Protocols for the Evaluating the Effects of Land-use Patterns and Runoff Management on Urban Streams

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Abstract

The design of urban runoff management facilities generally includes peak shaving for flood control, and best management practices (BMPs) for removing pollutants from the runoff. A number of scientists have concluded that the combination of these two control practices, which were developed independently of one another, is not sufficient to protect aquatic ecosystems. But these conclusions have focused solely on the bioassessment of urban streams without taking into account the design criteria used for peak flow reduction facilities and for BMPs. Previous studies at the Colorado State University Urban Water Center (CSU), have demonstrated that if the design storms for peak flow control are properly chosen and used in conjunction with the properly sized volumetric BMPs, it is possible to preserve the predevelopment peak-flow frequency curve and to minimize geomorphic instability in an urbanizing watershed.

Current research at CSU is now focusing on the development of a protocol for data collection along urban gradients combined with mathematical modeling to determine the ecologic impacts of urban runoff resulting from different land use patterns and/or implementation of alternative runoff management technologies. This study builds upon a previous study conducted for the Water Environment Research Foundation on the *Physical Effects of Wet Weather Discharges on Aquatic Habitats – Present Knowledge and Research Needs.* A protocol is being developed that includes a procedure for data collection and analysis to determine how statistical characteristics of stream-flow, i.e. “stream metrics,” change with urbanization and runoff management practices, and how these stream metrics can be used to estimate geomorphic stability and health of a stream ecologic system under alternative development and/or runoff control scenarios. This paper describes the protocol that has been developed and how it is being applied to test areas in the Raleigh, North Carolina area, using data gathered by the USGS in their Urban Gradient Studies under the NAWQA program.

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Introduction

Land use changes, especially those related to urbanization, can have profound impacts on the runoff characteristics, resulting in accelerated geomorphic changes that alter the quality of aquatic habitats and native biota of streams. WERF's recently completed research project *Research Needs: Physical Effects of Wet Weather Flows on Aquatic Habitats* (stock no. 00WSM4) concluded that significant knowledge gaps exist with respect to developing cause-effect relationships between urban stormwater management (such as land cover and drainage system modifications) and observed alterations of physical habitats in receiving waters, and that a high research priority should be the development of reliable protocols to diagnose the effects of urbanization and urban runoff controls on stream channel stability, and the healthiness of the aquatic biota in the receiving stream.

In this study, protocols and diagnostic measures are being developed to help standardize data generation for identifying the linkages between urban land use policies and practices, stormwater runoff characteristics, geomorphic parameters, and effects on aquatic habitat and biota. Identification of these linkages is needed when evaluating the effectiveness of urban stormwater runoff management, including the management of urban development and limiting percent of impervious surface cover to achieve the fewest ecological impacts and increase sustainable physical habitats and ecological conditions in urban streams. These linkages will also permit effective multi-scale functional stream restoration and rehabilitation activities.

Synopsis of Pertinent Literature

Review of recent literature reveals several notable advancements in research regarding the linkages between urbanization, hydrology, hydraulics, geomorphology, physical habitat, and stream ecology. Some promising work has been done exploring ways of moving beyond using gross measures of imperviousness as predictors of biologic integrity by developing more meaningful land use/land cover metrics, establishing clearer relationships between land cover and hydrologic response, and identifying mechanisms through which altered flow regimes affect stream ecosystems. Studies examining the factors important for the success of specific organisms or groups of organisms provide insight regarding critical physical habitat and flow requirements necessary to support healthy lotic ecosystems. For example, researchers have found that hydrologic metrics that indicate altered stream flows can in some cases provide a more direct mechanistic link between the changes associated with urban development and declines in stream biological condition.

The importance of hydrologic disconnect of impervious surfaces is underscored by a number of papers as a key factor determining the degree to which urban land use alters the hydrology and in turn impacts aquatic biota (Booth and Jackson 1997; Brabec et al. 2002; Alberti 2003; Lee and Heaney 2003; Booth et al. 2004; Walsh 2004; Walsh et al. 2004;). Walsh (2004) recommends that efforts to restore streams in urban catchments should start with attention to the catchment drainage system. He suggests that conflicting reports among studies of dominant scale effects (local land use vs. catchment-scale land use) could be explained by failure to account for differences in drainage connection. In response to implications by researchers that riparian buffers were possibly the most important elements in protecting streams from the effects of urbanization (Horner et al. 2001), Walsh points out that no formal comparison between the relative importance of riparian buffers and catchment-wide land use has been made.

Stream metrics that indicate altered stream flows can in some cases provide a more direct mechanistic link between the changes associated with urban development and declines in stream biological condition (Booth et al. 2004). Several researchers have conducted studies using principal component analysis (PCA) to identify groups of hydrologic metrics that are providing the similar information, in order to minimize the number of metrics necessary to describe aspects of the flow regime relevant to ecological studies (Clausen and Biggs 2000; Olden and Poff 2003). Olden and Poff (2003) provide a framework for identifying hydrologic indices that adequately characterize flow regimes in a non-redundant manner. Their framework is to be used, wherever possible, in conjunction with more intuitive index selection criteria based on the particular ecological question of interest. They found that indices explaining dominant patterns of variance were flow-regime-type-specific, demonstrating that hydroclimatic characteristics of a study region should be considered when determining appropriate hydrologic indices for a study. They also note that the question still remains whether hydrologic indices can be geographically transferred between regions of differing climatic and geologic settings.

Table 1 presents the hydrologic metrics found to be most useful in predicting biological integrity from four studies from four different regions, three of which were conducted along urbanizing gradients. The hydrologic metrics used in these studies are described in Table 2. It can be seen that measures of flow flashiness and predictability were determined to be most useful in predicting macroinvertebrate community status in the three urban gradient studies, in three notably different environmental settings. This seems reasonable biologically because measures of flow flashiness describe a variety of aspects of sub-bankfull flows, in which aquatic species spend more of their lives than in rare flood or drought events (Kirby 2003). From a geomorphic perspective it makes sense that flashiness was found to be an important variable to benthic macroinvertebrates. The measures of flashiness based on fraction of the year that the flow exceeds a geomorphically significant flow (i.e. high pulse duration or the half-year storm) (Richter et al. 1996; Booth et al. 2004) translate into extent of sediment transport and bed disturbance and in turn, persistence of ambient habitat (Booth et al. 2004).

Two of the primary elements determining habitat in lotic ecosystems are physical channel structure and the flow regime (Maddock et al. 2004); both factors are of primary interest in the present research. The observed hydraulic impacts on stream substrate can be used to infer, if not directly measure, effects on aquatic

Table 1: Comparison of hydrologic metrics found to be most useful for predicting biotic integrity.

Study	Location	Measure of Biotic Integrity	Most Useful Hydrologic Metric for Predicting Biotic Integrity	Flow Regime Characteristic Represented by Metric	Geomorphic Relevance
Clausen and Biggs (1997)	New Zealand	Periphyton	Q_{mean} or Q_{50}	Absolute Size of River	
		Invertebrates	FRE_3	Flow Variability and Flood Frequency	Bed Disturbance Frequency
Scoggins (2000)	Austin, TX	Invertebrates	% of floods in a 60-day period	Flood Predictability	N/A
			Mean Annual CV	Overall Flow Variability	
			High Pulse Duration	Flow Variability and Flashiness	Sediment Transport and Bed Disturbance
			Date of High Pulse	Timing/Predictabi lity	N/A
Booth et al. (2004)	Puget Sound, WA	Invertebrates	T_{Qmean}	Flow Variability and Flashiness	Sediment Transport and Bed Disturbance
			$T_{0.5yr}$	Flow Variability and Flashiness	Sediment Transport and Bed Disturbance
Kirby (2003)	Virginia	Invertebrates	Rise/Fall Rates of Hydrograph	Flashiness	Bank instability
			High Pulse Count	Flashiness	Sediment Transport and Bed Disturbance
			Date of High Pulse	Timing/Predictabi lity	N/A

Table 2: Definitions of hydrologic metrics displayed in Table 1.

Study	Hydrologic Metric	Definition
Clausen and Biggs (1997)	Q_{mean}	Mean Flow (m^3/s)
	Q_{50}	Median Flow (m^3/s), flow exceeded 50% of the time.
	FRE_3	Frequency of flows greater than three times the median flow.
Scoggins (2000)	**% of floods in a 60-day period**	Common 60-day period for multi-year flow record that contains the largest percentage of floods (Poff and Ward 1989).
	Mean Annual CV	The average over all years of the mean flow divided by the standard deviation times 100 (Poff and Ward 1989).
	High Pulse Duration	Mean duration of high flood pulses, where high flood pulses are defined as the 75^{th} percentile (Richter et al. 1996).
	Date of High Pulse	The mean Julian date of the 1-day annual maximum flow over all years (Richter et al. 1996).

Booth et al. (2004)	**T_{Qmean}**	The average annual fraction of a year that the daily mean flow exceeded the annual mean flow of the given year, which yields lower fractions for "flashy"streams and higher fractions for gradually varying flow regimes (Konrad and Booth 2002).
	$T_{0.5yr}$	The fraction of time that a stream channel is exposed to flows whose magnitude exceeds the half-year flood.
Kirby (2003)	**Hydrograph Rise Rates**	Means of all positive differences between consecutive daily values (Richter et al. 1996).
	Hydrograph Fall Rates	Means of all negative differences between consecutive daily values (Richter et al. 1996).
	High Pulse Count	Number of high pulses within each year (Richter et al. 1996).
	Date of High Pulse	The mean Julian date of the 1-day annual maximum flow over all years (Richter et al. 1996).

macroinvertebrate community structure and associated food web dynamics (Gore et al. 2001). The literature infers that there is significant potential for developing powerful planning tools by combining knowledge of urban development's effects on flow regimes with stream type classification and regional biological characteristics to identify critical physical and biological factors, on which a management plan can be based.

The Basis of the Protocol

The work of Booth et. al. (2004) relating the stream metrics T_{Qmean} and $T_{0.5yr}$ to the Benthic Macroinvertebrate Index (B-IBI), appears promising as the basis of an algorithm for relating B-IBI to land use development patterns and different runoff control methods. Figure 1 reproduced from Booth et. al. (2004) shows very good correlation between the B-IBI and the stream metric $T_{0.5yr}$ for streams in urbanized areas of Seattle, Washington. The data points in Figure 1 were measured in streams with various degrees of urbanization, ranging from 14 to 89 percent imperviousness. Furthermore, Booth et. al. (2004) show that there is a strong link between the value of $T_{0.5yr}$ and the degree of urbanization.

The authors have previously demonstrated through applications to the EPA SWMM model (see Nerhke and Roesner (2004)) that the peak flow frequency curve of an urban stream is highly dependent on the drainage structure infrastructure, and that through the proper sizing of detention basins and BMPs, it is possible for an urban development to nearly duplicate the pre-development peak flow-frequency curve for a given stream. Therefore, it seems reasonable to assume that by simulating

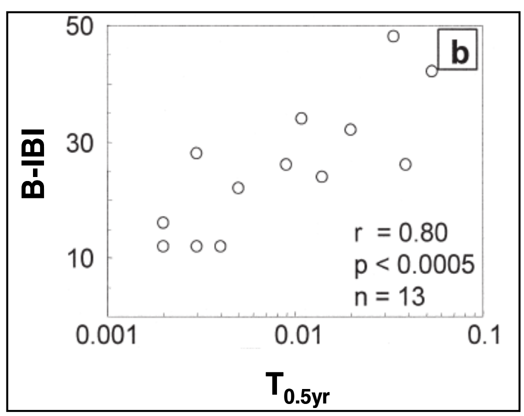

Figure 1. Example of an empirical relationship generated by an urban gradient study. Source: Booth et al. (2004)

the runoff from proposed urban developments under alternative land use patterns, and/or different runoff control scenarios, stream metrics like T_{Qmean} and $T_{0.5yr}$ can be computed. Then, using a measured relationship between the stream metrics and the B-IBI in stream that are typical of the stream under study, it would be possible to relate runoff control scenarios and/or different land use patterns to B-IBI values. This concept is illustrated in Figure 2. The linkage between stream metrics and land use

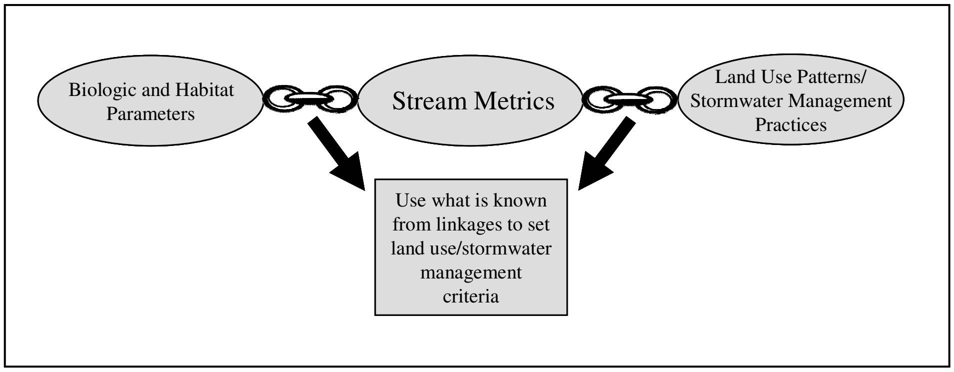

Figure 2. Establishing the link between urban development and stream ecologic health.

patterns/stormwater management practices can be developed using mathematical models for either existing developments or proposed developments. But the linkage between biologic and habitat parameters must made through monitoring studies in local watersheds with hydrogeomorphic properties similar to those of the area under study. Furthermore the monitoring studies must be done over an urban gradient similar to the study reported by Booth, or following the protocol of the USGS Urban Gradient monitoring program.

The Protocol

The linkages described above will be developed using the protocol outlined below, and illustrated in Figure 3. In addition to linkage development, this protocol recommends that as a first step, stream goals are set in order to determine the level of protection/restoration desired. Additionally a recommendation for continued monitoring is made to allow for the evaluation of the effectiveness of the set management criteria. Once community goals related to designated use, biological integrity, stable channel, or protection of a specific species or group of species have been identified, a list of which biologic and habitat parameters to measure is created so that linkages can be developed between these parameters and the hydrogeomorphic metrics. This is accomplished by a process to 1) identify sensitive and appropriate biological indicators, and 2) a list possible or potential stressors in the watershed. Biological and habitat parameters already collected by state and local agencies can provide the starting point for this process because they can provide existing data for this process, are often tied to existing goals for a region, and in some areas have already derived or explored the stressor gradients that may be important.

Biologic and habitat parameter measurements and continuous flow records will be obtained/developed at a sufficient number of locations to establish stressor-response gradients for a watershed or ecological region. For relatively intact watersheds nearby stressed systems could provide resolution along important habitat and hydrogeomorphic metrics. Urbanizing watersheds are typically affected by multiple stressors so that data locations should reflect the range of potential stressors thought to be important in an area. Relationships between the hydrogeomorphic metrics and biologic and habitat parameters will be established. Methods for developing these relationships include regression, logistic regression, a classification and regression tree (CART) analysis, or using Bayesian networks.

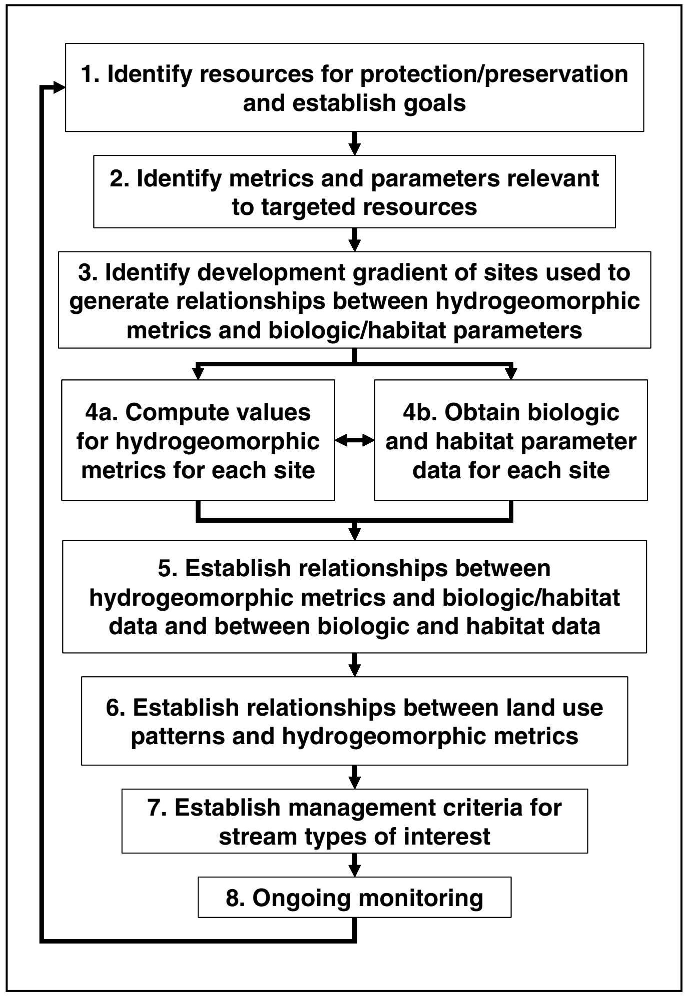

Figure 3. The Protocol

Land use and stormwater management patterns are linked to hydrogeomorphic metrics using model-generated continuous flow data. A hydrologic and hydraulic model is developed in software capable of performing continuous analysis such as the EPA Stormwater Management Model (SWMM). Multiple scenarios are evaluated in the model, representing varied levels of development, types of development (i.e., low-impact), as well as various stormwater management practices (i.e., various types of detention, retention, infiltration, etc.) The continuous flow output from model is processed to generate hydrogeomorphic metrics for the various scenarios. Finally, land-use and stormwater hydrogeomorphic metrics are compared to the established biologic and habitat parameter and hydrogeomorphic metric linkages to determine which types of development that allow the desired goals to be met.

The protocol is currently being tested using data collected by the USGS their Urban Gradient Studies under the NAWQA program. Ten watersheds ranging in size from three to nine square miles in the North Carolina Piedmont have been selected. Hydrologic and hydraulic models are being developed to generate a twenty-year continuous flow record, from which hydrologic and geomorphic metrics will be calculated for the establishment of relationships with benthic macroinvertebrate data collected at the outlet of each watershed. Stormwater controls will be modeled to identify those that create a flow regime whose characteristics most closely match those that are conducive to the desired goals.

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