

FRAMEWORK FOR RISK-BASED ASSESSMENT OF STREAM RESPONSE TO URBANIZATION

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Summary: The standard practice of using simplified predictors of stream impact, such as watershed imperviousness, can lead to, among other things, poor allocation of resources with sensitive streams left underprotected and relatively resilient streams potentially overprotected against instability. This article argues against standardization of stormwater controls across stream types and proposes an alternative framework for risk-based modeling and scientific assessment of hydrologic-geomorphic-ecologic linkages in urbanizing streams for improved watershed management. The framework involves: 1) *a priori* stratification of a region's streams based on geomorphic context and susceptibility to changes in water, sediment, and wood regimes, 2) field monitoring of these strata across a gradient of urban influence, 3) coupling long term hydrologic simulation with geomorphic analysis to quantify key hydrogeomorphic metrics, and 4) using probabilistic modeling to identify links between hydrogeomorphic descriptors of urbanization effects with geomorphic and biotic endpoints of primary interest to stakeholders and decision-makers. The proposed framework is illustrated with an example of using logistic regression analysis to link hydrologic alteration, stream type, and erosion potential with the morphologic stability of streams in the arid southwest US.

KEY WORDS: risk analysis, geomorphology, stream classification, erosion potential, urbanization

INTRODUCTION

Watershed modifications typically accompanying urbanization have profound impacts on hydrologic and geomorphic processes in receiving streams. Urbanization frequently results in reduced infiltration and interception, conversion of subsurface flow to surface runoff, and more rapid conveyance of runoff via engineered drainage systems. By reducing natural watershed storage and vegetative cover, urbanization often intensifies the geomorphic processes of erosion and sedimentation through cumulative increases in flow energy, and causes an "urban stream syndrome" (Meyer *et al.*, 2005; Walsh *et al.*, 2005) with flashier hydrographs, altered channel morphology, and reduced biotic integrity (Jacobson *et al.*, 2001; Konrad *et al.*, 2005; Booth, 2005). Although best management practices (BMPs) intended to mitigate the effects of urbanization on receiving waterbodies have been widely

implemented for decades, a lack of consideration of network scale hydrologic responses and geomorphic processes in standard design approaches can potentially exacerbate both flooding and geomorphic instability (Emerson *et al.*, 2005; MacRae, 1997).

Several efforts are underway to relate land-use changes to flow regimes with the intent of developing urban development practices that minimize hydrologic alteration of streams in urbanizing landscapes (e.g., King County Normative Flows Project, <http://dnr.metrokc.gov/wlr/BASINS/flows/>; State of New Jersey Ecological Flows Project, http://nj.usgs.gov/special/ecological_flow/). Exclusively focusing on the hydrologic effects of urbanization, however, is problematic because geomorphic responses to hydrologic change are mediated by channel boundary materials and context-specific geologic and human disturbance histories that may vary markedly within and among hydroclimatic regions (e.g., Knox, 1977; Trimble, 1974, 1983, 1997; Urban and Rhoads, 2003; Poff *et al.*, 2006). As a result, stream geomorphic responses tend to be difficult to correlate with gross measures of imperviousness that do not reflect context-specific differences in stream sensitivity (Bledsoe, 2002). Unless management tools are designed to account for the differential sensitivity of stream types (*sensu* Downs and Gregory 1995) within common management units (e.g., individual river basins, physiographic regions, or ecoregions), predicting the effects of urbanization on stream integrity is likely to be confounded by poor correlations between stream response, magnitude of developed area, and style of development and stormwater practices. Moreover, mitigation strategies may be confounded by one-size-fits all solutions that potentially underprotect the most vulnerable streams at the expense of overprotecting relatively resilient systems.

STATE OF THE ART – CURRENT KNOWLEDGE

Urbanization is a diverse collection of human influences as opposed to a single condition (Konrad and Booth, 2005). Accordingly, the effects of urbanization on fluxes of water, sediment, organic matter (including wood), nutrients, heat, and stream ecologic functioning vary significantly with watershed context and style of urbanization. Although all these fluxes affect stream integrity, the focus of this article is on the hydrologic and geomorphic processes controlling water and sediment regimes and the form of stream channels. The important influence of flow regime as mediated by geomorphic context on the structure, composition, and productivity of stream ecosystems is well-established (Konrad and Booth, 2006; Poff *et al.*, 2006), and geomorphic stability within some range of variability is often a prerequisite for stream ecological integrity (Jacobson *et al.*, 2001).

In a particular historical context, streams adjust over time to the flows of sediment and water delivered from their watershed (Schumm, 1969; Parker, 1991; Wilcock, 1997). As land uses change, spatial and temporal patterns in the transport capacity of stream channels relative to the type and amount of sediment supplied from the watershed are altered. Urban land uses tend to increase the frequency of high flows and daily variation in streamflows, and convert base flow to storm flow (Konrad and Booth, 2005; Poff *et al.*, 2006). The effects of these changes in runoff and, consequently, sediment yield are often further exacerbated by direct channel disturbances that increase flow energy, decrease channel roughness, and reduce

erosion resistance (Jacobson *et al.*, 2001). In general, the response of streams to land use change fundamentally depends on cumulative excess specific stream power relative to the erodibility of channel boundary materials (MacRae, 1997; Rhoads, 1995; Bledsoe, 2002; Grant *et al.*, 2003). For example, in an armored cobble bedded stream with sandy banks and little vegetative reinforcement, the dominant response to an increase in erosive power relative to sediment supply is likely to tend toward bank erosion and lateral adjustment (Downs, 1995). Conversely, in a sand bed stream with highly cohesive banks, the response will tend towards incision until bank failure results primarily from gravitational forces as opposed to direct hydraulic action (Schumm *et al.*, 1984; Simon, 1989). Vegetation can play a critical role in affecting erosion resistance and channel response to land use change (Thorne, 1990; Dunaway *et al.*, 1994; Anderson *et al.*, 2004). Response potential also varies with the sequence of channel types distributed throughout a basin as segments transition between supply- and capacity-limitation and as floodplain connectivity varies with valley type (Montgomery and Buffington, 1998; Montgomery and MacDonald, 2002).

Scale also influences interpretation of geomorphic responses to hydrologic change. The time scales addressed here are intermediate (decadal) in that water and sediment discharge are both primary independent variables (Schumm and Lichty, 1965; Schumm, 1991). Stream responses to changes in these variables occur at spatial scales ranging from drainage networks, to reaches, to streambed patches. At larger scales, incision of a channel segment due to hydrologic change may exert widespread influence on entire tributary drainage networks through base level lowering and headcutting. In contrast, a stream reach that largely maintains its pattern and profile in response to land use change may be altered in terms of habitat complexity and patch scale substrate stability (Hashenburger and Wilcock, 2003; Booth and Henshaw, 2001; Konrad *et al.*, 2005). Although some streams re-attain quasi-equilibrium in a coarse sense after land use change, this does not necessarily imply that the quality, quantity, and stability of habitats available to stream communities are comparable to pre-disturbance conditions.

Finally, geomorphic thresholds, temporal lags, non-linear behavior, and climatic variability further complicate stream responses to urbanization. Geomorphic thresholds relevant to the hydrologic changes frequently associated with urbanization include mass wasting of banks (Simon and Collison, 2002), planform change (Bledsoe and Watson, 2001), bedforms and flow resistance in sand bed channels (Simons and Richardson, 1966), and mobility of sediment mixtures (Jackson and Beschta, 1984; Wilcock, 1998). Yet, despite the recurring themes of non-linearity and uncertainty in the prediction of morphological change in hydrologically perturbed fluvial systems (Schumm, 1991; Richards and Lane, 1997), the following general conclusions may be drawn from previous research on the geomorphic effects of urbanization on streams:

- Different stream types have inherent system properties that create variable but predictable directional responses to urbanization.
- It is important to consider continuous flow regimes of both water and sediment as affected by the spatial and temporal aspects of land use change, drainage infrastructure, and BMPs.
- Effective stream assessment includes careful consideration of how time relates to responses observed in impacted streams. This includes response lag times, history,

and the temporal sequence of geomorphically effective events. Historical influences, antecedent events, and infrastructure may “prime” or limit the system for a particular response trajectory.

- Restabilization of streams sometimes occurs in a few decades after land use changes but does not imply a return of comparable habitat quality and biological potential.

Modeling Stream Responses Using Hydrogeomorphic Descriptors

Previous regional-scale studies of stream responses to changes in water and sediment regimes are often based on the assumption that the likelihood of channel instability can be assessed by identifying upper and lower boundary values of specific stream power for different stream types and boundary materials (Booth, 1990; Simon and Downs, 1995; Bledsoe and Watson, 2001a). This assertion is supported by several studies that have correlated bankfull specific stream power with channel stability. For example, surveys of channelized rivers in England, Wales, and Denmark indicated that for a limited range of channel gradients and bed material sizes, a threshold of specific stream power separating stable and unstable channels varies around a mean value of 35 Watts per square meter (W/m^2). Nanson and Croke (1992), in a classification of alluvial floodplains, suggested that floodplains of braided streams and rivers have specific stream power values ranging from 50 - 300 W/m^2 and that lateral migration, scrolled floodplains range from 10 - 60 W/m^2 . Watson *et al.* (1998) observed a substantial increase in stability as disturbed channels evolve to a specific stream power less than about 35 W/m^2 in severely incised sand bed streams in northern Mississippi.

In a study of 270 streams and rivers, Bledsoe and Watson (2001b) demonstrated that logistic regression models (Menard, 1995) could accurately predict unstable channel forms with a "mobility index" based on slope, median annual flood, and median bed material size. The logistic regression analyses of stable and unstable channel forms suggested that simple indices describing the ratio of erosive energy to boundary material resistance can be robust predictors of channel planform and stability. The logistic models generally predicted the occurrence of unstable sand and gravel channel forms with more than 80% accuracy. In many cases, the predictive accuracy of logistic models utilizing the mobility index as the only independent variable exceeded 95%. A benefit of the logistic regression approach is that explicit probability statements may be attached to diagrams depicting channel stability and proximity to geomorphic thresholds. This provides users with a more useful and realistic assessment of risk when compared to the discrete thresholds of traditional approaches.

Given the ubiquitous degradation of streams occurring in urban areas despite the common use of structural stormwater management practices, there is a pressing need for a more process-based management framework for protecting the geomorphic stability and biotic integrity of streams. Such a framework should guide the evaluation of potential impacts and tailoring mitigation strategies to different stream types and regional contexts. However, it is clearly impossible to fully capture the multiplicity of factors influencing stream responses to urbanization in a mechanistic modeling approach. The following sections briefly outline a risk-based framework for predicting geomorphic and/or biotic responses to urbanization that couples the energy-based approaches described above with more detailed description of hydrologic alteration and boundary conditions influencing stream susceptibility.

PREDICTING STREAM RESPONSE TO URBANIZATION

The proposed framework for risk-based analysis of stream response to urbanization and selection of appropriate mitigation strategies involves four general steps: 1) *a priori* stratification of a region's streams based on geomorphic context and susceptibility to changes in water, sediment, and wood regimes, 2) field monitoring of these strata across a gradient of urban influence, 3) coupling long term hydrologic simulation with geomorphic analysis to quantify key hydrogeomorphic metrics, and 4) using probabilistic modeling to identify links between hydrogeomorphic descriptors of urbanization effects with geomorphic and biotic attributes of broad interest to stakeholders and decision-makers (Figure 1).

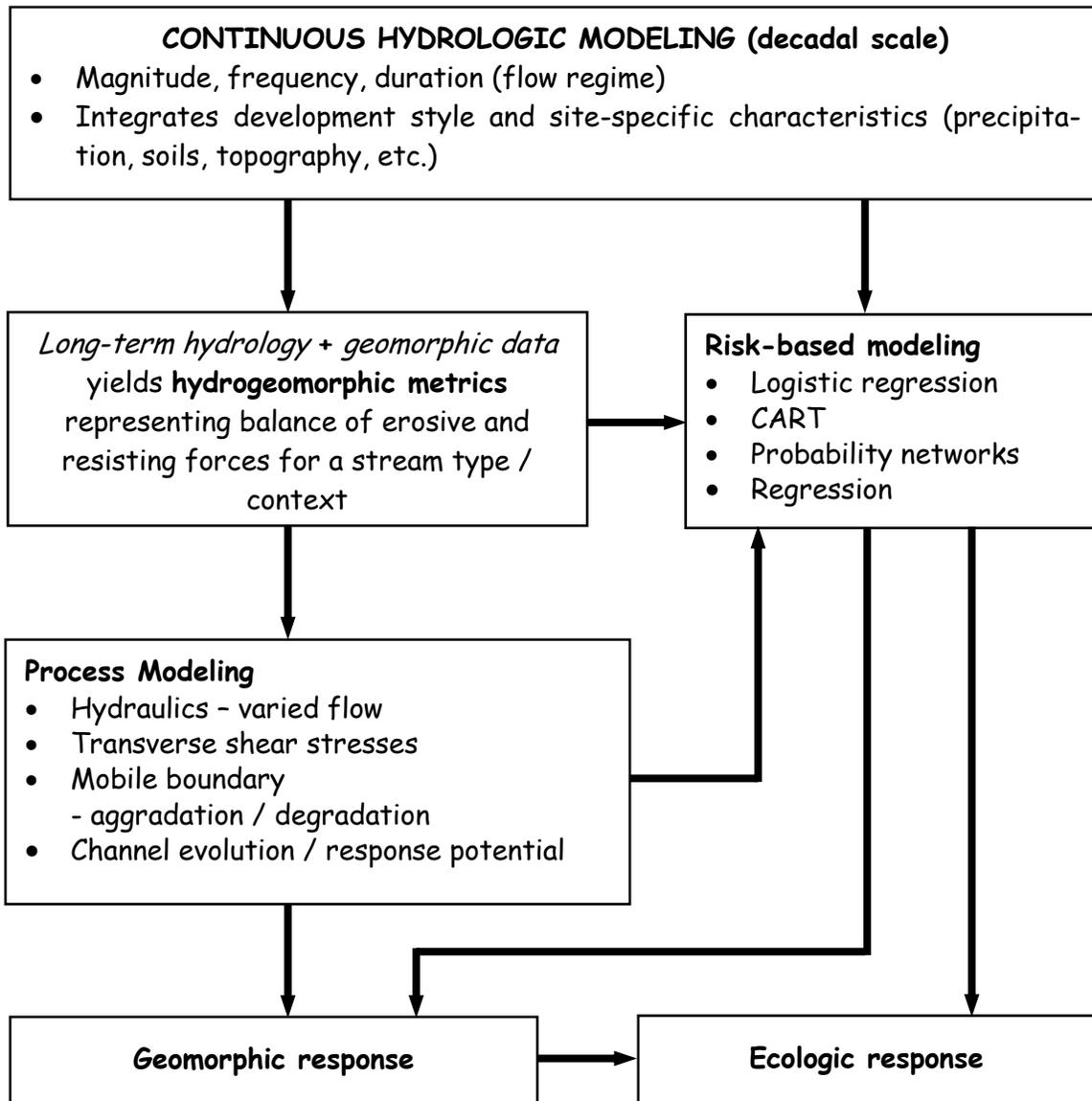


Figure 1: Modeling framework for risk-based assessment of stream response to urbanization

Because stream geomorphic types have inherent system properties that create variable responses to urbanization, the development of a region-specific, process-based classification of stream susceptibility to changes in water and sediment regimes provides a critical foundation for the other components of the approach. This is particularly true for regions that are relatively heterogeneous in terms of climate, geology, soils, topography, and geomorphic boundary conditions. Classification based on susceptibility can be accomplished through *a priori* stratification of the landscape into different geologic, valley, and stream segment types (Flores *et al.*, 2006) using a geographic information system (GIS), and then conducting field reconnaissance and synoptic geomorphic surveys across a gradient of urbanization in each mapped geomorphic context. These synoptic surveys can be used to identify sites in each geomorphic context for more intensive field assessment. Sites selected for detailed geomorphic surveys will ideally span a range of channel evolution stages and sequences (Schumm *et al.*, 1984; Simon, 1989; Downs, 1995) and variable degrees of hydromodification from least to heavily disturbed. Detailed geomorphic characteristics as well as development styles, drainage schemes (including connectivity of impervious areas and BMPs), and hydrologic regime should be documented and compared among study sites to the extent practicable.

Although heterogeneity in history, boundary conditions, and processes will necessitate regionally-calibrated classifications, it is likely that the streams exhibiting the least geomorphic sensitivity to hydromodification will tend to be bedrock and alluvial threshold channels that have coarse beds with high armoring potential, geologic control, densely vegetated banks and well connected floodplains of high flow resistance. At the opposite end of the spectrum, the most susceptible channels frequently tend to have fine-grained beds, steep valleys, sandy banks composed of noncohesive material that is unprotected from high shear stresses by vegetation (Table 1). Several studies suggest that the ratio of stream power per unit channel area relative to the most erodible channel boundary is a robust indicator of channel adjustment potential (MacRae, 1997; Bledsoe, 2002; Grant *et al.*, 2003).

Table 1: Stream characteristics associated with risk of instability and loss of physical habitat (modified from Bledsoe (2002))

High-risk characteristics	Lower-risk characteristics
<ul style="list-style-type: none"> • 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 • 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 • Increased woody debris input may destabilize banks and/or enhance vertical stability 	<ul style="list-style-type: none"> • 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

Risk-based Channel Response Analysis

Once the stream types of the region have been assessed in terms of their relative sensitivity to urbanization, potential changes in hydrology and sediment supply the remaining steps in the proposed framework involve development, calibration, and integration of a suite of probabilistic modeling tools for assessing the anticipated effects of urbanization. The first critical tool is continuous simulation modeling of the hydrologic changes anticipated with different urbanization and land use scenarios. Indeed, there is a growing consensus among experts familiar with the hydrologic effects of urbanization and stormwater controls on stream physical processes that long-term continuous simulations of hydrologic change are essential for adequately assessing the magnitude, frequency, and duration characteristics of post-development flow regimes. This level of description is critical for subsequent

geomorphic analyses and predictive assessment because it is the cumulative effect of all sediment transporting events that control geomorphic response.

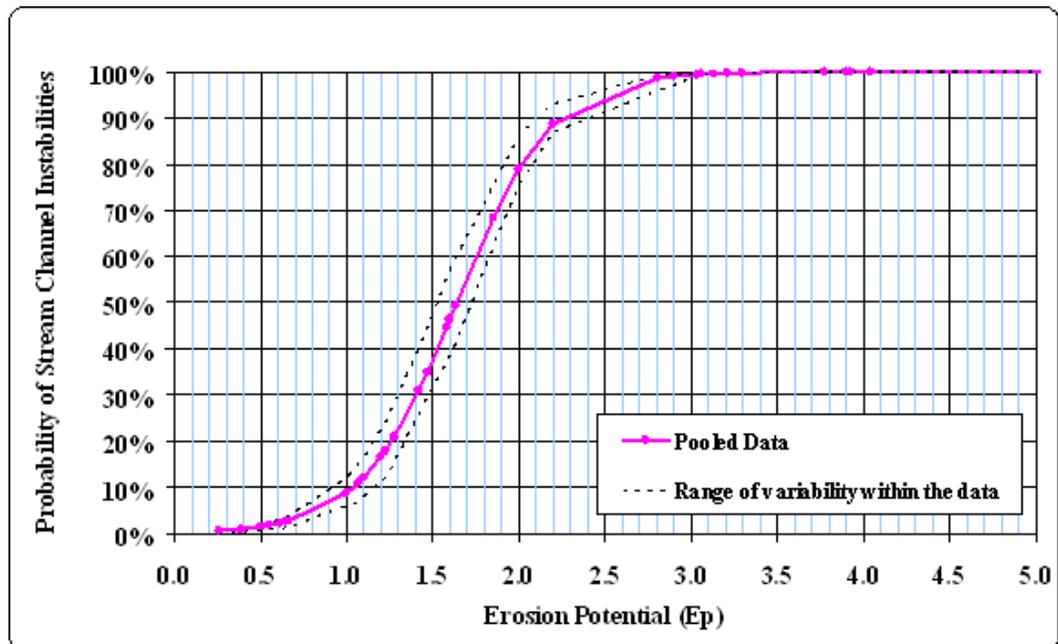


Figure 2: Logistic regression analysis showing the probability of channel instability given predicted changes in erosion potential (increase in time-integrated sediment transport capacity relative to pre-development condition)

Risk-based modeling as envisioned here is based on integrating hydrologic and geomorphic (hydrogeomorphic) data derived from the output of continuous hydrologic simulation models to generate metrics describing expected departures in fundamental geomorphic processes such as the cumulative distribution of specific stream power and sediment transport capacity (sometimes termed “erosion potential”) across the entire range of relevant flows (Bledsoe *et al.*, in press; Rohrer and Roesner, this volume). These physical metrics are provided as inputs to probabilistic models that estimate the risk of streams shifting to some undesirable state. Because the decision endpoint is often categorical (e.g. stable, good habitat, supporting aquatic life uses) the statistical tools of choice are often logistic regression, classification and regression trees (CART), and/or Bayesian probability networks. Figure 2 illustrates how logistic regression analysis can be used to estimate the likelihood of channel instability based on progressive degrees of erosion potential. This approach was recently used in the development of the Santa Clara Valley Urban Runoff Program Hydromodification Management Plan (www.SCVURPPP.org). This study demonstrated that a time-integrated index of erosion potential based on continuous hydrologic simulation and an assessment of stream power relative to the erodibility of channel boundary materials could be used to accurately predict which channels of a particular regional type are degraded by hydromodification in arid urban watersheds of southern California.

As suggested above, the variables included in risk-based models of stream response are not limited to the simple energy-based descriptors examined in previous research. Instead, additional multi-scale controls can be included. For example, simple categories of physical habitat condition and ecological integrity can be modeled by augmenting erosion potential metrics with descriptors of the condition of channel banks and riparian zones, geologic influences, floodplain connectedness, valley entrenchment, hydrologic metrics describing flashiness, proximity to known thresholds of planform change, and land use descriptors such as % connected imperviousness and BMP types.

The resulting probabilistic models can be used to conduct risk-based scientific assessments that account for geomorphic context and processes as opposed to simply defining “one-size-fits-all” threshold limits on imperviousness or some other surrogate. Risk-based modeling estimates the probability of stream states that are of interest to stakeholders. Decision-makers can then determine acceptable risk levels based on an explicit estimate of prediction error. This type of risk-based approach is consistent with recommendations of Reckhow (1999a,b) and the National Research Council panel on TMDLs (NRC, 2001) that 1) the focus of scientific study in support of decision making should ultimately be on the decisions (or objectives) associated with the resource and not on the model or basic science, and 2) prediction error, not perception of mechanistic correctness, should be the most important criterion reflecting the usefulness of a model. The predictive models suggested here should be thought of as predictive scientific assessments, that is, a flexible, changeable mix of small mechanistic models, statistical analyses, and expert scientific judgment. A predictive scientific assessment should be evaluated in terms of its utility in addressing decisions and objectives of primary concern to stakeholders. Predictive model selection criteria must include factors such as prediction uncertainty, cost of calibration and testing, meaningful endpoints, appropriate spatial and temporal detail, and simplicity in application and understanding (NRC, 2001; Reckhow, 1999a,b).

The approach described above can be readily extended to the prediction of biological states in urban streams. Although the large number of potentially confounding influences makes prediction of biological responses to urbanization very challenging, the framework suggested here has the potential to provide a more rational and transparent basis for prediction and decision making by explicitly recognizing uncertainty in both the reasoning about stream response and the quality of information used to drive the models. Some critical limitations in our understanding of biotic responses to urbanization that currently inhibit such an approach are addressed in the following section.

RECOMMENDATIONS AND FUTURE RESEARCH

The framework proposed above is based on using metrics describing process linkages in regionally-calibrated, probabilistic models of stream responses to various styles of urbanization. Successful implementation of this approach will undoubtedly necessitate communally developing strong conceptual models of the processes controlling stream response in urbanizing watersheds of different regions. Moreover, conceptual models developed for predicting and mitigating the effects of urbanization may also prove useful in

the inverse problem of stream restoration. After identifying classes of urban streams that provide desirable benefits and amenities despite altered regimes of water, sediment, wood, nutrients, and other materials, a similar risk-based approach could be used to determine which physical metrics best predict membership in the classes and thereby define potential restoration strategies. As high-resolution geospatial data become more widely available (e.g., LIDAR), it may become increasingly feasible to map both putative stream responses and restoration potential at the basin or regional scale by employing a risk-based assessment approach similar to that described above.

Effective implementation of risk-based assessments will also depend on continual reevaluation of models through targeted monitoring and research. Much of the existing body of research consists of one-time studies, which are only a static snapshot of ongoing processes (Roesner and Bledsoe, 2002). To be effective and defensible, strategies for protection and rehabilitation of streams impacted by urbanization must be underpinned with an understanding of fundamental geomorphic processes. First and foremost, this necessitates comprehensive, long-term monitoring augmented with mathematical modeling of the linkages between development style/drainage scheme, flow regime, and multi-scale changes in physical habitat and biotic condition. Improved diagnosis and predictive understanding of future change will require multifaceted, multiscale, and multidisciplinary studies based on a firm understanding of the history and processes operating in a drainage basin (Jacobson *et al.*, 2001). Such multidisciplinary studies will necessarily combine historical, associative, process-scale, and modeling approaches from hydrology, geomorphology, sediment transport, water quality, and aquatic ecology.

Several studies over the last decade have underscored the importance of watershed land use and vegetative cover as well as valley context on local habitat and biological condition. Despite this recognition, watershed managers currently lack a conceptual framework for predicting the impact of large-scale watershed modifications and urbanization on ecological processes that influence stream communities. Geomorphic disturbances resulting from urban land use have the capacity to alter ecological processes that operate over large spatial scales, while most studies have been conducted at smaller spatial scales (Mathews and Heins, 1987; Roesner and Bledsoe, 2002). A lack of understanding at this scale limits our ability to design effective restoration efforts in response to large-scale disturbances (Schlosser, 1995).

Although this article suggests that this general framework may be extended to developing predictive models of biological response in urban watersheds, the knowledge base for biota/habitat associations is not generally adequate to allow for prediction of how whole communities will change in response to environmental alterations associated with urbanization. Making such predictions requires a thorough knowledge of species-specific environmental responses, as well as an adequate (accurate) characterization of habitat structure and habitat dynamics (both of which are modified by urbanization). Viewing species in terms of their response potential to environmental factors is a common method in stream ecology, as seen for example in the use of functional feeding groups (Cummins, 1973) or pollution tolerance scores (Hilsenhoff, 1987; Lenat, 1993), which allow some expectation of how species may respond along environmental gradients of food resources or human pollution, respectively. However, it is difficult to predict biotic responses to environmental

alteration involving multiple stressors. For example, species vary in their abilities to tolerate natural high rates of disturbance through colonization ability, resistance to flow disturbance, life cycle adaptation, fecundity, and other traits; however, characterizing species according to multiple traits that may be important in predicting local community structure under a specified environmental regime is generally lacking (Poff, 1997). Attempts to characterize community composition in terms of traits that are sensitive to multiple environmental factors (including disturbance) have shown some success both for fish (e.g., Poff and Allan (1995)) and for invertebrates (e.g., Richards *et al.* (1997)). But, to date, a comprehensive, multi-trait characterization for invertebrates and fish that would incorporate sensitivity to disturbance, habitat conditions, and water quality has not been fully developed.

Finally, there is a need for better understanding of local biotic response in a landscape context. Aquatic organisms are highly mobile and generally excellent dispersers; therefore, it is not uncommon to find species in habitats not predicted from models (e.g., Poff (1997)). Further, this high mobility promotes rapid recolonization following disturbance, a phenomenon long appreciated in stream ecology literature (e.g., Larimore *et al.* (1959)). Thus, the recovery potential for any particular stream segment that experiences a disturbance will be a function of the dispersal ability of the fauna and the availability of refugia from the local disturbance. Stream ecologists do not have a general framework for assessing this “recovery” potential, as the identification and quantification of refugia, and the scales at which they occur, remains a largely unsolved problem (e.g., Lancaster and Belyea (1997); Lancaster (2000)). Further, the diversity of seemingly similar locations may be very different depending on neighboring habitat types. For example, small tributary streams to large rivers may have “inflated” species richness, because river fishes opportunistically move into them. Although there is growing appreciation of the importance of tributaries and other “anomalies” in influencing local diversity (Osborne and Wiley, 1992; Rice *et al.*, 2001), there is no general theory in stream ecology that quantitatively incorporates the network structure of a drainage in a way that allows for formulation of expected diversity (or other) deviations from average conditions (Benda *et al.*, 1998; Fisher, 1997). Thus, another heading of research needs would involve region-scale “neighboring” habitat issues.

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