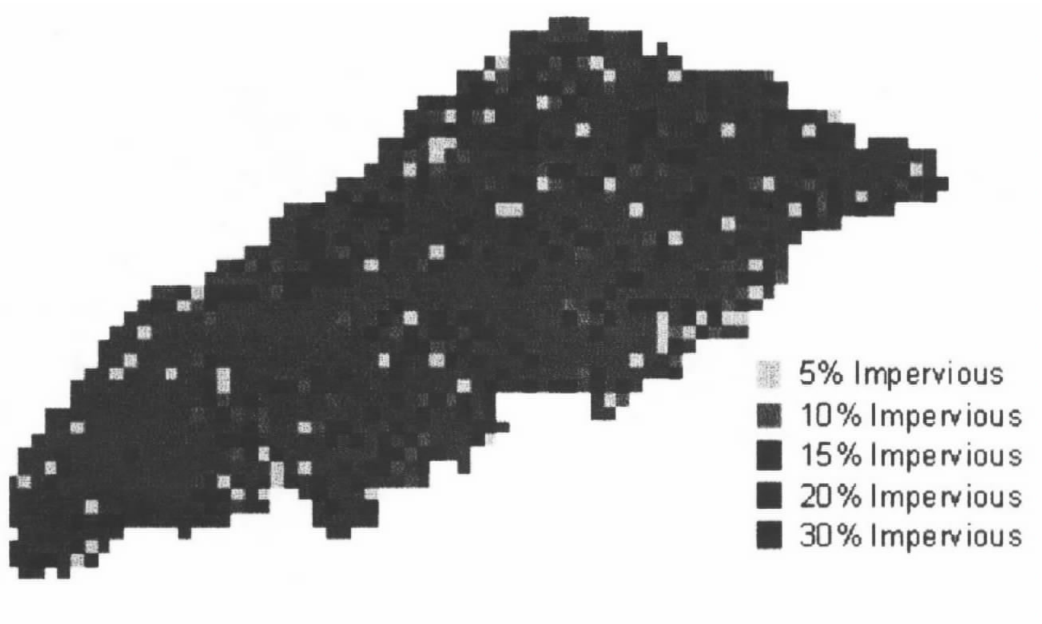
During the summer of 1987, Goodwin Creek experienced three runoff events that approached or exceeded 10 m^3/s (Events 1, 6, and 14; Figure 5). All CASC2D simulations resulted in increased discharge relative to base conditions at all levels of imperviousness. Connected impervious areas clearly increased peak flow magnitude with the effect particularly pronounced for the combination of high conveyance and connectivity (Figure 6). Increases in the peak discharge of Event 1 at 15 percent impervious area varied from 32 percent to 109 percent, depending on spatial configuration and overland Manning's *n* value.

None of these simulated flow events approached the magnitude of an annual flood at the outlet of Goodwin Creek watershed. Nonetheless, changes in the distribution of subbankfull flows at varying levels of imperviousness suggest some interesting implications for sediment transport processes in urbanizing watersheds. Incipient motion and sand transport computations were conducted using the scenario portraying disconnected impervious area with Manning's *n* for impervious areas equal to 0.1 to examine changes in the frequency and duration of disturbance as imperviousness increased in Goodwin Creek. The threshold for movement of coarse sand and gravel size classes was estimated using values of critical shear stress from Julien (1995). The duration of sediment movement for 15 percent and 30 percent imperviousness was compared to existing conditions (Figure 7). These estimates suggest that critical shear stress for transport of D_{84} was only exceeded during the large August event (Event 14) prior to the addition of impervious area. With the addition of 5 percent or more impervious area, critical shear stress for mobilizing D_{84} was exceeded during all three large events during summer of 1987. In addition, the duration of sand concentrations in excess of 500 ppm was increased over threefold at 30 percent imperviousness.

DISCUSSION OF HYDROLOGIC RESULTS

The preceding hydrologic analyses generally support the assertion of Hollis (1975) that a twofold or greater increase in the two-year discharge often results at 10 to 20 percent watershed imperviousness. It is clear, however, that the magnitude of the response is highly variable and sensitive to watershed context and the connectivity and conveyance characteristics of developed areas. Data from Sauer *et al.* (1983) indicate that measures of total imperviousness fail to reflect watershed-specific controls on runoff delivery and the ultimate effectiveness of impervious areas (Booth and Jackson, 1997). The wide ranges of runoff coefficients representing pervious areas and similar levels of imperviousness (USEPA, 1983; Schueler, 1995) reflect the sensitivity of the hydrologic response to pre-development conditions and the post-development efficiency of runoff delivery. The extremely variable effects of imperviousness on peak flows are echoed in theoretical analyses that couple kinematic wave theory and differing combinations of flow resistance and runoff coefficients (Wong and Li, 1999).

By including flows less than the annual flood magnitude, the NURP study and the continuous simulations indicate that flow magnification may be significant for flow events smaller than $Q2$. Increasing the frequency and duration of subbankfull flows can result in a marked increase in time-integrated sediment transport capacity in conjunction with more moderate changes in annual flood peaks. Thus, the continuous simulations and monitoring (Urbonas and Roesner, 1993) suggest that standard hydrologic design practices are inadequate for characterizing the cumulative effects of urbanization on flow events that are more frequent than $Q2$ but still significant in terms of sediment transport and channel disturbance



(a) Disconnected.

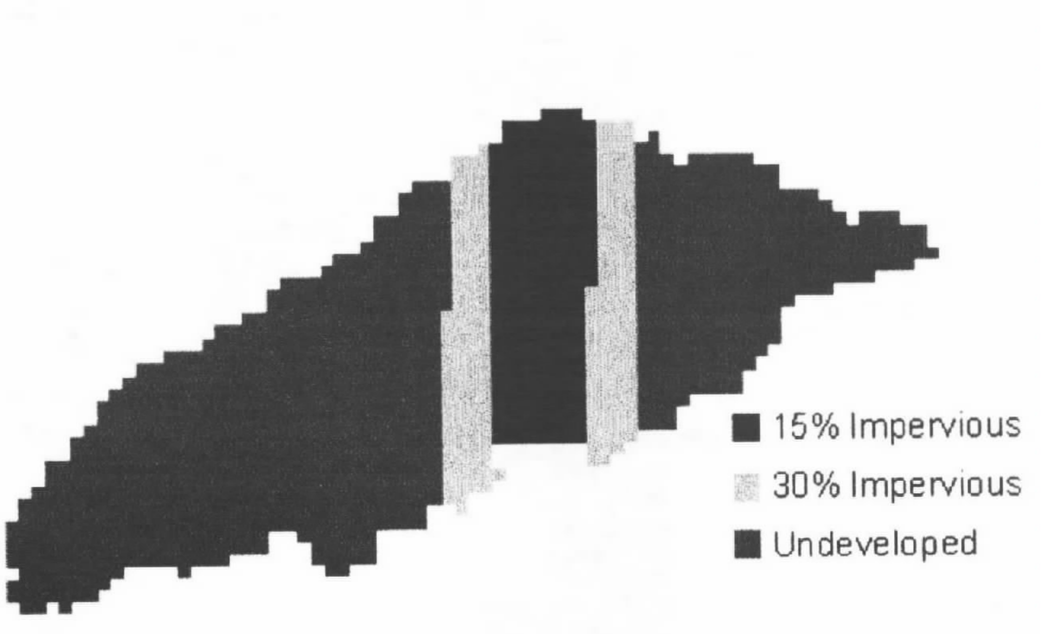


Figure 4. Maps of Imperviousness Scenarios in Goodwin Creek Watershed With Two Spatial Configurations Represented. Shades correspond to subsets of cells that were converted in each scenario to achieve the cumulative percent impervious area.

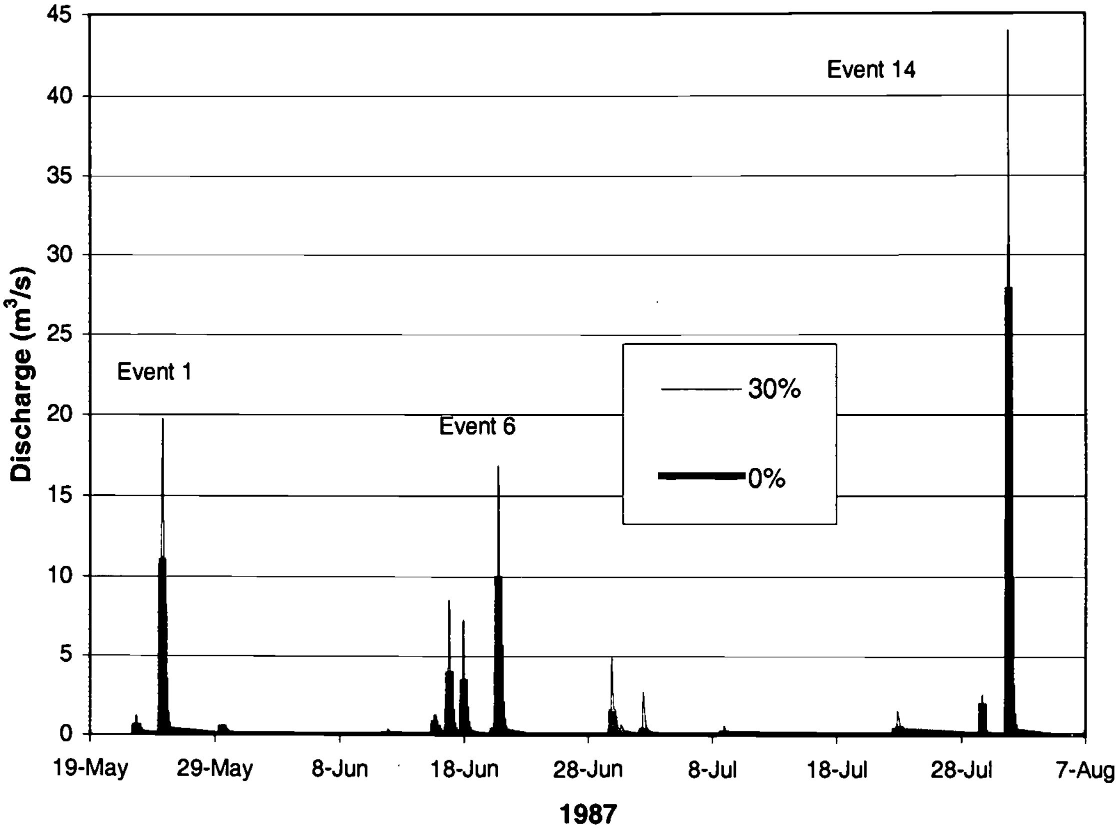


Figure 5. Continuous Simulation of Discharges in Goodwin at 0 and 30 Percent Disconnected Imperviousness During Summer and 1987 With Overland Manning's *n* Equal to 0.1.

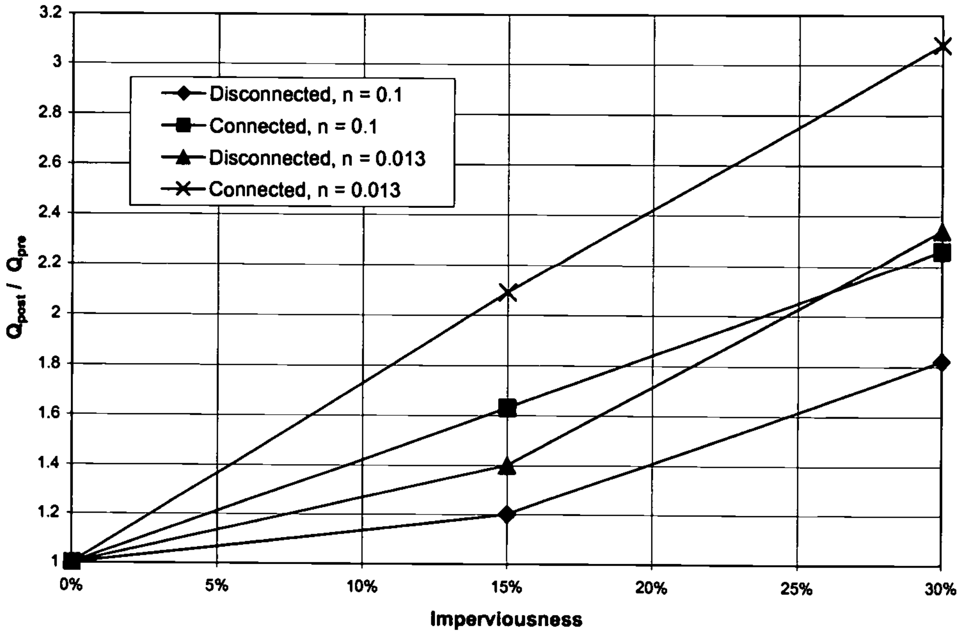


Figure 6. Effects of Connectivity and Conveyance of Impervious Areas on Flow Increases in CASC2D Simulation of Event 1.

potential. It also follows that the impacts of urbanization are likely to be greatest for suspended load channels where a large percentage of the bed material load is transported by frequent subbankfull flows.

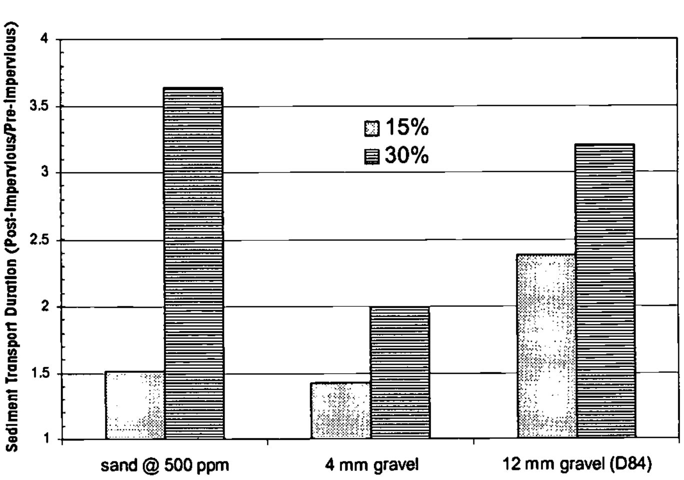


Figure 7. Duration of Transport for Various Bed Material Fractions in Goodwin Creek for Two Levels of Imperviousness Relative to Predevelopment Conditions.

Increases in the frequency and intensity of sediment transport events not only affect channel morphology, but in many instances may have adverse effects on ecological processes (Newcombe and Jensen 1996; Waters 1995). The effects might include a shift to small, vagile, and/or colonizing assemblages of invertebrates and fish, selection for fish species possessing a morphology that increases the likelihood of surviving flood flows, and reduced influence of biotic interactions on community structure (Poff and Ward, 1989). Altered stream hydraulics could also affect zonation patterns in stream insects (Statzner and Higler, 1986). Comprehensive analyses of the potential impact of land use change should therefore carefully consider effects on subbankfull flows and substrate disturbance regime in addition to peak flow magnitude.

FLOW ENERGY AND RISK OF CHANNEL INSTABILITY

In a study of 270 streams and rivers, Bledsoe and Watson (In Press) suggested that logistic regression models (Tung, 1985; Menard, 1995; Christensen, 1997) can accurately predict unstable channel forms with a "mobility index" based on slope (S; bedslope or valley slope), an estimate of channel-forming discharge (Q), and median bed material size (d_{50}). The mobility index is defined as:

$$S\sqrt{\frac{Q}{d_{50}}} \tag{3}$$

The numerator of this ratio is a surrogate for specific stream power (Bagnold, 1966; Schumm and Khan, 1972; Bull, 1979; Edgar, 1973, 1976; Brookes, 1988; Nanson and Croke, 1992; Rhoads, 1995) or the rate of potential energy expenditure per unit area. Specific stream power is proportional to the third power of depth-averaged velocity and is defined as (Leopold *et al.*, 1964):

$$\omega = \frac{\gamma QS}{w} \tag{4}$$

where γ is specific weight of the water and sediment mixture, Q is discharge, S is slope, and w is channel width. By assuming that channel width is proportional to the square root of dominant discharge (Knighton, 1998), a relation for approximating specific stream power is (Ferguson, 1987):

$$\omega \approx \frac{\gamma}{\alpha} Q^{0.5} S \propto S\sqrt{Q} \tag{5}$$

where α is a regression coefficient computed for a particular collection of streams. Equation (3) therefore represents an expression of flow energy relative to bed material size. Because we are often interested in predicting unstable channel forms *a priori*, Equation (3) does not require channel width or depth since these are often a consequence of the adjustment process and may not represent channel form prior to an increase in stream power. The logistic analyses performed by Bledsoe and Watson (in press) and a comparison of channel stability indices by Doyle *et al.* (2000) indicate that assessments of channel stability based on a ratio of erosive to resisting forces or some measure of excess power outperform absolute measures of flow energy where bed materials are variable.

Using Equation (3), logistic regression models depicting the risk of an incising or braided channel form were developed (Figure 8). These models explicitly provide the estimated risk of an unstable channel form with greater than 80 percent accuracy for the 270 streams and rivers examined. Moreover, analysis of the 270 channels suggested that sinuosity tends to decline abruptly at $S(Q/d_{50})^{0.5}$ values greater than approximately 0.5 $m/s^{0.5}$ and 0.2 $m/s^{0.5}$ in sand and gravel bed rivers, respectively (Bledsoe and Watson,

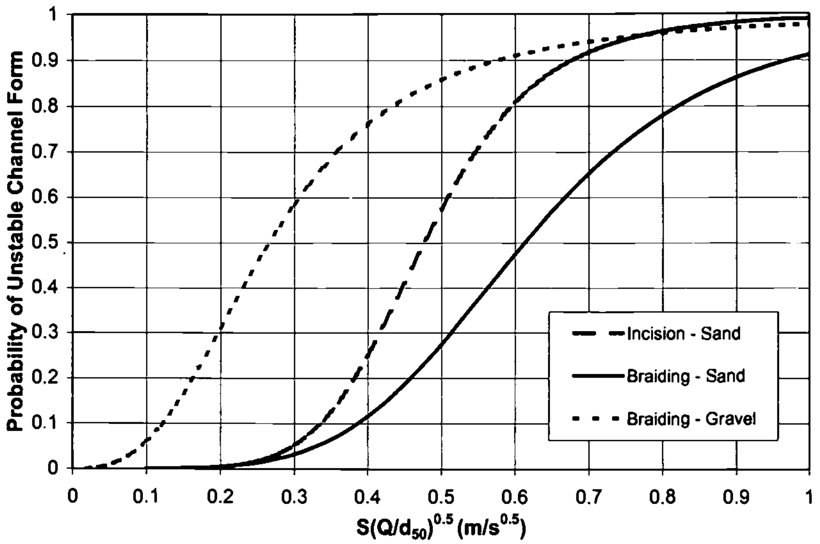


Figure 8. Results of Logistic Regression Models Comparing Stable Meandering Channels With Braiding and Incising Channels. Median particle sizes ranged from 0.075-1.69 mm and 10-190 mm in the sand and gravel channels, respectively (after Bledsoe and Watson, in press).

2000). In gravel channels, the threshold associated with a sharp decline in sinuosity may be more pertinent than the transition to braiding. Logistic regression models comparing meandering and braiding streams in gravel and coarser material suggested that an abrupt decline in sinuosity seems to occur at the mobility index associated with a 25 to 40 percent risk of braiding in gravel channels. Thus, $S(Q/d_{50})^{0.5}$ values of approximately 0.18 to 0.3 m/s$^{0.5}$ may bracket a region of accelerated widening and straightening in gravel bed channels where forms intermediate between meandering and braiding would be expected to predominate. To the extent that bank resistance to erosion is independent of bed material size, the mobility index described above is limited in its applicability to lateral adjustment processes. In reality, the severity of response to an increase in specific stream power in gravel bed channels may be controlled more by bank characteristics than bed material. As we obtain more information on how vegetation, materials, and stratigraphy affect the relative erodibility of various bank types, simple indices of flow energy may be useful in risk-based models of lateral adjustment potential.

INTERPRETING THE EFFECTS OF URBANIZATION

Examining the urban hydrology analyses in light of the logistic regression models provides a framework for explaining channel instability in terms of excess specific stream power. It appears that in many watersheds in humid regions, the increases in stream power associated with low levels of imperviousness (10 to 20 percent) are sufficient to markedly increase the likelihood of severe channel instability. This finding reinforces the observations of Booth and Reinelt (1993) and Morisawa and LaFlure (1979) that significant channel instability can occur at 10 percent watershed imperviousness in some contexts. Making general statements about the ultimate effects of a flow increase on channel stability, however, is hardly straightforward. A final look at the case studies on Hylebos, Des Moines and Goodwin Creeks illustrates this point and suggests some interesting implications for applying probabilistic models of channel pattern stability in the management of flow increases associated with urbanization.

Hylebos and Des Moines Creeks

Under existing land use conditions, Hylebos and Des Moines Creeks have mobility indices of 0.16 and 0.13 m/s$^{0.5}$, respectively. Although significantly higher than the estimated pre-development values, these existing values of the mobility index are still well below a 50 percent risk of braiding and the apparent limits of meandering in gravel bed channels. In reality, both channels have experienced bank erosion as a result of flow increases. For example, Hylebos Creek is reported to have a width that is approximately twice that of streams in undeveloped watersheds of similar size (King County, 1997). These results indicate that gravel bed channels may experience severe bank erosion at relatively low levels of risk for braiding.

It is interesting that although Des Moines Creek has experienced widening, it is apparently much less severe than that observed in Hylebos Creek, despite the fact that Des Moines Creek watershed contains about twice the impervious area of Hylebos. The geologic and land use histories of Hylebos and Des Moines Creek watersheds partly explain this difference. Both basins are underlain by a sheet of glacial till deposited during the most recent continental glacial advance (King County, 1991, 1997, 1998a, 1998b). In post-glacial time, Hylebos Creek has eroded through the till sheet and exposed the underlying advance outwash. The advance outwash is composed primarily of sand and is much more erodible and permeable than overlying till. In Hylebos watershed, sandy advance outwash underlies essentially the entire length of the stream bed. In contrast, the lower reach of Des Moines Creek has developed a graded profile into Puget Sound by incising through the upper glacial and lower mixed deposits to reveal compact and non-erosive deposits along most of the stream valley sidewalls. The urban development in Des Moines watershed is also relatively old compared to Hylebos (one to four decades). As a result, Des Moines Creek has had a longer period to adjust to the post-development hydrologic regime. Riparian disturbance is apparently greater along Hylebos Creek as well.

The differences in response between Des Moines and Hylebos Creeks underscore the fact that channel adjustment is always context dependent and influenced by historical processes. Des Moines Creek is formed in relatively resistant material while the banks of Hylebos Creek are highly susceptible to erosion as a result of geologic history and vegetation removal. Thus, descriptors of erosive power such as Equation (3) must be applied to the limiting channel boundary with some knowledge of its relative resistance to erosion. When viewed in terms of a limiting boundary, the significant lateral adjustment of Hylebos at a low value of $S(Q/d_{50})^{0.5}$ becomes less anomalous. If one assumes that channel width may be estimated with a typical downstream hydraulic geometry equation for gravel bed rivers ($w = 4Q^{0.5}$; Knighton 1998), it is likely that the actual specific stream power in Hylebos has increased from less than 35 W/m^2 to more than 50 W/m^2. These conditions are capable of mobilizing bank material that is noncohesive and sandy, especially in the absence of dense vegetation.

Goodwin Creek

Like Hylebos and Des Moines Creeks in the Pacific Northwest, Goodwin Creek has a history that will undoubtedly continue to influence the course of channel adjustments to watershed changes. During European settlement in the 1830s, much of Goodwin Creek watershed was deforested and converted to intensive cotton agriculture. Severe erosion followed and incision is still in progress in many reaches (Kuhnle *et al.,* 1996). At the watershed outlet, where the hydrologic modeling was focused, the stream is relatively stable when compared to several upstream reaches (Molnár and Ramírez, 1998). The mobility index of the stream at this location is 0.28 m/s$^{0.5}$. This value suggests that the stream may be poised near a geomorphic threshold since the risk of severe incision begins increasing very rapidly at this point and reaches a risk of 50 percent at a mobility index of 0.44 m/s$^{0.5}$. If we assume that specific stream power varies with the square root of discharge, a twofold increase in flow would correspond to a 41 percent increase in the mobility index. But such an approach is misleading since Goodwin Creek is a highly entrenched channel with very steep, cohesive banks. The channel has the capacity to contain a flow event much larger than $Q2$. As a result, shear stress and specific stream power will increase in direct proportion to discharge.

A key determinant of channel response to increased discharge is how the excess flow is conveyed, for example, in an entrenched channel or on a broad floodplain. If we assume that the increased discharge is conveyed at the approximate width of the pre-development channel, then stream power will increase in direct proportion to discharge. Conversely, if the excess flow is spread across a wide floodplain, the resulting change in specific stream power will be relatively small. It follows that entrenched channels are particularly susceptible to flow increases. Thus, even a modest increase in discharge might be adequate to initiate severe incision throughout the Goodwin Creek watershed, particularly in upstream reaches that have a much higher stream power when compared to the watershed outlet reach considered here (Molnár and Ramírez, 1998). Given the localized changes between sand and gravel bed materials that occur in the Goodwin watershed, areas of relatively high specific stream power are more difficult to interpret. In this regard, the Goodwin Creek context points to the importance of identifying spatial variability in stream power relative to sedimentary characteristics throughout the drainage network area potentially affected by flow increases.

CONCLUSIONS

The previous discussion indicates that probabilistic models do not provide a substitute for field observations, sound judgment, and an appreciation for the importance of antecedent events. Nonetheless, simple risk-based analyses of the potential impacts of land use change on aquatic ecosystems have the potential to redirect and improve the effectiveness of watershed management strategies by facilitating the identification of channels that may be most sensitive to changes in stream power. Energy-based indices of channel stability should, however, be applied with an understanding of context and be referenced to the erodibility of the limiting channel boundary. The variables included in risk-based models of channel response should be calibrated regionally and extended beyond those described in this study. Decision-based models of stream stability and ecological integrity may be developed using descriptors of key flow regime attributes, the condition of channel banks and riparian zones, geologic or wood influences, floodplain connectivity, and development style in addition to channel stability indices.

Low levels of imperviousness (10 to 20 percent) clearly have the potential to severely destabilize streams, but changes in discharge, and thus stream power associated with increased impervious area are highly variable and dependent on watershed-specific conditions. In addition to the storage characteristics of the pre-development watershed, the magnitude of alteration is sensitive to the connectivity and conveyance of impervious areas as well as the specific characteristics of receiving channels. Different stream types are likely to exhibit different levels of resilience, depending on entrenchment, relative erodibility of bed and banks, riparian condition, mode of sediment transport (bedload versus suspended load), and proximity to geomorphic thresholds. Thus, the relationship between channel instability and imperviousness is complex and involves several factors and processes (Bledsoe and Watson, 2000; Figure 9).

The potential impacts of urbanization on subbankfull flow frequency, time-integrated sediment transport capacity, and channel stability are difficult to characterize with single event hydrologic models that rely on measures of total impervious area. Since first and second order streams comprise over 70 percent of the stream length in the U.S. (Leopold *et al.,* 1964) and as much as 90 percent in some regions (Benda and Dunne, 1997), engineered systems with designs based on the rational method may directly affect a large percentage of the drainage networks in practice. Mitigating stream degradation in urban watersheds will often necessitate consideration of flow regime as opposed to a single design event in order to realistically assess the cumulative impacts of urbanization on fluvial systems.

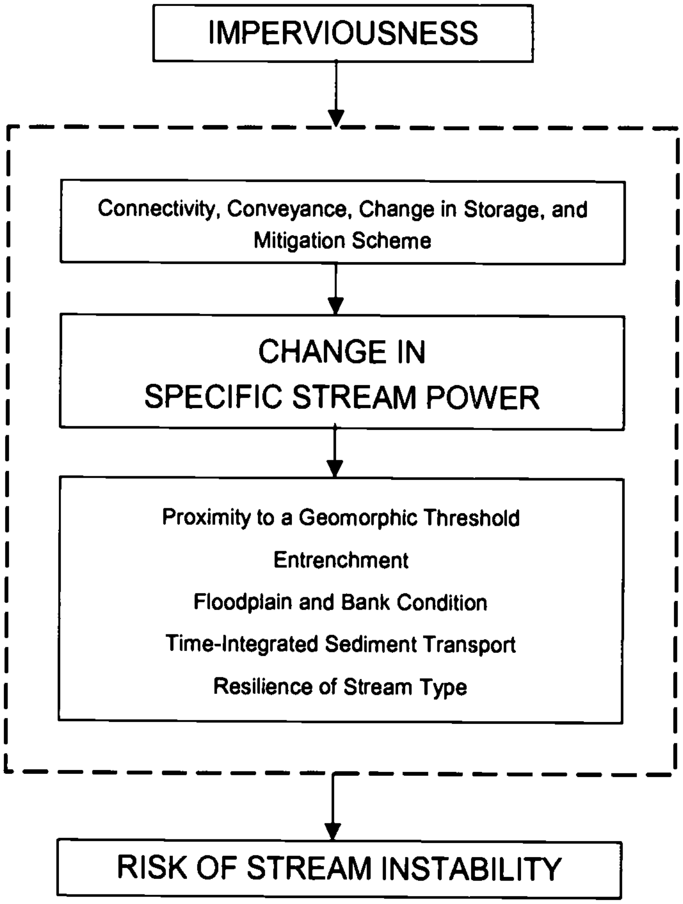


Figure 9. Linkages Between Imperviousness and Channel Stability.

Strategies intended to mitigate the degradation of urban streams should be guided by an understanding of the underlying processes. An incomplete understanding of the mechanisms involved, however, does not preclude immediate and meaningful improvements in existing management programs. Most studies associating urbanization with loss of stream integrity do not address the particular styles of development involved and their effects on specific physical processes (e.g., Kennen, 1999). Ultimately, the diverse responses of aquatic ecosystems to various types of development provide important feedback and an opportunity for adaptive management of urbanizing watersheds. Because all imperviousness is not created equal, there is a pressing need to link specific development styles, flow regime, risk-based models of stream integrity, and monitoring. Such a linkage

would provide an improved foundation for innovative site planning, ecologically effective stormwater practices, and meaningful estimates of watershed development capacity.

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LITERATURE CITED

ASCE, 1992. Design and Construction of Urban Stormwater Management Systems. Manual of Practice No. 77, American Society of Civil Engineers.

Arnold, C. L., P. J. Boison, and P. C. Patton, 1982. Sawmill Brook: An Example of Rapid Geomorphic Change Related to Urbanization. Jl. Geology 90:155-166.

Bagnold, R. A., 1966. An Approach to the Sediment Transport Problem From General Physics. U.S. Geological Survey Professional Paper 4221.

Bedient, P. B. and W. C. Huber, 1992. Hydrology and Floodplain Analysis. Addison-Wesley, Reading, Massachusetts.

Becker, L. D., 1986. Techniques for Estimating Flood Peak Discharges From Urban Basins in Missouri. U.S. Geological Survey Water-Resources Investigations Report 86-4322, 38 pp.

Benda, L. and T. Dunne, 1997. Stochastic Forcing of Sediment Supply to Channel Networks From Landsliding and Debris Flow. Water Resources Research 33(12):2849-2863.

Blackmarr, W. A. (Editor), 1995. Documentation of Hydrologic, Geomorphic, and Sediment Transport Measurements on the Goodwin Creek Experimental Watershed, Northern Mississippi, for the Period 1982-1993 (Preliminary Release). Research Report No. 3, USDA-ARS, National Sedimentation Laboratory, Oxford, Mississippi.

Bledsoe, B. P. and C. C. Watson (in press). Logistic Analysis of Channel Pattern Thresholds: Meandering, Braiding, and Incising. Geomorphology.

Bledsoe, B. P. and C. C. Watson, 2000. Observed Thresholds of Stream Ecosystem Degradation in Urbanizing Areas: A Process-Based Geomorphic Explanation. *In:* Watershed Management 2000: Science and Engineering Technology for the New Millennium, M. Flug and D. Frevert (Editors). American Society of Civil Engineers.

Booth, D. B., 1990. Stream Channel Incision Following Drainage Basin Urbanization. Water Resources Bulletin 26(3):407-417.

Booth, D. B., 1991. Urbanization and the Natural Drainage System-Impacts, Solutions and Prognoses. Northwest Environmental Jl. 7(1):93-118.

Booth, D. B. and L. E. Reinelt, 1993. Consequences of Urbanization on Aquatic Systems – Measured Effects, Degradation Thresholds, and Corrective Strategies. *In:* Proc. of Watershed '93. EPA 840-R-94-002, pp. 545-550.

Booth, D. B. and C. R. Jackson, 1997. Urbanization of Aquatic Systems – Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation. Jl. American Water Resources Association 33(5):1077-1090.

Brookes, A., 1988. Channelized Rivers: Perspectives for Environmental Management. John Wiley and Sons Ltd., Chichester, England.

Bull, W. B., 1979. Threshold of Critical Power in Streams. Geological Society of America Bulletin 90:453-464.

Christensen, R., 1997. Log-Linear Models and Logistic Regression. Springer-Verlag, New York, New York.

Conger, D. H., 1986. Estimating Magnitude and Frequency of Floods for Wisconsin Urban Streams. U.S. Geological Survey Water-Resources Investigations Report 86-4005, 18 p.

Doyle, M. W., J. M. Harbor, C. F. Rich, and A. Spacie, 2000. Examining the Effects of Urbanization on Streams Using Indicators of Geomorphic Stability. Physical Geography 21(2):155-181.

Edgar, D. E., 1973. Geomorphic and Hydraulic Properties of Laboratory Rivers. M.S. Thesis, Colorado State University, Fort Collins, Colorado.

Edgar, D. E., 1976. Geomorphology and Hydrology of Selected Midwestern Streams. Ph.D Dissertation, Purdue University, West Lafayette, Indiana.

Ferguson, R. I., 1987. Hydraulic and Sedimentary Controls on Channel Pattern. *In:* River Channels: Environment and Process, K. S. Richards (Editor). Blackwell, Oxford, pp. 129-158.

Gunter, H. C., R. R. Mason, and T. C. Stamey, 1987. Magnitude and Frequency of Floods in Rural and Urban Basins of North Carolina. U.S. Geological Survey Water-Resources Investigations Report 87-4096, 52 pp.

Hammer, T. R., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8:139-167.

HEC, 1990. HEC-1 Flood Hydrograph Package Users Manual. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

Hollis, G. E., 1975. The Effect of Urbanization on Floods of Different Recurrence Intervals. Water Resources Research 11(3):431-435.

Inman, E. J., 1988. Flood-Frequency Relations for Urban Streams in Georgia. U.S. Geological Survey Water-Resources Investigations Report 88-4085, 36 pp.

Jennings, M. E., W. O. Thomas, Jr., and H. C. Riggs, 1993. Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungaged Sites, 1993. U.S. Geological Survey Water-Resources Investigations Report 94-4002.

Johanson, R. C., J. C. Imhoff, and H. Dana, Jr., 1980. Users Manual for Hydrological Simulation Program B Fortran (HSPF). U.S. Environmental Protection Agency, EPA/9-80-015, Athens, Georgia.

Johnson, Jr., B. E., 1997. Development of a Storm Event Based Two-Dimensional Upland Erosion Model. Ph.D Dissertation, Colorado State University, Fort Collins, Colorado.

Julien, P. Y., B. Saghafian, and F. L. Ogden, 1995. Raster-Based Hydrologic Modeling of Spatially-Varied Surface Runoff. Water Resources Bulletin 31(3):523-536.

Julien, P. Y., 1995. Erosion and Sedimentation. Cambridge University Press, New York, New York.

Kennen, J. G., 1999. Relation of Macroinvertebrate Community Impairment to Catchment Characteristics in New Jersey Streams. Jl. American Water Resources Association 35(4):939-954.

King County, 1991. Executive Proposed Basin Plan, Hylebos and Lower Puget Sound. King County Public Works Department, Surface Water Management Division.

King County, 1997. Conceptual Alternative Design Report, South 360th Street Regional R/D Facility, Hylebos and Lower Puget Sound Basin Plan Project No. 0A1685. King County Public Works Department, Surface Water Management Division.

King County, 1998a. Des Moines Creek Basin Plan. King County Public Works Department, Surface Water Management Division.

King County, 1998b. Des Moines Creek Regional CIP Preliminary Design Report. King County Public Works Department, Surface Water Management Division.

Knighton, A. D., 1998. Fluvial Forms and Processes: A New Perspective. John Wiley and Sons Ltd., New York, New York.

Kuhnle, R. A., R. L. Binger, G. R. Foster, and E. H. Grissinger, 1996. Effect of Land Use Changes on Sediment Transport in Goodwin Creek. Water Resources Research 32:3189-3196.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Co., San Francisco, California, 522 pp.

Malcom, H. R., 1980. A Study of Detention in Urban Storm-Water Management. University of North Carolina Water Resources Research Institute Report No. 156, 78 pp.

McCuen, R. H., 1989. Hydrologic Analysis and Design. Prentice Hall, Englewood Cliffs, New Jersey.

Menard, S. W., 1995. Applied Logistic Regression Analysis. Sage Publications, Thousand Oaks, California.

Molnár, P., and J. A. Ramírez, 1998. An Analysis of Energy Expenditure in Goodwin Creek. Water Resources Research 34(7):1819-1829.

Morisawa, M. and E. LaFlure, 1979. Hydraulic Geometry, Stream Equilibrium and Urbanization. *In:* Adjustments of the Fluvial System, D. D. Rhodes and G. P. Williams (Editors). Kendall-Hunt, Dubuque, Iowa, pp. 333-350.

Nanson, G. C. and J. C. Croke, 1992. A Genetic Classification of Floodplains. Geomorphology 4:459-486.

Newcombe, C. P. and J. O. Jensen, 1996. Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact. North American Jl. Fisheries Management 16(4):693-727.

Ogden, F. L., 2000. CASC2D Reference Manual. Version 2.0, Department of Civil and Environmental Engineering, University of Connecticut.

Olin, D. A., 1984. Magnitude and Frequency of Floods in Alabama. U.S. Geological Survey Water-Resources Investigations Report 84-4191, 105 pp.

Olin, D. A. and R. H. Bingham, 1982. Synthesized Flood Frequency of Urban Streams in Alabama. U.S. Geological Survey Water-Resources Investigations Report 82-683, 23 pp.

Poff, N. L. and J. V. Ward, 1989. Implications of Streamflow Variability and Predictability for Lotic Community Structure: A Regional Analysis of Streamflow Patterns. Canadian Jl. Fisheries and Aquatic Sciences 46:1805-1818.

Price, M., 1979. Floods in Georgia, Magnitude and Frequency. U.S. Geological Survey Water-Resources Investigations Report 78-137, 269 pp.

Putnam, A. L., 1972. Effect of Urban Development on Floods in the Piedmont Province of North Carolina. U.S. Geological Survey Open-File Report, 87 pp.

Rhoads, B. L., 1995. Stream Power: A Unifying Theme for Urban Fluvial Geomorphology. *In:* Stormwater Runoff and Receiving Systems: Impact, Monitoring, and Assessment, E. E. Herricks (Editor). Lewis Publishers, Boca Raton, Florida, pp. 65-75.

Robbins, C. H., 1984. Synthesized Flood Frequency for Small Urban Streams in Tennessee. U.S. Geological Survey Water-Resources Investigations Report 84-4182, 24 pp.

Roberts, C. R., 1989. Flood Frequency and Urban-Induced Channel Change: Some British Examples. *In:* Floods: Hydrological, Sedimentological and Geomorphological Implications, K. J. Beven and P. A. Carling, (Editors). John Wiley and Sons Ltd., Chichester, England, pp. 57-82.

Sauer, V. B., W. O. Thomas, V. A. Stricker, and K. V. Wilson, 1983. Flood Characteristics of Urban Watersheds in the United States. U.S. Geological Survey Water Supply Paper 2207.

Schueler, T., 1994. The Importance of Imperviousness. Watershed Protection Techniques 1(3):100-111.

Schumm, S. A. and H. R. Khan, 1972. Experimental Study of Channel Patterns. Geological Society of America Bulletin 83:1755-1770.

Senarath, S. U. S., F. L. Ogden, C. W. Downer, and H. O. Sharif, 2000. On the Calibration and Verification of Two-Dimensional, Distributed, Hortonian, Continuous Catchment Models. Water Resources Research (in press).

Stamey, T. C. and G. W. Hess, 1993. Techniques for Estimating Magnitude and Frequency of Floods in Rural Basins of Georgia. U.S. Geological Survey Water-Resources Investigations Report 93-4016, 75 pp.

Statzner, B. and B. Higler, 1986. Stream Hydraulics as a Major Determinant of Benthic Invertebrate Zonation Patterns. Freshwater Biology 16:127-139.

Trimble, S. W., 1995. Catchment Sediment Budgets and Change. *In:* Changing River Channels, A. M. Gurnell and G. E. Petts (Editors). John Wiley and Sons Ltd., Chichester, England, pp. 201-215.

Trimble, S. W., 1997. Contribution of Stream Channel Erosion to Sediment Yield From an Urbanizing Watershed. Science 278:1442-1444.

Tung, Y., 1985. Channel Scouring Potential Using Logistic Analysis. Jl. Hydraulic Engineering 111(2):194-205.

USEPA, 1983. Results of the Nationwide Urban Runoff Program. Final Report, NTIS Access No. PB84-18552, Washington, D.C.

USEPA, 1984. Hydrologic Simulation Program – Fortran (HSPF). EPA-600-R93-174 and EPA-600-3-84-065.

Urbonas, B. R. and L. A. Roesner, 1993. Hydrologic Design for Urban Drainage and Flood Control. *In:* Handbook of Hydrology, D. R. Maidment (Editor). McGraw-Hill, Inc., Chapter 28, p. 28.1.

Wanielista, M., R. Kersten, and R. Eaglin, 1997. Hydrology Water Quantity and Quality Control. John Wiley and Sons Ltd, New York, New York.

Waters, T. F., 1995. Sediment in Streams: Sources, Biological Effects, and Control. American Fisheries Monograph 7, American Fisheries Society, Bethesda, Maryland, 251 pp.

Weaver, J. D. and C. R. Gamble, 1993. Flood Frequency of Streams in Rural Basins of Tennessee. U.S. Geological Survey, Water-Resources Investigations Report 92-4165, 38 pp.

Willis, J. C., 1991. Sand Transport on Goodwin Creek. *In:* Proc. 5th Fed. Interagency Sedimentation Conference, Las Vegas, Nevada, pp. 4-131 to 4-138.

Wolman, M. G., 1967. A Cycle of Sedimentation and Erosion in Urban River Channels. Geografiska Annaler 49A:385-395.

Wong, T. S. W. and Y. Li, 1999. Theoretical Assessment of Changes in Design Flood Peak of an Overland Flow Plane for Two Opposing Urbanization Sequences. Hydrological Processes 13:1629-1647.