RELATIONSHIPS OF STREAM RESPONSES TO HYDROLOGIC CHANGES

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ABSTRACT

Rural to urban land use change is a ubiquitous and formidable challenge in watershed management. Decades of research have revealed that urbanization frequently results in severe stream degradation, but the complexity and variability of stream responses inhibit prediction and informed decision-making. Associations between gross measures of total imperviousness or human population and stream characteristics provide little meaningful feedback for understanding key processes and creating practical mitigation strategies. In contrast, examining the effectiveness of mitigation strategies relative to fundamental biophysical linkages provides a foundation for improved management of aquatic ecosystems in rapidly changing watersheds. The objective of this paper is to provide a process-oriented view of what is known about the physical response of streams to urbanization and stormwater controls, to identify some critical information gaps, and to suggest useful approaches and analysis tools for filling these gaps. In particular, variable responses to altered flow and sediment regimes across different stream types, riparian conditions, and spatio-temporal scales are considered. Decision-based models of channel instability that account for the relative sensitivity of stream types to changes in flow and sediment regimes can improve our ability to set priorities and tailor mitigation strategies to the response potential of receiving waterbodies.

INTRODUCTION

Streams in urbanizing watersheds exhibit a diverse array of complex adjustments and threshold behaviors in response to changes in water and sediment delivery. Geomorphologists and engineers are only beginning to elucidate differences in response trajectories across stream corridor types, flow regimes, and watershed contexts. The difficulty of linking stream responses to specific development styles compounds the challenges of predicting the probable impacts of watershed development on stream integrity and devising effective mitigation schemes.

Physical habitat in streams is created and maintained by dynamic geomorphic processes. Physical habitat may be defined as the combined quality of instream, riparian, and watershed characteristics that influences aquatic community structure in streams across multiple temporal and spatial scales. Geomorphic processes are referred to herein as the hydrologic, erosional, and transportational characteristics of fluvial systems resulting from the integrated effects of climate, geology, land use, basin physiography, and human alteration. Geomorphic processes involving the spatial and temporal distribution of stream energy, bank erosion, and bed scour and deposition directly affect the quality of physical habitat in aquatic ecosystems including adjustments of channel features and linkages at local, reach, valley and watershed scales. In general, habitat characteristics at increasingly finer spatial scales (e.g., a patch of streambed) are: (1) viewed as being more temporally dynamic than broad scale characteristics, and (2) develop within constraints set by the larger scale systems (e.g., stream segments and watershed) of which they are a part (Frissell *et al.* 1986). Habitat characteristics may interact over time and during discrete events to create extreme conditions or disturbances that result in altered resources and mortality of aquatic biota. In particular, the impact of a discrete disturbance event is controlled by interactions between flow, channel morphology, substrate mobility, and available refugia. Thus, developing our understanding of relationships between flow regime and multi-scale geomorphic characteristics is a prerequisite for a process-based understanding of the key drivers that shape assemblages of aquatic biota.

HYDROLOGIC EFFECTS OF URBANIZATION

There are two primary linkages in evaluating potential responses to urbanization in the fluvial system: (1) changes in the flows of water and sediment associated with different types and phases of land disturbance, and (2) the associated morphologic response. Both linkages or phases involve temporal lags that complicate monitoring and interpretation. Changes in channel characteristics reflect the *temporal sequence* and combined action of water and sediment flows delivered to that channel. Interpretations of channel response that do not include consideration of both hydrologic and sedimentation regimes are incomplete and may produce erroneous conclusions. Specifically, the magnitude, frequency, duration, timing, and rate of change in the flows of water and sediment can influence both geomorphic and biological responses (Poff and Ward 1989, Poff *et al.* 1997, Waters 1995, Knighton 1998, Bledsoe and Watson 2001a). Gaging data of an adequate period and temporal density (e.g. characterizing flashy flows may require something on the order of ≤ 15-minute data) and/or the use of long-term continuous simulations are essential to adequately elucidate changes in the full range of geomorphically important flows (James 1995, Booth and Jackson 1997, Bledsoe and Watson 2001a).

The fundamental hydrologic changes that tend to be associated in varying degrees with urbanization are more frequent and higher magnitude flows (Hammer 1972, Hollis 1975), increased duration of geomorphically significant flows (Hollis 1975, McCuen and Moglen 1988, MacRae 1997), flashier / less predictable flows (Henshaw and Booth 2000, Konrad 2000), altered timing and rate of change relative to riparian and floodplain connections (Poff *et al.* 1997), altered duration of low flow periods (Simmons and Reynolds 1982), and conversion of subsurface discharge inputs to surface (point) discharge (Booth and Henshaw, in press). These observed changes are certainly not universal and depend on a variety of complex watershed and development characteristics. Several of these alterations, especially increased flow duration, have been observed in watersheds containing storage basins created for stormwater management (McCuen and Moglen 1988, MacRae 1997). Indeed, one of the fundamental issues related to channel adjustments and instability in developing watersheds is associated with the increased duration and geomorphic effectiveness of sub-bankfull flows.

Although addressing changes in flow regime is critical for improved management, it remains only a partial view unless it encompasses the variability and pulse nature of sediment delivery in developing watersheds. The important work of Wolman (1967), Wolman and Schick (1967), Leopold (1972), Trimble (1974, 1977, 1983, 1995, 1997a), and Benda and Dunne (1997) underscores the stochastic nature of water and sediment loading in disturbed watersheds, the importance of historical influences, and the complexities associated with sporadic phases of development and the spatial distributions of sources relative to hillslope / drainage network linkages. Of particular importance is development style (the extent, connectivity, and conveyance of manmade surfaces, compacted areas and drainage facilities) which profoundly influences the nature and extent of hydrologic and sedimentary impacts on receiving streams. For example, in a paired watershed study in NC, water yield from sites with curb and gutter was 6 times greater than sites with similar levels of imperviousness but without curb and gutter (Bales *et al.* 1999). Sediment yield varied by two orders of magnitude between stable residential areas and developing sites (77 vs. 4700 ton/ sq mi).

EFFECTS OF URBANIZATION ON CHANNEL MORPHOLOGY AND FLUVIAL PROCESSES

Streams and rivers are dynamic systems with forms that adjust over time to the flows of sediment and water delivered from their watershed. As land uses change, the balance between a stream's capacity to move sediment and the amount of sediment delivered from its watershed is disrupted. Numerous studies have generically reported channel enlargement as the primary response to urbanization; very few have explored differences in response across streams and contexts. Some streams exhibit widening and a tendency toward braiding (Arnold *et al.* 1982) while others exhibit, at least initially, a predominantly vertical response i.e., incision (Booth 1990). Exploring the mechanisms controlling the direction and magnitude of these disparate responses can yield insights into the general nature of channel adjustment to altered hydrologic regimes, identifying which stream corridor types are probably most sensitive to urbanization, and ultimately aid in developing models for assessing the probable form and magnitude of channel response. To a large extent, channel adjustment potential in the early stages of a departure from quasi-equilibrium conditions is controlled by the ratio of stream power per unit channel area relative to the most erodible channel boundary. For example, in an armored cobble bed stream with sandy banks and little vegetation, the dominant response to an increase in stream power relative to sediment supply will tend to be bank erosion and lateral adjustment. Conversely, in a sand bed stream with clayey banks, the response will tend to be vertical until bank failure results primarily from gravitational forces as opposed to direct hydraulic action. In reality, responses to urbanization involve much more than channel enlargement (Table 1) and tend to be context-specific and difficult to correlate with gross measures of development. Most of these potential effects are influenced to various degrees by the five key elements of flow regimes identified by Poff *et al.* (1997). For example, bank erosion may be influenced by the rate of change of flows in addition to frequency and magnitude attributes.

Low levels of imperviousness (5 - 20%) clearly have the potential to severely destabilize streams, but changes in stream power and sediment delivery associated with sub/urban development are highly variable and dependent on watershed-specific conditions including the connectivity and conveyance of the drainage scheme and stormwater controls. In turn, different stream types are likely to exhibit varying levels of sensitivity to these changes, depending on entrenchment, relative erodibility of bed and banks, riparian condition, mode of sediment transport (bedload versus suspended load), sediment delivery, and proximity to geomorphic thresholds (Bledsoe and Watson 2001a). It is obvious why a simple, quantitative delineation of a threshold between healthy and unhealthy streams is very desirable from a management perspective, but we should avoid identifying "one size fits all" thresholds that actually correspond to various levels of risk across contexts.

Despite the many factors involved, total watershed imperviousness is frequently used as the sole explanatory variable in simple regression models of biotic integrity or channel instability. Some workers have focused on developing a general relationship between imperviousness and channel enlargement of the form:

$$\text{Channel enlargement} = a(\%\text{imperviousness})^b \qquad (1)$$

Such a relationship grossly oversimplifies the complexity of responses across contexts and the manifold forms and consequences of enlargement. One only has to look as far as studies on the effects of dams by Williams and Wolman (1984) and Petts (1984) which reveal both width increase and decrease, varying degrees of vertical adjustments, and response times thought to range from 10 to more than 500 years. Recent research indicates that magnitudes and rates of channel change have little or no correlation with development intensity and gross measures of imperviousness, even in urbanized watersheds of a common region (Booth and Henshaw, in press, Pizzuto *et al.* 2000, Doll *et al.* 2000, Neller 1989). Again, the science of fluvial geomorphology suggests that generic relationships that do not incorporate key differences in process associated with watershed context, mode of sediment transport, floodplain connectivity, direction of base level changes, and other fundamental drivers will likely fall short of providing the linkages between land use, hydrologic regime, and alterations in stream physical habitat that are essential for management.

Table 1. Some potential effects of modifications related to urbanization on stream processes and morphology.

Changes in stream morphology and response	Sources
Some form of channel enlargement via widening, incision, and/or braiding	Hammer (1972), Roberts (1989), Arnold *et al.* (1982), Booth (1990, 1991), Doll *et al.* (2000), Pizzuto *et al.* (2000)
Planform changes – e.g., decrease in sinuosity associated with widening, accelerated migration rates	Arnold *et al.* (1982), Richardson *et al.* (1990), Pizzuto *et al.* (2000)
Post development / restabilized channel less heterogeneous and geomorphically complex, cross-section more rectangular and prismatic, straighter channel, less pool volume, less form roughness	Brown (1999), Pizzuto *et al.* (2000), Doll *et al.* (2000), Henshaw and Booth (2000)
Geomorphic thresholds may be crossed – stream power, sinuosity, substrate armoring or breaching, expose new bed or bank strata, bank height, etc.	Schumm (1977), Arnold *et al.* (1982), Bledsoe and Watson (2001a,b)
Diversity of habitats such as pool-riffle frequency, depth-velocity combinations altered, debris dams reduced	Pizzuto *et al.* (2000), Henshaw and Booth (2000), Duncan (2000), Jackson and Beschta (1984)
Overbank flows necessary for energy dissipation, habitat / timing may be altered via incision and/or widening	Schumm *et al.* (1984), Simon and Darby (1999), Poff *et al.* (1997)
Incision / entrenchment increases geomorphic effectiveness of infrequent events	Schumm *et al.* (1984), Simon and Darby (1999)
More frequent crossing of threshold into upper regime bedforms in sand bed channels – creates opposing system equilibria	Simons and Richardson (1966), Chang (1988)
Removal of vegetation may induce lateral instability	Beschta (1998), Millar and Quick (1993), Bledsoe and Watson (2000)
Riparian zone may be destabilized via bank toe erosion – may increase wood input thereby changing morphology, diel temperature regime of bank	Trimble (1997b), Davies-Colley (1997), LeBlanc *et al.* (1997), Lyons *et al.* (2000)
Flashy flows result in bank instability via pre-wetting, desiccation, and/or rapid drawdown	Thorne (1990)
Change in flow regime affects plant community location on bank which in turn may affect roughness, bank stability, and deposition of fine material	Bledsoe (unpublished data)
Bank stability diminished by piping resulting from vegetation isolation from water table (root / stem decomposition)	Thorne (1990)
Fine sediment and embeddedness typically increased during construction phase	Wolman and Schick (1967), Wolman (1967), Waters (1995), Bales *et al.* (1999)
Substrate coarsening after construction *OR* continued embeddedness via fluvial instability, potential loss of bimodal sediment gradation observed in gravel streams	Finkenbine *et al.* (2000), Pizzuto *et al.* (2000), Bledsoe (unpublished data)
Changes in mobility of coarser bed material fractions as affected by intrusion of sand (can increase mobility) or cohesive sediments (can reduce mobility) into gravel framework	Beschta and Jackson (1979), Wilcock (1997), Montgomery *et al.* (1999)
More intense and frequent bedload transport and scour	King County (1997, 1998a, 1998b), Bledsoe and Watson (2001a)
Higher suspended sediment concentrations, especially if upstream channels become unstable	Waters (1995), Trimble (1997), Shields *et al.* (1995)
Induces system level / network fluvial response via base level lowering of tributaries, downstream deposition, or other mechanisms	Harvey and Watson (1986), Shields *et al.* (1995), Galay (1983), Schumm *et al.* (1984)
Alters multi-scale mosaic of habitats and refugia	Frissell *et al.* (1986), Sedell *et al.* (1990)

Sensitivity of Different Stream Types

In a process-based approach to stream classification, Montgomery and Buffington (1997, 1998) suggested that lower-gradient channels become progressively more responsive to changes in discharge and sediment supply as transport capacity, grain size, and channel confinement decrease in the downstream direction. Channel reaches with a high sediment transport capacity, i.e., stream power, relative to supply should recover quickly from increased sediment loading (at least from a purely physical standpoint) because the additional load is rapidly transported through the system. Reaches with a low transport capacity should exhibit more persistent morphologic response to a comparable increase in sediment supply. Following these lines of reasoning, the alluvial streams that are least sensitive to increases in specific stream power and sediment supply will probably be threshold channels that have coarse beds, densely vegetated banks and connected floodplains of high flow resistance. At the opposite end of the spectrum, the most sensitive channels will tend to have sand beds or sandy banks composed of noncohesive material that is unprotected from high shear stresses by vegetation and/or floodplain energy dissipation.

Unless we recognize and classify fundamental types, predicting response potential is likely to be confounded by poor correlations between response, the degree of post-development stabilization and the magnitude of developed area or rate of recent development. This is perhaps most true with regard to sand versus gravel bed streams, incising versus widening streams, different floodplain types, and streams from different hydroclimatic regions. Because sand and gravel bed streams have several system properties that are fundamentally different (Table 2), it is unrealistic to expect the responses of sand and gravel bed streams to follow the same trajectories, display similar relaxation times, and to be comparable in magnitude and form across spatial scales. Similarly, channels in arid watersheds are generally unstable, more profoundly affected by extreme events, and less likely to achieve some semblance of an equilibrium form. In general, recovery times are thought to be longer in arid than in humid systems (Bull 1991).

Even the same stream type may exhibit very different types and rates of adjustment, depending on network scale processes. For example, Galay (1983) has differentiated between migration rates associated with upstream-progressing and downstream-progressing degradation. Although both responses tend to ultimately reduce longitudinal profile slope, headward migration generally occurs more rapidly as it increases slope locally at the headcut or knickpoint zone. One implication is that incision moving slowly downstream could abruptly create a rapid network scale response when the degradation reaches a tributary and lowers its base level thereby creating a complex series of upstream-progressing adjustments. Thus, incision may have a much larger zone of influence in the drainage network and broader repercussions for biotic communities when compared to localized widening and bank erosion.

Table 2. Generalized relative differences in sand and gravel bed streams (modified from Simons and Simons 1987).

Parameter	Sand bed	Gravel bed
Bed material transport	Continuous	Episodic
Variation in sediment transport	$(Velocity)^5$	$(Velocity)^3$
Armoring	Ineffective	Significant
Bed forms and changes in bed roughness / configuration	Rapidly adjusting across flow events	Not rapidly adjustable / formed by relatively infrequent events
Scour depth	Deep	Shallow
Variation in scour depth	Rapid	Slow
Slope and Stream Power	Low	High
Channel response to changed hydrology	Rapid	Slower
Sensitivity to changed sediment loads	High	Low
Variation in bed material size	Small	Large

The Importance of Vegetation

Although we know that vegetation can be an extremely important control on stream form and processes, we currently cannot predict the net effects of vegetation on channel forms and evolution sequences. Thorne *et al.* (1998) summarized some the key effects of bank vegetation:

- Foliage and plant residues intercept and adsorb rainfall energy and prevent compaction by rainfall impact
- Root systems physically restrain soil particles
- Near bank velocities are retarded by increased roughness
- Plants dampen turbulence and to reduce instantaneous shear stresses
- Roots and humus increase permeability and reduce excess pore water pressures
- Depletion of soil moisture reduces water-logging

Bank vegetation probably increases resistance to fluvial erosion by 1-2 orders of magnitude depending on both root volume density and roughness characteristics such as height and stiffness. Vegetation tends to override sedimentary influences on bank stability and channel width (Edgar 1976, Hey and Thorne 1986, Dunaway *et al.* 1994, Rowntree and Dollar 1999). A high silt clay content in the absence of vegetation tends to increase lateral stability but a high clay content may inhibit root volume density and vegetation growth on the lower portions of the bank that disproportionately control stability. Woody vegetation may enhance or diminish lateral stability depending on the size of wood inputs relative to the size of the channel and the degree to which canopy closure inhibits development of a high root volume density in the understory vegetative layer. Bank vegetation also tends to reduce the frequency of saturated conditions by creating soil suction and negative pore pressures. Despite the many benefits of vegetation for lateral stability, trees may in some instances become a liability in terms of wind throw potential and creating a surcharge on excessively steep and/or high banks.

In general, the ratio of vertical to horizontal adjustment in unstable channels may be controlled by the rate of bank erosion relative to channel transport capacity *and* vegetation. Severe incision and widening may be viewed as endpoints across a continuum of potential responses to excess stream power that is highly dependent on the availability of bank sediments. Thus, quantifying the potential for bank sediment contributions relative to both sedimentary and vegetative characteristics is critical for developing predictive models.

Useful Concepts from Systems Theory and Impact Assessment

The complex behavior of geomorphic systems lends itself to the application of concepts from nonlinear dynamical systems theory in describing the response and "sensitivity" of stream corridor types. Channel adjustment often involves abrupt discontinuities and intrinsic thresholds which are directly analogous to bifurcations (Knighton 1998). One implication is that channel adjustment may proceed gradually between bifurcations and but relatively rapidly at them. Two concepts from impact assessment that are especially relevant to an understanding of complex stream adjustments are inertia and resilience (Westman 1985). Inertia may be defined as the resistance of a system in the face of a perturbing force i.e., resistance to change. In contrast, resilience refers to ways in which a disturbed system responds i.e., the degree, manner, and pace of restoration of initial structure and function *after* disturbance. Four primary components of resilience are recognized and may be applied a various spatial scales:

1. Elasticity - rapidity of restoration of a stable state after disturbance
2. Amplitude – zone from which the system will return to a stable state
3. Hysteresis – degree to which the path to restoration is an exact reversal of path of degradation
4. Malleability – degree to which stable state established after disturbance differs from the original steady state

Brunsden (1980) suggested a scheme wherein geomorphic time may be divided into two periods: (1) the time for a system to react to a change in conditions (reaction time) and (2) the time taken for the system to attain a characteristic equilibrium state (relaxation time). Thus, the total response time is equal to the reaction time plus the relaxation time. Brunsden and Thornes (1979) also defined two states of temporal response in geomorphic systems that are a function of relaxation time relative to the recurrence time of disturbance events:

1. Relaxation time is *less* than the average recurrence time of disturbance events: The system may adjust to new conditions before the next major disturbance so that characteristic forms tend to prevail and facilitate recognition of process-response relationships
2. Relaxation time is *greater* than the average recurrence time of disturbance events: the system is unlikely to recover or equilibrate and thus forms are likely to be transient and difficult to link with process agents

This second state may partly explain the common lack of correlation between channel geometry and development intensity. Moreover, it is not surprising that channel width, which tends to adjust on the shortest timescales relative to other geometric characteristics, is usually more related to development intensity than channel depth or cross-sectional area. In general, the terminology and conceptual framework of systems theory is an attractive vehicle for improving both description and understanding of geomorphic response and "sensitivity" across stream types and spatial scales.

PERCEPTION ISSUES

Channel instability is in the eye of the beholder as there is no widely accepted system for its quantification. Systematic analysis of channel instability is limited by qualitative assessments that lack explicit descriptions of space / time scales and watershed / drainage network context. Perception and assessment of channel instability are influenced by the following important factors that are frequently overlooked in the literature (Booth and Henshaw in press, Pizzuto *et al.* 2000):

- Location of measurement in channel network
- Location of urbanization relative to the channel network
- Interplay of timing of development, large storms, and field observations
- Culverts and other hydraulic structures can have a profound effect on perception of erosion vs. deposition
- Age of development and lag time
- Rate of sediment supply depletion from hillslope and channel sources
- Use of "bankfull" indicators in disturbed channels can introduce significant error into field estimates of cross-sectional geometry
- Stream type
- Historical influences

TOOLS

Frameworks for qualitative analysis of channel response to modified water and sediment delivery (e.g. Schumm's 1969 "river metamorphosis" and its variations) are very useful in predicting the general *direction* of adjustment. These tools when combined with process-based stream classification and concepts from applied fluvial geomorphology (including the conceptual frameworks of thresholds and catastrophes in geomorphic systems) provide some general guidance on probable response and which characteristics increase sensitivity to the alterations in flow regime and sediment loading that often accompany urbanization (Table 3).

Process and historical studies of individual streams suggest that channel adjustments may be historically contingent on how intrinsic variables have 'primed' a reach for instability and on the state of the channel at the time of an impact (Brewer and Lewin, 1998). Because channel forms are frequently transitional and shaped by complex sequences of disturbance events, stochastic alternatives to deterministic thresholds have the potential to improve prediction and decision making in a context of uncertainty. Bledsoe and Watson (2001a,b) suggest that logistic analysis (Tung, 1985; Menard, 1995) is a useful way to attach explicit statements of risk and uncertainty to associations between controlling variables and unstable channel forms. Logistic regression models of channel stability developed with an extensive data set generally exhibit 80-100% accuracy in predicting stable vs. incising or braiding channel forms using only annual flood, slope, and median bed material data (Bledsoe and Watson, 2001b). Such probabilistic models provide a starting point for risk-based management of stream systems and may provide an improved means of gauging channel sensitivity to changes in controlling variables.

Table 3. Stream characteristics associated with risk of instability and response magnitude.

High Risk Characteristics	Lower Risk Characteristics
• High specific stream power relative to the most erodible channel boundary • Capacity limited - fine bed material, esp. sand • Little or no grade control (geologic, wood, or artificial) • Low density of vegetation root volume in banks • Non-cohesive, fine grained, sparsely vegetated banks • Large ratio of woody debris size / channel width? - increased input may destabilize banks and/or enhance vertical stability • Entrenched channel - minimal floodplain energy dissipation at $Q > Q_2$, flows > Q_2 contained in channel • Near an energy threshold associated with abrupt changes in planform or initiation of incision • Flashy flows result in pre-wetting / rapid wetting, drying, and drawdown • Low roughness – form and vegetative • Floodplain susceptible to chutes cutoffs and avulsions • Steep bank angles	• Low specific stream power relative to the most erodible channel boundary • Supply limited - coarse bed material with potential for armoring • Grade control sufficient to check incision (geologic, wood, or artificial) • High vegetation root volume density in banks or cohesive / consolidated bank sediments (vegetation tends to override influence of cohesive bank material) • Instream form roughness and vegetation roughness on banks • Small ratio of woody debris size / channel width • Channel well-connected with rough riparian zone / floodplain that resists chutes cutoffs and avulsions / provides substantial overbank energy dissipation at $Q > Q_{1.5} - Q_2$ • Energy level not proximate to geomorphic threshold • Flow regime results in gradual bank wetting and drawdown

There are several indices or descriptors of channel energy and stability that may be computed from a flow series and basic hydraulic information. These descriptors include:

- Specific stream power (Bagnold 1966, Brookes, 1988; Rhoads, 1995) --

$$\omega = \frac{\gamma QS}{w} \tag{2}$$

where: γ = specific weight of water;
Q = dominant discharge;
S = slope; and
w = width.

- Mobility index (Chang, 1988; Bledsoe and Watson, 2001b) --

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

where: d_{50} = median bed material size of the surface layer.

- Bed stability indicator (Olsen *et al.*, 1997) --

$$\frac{\tau_i}{\tau_{c_i}} \tag{4}$$

where: τ_i = bankfull shear stress; and
τ_{c_i} = critical shear stress for motion of d_{84} or other particle size.

- Time-integrated erosion index (MacRae, 1991) --

$$E_P = \frac{\sum q_{spost}\Delta t}{\sum q_{spre}\Delta t} \tag{5}$$

where: q_s = sediment transport capacity; and
t = time.

Energy-based indices of channel stability should be applied with an understanding of context and be referenced to the erodibility of the limiting channel boundary. The time-integrated erosion index when combined with effective discharge / sediment yield analysis (Andrews 1980, Biedenharn *et al.* 2000, Bledsoe *et al.* 2001) is especially useful in revealing the effects of all geomorphically important events as opposed to a single estimated value of dominant discharge.

In addition to the stability indices described above, a suite of descriptive statistics that relate flow regime and channel processes may be examined. These statistics include:

- Recurrence Interval of Critical Discharge;
- Mean Annual Discharge Exceedence (% time);
- Coefficient of Variation of the Annual Maximum Q's; and
- Coefficient of Skewness.

Through application of these indices, predictive scientific assessments (Reckhow 1999), and risk-based models of the potential impacts of land use change on aquatic ecosystems may be developed. Decision-based models of stream stability and ecological integrity may include 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 hydraulic and flashiness indices.

SOME GAPS IN OUR KNOWLEDGE

At this point we have hardly begun to explore the relationships between various development styles, drainage strategies, changes in flow regime, and stream corridor response. To be effective and defensible, strategies for protection and rehabilitation of urban streams must be underpinned with an understanding of how fundamental geomorphic processes are manifested across scales and contexts.

First and foremost, this necessitates comprehensive, long-term monitoring of the linkages between development style / drainage scheme, flow regime, multi-scale changes in physical habitat, and biotic response. Fundamental questions include:

- How do inertia and resilience vary across stream types and watershed contexts relative to changes in flow regime (water and sediment)?
- Can we use remotely sensed data to identify streams that are proximate to geomorphic thresholds and presumably at greatest risk?
- Given that urban streams sometimes achieve some semblance of quasi-equilibrium after a few decades of adjustment to post-development conditions, how does the "re-stabilized" state differ from the original physical conditions and processes? Specifically, how does physical habitat recovery and relaxation time differ at local, reach, valley, and watershed scales?
- Interactions between flow energy in three dimensions, bank composition, vegetation, bank moisture content, and erosive processes are poorly understood. What are the effects of bank and riparian vegetation on the inertia and resilience of different stream types?
- Are the long-term ecological impacts associated with altered fluvial processes more severe in systems that receive a large sediment load during the "construction phase"?
- How do we transform cumbersome and costly mechanistic models of channel adjustments into decision-based assessments that are augmented with probabilistic / stochastic models, expert judgment, and explicit statements of uncertainty?
- How do we tailor development and mitigation strategies to specific stream types and uses?
- How do we balance geomorphic and traditional water quality concerns in stormwater management, BMP recommendations, and site design?

CONCLUSIONS

The management of streams in urbanizing watersheds stands to benefit from increased recognition of the following principles:

- Not all imperviousness is created equal – development styles, drainage schemes, and BMPs must be quantitatively linked with observed changes in flow regime. Total imperviousness is inadequate as a predictive variable, effective imperviousness is better, but direct analysis of flow regimes will yield the most useful relationships between urbanization and biophysical response.
- Different stream types have inherent system properties that create highly variable responses to urbanization.
- It is important to consider all aspects of the continuous flow regimes of water and sediment (magnitude, frequency, duration, timing, and rate of change) as affected by the spatial and temporal aspects of land use change, drainage infrastructure, and BMPs.
- Effective assessment includes careful consideration of how time "fits into" responses observed in impacted streams. This includes response lag times, history, and the temporal sequence of geomorphically effective events (water and sediment).

- Perceptions and interpretations of channel stability and geomorphic change are variously affected by scale, hydraulic structures, age of development, location in the network, bankfull estimates, and visual thresholds that vary among people.
- Shifts in sediment supply (source locations, volume, size) can be abrupt and assessment of these shifts requires careful monitoring that encompasses high flow events.
- Historical influences and antecedent events may 'prime' the system for a particular response trajectory.
- Reach scale restabilization *sometimes* occurs in a few decades after land use changes but restabilization does not imply a return of comparable habitat heterogeneity and quality.
- Vertical stability is generally a prerequisite for lateral stability as relatively small amounts of incision may destabilize the basal endpoint or "toe" of banks.
- Understanding is predicated upon consistent terminology and quantification of channel changes across spatial scales (reach perspective expanded to include both system and local features).

We have developed the ability to, more often than not, qualitatively predict the general direction of response in geomorphic systems subjected to altered loads of water and/or sediment. Predicting and quantifying the *magnitude* of response is another matter entirely. Accurately predicting the magnitude of stream response in all its complexity and varieties remains one of the most difficult and pressing problems in fluvial geomorphology, a point nicely summarized by Richards and Lane (1997):

> *Scale, environment and uncertainty may be the three themes that are central to understanding the problems of prediction of morphological changes in unstable channels. ... Often attached to the results* [of simulation models that are physically based and distributed] *is a spurious impression of accuracy which should remind us that these models, whilst they may be used for predictive purposes, may be little more than tools for probing the depths of our uncertainty.*

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LINKING STORMWATER BMP DESIGNS AND PERFORMANCE TO RECEIVING WATER IMPACT MITIGATION

PROCEEDINGS OF AN ENGINEERING FOUNDATION CONFERENCE

August 19–24, 2001
Snowmass Village, Colorado

SPONSORED BY
United Engineering Foundation
Environmental and Water Resources Institute of
the American Society of Civil Engineers

EDITED BY
Ben R. Urbonas

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Abstract: *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation,* consist of papers presented at the Engineering Foundation Conference held in Snowmass, Colorado, August 19–24, 2001. It brought together professionals of many disciplines to discuss and debate the linkages between various BMP designs and their performance and ability to mitigate receiving water impacts of urbanization. Specific areas addressed included urban watershed trends; regulatory and institutional perspectives; what is known about impacts of urbanization on receiving waters; BMPs and linkages to in-stream integrity; need for and examples of in-stream controls and habitat enhancements; policy issues related to zero and de-minims impact development policies; design for sustainable water resources; information and monitoring needs to evaluate impacts mitigating potential of BMPs; and experience and science outside the United States.

Library of Congress Cataloging-in-Publication Data

Linking stormwater BMP designs and performance to receiving water impact mitigation : proceedings of an Engineering Foundation conference, August 19-24, 2001, Snowmass Village, Colorado / edited by Ben R. Urbonas ; sponsored by United Engineering Foundation, Environmental and Water Resources Institute of ASCE.

p. cm.

Includes bibliographical references and index.

ISBN 0-7844-0602-2

1. Urban runoff—Management—Congresses. 2. Water quality management—Congresses. 3. Best management practices (Pollution prevention)—Congresses. I. Urbonas, Ben. II. Engineering Foundation (U.S.)

TD657 .L55 2002
628'.21--dc21 2001056657

Library of Congress Catalog Card No: 2001056657
ISBN 0-7844-0602-2
Manufactured in the United States of America.