# A North Carolina Piedmont Application of Protocols for Studying Wet Weather Impacts and Urbanization Patterns

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***Abstract***

Eight watersheds spanning a gradient of urbanization were used to identify linkages between indicators of aquatic ecosystem health and hydrologic and geomorphic metrics derived from a 20-year continuous stream flow record. The geomorphic metric used to evaluate linkages is erosion potential calculated using excess shear stress, which describes the energy exerted on the stream channel that is capable of causing bed scour and bank erosion. The hydrologic metric used to evaluate linkages is the duration of time that in-stream flows are above the 0.5-year return interval peak discharge rage, which is a measure of stream flashiness. The 20-year continuous stream flow records for each watershed were generated using EPA Storm Water Management (SWMM5) Models calibrated to 18 months of measured flow data. A benthic index of biotic integrity was used as one indicator of aquatic ecosystem health, and was calculated from aquatic macroinvertebrate sampling data collected by the United States Geological Survey in the eight watersheds, ranging from three to eight square miles in size.

Various land use and stormwater management practices were modeled in one of the eight gradient watersheds to determine the effect of these practices on the hydrologic and geomorphic metrics. The influence of development density (percent imperviousness) and of land use patterns, such as the proximity of dense urban development to stream corridors and headwater development versus downstream development, on hydrologic and geomorphic metrics was examined. Additionally, the effects of stormwater management practices such as traditional stormwater detention, water quality control and low impact development on hydrologic and geomorphic metrics were also examined. Hydrologic and geomorphic metric values generated by the various practices were compared to those generated along the urbanization gradient to identify the management practices that best generated conditions favorable to meet ecologic targets.

***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. In the Water

Environment Research Foundation (WERF) funded study, *Protocols for Studying Wet Weather Impacts and Urbanization Patterns*, protocols and diagnostic measures were developed to help standardize data generation for identifying the mechanistic linkages between urban land use policies and practices and the associated geomorphic and ecological consequences in urban streams. Identification of these linkages is needed when evaluating the effectiveness of urban stormwater runoff management practices, 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. This paper describes the application of these protocols in the North Carolina Piedmont.

In this study, protocols and diagnostic measures were 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, as illustrated in Figure 1. 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.

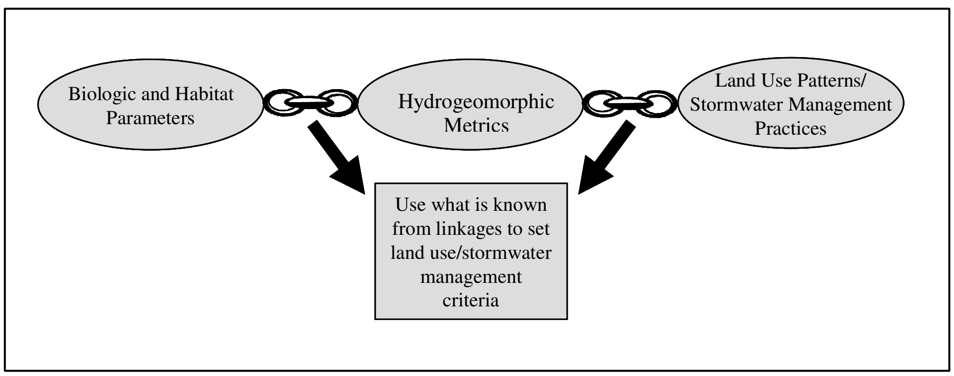


Figure 1. Establishing the link between urban development and stream ecologic health.

***Protocols for Evaluating Wet Weather Impacts and Urbanization Patterns***

The linkages described above can be developed using the protocol illustrated in Figure 2. 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.

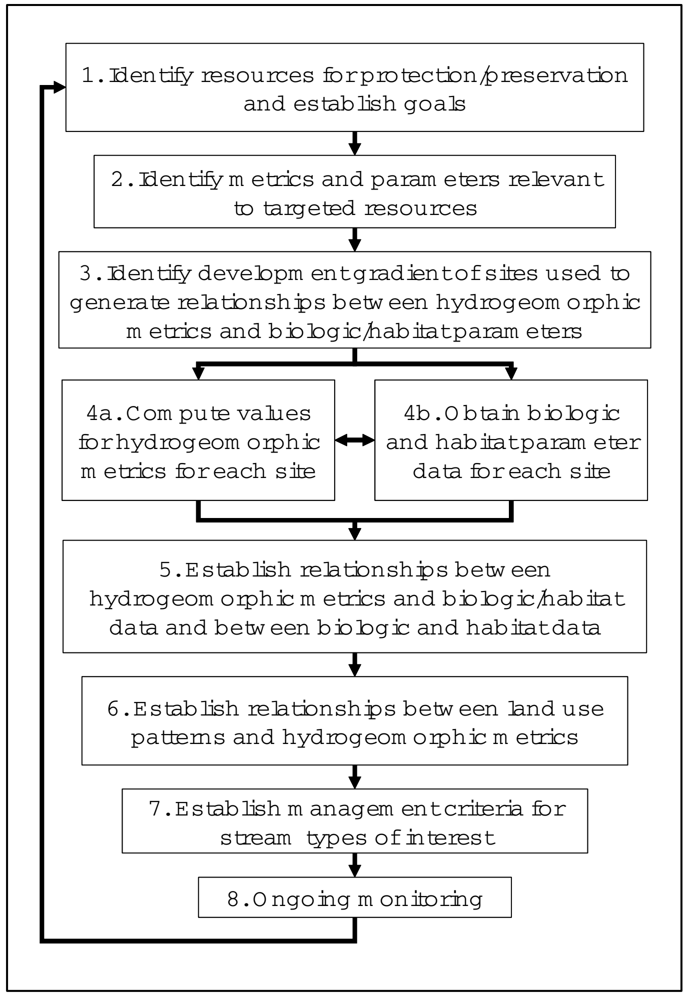

Figure 2. The Protocol

Biologic and habitat parameter measurements and continuous flow records must 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 can 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.

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.

***Application of the Protocol***

Eight watersheds spanning a gradient of urbanization in the North Carolina Piedmont were used to identify linkages between indicators of aquatic ecosystem health and hydrologic and geomorphic metrics derived from a 20-year continuous stream flow record. The eight watersheds evaluated in this project are also part of the United State's Geological Survey National Water Quality Assessment Program study of the effects of urbanization on stream ecosystems (USGS, 2007). The eight sites were selected as a subset of 30 in the USGS study, and were identified to represent a gradient of urbanization, but represent homogenous land use within the watershed, that is, land use was fairly uniform throughout the watershed. Basin size was restricted to less than 10 square miles, and sites with similar stream bed substrate were selected to minimize the effects of substrate on biologic sampling results. Lastly, watersheds without confounding factors such as point source discharges and dams were sought to minimize the additional impact of these impediments to aquatic health. Characteristics of the eight watersheds are given in Table 1.

Table 1. Watershed characteristics.

| Watershed | Area ($mi^2$) | UII[1] | 2000 Pop. Density (# / $mi^2$) | Housing Unit Density (# / $mi^2$) | Road Density (mi / $mi^2$) | Urban Land Cover (%) | Percent Total Impervious Area |
|---|---|---|---|---|---|---|---|
| STROUDS | 8.9 | 7.2 | 178 | 12 | 3.9 | 12.4 | 1.7 |
| MORGAN | 8.3 | 4.9 | 183 | 10 | 3.8 | 5.2 | 0.4 |
| CAMP | 3.2 | 12.9 | 414 | 31 | 4.2 | 18.1 | 5.6 |
| DUTCHMANS | 4.6 | 28.6 | 987 | 51 | 7.4 | 39.0 | 6.0 |
| WILSON | 3.5 | 24.1 | 767 | 61 | 6.1 | 23.6 | 9.0 |
| SW PRONG | 3.0 | 90.8 | 3204 | 198 | 16.4 | 94.4 | 11.7 |
| PIGEON | 4.5 | 100.0 | 3093 | 239 | 18.5 | 98.5 | 30.6 |
| BLACK | 3.6 | 79.6 | 3275 | 198 | 13.1 | 78.7 | 20.5 |

[1]Urban Intensity Index calculated by UGSS. (McMahon and Cuffney, 2000.)

Model Development and Calibration

Watersheds were modeled in EPA-SWMM using USGS GIS land coverages and field-determined data. Ground slope was calculated for the watershed using the Spatial Analyst tool in ArcGIS and a 10-m Digital Elevation Map (DEM) downloaded from the USGS (USGS Seamless 2006). The watershed was discritized into subcatchments using the ArcHydro extension of ArcGIS soils, imperious areas and calculated slopes were estimated for each subcatchment. Subcatchment infiltrations were then calculated using each soil's Hydrologic Group and an area-weighting method. Channel inverts were measured from North Carolina Department of Transportation (NC-DOT) contour maps and channel lengths were calculated in GIS.

Five watershed parameters determined from ArcGIS processing were then built into the EPA-SWMM 5 models; these parameters included area, slope, infiltration, runoff length, and imperviousness. Widths were estimated from aerial photos and used with estimated lengths to calculate the area of the roads in each subcatchment. Percent imperviousness was initially estimated from 30-m impervious surface coverages downloaded from the USGS but the values obtained were unrealistically small (1.6 % at largest). For this reason, the directly connected impervious area (DCIA) for all four rural catchments was assumed to be equal to the area of the roads based on the findings of Lee and Heaney (2003). The directly connected impervious area (DCIA) was then calculated through a weighted average in which the roads were 100% imperviousness and the rest of the subcatchment area was assumed to be totally pervious. Stream channels were modeled using irregularly-shaped cross sections using data collected measured during field surveys and their banks extended based on slopes determined from the NC-DOT contour maps to allow for the simulation of overbank flow in the model without creating a "flooding" condition within the model. Channel inlet offsets were also determined to prevent unrealistic flooding of the side channels during large flows.

Models were calibrated to 15-minute flow data collected by the USGS at the outlet of each watershed over a period of approximately 18 months, July 2002 – November 2003. Initially, models were calibrated to individual events with the adjustment of watershed parameters like percent imperviousness, infiltration, overland roughness, and conduit roughness, as is done in traditional stormwater modeling calibration. Peak discharges and volumes were matched for individual storms, but this calibration proved unsatisfactory when flow-duration curves and peak-flow frequency exceedance curves were examined. The duration of flows was of specific importance because this information is used to compute the hydrologic and geomorphic metrics used as part of the protocol.

Calibration of flow duration curves was not achieved for all events of record through the adjustment of watershed parameters alone. This was due to the large amount of base flow and interflow volume not modeled in the Storm Water Management Model (SWMM) but monitored at the USGS station. The elimination of base flow on a monthly basis from the USGS monitored record produced a better fit between the monitored and modeled flows for runoff events larger than the one percent cumulative exceedance but events smaller and more frequent than this were still not represented realistically due to the presence of interflow. It was determined that modeling this interflow through groundwater with default aquifer materials and changes to the coefficients of the SWMM groundwater equation did not result in realistic calibrations. However, it was determined that changes in aquifer materials did result in realistic calibrations along the entire length of the flow-duration curve.

<u>Preliminary Results</u>

One of the hydrologic metrics studied was the $T_{0.5}$ yr, the percent of time the 6-month discharge is exceeded, which was related by Booth et al. (2004) to the total impervious areas. The reduction of the value of this metric as imperviousness increases was observed by modeling the North Carolina watersheds, and is illustrated in Figure 1, which shows the $T_{0.5}$ yr for different watersheds in the North Carolina Piedmont, with Morgan (8.3 $mi^2$) and Pigeon (4.5 $mi^2$) having the lowest and highest imperviousness, respectively.

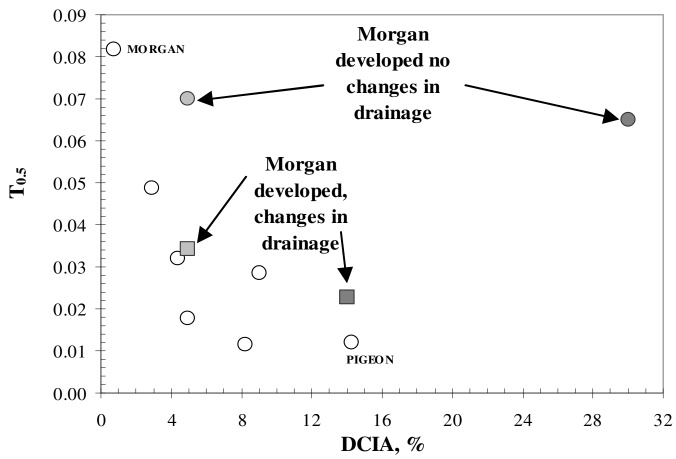


Figure 1. Changes in the T0.5 metric as related to DCIA.

When the watershed parameters were changed in Morgan to represent an urbanized watershed, (DCIA is increased form 4.92%, 30%) the model was not able to represent the reductions in this metric, i.e. $T_{0.5}$ yr = 0.08 for the undeveloped case, and $T_{0.5}$ yr = 0.065 for the completely urbanized case. These new urban developments were simulated applying the typical approach used to evaluate effects of small developments, which is to increase the percent directly connected impervious area, and reduce the manning coefficient, the initial storage and time of concentration. However, if stream channel cross sections that are typical of an urbanized stream are substituted for the existing channel cross sections (which represent the current undeveloped condition), the resulting $T_{0.5}$ yr is right in line with the value of the other watersheds that are currently urbanized. This finding reveals that modifications to the natural drainage structure must also be considered in evaluating the effects of urbanization on stream metrics, especially at watershed scales larger than a typical subdivision.

EPT (Ephemeroptera, Plecoptera, Trichoptera) richness was used as an indicator of aquatic ecosystem health, and was calculated from aquatic benthic macroinvertebrate sampling data collected by the USGS in 2004 for the Richest Targeted Habitat (RTH) and Qualitative Multi-Habitat (QMH). These results are compared with the $T_{0.5}$ year calculated from model output for each watershed, and are shown in Figure 2.

Next Steps

Geomorphic metrics used to evaluate linkages is erosion potential calculated using excess shear stress, which describes the energy exerted on the stream channel that is capable of causing bed scour and bank erosion. Methods described by Rohrer and Roesner (2006) will be used for this analysis.

The T0.5 metric values will be generated for the various land use and stormwater management practices and will be compared to those generated along the urbanization gradient to identify the management practices that best generate conditions favorable to meet ecologic targets. Anticipated results are shown in Figure 3.

***Acknowledgements***

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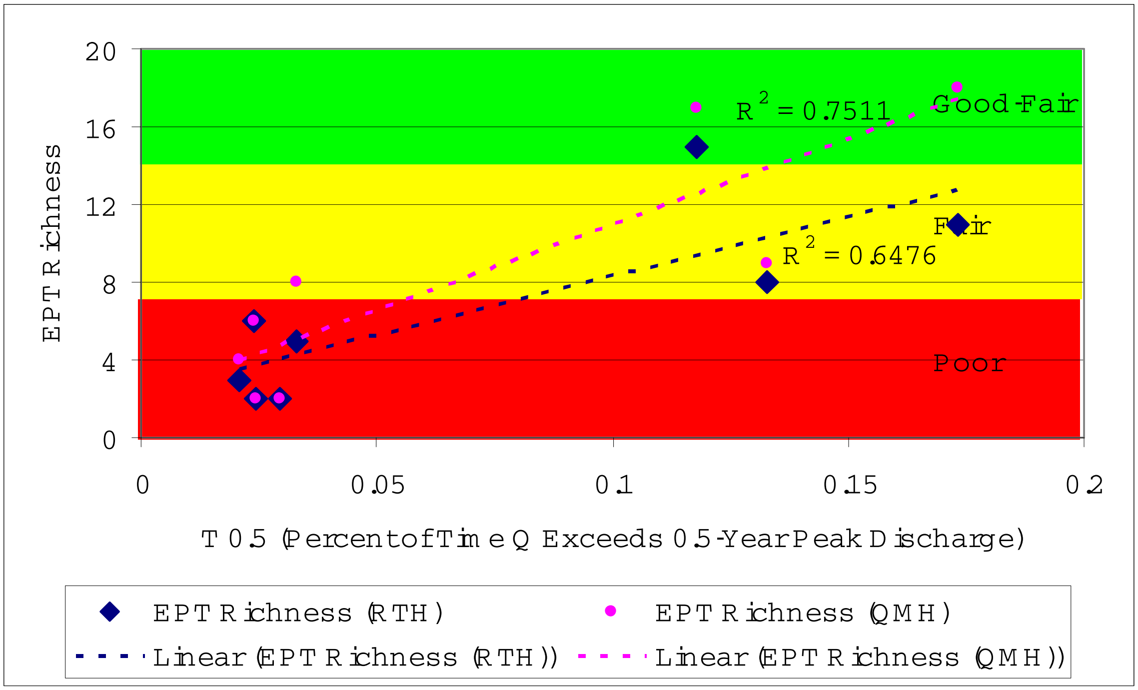


Figure 2. Relationship between EPT richness and $T_{0.5}$

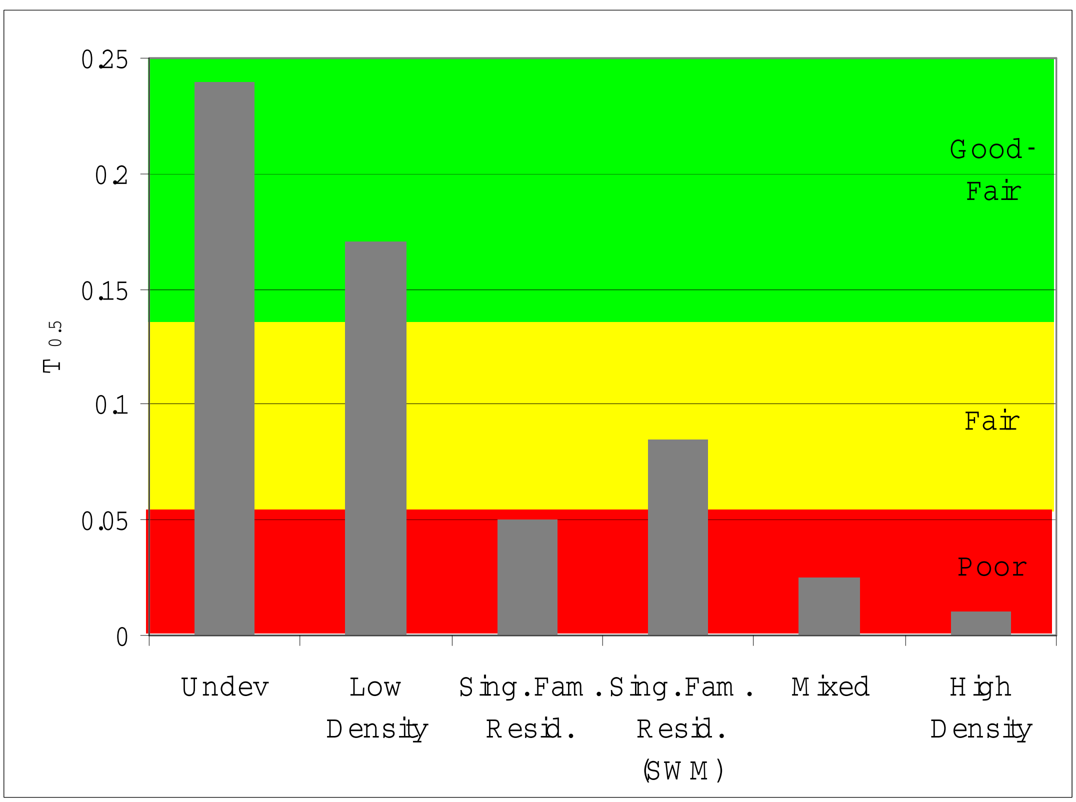


Figure 3. Anticipated $T_{0.5}$ values for various land use management practices