

THESIS

QUANTIFYING URBAN-INDUCED FLOW REGIME ALTERATION  
USING MATHEMATICAL MODELS AND HYDROLOGIC METRICS

Submitted by

John Lewis Edgerly

Department of Civil Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2006

COLORADO STATE UNIVERISTY

March 31, 2006

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JOHN LEWIS EDGERLY ENTITLED "QUANTIFYING URBAN-INDUCED FLOW REGIME ALTERATION USING MATHEMATICAL MODELS AND HYDROLOGIC METRICS" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

---

---

---

---

---

---

---

**Adviser**

---

**Department Head/Director**

# **ABSTRACT OF THESIS**

## **QUANTIFYING URBAN-INDUCED FLOW REGIME ALTERATION USING MATHEMATICAL MODELS AND HYDROLOGIC METRICS**

There is growing interest in identifying mechanistic linkages between watershed urbanization and associated geomorphic and ecological consequences in urban streams. Recognizing watershed hydrology as a key determinant in the structuring of ecological systems, an increasing number of researchers are attempting to characterize the ecologically important aspects of long-term stream flow patterns using statistically-based hydrologic metrics. This study brings a hydrologic metric approach to the context of stormwater controls at the scale of new urban development (10 ha), integrating a model-based scenario comparison approach, with a hydrologic metric approach aimed at quantifying ecologically important aspects of flow regime. Hydrologic metrics from previous studies were tailored to better suit the small-scale, urban context. In addition to a modified version of  $T_{0.5yr}$ , a set of event-based metrics, including three new flashiness metrics were proposed to quantify the magnitude, frequency, duration, and rates of change of storm flows. Algorithms were then programmed in MATLAB© to calculate the select set of metrics from 48-year, 15-minute continuous flow time series, generated by EPA SWMM4.4h. Potential climatic influences on metric behavior were examined by comparing metric behavior obtained by using rainfall from Fort Collins, CO and Atlanta,

GA. The influence of temporal resolution of flow data on metric values and its implications for the metric selection process were also investigated by comparing metrics computed at daily and 15-minute time-step resolutions. The modified  $T_{0.5yr}$ , along with the  $Q_p$ ,  $R_N$ ,  $F_N$ ,  $D$ ,  $t_p$ , and  $D_{peak}$  were found to be sensitive to differences between development scenarios and are thought to have potential for improving design of stormwater controls by providing a more complete consideration of flow regime than traditional design criteria. The  $t_p/D$  and  $D_{peak}/D$  metric were found to be relatively insensitive to development alternatives and were not recommended for use in future studies.

John Lewis Edgerly  
Department of Civil Engineering  
Colorado State University  
Spring 2006

## **ACKNOWLEDGEMENTS**

I would like to thank my advisor, Dr. Larry Roesner, for having confidence in me from the beginning and helping me grow as an engineer over the past two years. I feel fortunate to have had an advisor, who not only had a wealth of practical experience to share, but also had a perceptive understanding of people. I learned a lot from you Larry, thank you. I also appreciate the input and encouragement provided by my other committee members, Dr. LeRoy Poff and Dr. Jorge Ramirez.

I am grateful for the generosity of Harold H. Short and the Water Environment Research Foundation, whose financial support enabled me to complete this research.

Thank you, Christine Rohrer, for your continuous flow data, as well as your veteran insights and friendship along the way. I give special thanks to Jorge Gironàs, who not only helped me overcome my MATLAB illiteracy, but also served as an excellent brainstorming partner and an even better friend. Thank you, Ernesto Trujillo for your willingness to share programming tips. Thank you Dae Ryong Park and Yongdeok Cho for keeping me company on many late nights and weekends in the lab. Thanks to all my other HHS Lab cohorts, Ramadan Alkhatib, Jennifer Davis, Ivan Rivaz, and Liz Kidner for your encouragement over the years.

Lastly, I would like to thank my family and especially my mother for the love, guidance, and support given to me throughout my academic career and throughout my life.

## TABLE OF CONTENTS

|            |  |               |
|------------|--|---------------|
| <b>1.0</b> | <b>INTRODUCTION.....</b>   | <b>- 1 -</b>  |
| <b>2.0</b> | <b>LITERATURE REVIEW .....</b>                                       | <b>- 4 -</b>  |
| <b>2.1</b> | <b>Hydrologic and geomorphic effects of stormwater controls.....</b> | <b>- 5 -</b>  |
| <b>2.2</b> | <b>Ecologically-relevant hydrologic metrics.....</b>                 | <b>- 7 -</b>  |
| <b>2.3</b> | <b>Measuring ecological response to development .....</b>            | <b>- 11 -</b> |
| <b>2.4</b> | <b>Synthesis of literature review.....</b>                           | <b>- 14 -</b> |
| <b>3.0</b> | <b>STUDY APPROACH .....</b>  | <b>- 17 -</b> |
| <b>3.1</b> | <b>Study watershed and development scenarios.....</b>                | <b>- 18 -</b> |
| <b>4.0</b> | <b>METRIC SELECTION.....</b>   | <b>- 26 -</b> |
| <b>4.1</b> | <b>Spatial and temporal scale considerations.....</b>                | <b>- 26 -</b> |
| <b>4.2</b> | <b>Refining the select set of metrics.....</b>                       | <b>- 32 -</b> |
| <b>5.0</b> | <b>RESULTS AND DISCUSSION .....</b>                                  | <b>- 35 -</b> |
| <b>5.1</b> | <b>Patterns of annual metric behavior.....</b>                       | <b>- 35 -</b> |
| <b>5.2</b> | <b>Patterns of event-based metric behavior .....</b>                 | <b>- 37 -</b> |
| <b>6.0</b> | <b>CONCLUSIONS AND RECOMMENDATIONS.....</b>                          | <b>- 47 -</b> |
|            | <b>REFERENCES.....</b>   | <b>- 52 -</b> |
|            | <b>APPENDIX A: RAINFALL AND RUNOFF VOLUMES .....</b>                 | <b>- 55 -</b> |
|            | <b>APPENDIX B: MATLAB M-FILES CODE FOR EACH METRIC.....</b>          | <b>- 57 -</b> |
|            | <b>APPENDIX C: NUMERICAL VALUES OF METRICS .....</b>                 | <b>- 66 -</b> |

## LIST OF TABLES

|   |             |
|---|-------------|
| <b>Table 1: Comparison of runoff for undeveloped and developed scenarios.....</b>                                     | <b>5 -</b>  |
| <b>Table 2: Ecologically important aspects of flow regime.....</b>  | <b>8 -</b>  |
| <b>Table 3: Stream-type-specific optimal sets of hydrologic metrics.....</b>  | <b>10 -</b> |
| <b>Table 4: Hydrologic metrics most useful in urbanizing streams.....</b>   | <b>15 -</b> |
| <b>Table 5: Definitions of hydrologic metrics displayed in Table 2. ....</b>  | <b>16 -</b> |
| <b>Table 6: Watershed Characteristics: Developed Conditions.....</b>  | <b>21 -</b> |
| <b>Table 7: <math>T_{Q_{mean}}</math> values from 15-minute and daily mean flow time series. ....</b>                 | <b>29 -</b> |
| <b>Table 8: Select set of hydrologic metrics for model-based scenario analysis .....</b>                              | <b>34 -</b> |
| <b>Table 9: Event-based metrics Fort Collins .....</b>  | <b>40 -</b> |
| <b>Table 10: Event-based metrics Atlanta.....</b>   | <b>41 -</b> |
| <b>Table 11: Numerical values of metric medians and IRs <math>T_{Q_{mean}}</math> and <math>T_{0.5yr}</math>.....</b> | <b>67 -</b> |

## LIST OF FIGURES

|  |        |
|--|--------|
| Figure 1: Effects of extended detention basin .....                                      | - 6 -  |
| Figure 2: $T_{Q_{mean}}$ and $T_{0.5yr}$ versus percent impervious area.....             | - 11 - |
| Figure 3: $T_{Q_{mean}}$ and $T_{0.5yr}$ versus B-IBI area Pacific Northwest.....        | - 11 - |
| Figure 4: The study watershed in Fort Collins, CO. ....                                  | - 19 - |
| Figure 5: The hypothetical medium density residential neighborhood .....                 | - 20 - |
| Figure 6: Peak flow exceedance frequency in Subarea 1300: Atlanta. ....                  | - 23 - |
| Figure 7: Peak flow exceedance frequency in Subarea 1300: Fort Collins .....             | - 23 - |
| Figure 8: Flow duration curves for development scenarios in Fort Collins.....            | - 27 - |
| Figure 9: $T_{Q_{mean}}$ for increasing percentages of impervious area .....             | - 30 - |
| Figure 10: $T_{0.5yr}$ for increasing percentages of impervious area. ....               | - 31 - |
| Figure 11: <i>modified</i> $T_{0.5yr}$ for multiple scenarios of development.....        | - 36 - |
| Figure 12: Total number of events occurring for each scenario. ....                      | - 38 - |
| Figure 13: Event-based metrics for Fort Collins and Atlanta $Q_p$ , $R_n$ , $F_n$ ... .. | - 39 - |
| Figure 14: Event-based metrics for Fort Collins and Atlanta $D$ , $tp$ , $tp/D$ .....    | - 39 - |
| Figure 15: Peak duration and peak duration ratio.....                                    | - 45 - |
| Figure 16: Rainfall duration versus volume Ft. Collins and Atlanta.....                  | - 56 - |

## **1.0 INTRODUCTION**

The hydrologic consequences of urban development include increased magnitude and frequency of erosive peak flows, decreased lag time to peak, increased rise and fall rates, as well as increased cumulative duration of storm flows (Walsh et al. 2005). These increases in the peak discharges and cumulative durations of storm flows have logical implications for the geomorphic stability and ecological integrity of receiving streams. Further urban development is inevitable; the question that needs to be answered is how to design runoff controls for new developments to minimize the detrimental effects on stream ecosystems. Research regarding the effect of structural stormwater controls on peak flow frequency curves (Nehrke and Roesner 2004), flow duration curves, and sediment transport in urban streams (Rohrer 2004) has answered part of this question by demonstrating that stormwater controls can achieve post-development peak flow frequency and flow duration curves that are much closer to the pre-development case than those for development without stormwater controls. The next step is to find a way of linking the hydrologic consequences of urban development to ecological outcomes in receiving streams. The overall objective of this thesis is to explore the possibility of establishing this link between runoff controls and ecological outcomes in receiving streams by use of hydrologic metrics.

Previous research efforts investigating the ecological effects of urbanization have been conducted at spatial scales that are too large to draw conclusions about individual system components or to evaluate specific combinations of structural runoff controls

(Roesner and Bledsoe 2003). Analyzing urban-induced hydrologic alteration at the neighborhood scale is meaningful from an engineering perspective, as this is the typical design scale of new urban developments and their respective runoff controls.

Flow is a major driver behind many processes that ultimately determine the state of stream ecosystems (Poff et al. 1997; Bunn and Arthington 2002; Roesner and Bledsoe 2003); however, it can be very difficult to determine which mechanism is directly responsible for observed impacts in a stream (Bunn and Arthington 2002). The five aspects of flow regime identified in the natural flow paradigm as most important to the geomorphology, physical habitat, and ultimately stream biota are: magnitude, frequency, duration, timing, and rate of change (Poff et al. 1997). Hydrologic metrics that demonstrate altered stream flow regimes can provide a direct mechanistic link between aspects of urban development and degraded stream ecosystems (Booth et al. 2004).

A key disadvantage of empirical urban gradient and paired watershed approaches is the potential difficulty of differentiating between hydrologic differences due to watershed characteristics, other than degree of urbanization, and those actually caused by urbanization. Similarly, such an approach is restricted in its ability to isolate and evaluate the hydrologic effects of specific aspects of drainage design or various mitigation strategies. These weaknesses are due in large part to a lack of flow data in watersheds of this scale, (Roesner and Bledsoe 2003), restricting empirical approaches to the large scale. Since flow regime analyses require long-term, continuous flow data (i.e. greater than 10 to 20 years of record) (Konrad and Booth 2002; Richter et al. 1997), which is not readily available in small watersheds, it is hypothesized in this paper that continuous simulation with mathematical models, in conjunction with a hydrologic metric approach, can provide an approximate quantification of the flow regime alteration expected for

various scenarios of development. In addition to being a common design tool for stormwater controls, mathematical models can isolate the effects of specific aspects of urban development by holding all other watershed properties constant. Runoff resulting from multiple development scenarios for the same watershed can then be simulated and used to evaluate the efficacy of mitigation strategies in terms of ecologically-relevant hydrologic metrics. Such an approach has potential for improving drainage design and mitigation strategies.

## **2.0 LITERATURE REVIEW**

Review of recent literature has revealed 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 methods that move beyond using gross measures of imperviousness as predictors of biologic integrity by establishing clearer relationships between land cover and hydrologic response, and identifying mechanisms through which altered flow regimes affect stream ecosystems. Studies that examine the factors important for the success of specific organisms, or groups of organisms, provide insight regarding vital physical habitat and flow requirements necessary to support healthy lotic ecosystems. Increasingly, researchers are taking an ecosystem-based approach to studying the effects of urbanization on streams that starts with an ecological endpoint and reasons backwards to identify the causal chain of determining factors for desired ecological outcomes. There is much potential for integrating engineering and ecological approaches to better understand the mechanisms impacting urban streams and ultimately improve mitigation strategies.

In the past, studies have typically referred to the influences of urbanization in terms of percent impervious area or percent land cover, without specifically addressing land use types or stormwater management practices such as conveyance characteristics, (e.g. pipes or swales), the use of detention, or best management practices (BMPs). The dominant trend in these studies was to use simple linear regressions to link gross percentage of impervious area in a watershed with biological populations (Center for

Watershed Protection 2002; Roesner and Bledsoe 2003). Walsh (2004) recommends that efforts to restore streams in urban catchments should start with attention to the catchment drainage system.

## 2.1 Hydrologic and geomorphic effects of stormwater controls

Consideration of drainage design is essential for an adequate analysis of how to mitigate the impacts of urban stormwater runoff on stream ecosystems (Roesner and Bledsoe 2003; Walsh 2004). Models have proven useful in scenario analyses of the effects of alternative development scenarios on peak flow frequency curves (Nehrke and Roesner 2004) and flow duration and sediment transport potential in urban streams (Rohrer 2004). Table 1, taken from Nehrke and Roesner (2004), demonstrates the extent to which urban development increases the number of runoff events per year and the total volume of runoff.

**Table 1: Comparison of runoff events for undeveloped and developed scenarios in Fort Collins, CO and Atlanta, GA**

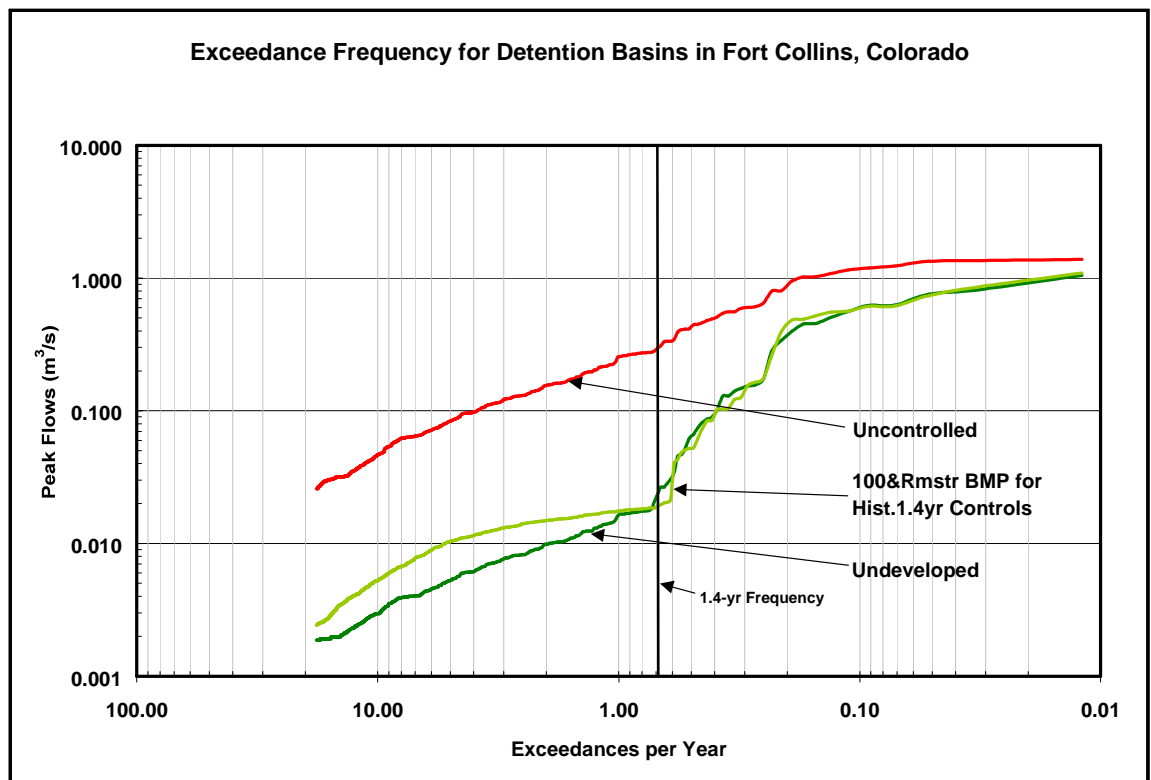
| Location               | Annual Precipitation | Mean Storm Depth* | Runoff Events per Year |           | Annual Runoff (mm) |           |
|------------------------|----------------------|-------------------|------------------------|-----------|--------------------|-----------|
|                        | mm/Year              | mm                | Undeveloped            | Developed | Undeveloped        | Developed |
| <b>Ft. Collins, CO</b> | 335                  | 11                | 27                     | 47        | 12                 | 124       |
| <b>Atlanta, GA</b>     | 1262                 | 18                | 48                     | 78        | 36                 | 500       |

\* Values obtained from Fig. 5.3 ASCE MOP (1998)

Source: Nehrke and Roesner (2004)

Nehrke and Roesner (2004) used the United States Environmental Protection Agency's Stormwater Management Model (SWMM) (OSU 2001) to show that the appropriate outlet configuration for detention pond storage was effective at producing a post-development peak flow frequency curve that closely resembles the undeveloped peak flow frequency curve, as shown in Figure 1. Rohrer (2004) used SWMM to

analyze the effects of development and extended detention controls on flow duration curves and quantified the consequences of modified flow duration curves for sediment transport in urban stream channels. Rohrer (2004) found that the critical portion of the post-development flow duration curve could be matched to the corresponding portion of the pre-development flow duration curve to minimize the increase in erosion potential in urban stream channels in response to urban development.



**Figure 1: Effects of extended detention basin designed to historical levels in Fort Collins, CO.**

Source: Nehrke and Roesner (2004)

The increases in the peak discharges and cumulative durations of storm flows, documented in these two studies, have logical implications for the geomorphic stability and ecological integrity of receiving streams and their findings point toward engineering solutions to these problems. However, a more direct method of relating hydrologic changes associated with urban development to stream ecology is needed.

## **2.2 Ecologically-relevant hydrologic metrics**

Stream ecologists have long been studying the effects of flow alteration on aquatic ecosystems, primarily in the context of flow regulation following dam construction (Bovee et al. 1998; Gore et al. 2001, Tharme 2003). Early efforts in this regard were criticized for oversimplification of the system and lack of proven relevance to biotic integrity (Jacobson et al. 2001). Another common weakness of many environmental flow methodologies was that they focused on meeting the needs of a few target species and, in doing so, failed to meet the needs of many non-target species (Gore et al. 2001). Recognition of these weaknesses led to the development of a natural flow paradigm, viewing entire stream ecosystems as single entities that are shaped and maintained over time by unique flow regimes. The aspects of flow regime thought to be ecologically important are magnitude, duration, frequency, timing, and rate of change of flows (Poff and Ward 1989; Poff 1996; Richter et al. 1996; Poff et al.1997). The five ecologically important flow components are shown in Table 2 along with some examples of how their alteration influences ecology.

The natural flow paradigm was operationalized by Richter et al. (1996) with the Indicators of Hydrologic Alteration (IHA), which gained popularity because of its associated software package that provided ease of computation. The IHA is a set of 32 statistical flow metrics, computed from long-term time-series of daily mean flow, to quantify the ecologically relevant aspects of flow regimes. A method for using the IHA to set management targets, called the Range of Variability Approach (RVA), was later developed by Richter et al. (1997). The RVA uses a range of natural variability about a measure of central tendency to determine acceptable degrees of flow regime alteration resulting from human activity in a watershed. This approach recommends that non-

parametric measures of central tendency and variation be used because of the unequal variances common in hydrologic data (Richter et al. 1999; IHA Software User's Manual 2001).

**Table 2: Ecologically important aspects of flow regime.**

| Flow component          | Specific alteration          | Ecological response   | Reference(s)   |
|-------------------------|------------------------------|---|--|
| Magnitude and frequency | Increased variation          | Wash-out and/or stranding<br>Loss of sensitive species  | Cushman 1985, Petts 1984<br>Gehrke et al. 1995, Kingsolving and Bain 1993, Travnicek et al. 1995   |
|                         |                              | Increased algal scour and wash-out of organic matter  | Petts 1984   |
|                         |                              | Life cycle disruption   | Scheidegger and Bain 1995  |
|                         | Flow stabilization           | Altered energy flow<br>Invasion or establishment of exotic species, leading to:<br>Local extinction<br>Threat to native commercial species<br>Altered communities   | Valentin et al. 1995<br>Kupferberg 1996, Meffe 1984<br>Stanford et al. 1996<br>Busch and Smith 1995, Moyle 1986, Ward and Stanford 1979  |
|                         |                              | Reduced water and nutrients to floodplain plant species, causing:<br>Seedling desiccation<br>Ineffective seed dispersal<br>Loss of scoured habitat patches and secondary channels needed for plant establishment  | Duncan 1993<br>Nilsson 1982<br>Fenner et al. 1985, Rood et al. 1995, Scott et al. 1997, Shankman and Drake 1990  |
|                         |                              | Encroachment of vegetation into channels  | Johnson 1994, Nilsson 1982   |
| Timing                  | Loss of seasonal flow peaks  | Disrupt cues for fish:<br>Spawning  | Fausch and Bestgen 1997,<br>Montgomery et al. 1993, Nesler et al. 1988   |
|                         |                              | Egg hatching<br>Migration   | Næsje et al. 1995<br>Williams 1996   |
|                         |                              | Loss of fish access to wetlands or backwaters<br>Modification of aquatic food web structure<br>Reduction or elimination of riparian plant recruitment<br>Invasion of exotic riparian species<br>Reduced plant growth rates  | Junk et al. 1989, Sparks 1995<br>Power 1992, Wootton et al. 1996<br>Fenner et al. 1985<br>Horton 1977<br>Reilly and Johnson 1982   |
|                         |                              | Concentration of aquatic organisms<br>Reduction or elimination of plant cover<br>Diminished plant species diversity<br>Desertification of riparian species composition<br>Physiological stress leading to reduced plant growth rate, morphological change, or mortality | Cushman 1985, Petts 1984<br>Taylor 1982<br>Taylor 1982<br>Busch and Smith 1995, Stromberg et al. 1996<br>Kondolf and Curry 1986, Perkins et al. 1984, Reilly and Johnson 1982, Rood et al. 1995, Stromberg et al. 1992 |
|                         |                              | Downstream loss of floating eggs  | Robertson 1997   |
| Duration                | Prolonged low flows          |   |  |
|                         | Prolonged baseflow "spikes"  | Altered plant cover types   | Auble et al. 1994  |
|                         | Altered inundation duration  | Change in vegetation functional type<br>Tree mortality<br>Loss of riffle habitat for aquatic species  | Bren 1992, Connor et al. 1981<br>Harms et al. 1980<br>Bogan 1993   |
|                         | Prolonged inundation         |   |  |
| Rate of change          | Rapid changes in river stage | Wash-out and stranding of aquatic species   | Cushman 1985, Petts 1984   |
|                         | Accelerated flood recession  | Failure of seedling establishment   | Rood et al. 1995   |

Source: Poff et al. 1997

Regression of hydrologic metrics with biological data has become increasingly common in recent years. The use of large numbers of metrics, while providing a computational burden, also poses the risk of multicollinearity, leading to confounded

results when used for regression with biological data (Olden and Poff 2003). To address this issue, several researchers have conducted studies using principal components analysis (PCA) to identify groups of hydrologic metrics that provide similar information, in order to minimize the number of metrics necessary for ecological studies (Clausen and Biggs 2000; Olden and Poff 2003). The most extensive study of this kind was conducted by Olden and Poff (2003), in which they computed 171 hydrologic metrics for 420 streams throughout the United States, which were then used in a PCA. They provided a framework for identifying sets of hydrologic metrics that adequately characterize flow regimes in a non-redundant manner. Its authors recommend that this framework be used, whenever possible, in conjunction with more intuitive metric selection criteria based on the particular ecological question of interest. In addition to the nation-wide PCA, using data from all streams, they performed multiple PCA's on metrics from groups of flow data, which was separated into stream types according to criteria from Poff (1996). A notable finding in their analysis was that optimal sets of metrics explaining dominant patterns of variance in hydrologic data were flow-regime-type-specific, demonstrating that hydroclimatic characteristics of a study region should be considered when determining appropriate hydrologic indices for a particular study. The metrics with the highest absolute loadings in the PCA are grouped by 'stream type' in Table 3. They also note that the question still remains as to whether hydrologic metrics can be geographically transferred between regions of differing climatic and geomorphic settings.

**Table 3: Stream-type-specific optimal sets of hydrologic metrics**

| Flow component                                      | Stream classification                                   |  |                                      |                                      |   |   | All streams  |
|---|---|--|--------------------------------------|--------------------------------------|---|---|--|
|   | Intermittent  |  |                                      | Perennial                            |   |   |  |
|   | Harsh intermittent                                      | Intermittent flashy or runoff  | Snowmelt                             | Snow and rain                        | Superstable or stable groundwater                       | Perennial flashy or runoff                              |  |
| Magnitude of flow events<br>Average flow conditions | M <sub>A</sub> 34, M <sub>A</sub> 22, M <sub>A</sub> 16 | M <sub>A</sub> 37, M <sub>A</sub> 18, M <sub>A</sub> 21, M <sub>A</sub> 9  | M <sub>A</sub> 29, M <sub>A</sub> 40 | M <sub>A</sub> 3, M <sub>A</sub> 44  | M <sub>A</sub> 3, M <sub>A</sub> 41, M <sub>A</sub> 8   | M <sub>A</sub> 26, M <sub>A</sub> 41, M <sub>A</sub> 10 | M <sub>A</sub> 5, M <sub>A</sub> 41, M <sub>A</sub> 3, M <sub>A</sub> 11   |
| Low flow conditions                                 | M <sub>L</sub> 13, M <sub>L</sub> 15, M <sub>L</sub> 1  | M <sub>L</sub> 16, M <sub>L</sub> 6, M <sub>L</sub> 22, M <sub>L</sub> 15  | M <sub>L</sub> 13, M <sub>L</sub> 22 | M <sub>L</sub> 13, M <sub>L</sub> 14 | M <sub>L</sub> 18, M <sub>L</sub> 14, M <sub>L</sub> 16 | M <sub>L</sub> 17, M <sub>L</sub> 14, M <sub>L</sub> 16 | M <sub>L</sub> 17, M <sub>L</sub> 4, M <sub>L</sub> 21, M <sub>L</sub> 18  |
| High flow conditions                                | M <sub>H</sub> 23, M <sub>H</sub> 14, M <sub>H</sub> 9  | M <sub>H</sub> 23, M <sub>H</sub> 4, M <sub>H</sub> 14, M <sub>H</sub> 7   | M <sub>H</sub> 1, M <sub>H</sub> 20  | M <sub>H</sub> 17, M <sub>H</sub> 20 | M <sub>H</sub> 17, M <sub>H</sub> 19, M <sub>H</sub> 10 | M <sub>H</sub> 23, M <sub>H</sub> 8, M <sub>H</sub> 14  | M <sub>H</sub> 16, M <sub>H</sub> 8, M <sub>H</sub> 10, M <sub>H</sub> 14  |
| Frequency of flow events<br>Low flow conditions     | F <sub>L</sub> 2, F <sub>L</sub> 3, F <sub>L</sub> 1    | F <sub>L</sub> 3, F <sub>L</sub> 2, F <sub>L</sub> 1                       | F <sub>L</sub> 3, F <sub>L</sub> 2   | F <sub>L</sub> 3, F <sub>L</sub> 2   | F <sub>L</sub> 3, F <sub>L</sub> 1, F <sub>L</sub> 2    | F <sub>L</sub> 3, F <sub>L</sub> 2, F <sub>L</sub> 3    | F <sub>L</sub> 3, F <sub>L</sub> 2, F <sub>L</sub> 3, F <sub>L</sub> 1     |
| High flow conditions                                | F <sub>H</sub> 2, F <sub>H</sub> 5, F <sub>H</sub> 7    | F <sub>H</sub> 3, F <sub>H</sub> 7, F <sub>H</sub> 2, F <sub>H</sub> 10    | F <sub>H</sub> 8, F <sub>H</sub> 11  | F <sub>H</sub> 3, F <sub>H</sub> 5   | F <sub>H</sub> 3, F <sub>H</sub> 6, F <sub>H</sub> 11   | F <sub>H</sub> 4, F <sub>H</sub> 6, F <sub>H</sub> 7    | F <sub>H</sub> 3, F <sub>H</sub> 6, F <sub>H</sub> 7, F <sub>H</sub> 2     |
| Duration of flow events<br>Low flow conditions      | D <sub>L</sub> 13, D <sub>L</sub> 1, D <sub>L</sub> 2   | D <sub>L</sub> 18, D <sub>L</sub> 16, D <sub>L</sub> 13, D <sub>L</sub> 1  | D <sub>L</sub> 5, D <sub>L</sub> 16  | D <sub>L</sub> 6, D <sub>L</sub> 13  | D <sub>L</sub> 9, D <sub>L</sub> 11, D <sub>L</sub> 16  | D <sub>L</sub> 10, D <sub>L</sub> 17, D <sub>L</sub> 6  | D <sub>L</sub> 18, D <sub>L</sub> 17, D <sub>L</sub> 16, D <sub>L</sub> 13 |
| High flow conditions                                | D <sub>H</sub> 19, D <sub>H</sub> 5, D <sub>H</sub> 22  | D <sub>H</sub> 13, D <sub>H</sub> 15, D <sub>H</sub> 12, D <sub>H</sub> 23 | D <sub>H</sub> 19, D <sub>H</sub> 16 | D <sub>H</sub> 12, D <sub>H</sub> 24 | D <sub>H</sub> 11, D <sub>H</sub> 20, D <sub>H</sub> 15 | D <sub>H</sub> 13, D <sub>H</sub> 16, D <sub>H</sub> 24 | D <sub>H</sub> 13, D <sub>H</sub> 16, D <sub>H</sub> 20, D <sub>H</sub> 15 |
| Timing of flow events                               | T <sub>H</sub> 1, T <sub>L</sub> 2, T <sub>H</sub> 2    | T <sub>A</sub> 1, T <sub>A</sub> 2, T <sub>L</sub> 1, T <sub>H</sub> 3     | T <sub>A</sub> 1, T <sub>A</sub> 3   | T <sub>A</sub> 1, T <sub>L</sub> 1   | T <sub>A</sub> 1, T <sub>H</sub> 1, T <sub>L</sub> 2    | T <sub>A</sub> 1, T <sub>A</sub> 3, T <sub>H</sub> 3    | T <sub>A</sub> 1, T <sub>H</sub> 3, T <sub>A</sub> 1, T <sub>L</sub> 2     |
| Rate of change in flow events                       | R <sub>A</sub> 4, R <sub>A</sub> 1, R <sub>A</sub> 5    | R <sub>A</sub> 9, R <sub>A</sub> 6, R <sub>A</sub> 5, R <sub>A</sub> 7     | R <sub>A</sub> 1, R <sub>A</sub> 8   | R <sub>A</sub> 9, R <sub>A</sub> 8   | R <sub>A</sub> 9, R <sub>A</sub> 8, R <sub>A</sub> 5    | R <sub>A</sub> 9, R <sub>A</sub> 7, R <sub>A</sub> 6    | R <sub>A</sub> 9, R <sub>A</sub> 8, R <sub>A</sub> 6, R <sub>A</sub> 5     |

For example, based on all 420 streams the hydrologic indices M<sub>A</sub>5, M<sub>A</sub>41, M<sub>A</sub>3, M<sub>A</sub>11 exhibit the largest absolute loadings; on first, second, third and fourth principal components, respectively, for the magnitude of average flow conditions. Bold indices represent Indicators of Hydrologic Alteration.

Source: Olden and Poff (2003)

The same rationale for setting target ranges of variability, recommended in the RVA, was later employed by the authors of the National Hydroecologic Assessment Tool (NATHAT) at the United States Geological Survey (USGS). The NATHAT software, which is conceptually similar to the IHA software, is capable of computing the 171 hydrologic metrics, examined in Olden and Poff (2003), from a continuous time series of mean daily flows. In the NATHAT approach, results from the Olden and Poff (2003) nation-wide PCA are provided as guidance for selecting optimal sets of metrics based on stream type (Henriksen et al. 2006). The software is only available in a Beta version, but its first major application is underway in New Jersey, where the Olden and Poff (2003) framework was used to identify optimal sets of metrics for New Jersey's own refined list of stream types. Characterizing unique natural stream flow regimes with metrics is gaining interest among environmental managers at the state level throughout North America (Jim Henriksen, personal communication 2005).

### **2.3 Measuring ecological response to development**

Hydrologic metrics that indicate altered stream flows have the potential to provide more direct mechanistic links between specific hydrologic changes associated with urban development and declines in stream biological condition (Booth et al. 2004). A number of researchers have used hydrologic metrics in urban gradient studies to establish statistical relationships between urbanization, hydrology, hydraulics, and biota (Scoggins 2000; Kirby 2003; Booth et al. 2004).

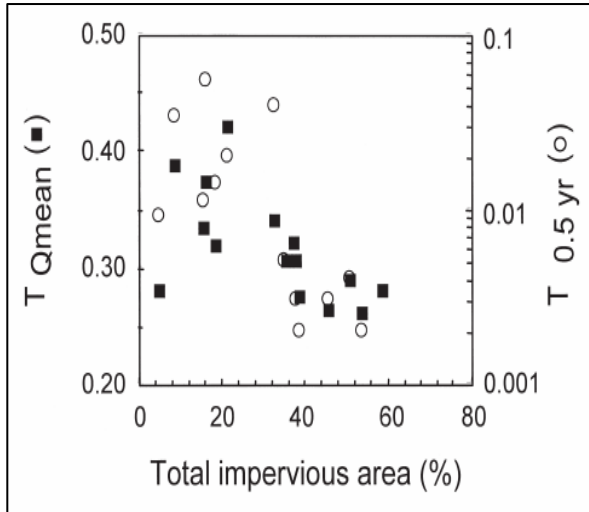
Scoggins (2000) analyzed six years of Rapid Bioassessment (RBA) data from urban streams in the city of Austin, TX in conjunction with continuous daily mean flow data from United States Geological Survey (USGS) gages at the outlets of catchments. He demonstrated that these procedures were useful for differentiating between effects of

varying levels of development, and the influence of natural geologic and hydrologic conditions, on the structure and composition of biology present in streams. Parameters such as rise rate, number of high pulses and number of zero flow days were found to be much higher in the developed stream than in the undeveloped stream. The results of his regression analysis indicated significant relationships between the biological metrics and the duration of high pulses, the date of the one-day maximum flow, percent of floods in a 60-day period and the annual coefficient of variation.

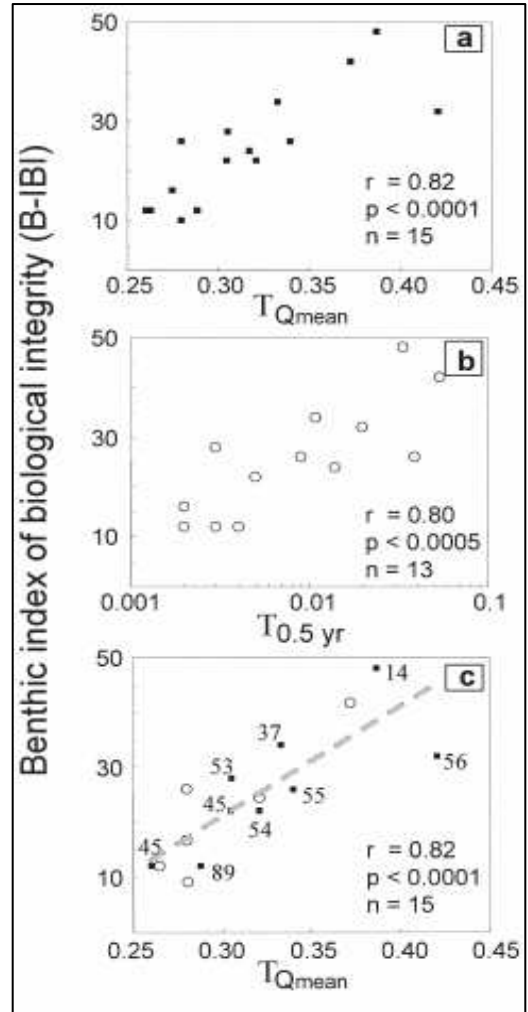
Kirby (2003) found relationships between hydrology, hydraulics and stream biotic condition, using the IHA method to characterize flow regimes along an urban gradient in the Potomac River Basin. Additionally, some in-stream hydraulic parameters were estimated using HEC-RAS. In that analysis, statistical relationships were established between specific hydrologic and hydraulic variables and macroinvertebrate community integrity. The results of a PCA and a non-parametric correlation analysis between hydrologic metrics and macroinvertebrate indices, showed altered flow predictability and flashiness (rise and fall rates) to be the most significant hydrologic parameters related to benthic macroinvertebrate community health in terms of the normalized number of significant relationships with macroinvertebrate metrics.

Booth et al. (2004) used hydrologic metrics to characterize annual distribution of storm flow relative to recessional and base flow patterns for a twelve-year period. The fraction of the year that the daily mean discharge rate exceeds the annual mean discharge rate,  $T_{Q_{mean}}$ , was calculated as an indicator of flashiness. They chose the  $T_{0.5yr}$  metric, the fraction of time in a multiple-year period that the flow rate exceeds the peak discharge with a historical six-month return period, as a measure of flashiness as well as for its plausible geomorphic and ecologic importance (Konrad 2000). Regression of these

metrics with total impervious area and index of biological integrity are shown in Figures 2 and 3. For these metrics, lower values indicate a flashier flow regime because high flows tend to increase in frequency, but not event-duration, as a result of urban development. In other words, there are more high flow events following development and this is the cause of increased cumulative flow durations (Booth et al. 2004).



**Figure 2: Discharge flashiness as measured by two hydrologic metrics.  $T_{Qmean}$  on the left axis;  $T_{0.5yr}$  on the right axis; lower values are flashier (Booth et al. 2004).**



**Figure 3: Relationship between B-IBI and (a)  $T_{Qmean}$  and (b)  $T_{0.5yr}$ . In (c) numbers indicate local urban land cover percentage - sites plotted as circles lack local land cover data (Booth et al. 2004).**

## **2.4 Synthesis of literature review**

In summary, research efforts involving hydrologic metrics in an urban context have predominantly been aimed at examining correlations between hydrologic metrics, calculated from daily mean flow gage data for multiple watersheds along an urbanizing gradient, where the degree of urbanization was measured by various land-use metrics (i.e. percent impervious area, road density, etc.) The hydrologic metrics were then used in multiple regression analyses with biological data (usually benthic macroinvertebrates) to establish relationships. The results of these studies provide clues about types of metrics likely to be meaningful in urban applications. Measures of flow flashiness, variability, and timing were determined to be useful predictors of macroinvertebrate community status in three urban gradient studies, in three climatically different regions. Table 4 presents the hydrologic metrics found to be most useful in each study and Table 5 lists the metric definitions. The fact that similar observations were made, regarding the types of metrics important to biota, in areas with very different rainfall patterns and stream types, lends support to the idea that some general insights may be transferable among regions.

From a geomorphic perspective, it makes sense that flashiness was found to be an important variable for benthic macroinvertebrates. Increased flashiness is thought to be a cause of bank instability via pre-wetting, desiccation, and/or rapid drawdown (Bledsoe 2002). Bank failure could affect macroinvertebrates by filling the interstitial spaces with sudden excesses of sediment (Waters 1995). Also, measures of flashiness based on fraction of the year that the flow exceeds a geomorphically significant flow (i.e. the half-year storm) are likely related to the extent of sediment transport and extent of bed disturbance and in turn, persistence of ambient habitat (Booth et al. 2004).

**Table 4: Comparison of hydrologic metrics found to be most useful for predicting biotic integrity in urbanizing streams.**

| Study               | Location        | Watershed Areas       | Measure of Biotic Integrity | Useful Hydrologic Metric for Predicting Biotic Integrity | Flow Regime Characteristic Represented by Metric | Geomorphic Relevance                   |
|---------------------|-----------------|-----------------------|-----------------------------|--|--|--|
| Scoggins (2000)     | Austin, TX      | 31-57 km <sup>2</sup> | 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 the One-day Maximum Flow                         | Timing/Predictability                            | N/A                                    |
| Booth et al. (2004) | Puget Sound, WA | 5-69 km <sup>2</sup>  | Invertebrates               | T <sub>Qmean</sub>                                       | Flow Variability and Flashiness                  | Sediment Transport and Bed Disturbance |
|                     |                 |                       |                             | T <sub>0.5yr</sub>                                       | Flow Variability and Flashiness                  | Sediment Transport and Bed Disturbance |
| Kirby (2003)        | Virginia        | Not specified         | Invertebrates               | Rise/Fall Rates of Hydrograph                            | Flashiness                                       | Bank instability                       |
|                     |                 |                       |                             | High Pulse Count   | Flashiness                                       | Sediment Transport and Bed Disturbance |
|                     |                 |                       |                             | Date of the One-day Maximum Flow                         | Timing/Predictability                            | N/A                                    |

Stormwater controls for new developments are commonly designed using mathematical models, such as the US EPA's Stormwater Management Model (SWMM) (OSU 2001), making mathematical models a convenient entry point from an engineering perspective. A model-based analysis, that considers multiple aspects of flow regime

with ecological importance, could address some of the questions left unanswered by empirical metric applications. Such an approach is a necessary first step towards improved drainage design through the integration of analytical approaches from stream ecology and engineering. If the output from models can be translated into a form that is both relevant to design and meaningful to statistically-based studies of urban stream ecology, a more complete assessment of tradeoffs can be incorporated into the design process. Hydrologic metrics could be used to determine the effects of stormwater controls on ecologically-relevant aspects of flow regime, providing an inferred link between alternative drainage designs and plausible ecological consequences associated with each alternative.

**Table 5: Definitions of hydrologic metrics displayed in Table 2.**

| <b>Study</b>               | <b>Hydrologic Metric</b>                | <b>Definition</b>  |
|----------------------------|---|--|
| <b>Scoggins (2000)</b>     | <b>% of floods in a 60-day period</b>   | Common 60-day period for multi-year flow record that contains the largest percentage of floods (Poff and Ward 1989).   |
|                            | <b>Mean Annual CV</b>                   | The average over all years of the mean flow divided by the standard deviation times 100 (Poff and Ward 1989).  |
|                            | <b>High Pulse Duration</b>              | Mean duration of high flood pulses, where high flood pulses are defined as the 75 <sup>th</sup> percentile (Richter et al. 1996).  |
|                            | <b>Date of the One-day Maximum Flow</b> | The mean Julian date of the 1-day annual maximum flow over all years (Richter et al. 1996).  |
| <b>Booth et al. (2004)</b> | <b>T<sub>Qmean</sub></b>                | 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 2000). |
|                            | <b>T<sub>0.5yr</sub></b>                | The fraction of time that a stream channel is exposed to flows whose magnitude exceeds the half-year flood (Konrad 2000).  |
| <b>Kirby (2003)</b>        | <b>Hydrograph Rise Rates</b>            | Means of all positive differences between consecutive daily values (Richter et al. 1996).  |
|                            | <b>Hydrograph Fall Rates</b>            | Means of all negative differences between consecutive daily values (Richter et al. 1996).  |
|                            | <b>High Pulse Count</b>                 | Number of high pulses within each year (Richter et al. 1996).  |
|                            | <b>Date of the One-day Maximum Flow</b> | The mean Julian date of the 1-day annual maximum flow over all years (Richter et al. 1996).  |

### **3.0 STUDY APPROACH**

The literature review reveals that linkages have been established between stream ecologic condition and hydrologic metrics, and that these hydrologic metrics respond to broad measures of urbanization (i.e. percent impervious area). What has yet to be tested is how hydrologic metrics respond to urban development that includes structural stormwater controls. The goal of this research was to determine the potential for relating stormwater controls to ecological integrity through hydrologic metrics. The approach taken was to build on the work of Rohrer (2004), who conducted a model-based scenario comparison of development alternatives using EPA SWMM 4.4h. The stormwater controls modeled by Rohrer (2004) were detention structures sized to control peak flow from storms of various return intervals to their pre-development peak flow rates. Some control scenarios included extended detention facilities for removal of suspended solids (WEF and ASCE 1998). Detention controls were chosen because they are the most common practice applied in stormwater management throughout the United States. It is important to emphasize that this study considered a small-scale (10 ha) development draining to a headwater stream, which is the typical design scale of many urban developments, because all previous metric applications found in the literature were conducted at much larger watershed scales. The first phase of this project was to select a potentially meaningful set of hydrologic metrics to characterize hydrologic alteration in a small-scale, urban context. This was done by starting with a list of metrics that were successfully linked to biological data in previous studies and reducing this list of metrics

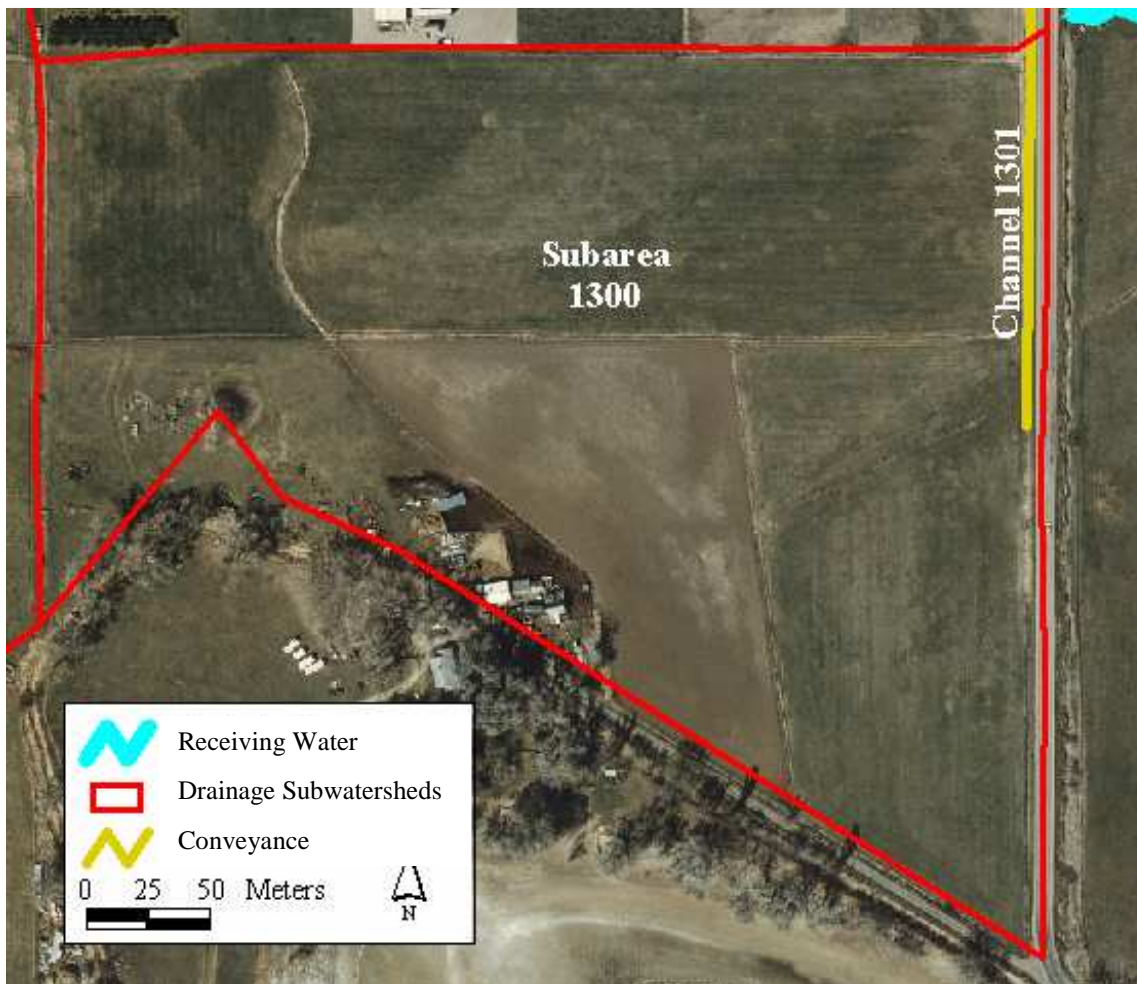
by eliminating metrics that are insensitive to urban development or are subject to large model uncertainties. The reduced list of metrics was then modified to better represent hydrologic response at the small scale. In the second phase, algorithms for computing the select set of metrics from a continuous time series of flow at 15-minute intervals were programmed in MATLAB©. The MATLAB© algorithms were used to calculate these metrics from 48-year records for the ten scenarios modeled by Rohrer (2004). Potential climatic influences on metric behavior were examined by comparing results from Atlanta, GA and Fort Collins, CO. Hydrologic metrics computed from time series of daily mean flows were compared to those computed from time series of 15-minute mean flow values to investigate the influence of temporal resolution of flow data on metric values. The metric behavior across scenarios was interpreted and recommendations were made regarding the potential utility of the metrics for improving the design of stormwater controls.

### **3.1 Study watershed and development scenarios**

The study watershed, shown in Figure 4, is a 10 ha parcel of pastureland in Fort Collins, CO. In terms of model parameters, the pre-development pastureland was modeled as five percent impervious area and all runoff was routed as overland flow draining directly to the outlet (Channel 1301), which is assumed to be a first order stream channel. The developed watershed was modeled as a medium-density residential neighborhood. The newly constructed residential area was delineated into six sub-areas, shown in Figure 5, draining to a network of gutters and swales and ultimately to the receiving stream. The runoff processes in the post-development scenarios are a combination of overland flow, open-channel flow in gutters and swales and, in the three

scenarios with stormwater controls, routing through detention and orifice structures (Rohrer 2004). The characteristics of the developed watershed are shown in Table 6.

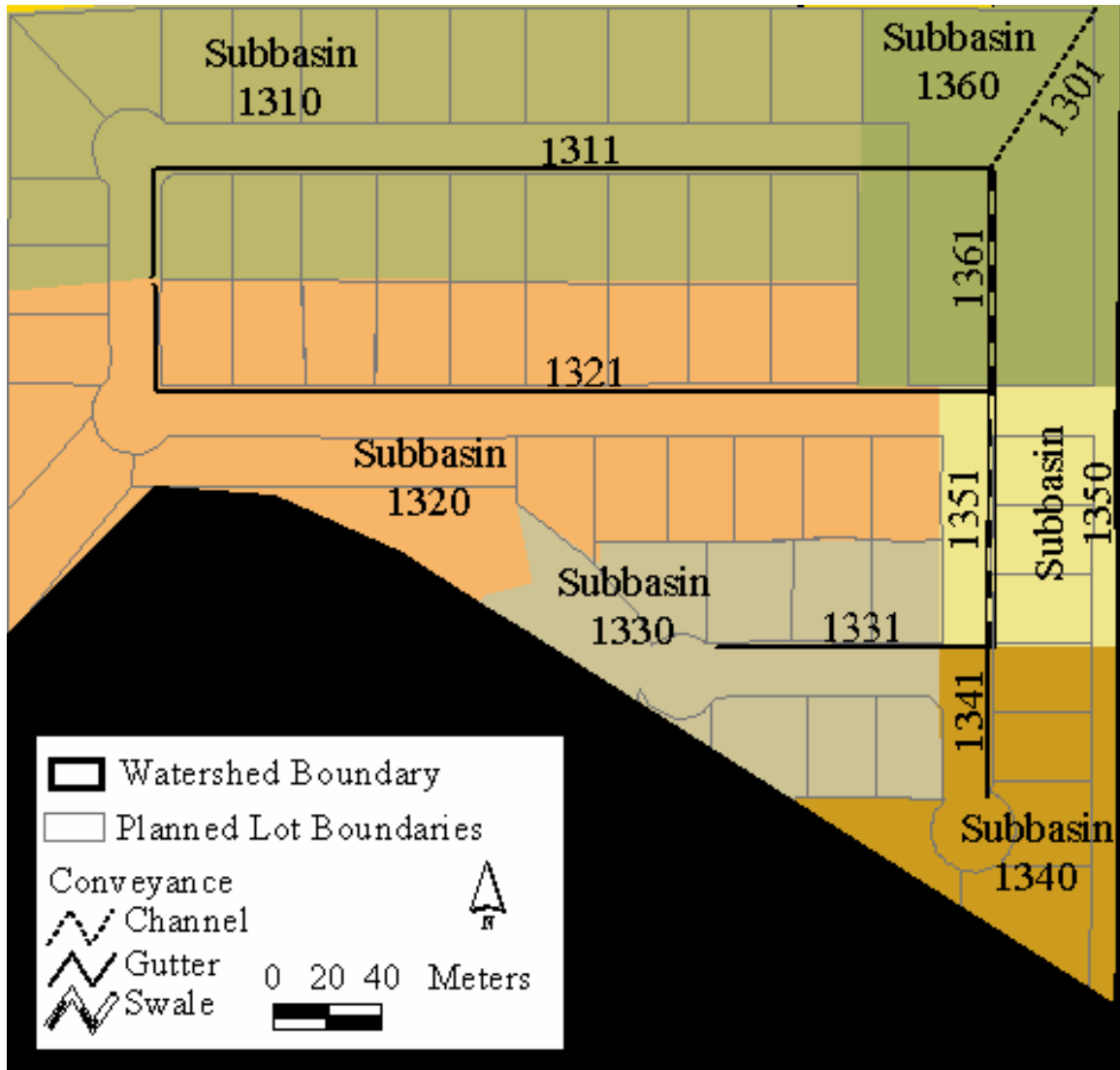
The watershed models and resultant flow time series used in this study were created by Rohrer (2004) using the U.S. Environmental Protection Agency's Stormwater Management Model (SWMM) Version 4.4h (OSU 2001).



**Figure 4: The study watershed: A 10ha parcel of pastureland in Fort Collins, CO.**  
Source: Rohrer (2004)

EPA SWMM is a mathematical model that simulates the hydrologic and hydraulic processes likely to occur within a watershed in response to given rainfall events, based on the hydrogeometric properties of the watershed and the drainage network. SWMM RUNOFF uses a non-linear reservoir method to simulate the rainfall-runoff

transformation and the kinematic wave as the routing equation. Discharge from the detention basins was modeled by Rohrer (2004) using stage-volume-surface area-discharge data sets, created from simulation results generated by SWMM EXTRAN, which solves the full Saint-Venant equation.



**Figure 5: The hypothetical medium density residential neighborhood designed for the study watershed.**

Source: Rohrer (2004)

**Table 6: Watershed Characteristics: Developed Conditions**

| Subbasin | Width (m) | Area (ha) | Percent Impervious | Slope  |
|----------|-----------|-----------|--------------------|--------|
| 1310     | 906       | 3.11      | 29.2               | 0.0141 |
| 1320     | 812       | 2.97      | 24.6               | 0.0130 |
| 1330     | 232       | 1.13      | 26.6               | 0.0202 |
| 1340     | 189       | 0.81      | 29.2               | 0.0222 |
| 1350     | 157       | 0.59      | 29.2               | 0.0077 |
| 1360     | 614       | 1.31      | 10.9               | 0.0136 |

Source: Rohrer (2004)

SWMM RUNOFF also requires input of watershed characteristics related to soil infiltration, overland flow roughness, evaporation, and depression storage. The integrated form of the Horton equation was used to calculate infiltration capacity as a function of cumulative rainfall, avoiding an unjustifiable reduction of infiltration capacity ( $f_p$ ) during periods of light rainfall (Huber and Dickenson, 1988). For the continuous simulations, infiltration capacity was regenerated during dry weather. Input parameters for infiltration used in the Atlanta and Fort Collins simulations were taken directly from the City of Fort Collins Storm Drainage Design Criteria (1997) and are as follows:

- minimum or ultimate value of  $f_p$ : 12.7 mm/hr,
- maximum or initial value of  $f_p$ : 13.0 mm/hr, and
- decay coefficient for reduction of infiltration capacity:  $0.108 \text{ min}^{-1}$ .

All simulations performed using SWMM RUNOFF had the following input parameters:

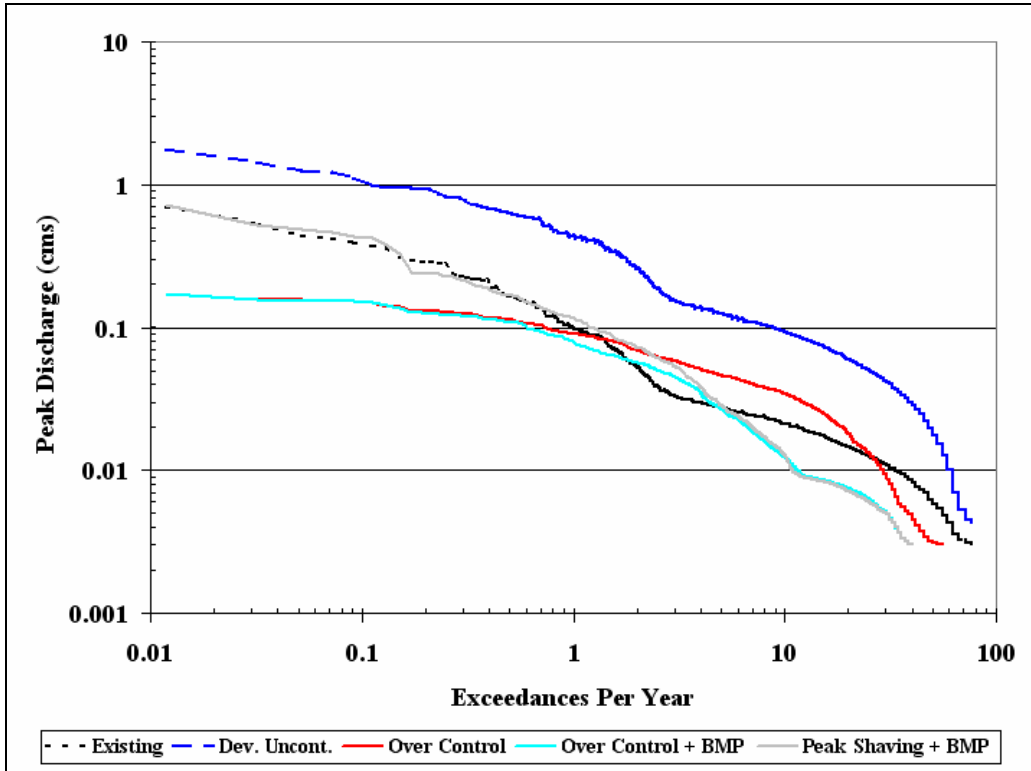
- Snowmelt was not simulated,
- Evaporation from channels was not allowed,
- Default evaporation rate = 0.254 cm/day,
- Impervious area Manning's roughness = 0.016,
- Pervious area Manning's roughness = 0.250,
- Impervious area depression storage = 2.54 mm, and

- Pervious area depression storage = 7.62 mm.

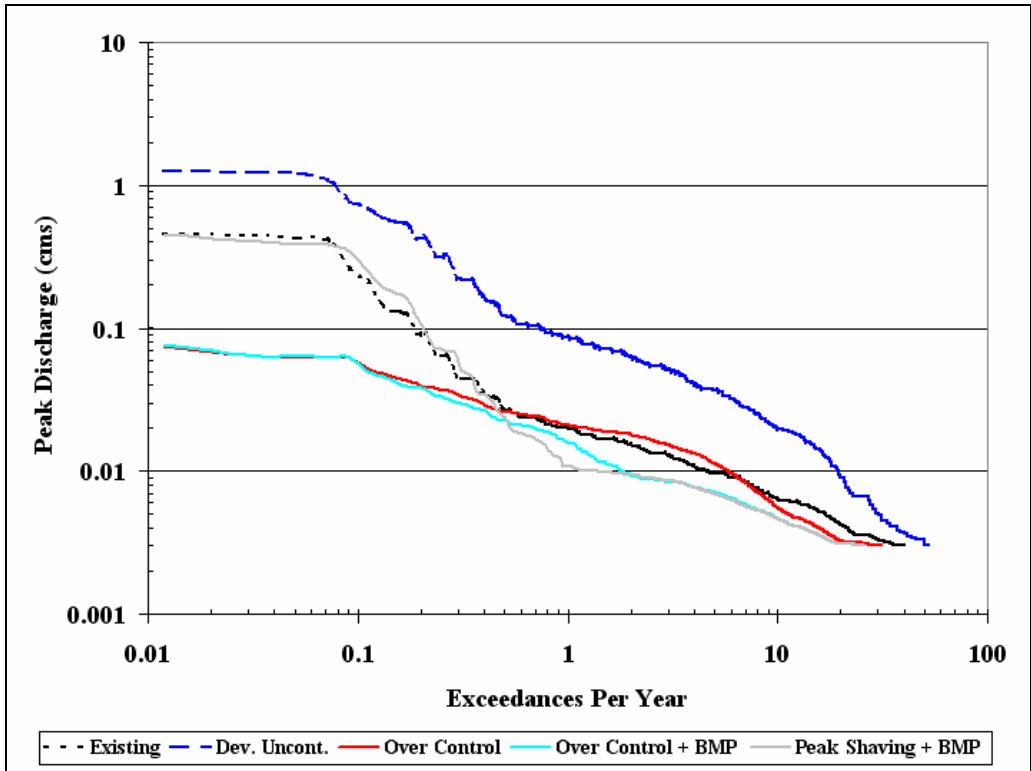
These parameters were also taken from the City of Fort Collins Storm Drainage Design Criteria (1997), (Rohrer 2004).

An *event* was defined as any storm flow greater than zero cubic feet per second that follows a no flow period of at least six hours. If there are two or more storm flow events separated by no flow periods of less than six hours, they were considered to be a single event. Since the impervious area depression storage is 2.54 mm, a rainfall event would have to have a depth of at least this much in order to produce an *event*.

Rohrer (2004) compared peak flow frequency, shown in Figures 6 and 7, and flow duration curves for five different land use and runoff control scenarios, generated by simulating runoff from a 50-year time series of hourly precipitation data for Fort Collins and Atlanta. In the uncontrolled development scenario, runoff was routed through gutters and swales directly to the receiving stream. In the last three scenarios, runoff was routed through stormwater controls before reaching the stream. The stormwater controls considered in this study are essentially storage basins that detain excess runoff volume and release it at a controlled rate. The rate of discharge from the detention basins is regulated by the size and configuration of the orifices at the outlet. Since the relationship between basin geometry, stage (depth of water) in the basin and the rate of discharge through the outlet is non-linear, it is common practice for detention basins and their outlet orifice configurations to be sized and tested through trial and error using models such as SWMM.



**Figure 6: Peak flow exceedance frequency in Subarea 1300: Atlanta.**  
 Source: Rohrer (2004)



**Figure 7: Peak flow exceedance frequency in Subarea 1300: Fort Collins**  
 Source: Rohrer (2004)

An explanation of the five watershed scenarios modeled in Rohrer (2004) is as follows:

- **U: *Undeveloped*** watershed was simulated as a parcel of pastureland with five percent impervious area, where runoff was considered travel as overland flow to the outlet.
- **D-NC: *Developed No Controls*** medium-density residential development with an average of thirty percent impervious area and a system of gutters, pipes, and swales directly connected to the outlet (1301 in Figure 5).
- **D-OC: *Over-control*** runoff from the same medium-density residential development described above was routed through controls designed to reduce post-development 2-year and 100-year peak flow rates to the pre-development 2-year flow rate. This practice is unique to Fort Collins and is intended to compensate for high-impact development that has already occurred by “over-controlling” runoff from all new developments.
- **D-OC/BMP: *Overcontrol + Best Management Practices (BMP)*** combines the OC scenario controls with a water quality control BMP designed to capture 70-90 percent of all runoff-producing events and have a draw-down time of 24 hours. These structures are designed to capture the “first flush” of runoff, which typically has the highest concentrations of pollutants. The volume necessary to capture the first flush is referred to as the water quality capture volume (WQCV). The WQCV is intended to allow time for pollutants contained in the runoff to settle out before the detained water is discharged to the stream.
- **D-PS/BMP: *Peak Shaving + BMP*** controls were designed using the standard practice of reducing the post-development 2-year and 100-year peak flow rates to

pre-development 2-year and 100-year peak flow rates, combined with a water quality BMP.

It is important to note that all of the stormwater control designs are based on design storms derived from the respective rainfall records and are therefore different for Atlanta and Fort Collins in terms of size, but the design methods used for peak shaving and over-control were the same for both locations. The WQCV for Atlanta was calculated to be 0.046 ha-m, using the WEF and ASCE (1998) procedures, while the WQCV for Fort Collins was calculated to be 0.041 ha-m, using the UDFCD (2001) procedure (Rohrer 2004).

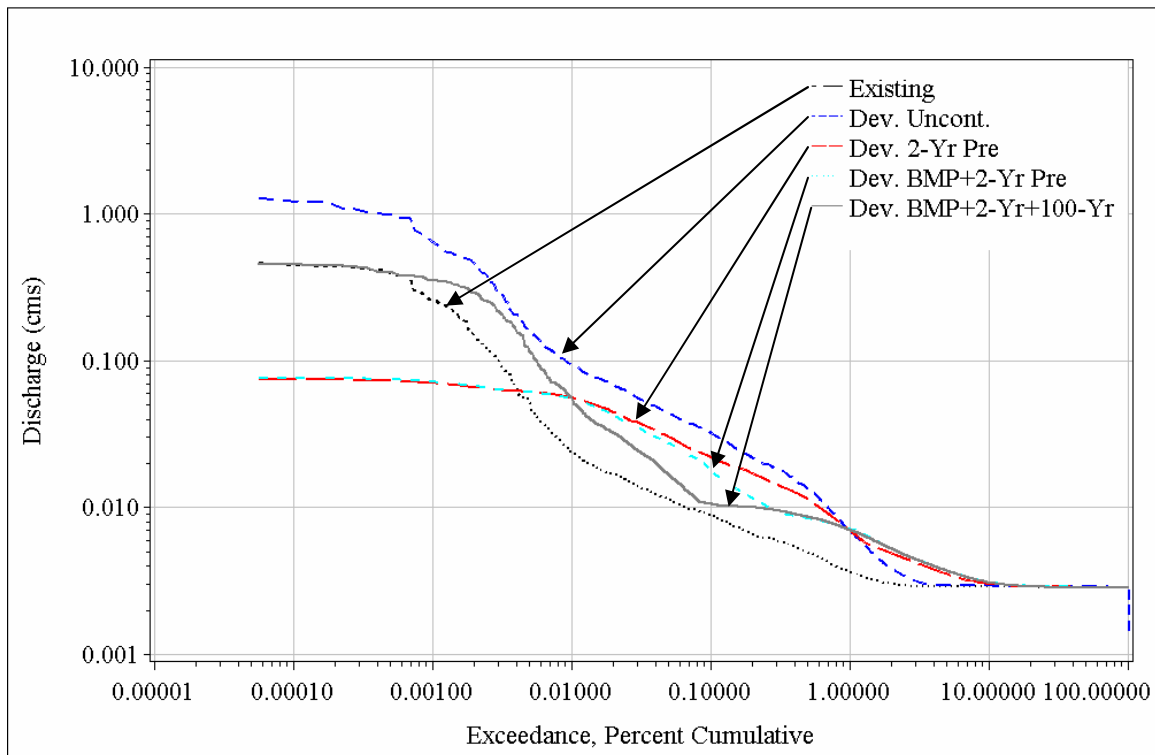
## 4.0 METRIC SELECTION

### 4.1 Spatial and temporal scale considerations

Without data from multiple streams, on which to perform a principal components analysis (PCA) as was done in Olden and Poff (2003), and lacking site-specific biological and geomorphic data for determining key aspects of flow (i.e. critical shear stress), it was decided to base metric selection on sensitivity to urban development, limitations of the model, and demonstrated ecological relevance in previous studies. Since urbanization was not expected to alter the seasonal timing of flows, seasonal flow timing metrics were excluded from consideration. Low flow metrics, although likely to be very important ecologically, were not considered in this analysis due to an inability of the SWMM model to accurately simulate interactions between land development, infiltration, groundwater recharge, and base flow. The remaining categories of metrics quantify magnitude, duration, frequency and rates of change of storm flows, all of which are known to be sensitive to urban development (Roesner and Bledsoe 2003). Once the *categories* of potential metrics were reduced, *metrics* which have been successfully linked to biological data in previous urban applications were selected from the remaining categories: magnitude, duration, frequency, and rates of change of storm flows. The final set of metrics was then modified or replaced by analogous substitutes to better suit a small-scale, urban context.

The spatial scale of most new suburban developments is generally less than 1 km<sup>2</sup>. The first order study watershed considered here is 10ha - a mere fraction of the

watershed size in the urban gradient studies found in the literature (greater than 5 km<sup>2</sup>). The mismatch of spatial and temporal scales had several consequences for the metric selection process. First, storm flow occurred less than 5 percent of the time, as can be seen in Figure 8. As a result, the mean flows for these hydrographs, as well as the metrics that use lower percentiles of flow occurrence (i.e. 25<sup>th</sup>, 50<sup>th</sup>, and 75<sup>th</sup> percentiles), are all essentially equal to base flow, which cannot be accurately simulated using SWMM.



**Figure 8: Flow duration curves for development scenarios in Fort Collins**

Source: Rohrer (2004)

Another issue related to scale that influences metric choice is that smaller spatial scales translate into shorter times of concentration and, therefore, smaller temporal scales of hydrologic response. The mean durations of storm flow events in the undeveloped watershed scenarios for Atlanta and Fort Collins were estimated to be seven hours and

five hours respectively, supplying evidence that time series of daily mean flows are temporally too coarse for depicting watershed response at this scale.

The fraction of the year that the *daily mean flow rate* exceeds the annual mean flow rate for that year ( $T_{Q_{\text{mean}}}$ ) is one of the metrics that successfully explained variance in biological data in Booth et al. (2004).

$$T_{Q_{\text{mean}}} = \left[ \frac{\sum_{\text{yr}} t \left[ \left( \frac{Q(t)}{Q_{\text{mean}}} \right) > 1 \right]}{1\text{year}} \right]$$

Where

- t = time-step (i.e. 1 day, 15 min)
- Q(t) = mean flow rate for time-step “t”
- Q<sub>mean</sub> = annual mean flow for that year

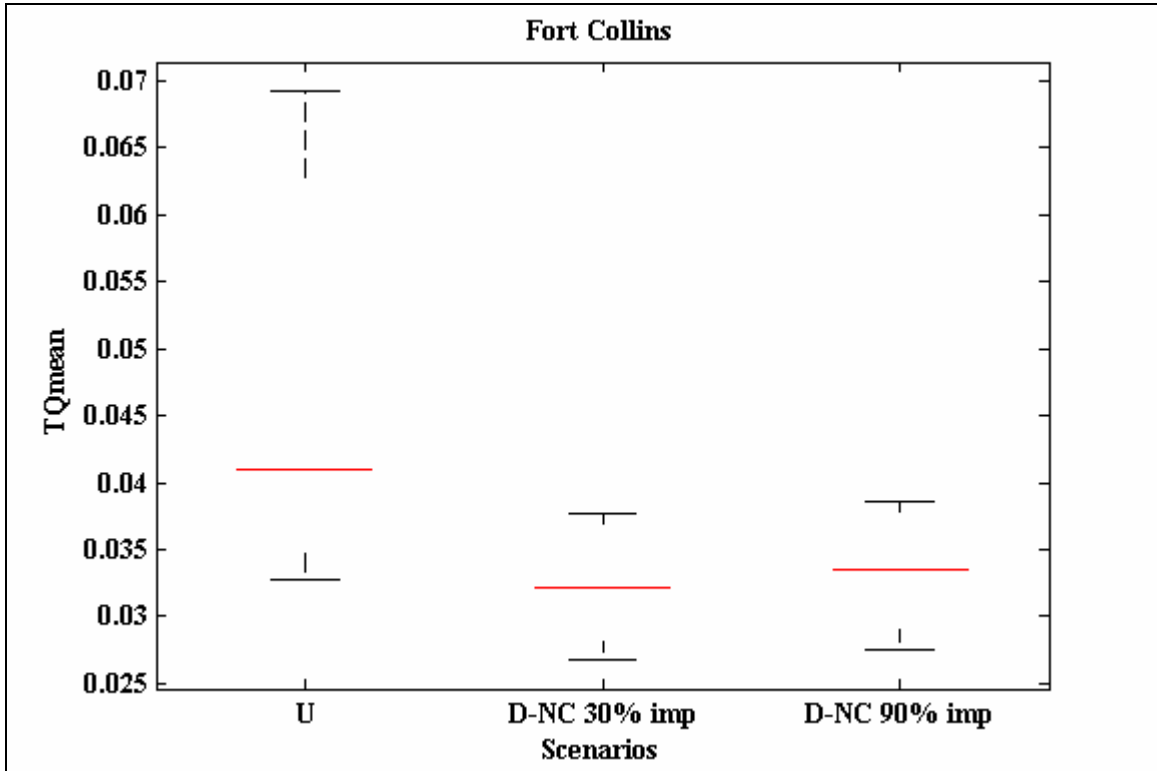
A comparison of  $T_{Q_{\text{mean}}}$  computed from a time series of *15-minute mean flow rates*, presented in Table 7, reveals that computing this metric from a time series of daily mean flow rates underestimates the degree of flashiness at this watershed scale. This underestimation is caused by storm flow events that only last for several hours being averaged over an entire day, resulting in an overestimation of the duration that the annual mean flow is exceeded.  $T_{Q_{\text{mean}}}$  is known to be sensitive to basin size and is only recommended for comparing basins of similar sizes because larger streams tend to have more attenuated flow patterns and higher values of  $T_{Q_{\text{mean}}}$  than small streams (Konrad 2000). Lower values of this metric indicate flashier flow regimes with higher peaks and faster recession rates, resulting in less time that the annual mean flow rate is exceeded per year (Konrad and Booth 2002). Konrad (2000) noted that  $T_{Q_{\text{mean}}}$  might have limited applicability in basins smaller than 20km<sup>2</sup>.

**Table 7:  $T_{Q_{mean}}$  values computed for five scenarios of development in Atlanta and Fort Collins using 48 years of 15-minute and daily mean flow time series.**

| Scenario     |                      | $T_{Q_{mean}}$<br>( $\Delta t=1$ Day) | $T_{Q_{mean}}$<br>( $\Delta t=15$ min) | % Difference |
|--------------|----------------------|---------------------------------------|--|--------------|
| Fort Collins | Undeveloped          | 0.104                                 | 0.041                                  | -60.6        |
|              | Developed No Control | 0.088                                 | 0.032                                  | -63.3        |
|              | Overcontrol          | 0.114                                 | 0.093                                  | -17.9        |
|              | Overcontrol+BMP      | 0.129                                 | 0.112                                  | -12.5        |
|              | Peak Shaving+BMP     | 0.130                                 | 0.112                                  | -13.9        |
| Atlanta      | Undeveloped          | 0.163                                 | 0.050                                  | -69.4        |
|              | Developed No Control | 0.164                                 | 0.053                                  | -67.7        |
|              | Overcontrol          | 0.187                                 | 0.137                                  | -26.7        |
|              | Overcontrol+BMP      | 0.219                                 | 0.178                                  | -18.8        |
|              | Peak Shaving+BMP     | 0.219                                 | 0.178                                  | -18.5        |

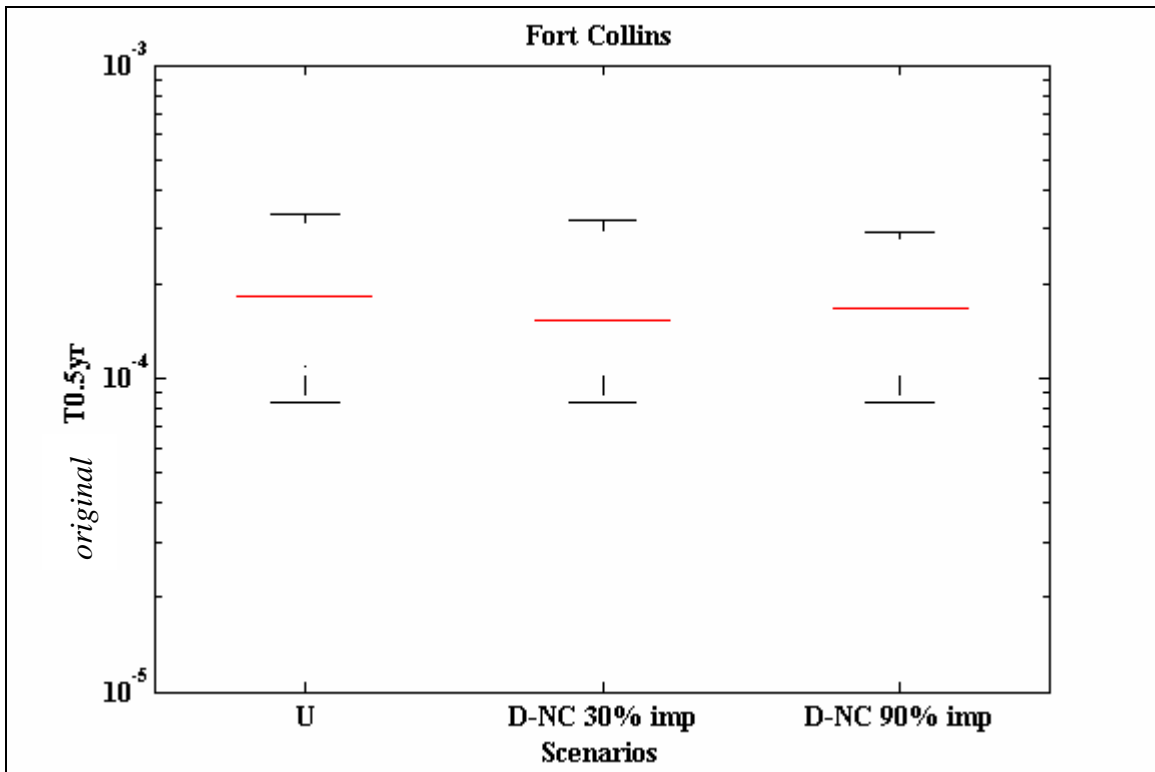
Comparing  $T_{Q_{mean}}$  values for uncontrolled development with increasing percentages of impervious area confirmed that  $T_{Q_{mean}}$  is not sensitive to urban development at this scale. Figure 9 shows that even when developed at 90 percent impervious area,  $T_{Q_{mean}}$  is not significantly lower than the undeveloped scenario value for Fort Collins, according to the median-interquartile range method for assessing significance of median differences. This is because the *undeveloped* scenario in this 10 ha watershed has such flashy flow patterns to begin with, that  $T_{Q_{mean}}$  is already at the lower limit of its range of possible values and the changes that occur due to urbanization cannot be distinguished from interannual variability. Based on the results of this evaluation, along with the recognition that  $Q_{mean}$  is representative of base flow and is therefore subject to high model uncertainty, it was decided that  $T_{Q_{mean}}$  is not appropriate for the analysis of small watershed response to urbanization using flow data from SWMM.

Another measure of flashiness found useful by Booth et al. (2004) for explaining variability in biological data was the cumulative duration that the flow rate exceeds the 0.5-year peak flow rate ( $T_{0.5yr}$ ). The 0.5-year peak flow rate is the peak flow rate with an



**Figure 9: Comparison of  $T_{Qmean}$  for increasing percentages of impervious area in Fort Collins.**

exceedance frequency of six months. Peak flow exceedance frequency was determined according to the Cunnane (1978) procedure. Unlike the  $T_{Qmean}$ , the  $T_{0.5yr}$  is thought to be insensitive to basin size in Puget lowland stream basins (Konrad 2000). Since this metric was originally defined as the cumulative duration over the entire record that the flow rate exceeds the 0.5-year peak flow rate, its results were presented as a single numerical value, which is not conducive to graphical analyses using medians and interquartile ranges. For this reason,  $T_{0.5yr}$  was computed on an annual basis, (similar to  $T_{Qmean}$ ). The sensitivity of  $T_{0.5yr}$  to development in the study watershed was tested by computing this metric for two scenarios of uncontrolled development with increasing percentages of impervious area, the results of which are shown in Figure 10.



**Figure 10: Comparison of  $T_{0.5yr}$  for increasing percentages of impervious area in Fort Collins.**

$T_{0.5yr}$  represents the distribution of flows above and below a threshold, in this case the 0.5-year storm. Based on the results in Figure 10, the distribution of flow durations relative to the 0.5-year peak flow rate is essentially unchanged by uncontrolled development. This implies that the magnitude of the threshold is increasing proportionally to the cumulative duration that it is exceeded. According to the results shown in Figure 10, it appears that the spatial limit to the applicability of  $T_{0.5yr}$  is probably greater than 10 ha since it is insensitive to uncontrolled urban development in this watershed.

What is not evident from looking at  $T_{0.5yr}$  in Figure 10 is that, while the ratio may stay the same, the magnitude of the flow threshold and the flows exceeding it are increased significantly following development (see Figure 1). In other words, standardized flow durations may not change significantly with uncontrolled development

at this scale, but actual flow durations do increase relative to pre-development. This can be seen in the flow duration curves from Rohrer (2004), shown in Figure 8. Furthermore, a more important aspect of flow regime for the physical and biological integrity of a receiving stream is the actual duration of flows above a fixed pre-development threshold rather than the distribution of flows above or below a moving flow threshold. It was through this reasoning that a *modified* version of  $T_{0.5yr}$ , computed using a fixed pre-development 0.5-year peak flow rate to standardize flow duration curves, was chosen to replace the *original*  $T_{0.5yr}$  in this analysis.

## 4.2 Refining the select set of metrics

In addition to a *modified*  $T_{0.5yr}$ , which is standardized by the 0.5-year peak flow rate of the undeveloped scenario, the remaining metrics that were previously computed in terms of daily flow changes (Richter et al. 1996; Scoggins 2000; Kirby 2003) were modified for computation on an event-basis from long-term, continuous flow time series. Event-based metrics avoid the effects of base flow dominance and allow for particular types of events to be analyzed, a potentially useful tool for designing stormwater controls. In this analysis an event was defined by the same criteria as Rohrer (2004) as any flow event having flow greater than 0.003 cubic meters per second, with a minimum inter-event time of six hours. The high pulse duration, rise rate, and fall rate metrics from Richter et al. (1996), previously found to be biologically meaningful in urban streams (Scoggins 2000; Kirby 2003), were replaced by event-based substitutes. The event-duration,  $D$ , and event-peak-duration,  $D_{peak}$ , are event-based versions of high pulse duration metrics.  $D$  is simply the total duration of an event, while  $D_{peak}$  is defined as the duration that the flow rate exceeds 75 percent of the peak flow rate for that event. The event-mean rise and fall rates,  $R_N$  and  $F_N$ , are analogous to average daily rise and fall rate

metrics. The distribution of event-peak flows for the entire record,  $Q_p$ , serves a similar purpose as the coefficient of variation of the annual maximum flood (Konrad and Booth 2002), where flow variability is represented by the interquartile range of  $Q_p$ , and the magnitude of flows is shown by the median value for  $Q_p$ . The time-to-peak was suggested as another measure of flashiness, along with the ratio of time-to-peak to total duration of storm flow events,  $t_p/D$ , which shows the ratio of rising to falling limbs of event hydrographs for storms and how they are affected by controls. Finally, the ratio of event-peak-duration to total event duration,  $D_{\text{peak}}/D$ , metric is proposed to represent the distribution of storm peak durations relative to total storm duration, as an event-based analogy to  $T_{0.5\text{yr}}$ , used in Booth et al. (2004). The advantage of an event-based metric is its ability to analyze specific event types that may be of interest. All metrics were computed from long-term time series of flow rates, using algorithms programmed in Matlab©. The basic mathematical expressions for each metric are shown in Table 8.

**Table 8: Select set of hydrologic metrics to be computed in the model-based scenario analysis**

| <b>Annual Metrics</b>   | <b>Description</b>  | <b>Units</b>                   |
|---|---|--------------------------------|
| $T_{Q_{0.5\text{ yr}}}^{\text{modified}} = \left[ \frac{\sum_{\text{yr}} t \left[ \left( \frac{Q(t)}{Q_{0.5}} \right)^{\text{yr}} > 1 \right]}{1\text{year}} \right]$ | Fraction of a year that the 15-min mean flow rate exceeds a fixed pre-development half-year peak flow rate. | Fraction of time               |
| <b>Event-based Metrics*</b>   | <b>Description</b>  | <b>Units</b>                   |
| $Q_p = \max Q(t) \text{ from } t_i \text{ to } t_f$   | Event peak flow rate  | Cms                            |
| $D = t_f - t_i + 1$   | Event storm flow duration   | Hrs                            |
| $t_p = t(Q_p) - t_i + 1$  | Time-to-peak  | Hrs                            |
| $\frac{t_p}{D} = \frac{t(Q_p) - t_i + 1}{t_f - t_i + 1}$  | Ratio of time-to-peak to storm flow event duration  | Ratio                          |
| $R_N = \left( \frac{Q_p - Q_b}{t_p - t_i + 1} \right)$  | Event-mean rise rate  | $\frac{\text{cms}}{\text{hr}}$ |
| $F_N = \left( \frac{Q_b - Q_p}{t_f - t_p + 1} \right)$  | Event-mean fall rate  | $\frac{\text{cms}}{\text{hr}}$ |
| $D_{\text{peak}} = \sum_{t=t_i}^{t_f} t \left[ \left( \frac{Q(t)}{0.75 \times Q_p} \right) > 1 \right]$   | Duration that the flow rate exceeds 75% of the peak flow rate in an event.                                  | Hrs                            |
| $\frac{D_{\text{peak}}}{D}$   | Ratio of event-peak-duration to total event duration  | Ratio                          |

where

$t$  = time-step

$t(Q_p)$  = time-step of peak flow

$t_i$  = start time-step of event

$t_f$  = end time-step of event

$Q(t)$  = flow rate at time= $t$

$Q_p$  = peak flow rate of the event

$Q_b$  = base flow rate

$Q_{0.5\text{yr}}$  = peak flow with 6-month return period

\*An event is defined as having a flow rate greater than 0.003 cubic meters per second, with a minimum interevent time of six hours.

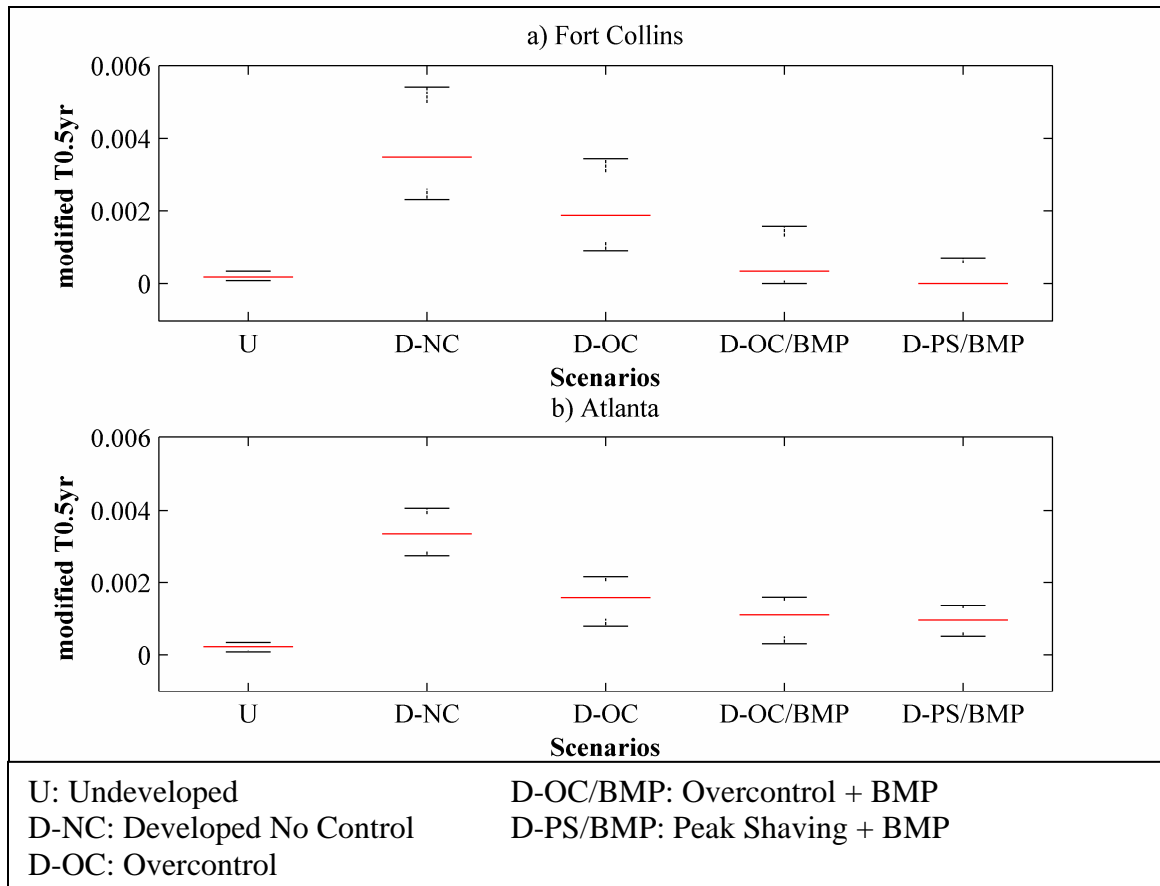
## 5.0 RESULTS AND DISCUSSION

Metric computation results were plotted for comparison in terms of their medians and interquartile ranges (IR). The IR is the difference between the 75<sup>th</sup> and 25<sup>th</sup> percentiles of a sample. Apart from the metrics that are ratios and fractions of time (i.e. *modified*  $T_{0.5yr}$ ,  $D_{peak}/D$ ,  $t_p/D$ ) that, by definition, are already standardized; all other metrics were standardized by dividing by the median of a common base scenario to illustrate relative deviation from a common base scenario. In this study the *undeveloped scenario* was used as the base scenario for comparison to alternative runoff controls on the developed area. In other words, the median of the base scenarios in the following plots are equal to one, except for metrics that are fractions of a year or fractions of a storm such as the *modified*  $T_{0.5yr}$ ,  $D_{peak}/D$ , and  $t_p/D$  metrics, which range from zero to one. The effects of uncontrolled development versus development with stormwater controls were examined by comparing the medians and IRs of annualized and event-based metrics for *alternative development scenarios* relative to the *undeveloped scenario* median and IR. Median differences are considered to be significant if the alternative scenario median falls outside of the IR for the base scenario, similar to the method used by (Richter et al. 1997; Henriksen et al. 2006).

### 5.1 Patterns of annual metric behavior

The *modified*  $T_{0.5yr}$  is shown in Figure 11 to increase in response to uncontrolled urban development for Atlanta and Fort Collins. As expected, the controls were most effective at mitigating the effects of urban development on the *modified*  $T_{0.5yr}$  since they

were designed to prevent post-development flow rates from exceeding target flow rates. In both Atlanta and Fort Collins, the *peak shaving + BMP* controls also appeared to bring this metric closer to pre-development levels than the other designs. This makes sense because BMPs limit the range of possible flows by controlling smaller storms, closer in size to the half-year storm. Also, by reducing the 100-year peak to the pre-development 2-year peak discharge, the over-control designs increase the durations of intermediate flows by releasing the excess volumes at lower rates for longer durations than the peak shaving designs.



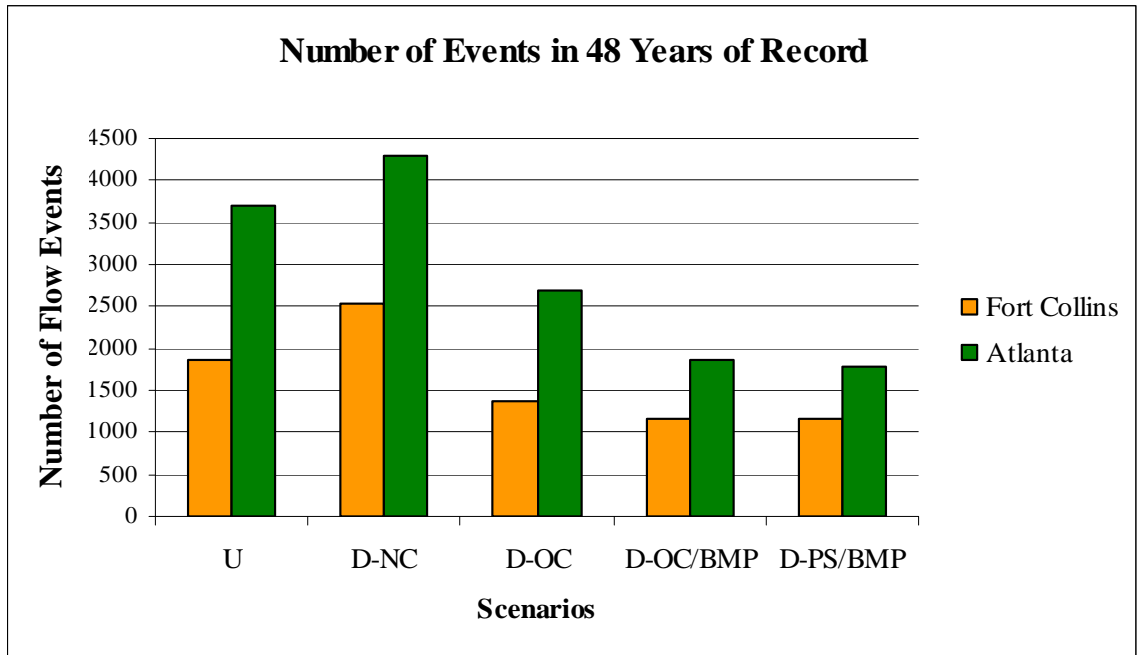
**Figure 11: Median and interquartile range values of *modified*  $T_{0.5yr}$  for multiple scenarios of development in Fort Collins and Atlanta.**

The *modified*  $T_{0.5yr}$  is the most promising metric considered in this analysis with respect to its potential utility as a design parameter. As a measure of the cumulative durations of flows above the pre-development 0.5-year storm, it has plausible importance

to the physical and ecological integrity of the stream and effectively translates the information contained in a flow duration curve into a form that can be used in regression analyses with biological data. For these reasons, along with its sensitivity to the hydrologic consequences of uncontrolled development and various stormwater control scenarios, the  $T_{0.5yr}$  is an ideal candidate for use as a design metric.

## **5.2 Patterns of event-based metric behavior**

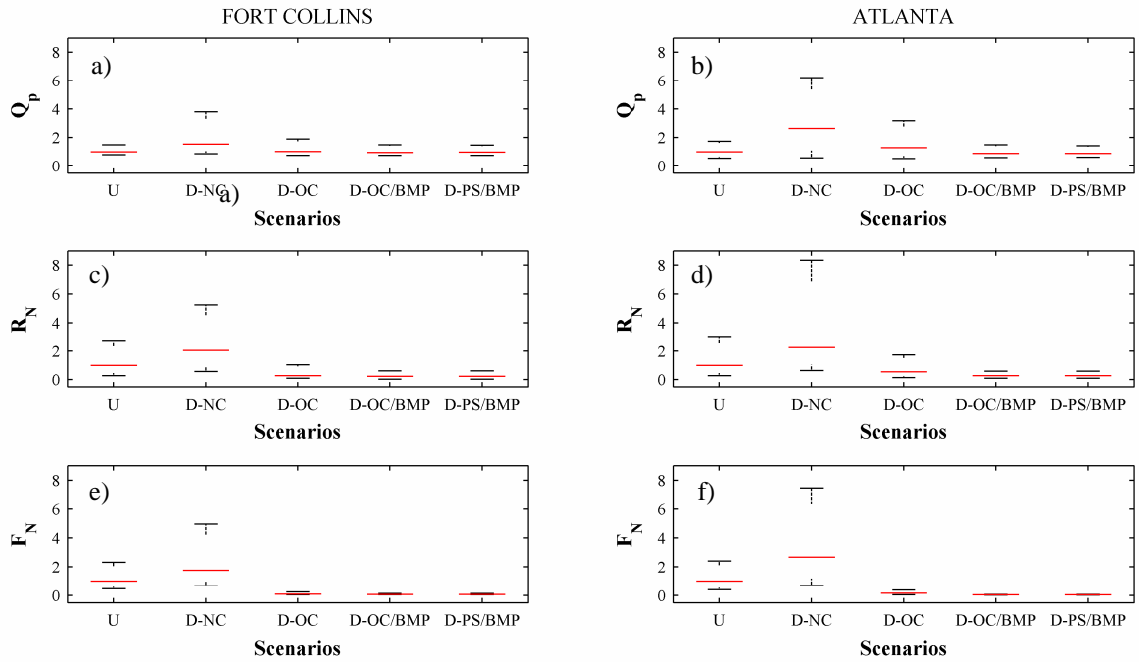
Unlike the two versions of  $T_{0.5yr}$ , which have fixed sample sizes of 48 (equal to the number of years of flow data), the event-based metrics have sample sizes equal to the total number of events in the period of record as shown in Figure 12. Since the sample sizes were all greater than one thousand, the medians and interquartile ranges were not affected by variations in sample size. As expected the total number of events increased with uncontrolled development in Fort Collins and Atlanta because the increased amount of impervious area lowered the infiltration capacity of the watershed and small storm events that did not generate runoff in the undeveloped watershed were shown to produce runoff in the developed watershed. The total number of events was reduced to less than pre-development numbers in all controlled scenarios. This reduction in number of events by controls is the result of increased drawdown times leading to the merger of what were once separate events in the developed without controls scenario, into single events with longer durations.



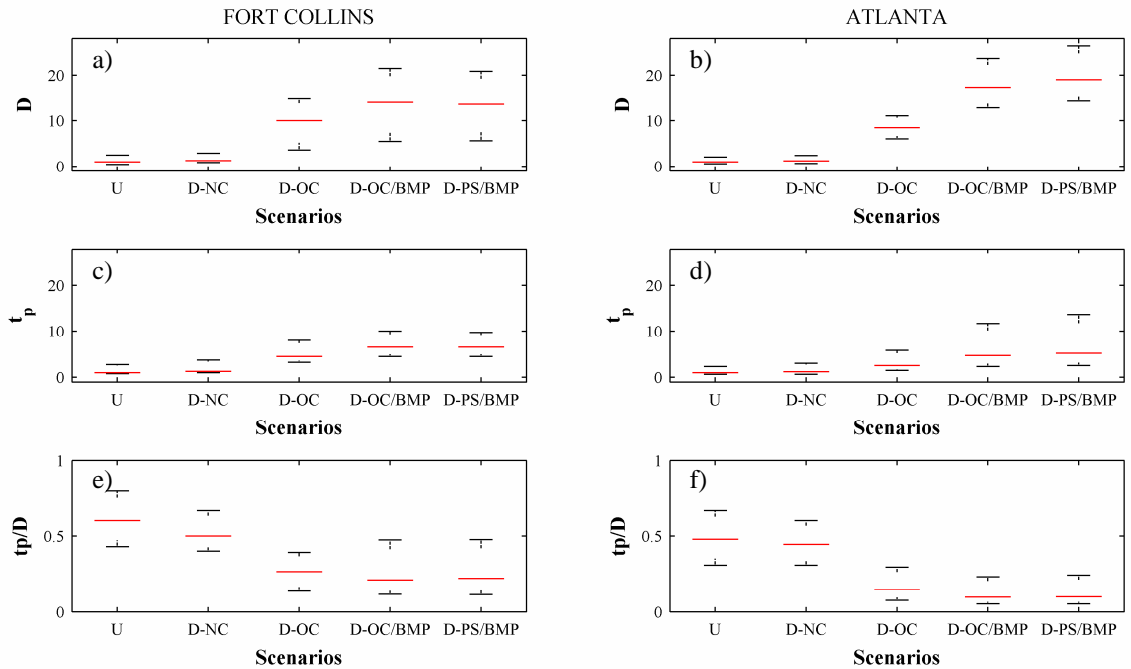
**Figure 12: Total number of events occurring in the 48 years of record for each watershed scenario.**

The event-based metrics computed for Atlanta and Fort Collins showed very similar behavior across scenarios. All of the fundamental changes in storm response associated with urbanization were observed in the event-based metric behavior, shown in Figures 13 and 14. The numerical values for all event-based metrics are given in Tables 9 and 10. Increased peak flow rates, but not event-durations of flow resulted from uncontrolled development, while decreased peak flow rates and rates of change resulted from extended detention at the expense of increased flow durations.

The increased IR of  $Q_p$ , shown in Figures 13a and 13b, represents increased flow variability and is corrected by the stormwater controls in Fort Collins and Atlanta. The medians of the event-mean rise rates,  $R_N$ , shown in Figures 13c and 13d, were not significantly altered relative to the pre-development IR as a result of uncontrolled development in either Fort Collins or Atlanta. The median of the event-mean fall rates,  $F_N$ , for the uncontrolled development scenario showed a significant increase relative to



**Figure 13: Event-based metrics for Fort Collins and Atlanta. Plots are standardized by the medians of the undeveloped scenarios to show relative sensitivity.**



|                            |                              |                   |
|----------------------------|------------------------------|-------------------|
| U: Undeveloped             | D-OC/BMP: Overcontrol + BMP  | D-OC: Overcontrol |
| D-NC: Developed No Control | D-PS/BMP: Peak Shaving + BMP |                   |

**Figure 14: Event-based metrics for Fort Collins and Atlanta. Plots a) through d) are standardized by the medians of the undeveloped scenarios to show relative sensitivity.**





undeveloped scenario in Atlanta, shown in Figure 13f. The Fort Collins median  $F_N$  exhibited similar behavior in Figure 13e to what was observed for Atlanta, but the difference between the median values for the undeveloped and uncontrolled development scenarios was not significant. For all controlled development scenarios in Fort Collins and Atlanta, the median event-mean rise and event-mean fall rates were reduced to below the pre-development IRs for these metrics.

As seen in Figure 13,  $Q_p$ ,  $R_N$ , and  $F_N$  are closely related to one another and exhibit similar patterns of behavior across scenarios in Fort Collins and Atlanta. This is because the magnitude of the peak above the base flow is the numerator in the definitions of the rates of change metrics,  $R_N$ , and  $F_N$ . Only the  $Q_p$  and  $F_N$  for Atlanta showed significant median differences between the undeveloped and uncontrolled development scenarios, but all three of these metrics showed some degree of sensitivity to both uncontrolled development and stormwater controls in Fort Collins and Atlanta. One possible explanation for the lack of significance in the sensitivity of these metrics is the fact that the flow regime in the study watershed is naturally flashy, making it more difficult to see significant increases in flashiness caused by urban development relative to an already flashy pre-development metric value. It is clear from Figure 13 that stormwater controls result in smaller event-peaks and rates of change, effectively decreasing the flashiness of the flow regime. In the case of the  $F_N$ , shown in Figures 13e and 13f, the flashiness is reduced to below pre-development values by stormwater controls because of the lengthened recessional flows caused by detention facilities. Whether or not this result is desirable ecologically requires further study. Given the similar behavior of these metrics across scenarios and the significant sensitivity of  $Q_p$  and  $F_N$  to uncontrolled development

and stormwater controls in Atlanta, the event-peak flow and event-mean rates of change have potential to be used as design metrics in the small-scale, urban context.

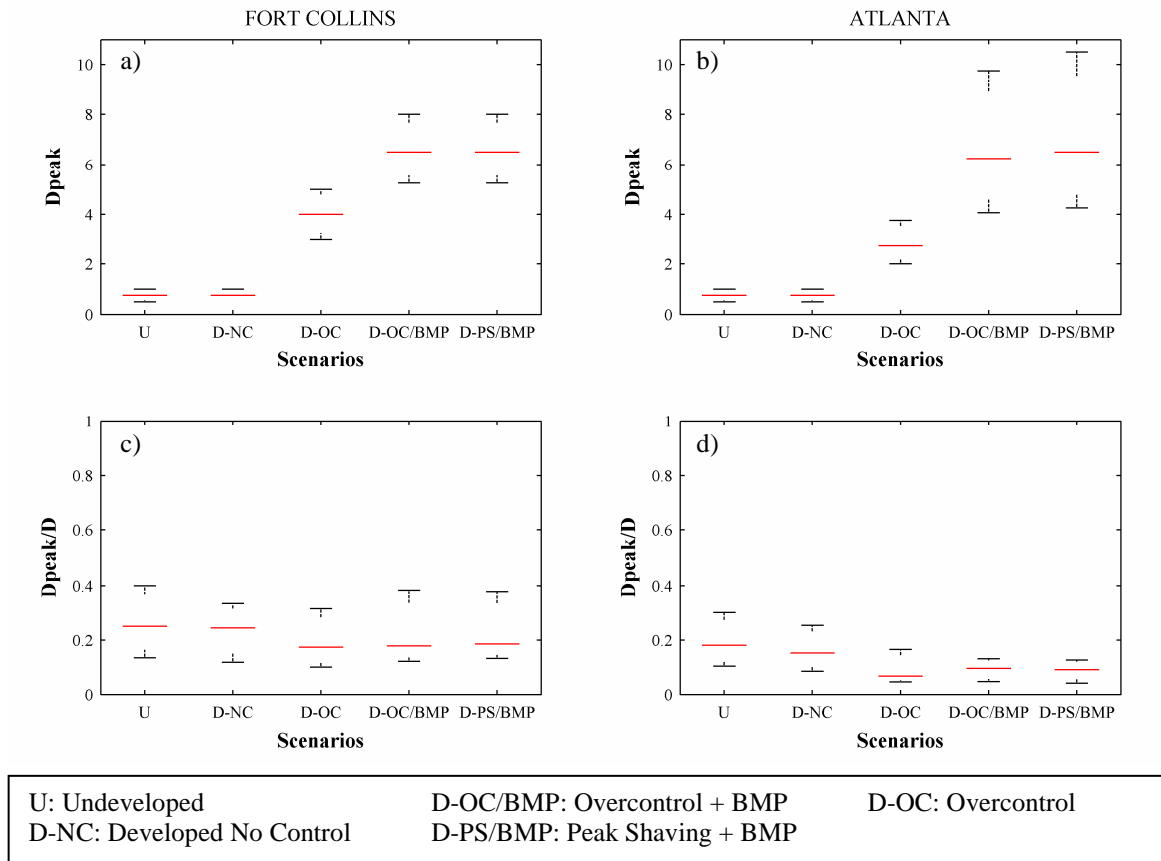
In terms of magnitude of metric sensitivity relative to the undeveloped scenario, the event duration,  $D$ , was by far the most sensitive metric in this analysis. This sensitivity, shown in Figures 14a and 14b occurred not in response to uncontrolled development, but in response to development with stormwater controls. This comes as no surprise since the increased volume of runoff caused by urban development, when detained and released at a restricted flow rate, will inevitably have to be released for a longer period of time. This metric may be useful in a situation where increased durations are detrimental the stream ecosystem. In such a situation, this metric could be used to demonstrate that perhaps infiltration or low-impact developments are better mitigation options.

The  $t_p$ , shown in Figures 14c and 14d, was not significantly altered by uncontrolled development, although controls increased median values of this metric by up to six times the undeveloped value in Fort Collins and more than four times in Atlanta. These increases were due to increased travel time resulting from routing the runoff through an increased storage volume prior to reaching the outlet. When storage is added to the system, the peak of the new hydrograph will intersect the falling limb of the original system hydrograph. Conventional hydrologic theory suggests that the  $t_p$  should decrease in response to uncontrolled development due to a shorter time-of-concentration in gutters and pipes than in the natural overland flow paths, as well as less flow resistance. However, the  $t_p$  was not observed to decrease in response to uncontrolled development in either Fort Collins or Atlanta. What is less obvious from Figure 14 is that although  $t_p$  does not decrease with uncontrolled development, the fact that it does not

increase represents increased flashiness because it is taking the same amount of time to reach a much higher peak than was reached in the pre-development scenario. The increases in  $t_p$  caused by adding storage to the system represent decreases in flashiness. In addition to serving as a measure of a particular aspect of flashiness, this parameter could be useful for design when an organism of concern requires a certain amount of “warning” time from the beginning of storm flow to seek refuge during a flood event.

The ratio of time-to-peak to duration of flow event,  $t_p/D$ , plotted in Figures 14e and 14f, was shown to be relatively insensitive to uncontrolled development in Fort Collins and Atlanta, but decreased significantly in the controlled development scenarios for both locations to approximately one fourth of the pre-development values. The decreased  $t_p/D$  ratios represent increased positive skewness of event hydrographs due to extended detention with a controlled release of runoff, lengthening the falling limbs of event hydrographs. These results show that the time-to-peak in this watershed was not significantly decreased by uncontrolled development nor were the event durations. However, both the  $D$  and  $t_p$  increased with controls and the  $t_p/D$  ratios show that these increases were not proportional, but rather  $D$  is increased by a much greater margin than  $t_p$  in the scenarios with stormwater controls. This metric was proposed in section 4.0 as another measure of flashiness that would indicate where in time the peak occurs with respect to the total storm flow duration. This metric is not appropriate as a design metric because the response to stormwater controls is in the same direction as the response to uncontrolled development, albeit for different reasons (i.e. increased storm flow duration versus decreased time-to-peak).

Figures 15a and 15b show that the peak durations,  $D_{\text{peak}}$ , are unaffected by uncontrolled development, but are increased considerably by development with controls. The largest increases in  $D_{\text{peak}}$  occur for scenarios that have BMPs. This makes sense because BMPs are designed to act on the most frequent storms and release them slowly over a 40-hour draw-down period. This metric can be used to evaluate the effect of controls on the peak durations of intermediate size storm flow events and determine whether or not these effects pose a threat to the stream ecosystem of interest in future regression analyses with biological data.



**Figure 15: Peak durations and peak duration ratios for Fort Collins and Atlanta. Plots a) and b) are standardized by the medians of the undeveloped scenarios to show relative sensitivity.**

The peak duration ratio,  $D_{\text{peak}}/D$ , shown in Figures 15c and 15d, does not show significant sensitivity to uncontrolled development or stormwater controls across scenarios. These results indicate that, with the exception of the *over-control* scenario for Atlanta, the increase in peak duration was essentially proportional to the increase in total event duration caused by controls. This metric is not sensitive to the hydrologic consequences of development and stormwater controls, nor is it easy to imagine a plausible physical connection between the  $D_{\text{peak}}/D$  and stream ecosystem health. Therefore, the  $D_{\text{peak}}/D$  is not useful for future studies to improve design of runoff controls.

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

An integration of engineering and ecological approaches is needed to facilitate a more complete assessment of the consequences associated with various alternatives facing decision makers at the planning and design stage of development. This study took some exploratory first steps in this regard by tailoring a generic hydrologic metric approach to the scale and context of stormwater controls for new urban developments. Recognizing that site-specific considerations will serve as the ultimate guide in future studies of this kind, the aim of this general investigation was to provide insights regarding metric selection and metric utility for model-based analyses at the design scale of urban stormwater controls.

Metrics were initially chosen for their success in establishing linkages between hydrology and biology in previous urban applications. The list of metrics was reduced by eliminating metrics that lack meaning at this scale or are subject to high model uncertainties. As a result of the extremely small basin size (10 ha), the flow regimes examined in this study were extremely flashy and intermittent with storm flow occurring less than 5 percent of the time. Also, regardless of basin size, the SWMM model is not capable of accurately simulating the relationships between infiltration, subsurface flow, and base flow. For these reasons, low flow metrics and metrics based on percentiles of flow (i.e. 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup> percentiles of flow occurrence) were excluded from the final metric analysis.  $T_{Q_{\text{mean}}}$  and *original*  $T_{0.5\text{yr}}$  were determined to be insensitive to urbanization at this scale and were omitted from the final list of metrics. The fact that

mean flows are closely tied to base and recession flows and are subject to large model uncertainties was also a factor in the omission of  $T_{Q_{\text{mean}}}$  from the model-based scenario analysis. Another issue related to conducting metric analyses at the design scale of new developments is that time series of daily mean flows are temporally too coarse to represent hydrologic response at this scale. For this reason, time series of 15-minute mean flow rates were used in this analysis.

In addition to a set of event-based metrics, analogous to the reduced set of metrics from the literature review, a *modified* version of  $T_{0.5\text{yr}}$  that uses a fixed pre-development 0.5-year peak flow rate for standardization of flow duration curves was included in the final set of metrics. Also, the  $t_p$ ,  $t_p/D$ , and  $D_{\text{peak}}/D$  were proposed in this study as new flashiness metrics. Algorithms for the final set of metrics was programmed in MATLAB© and computed in a multiple scenario comparison of development alternatives using 48-year time series of 15-minute mean flow rates generated by SWMM.

While the *original*  $T_{0.5\text{yr}}$  was found to be insensitive to urbanization in the study watershed, the scenario comparison analysis indicated that the *modified*  $T_{0.5\text{yr}}$  was found to be sensitive to urbanization and the deviations of this metric from pre-development values were mitigated by extended detention and BMP controls in Fort Collins and Atlanta. The results of the model-based scenario analysis also confirmed that the event-based metrics were sensitive to differences between scenarios of urban development and stormwater controls for a 10 ha parcel of land and exhibited similar patterns of behavior for Fort Collins and Atlanta rainfall regimes. Two of the event-based metrics proposed in this study, the ratio of time-to-peak to total storm flow duration and the peak duration ratio, were deemed inappropriate for the study of the hydrologic and ecological

consequences of urban development because of a relative insensitivity to differences between scenarios. The event-based peak flow rates, rates of change, storm flow durations, peak durations and time-to-peak metrics demonstrated the fundamental changes in storm flow response that result from urban development and translated them into a form that could be used in regression with biological data. These metrics along with the *modified*  $T_{0.5yr}$  have potential as design metrics in future studies of ecological outcomes associated with various stormwater controls.

Since stormwater controls are typically designed using a limited number of design storms, event-based flow metrics computed from continuous flow records are more intuitive for engineers than metrics defined in terms of daily mean flows. Continuous simulation can be used in conjunction with event-based metrics to observe the effects of the design alternatives on non-target event types, and serve as a potential method of testing and refining drainage designs. The next step is to test the recommended set of metrics with biological data in an urban gradient study at a small watershed scale. If metrics can be identified that are sensitive to hydrologic differences between stormwater control alternatives and uncontrolled development, in addition to being well correlated with aquatic ecosystem health, the linkage can be made between stormwater controls and inferred ecological outcomes in receiving streams. Such linkages would help municipalities and developers collaborate with regional efforts to protect watersheds from urbanization.

An underlying assumption of this analysis was that controlling hydrologic change locally would contribute to overall watershed protection. Future research is needed regarding how to translate small-scale flow regime alteration at headwater portions of a drainage network into larger-scale flow regime alteration downstream. This is

particularly important given scale considerations in stream ecology. For example, organisms living in the harsh pre-development flow environment studied in this analysis would probably be very resilient and relatively unsusceptible to the hydrologic effects of urbanization. In such a stream network, the “ecologically critical stream segments,” where flow-regime-biota relationships would be developed and used to set management targets may be further downstream. In order to translate downstream flow regime targets into design guidance for stormwater controls in small subbasins upstream, it is necessary to consider the influence of network topology on hydrologic response at various scales within a drainage network and how this relationship is altered by urban development. Research in this area has potential to give mechanistic answers to questions about hydrologic metric applicability at various scales within a drainage network.

An alternate approach to investigating the scale-dependence of hydrologic metric behavior that could potentially compliment a deterministic approach to explaining the network topology, described above, is to consider a stream in terms of where its metric value falls on a flashy-stable continuum. Empirical relationships could be developed between basin area and metric behavior, depending on where you are on the flashy-stable continuum.

While this study does provide a more complete consideration of flow regime in the context of stormwater control design than the traditional analyses related to peak flows and water quality, it still neglects to consider urbanization’s effects on low flows. Whether low flows increase or decrease in response to urban development is widely variable and depends on a number of factors, both natural and anthropogenic (i.e. subsurface flow and lawn watering), that cannot accurately be accounted for in a SWMM simulation.

Lastly, additional research is needed to estimate the error associated with model-based calculations of hydrologic metrics, relative to metrics computed from measured flow data. This would require a small watershed that has long-term, concurrent rainfall and stream flow data. Error estimates could be obtained by computing the metrics from gage data and comparing these values to those obtained from continuous simulation. Similarly, metrics computed from a calibrated model could be compared to those computed from an uncalibrated model.

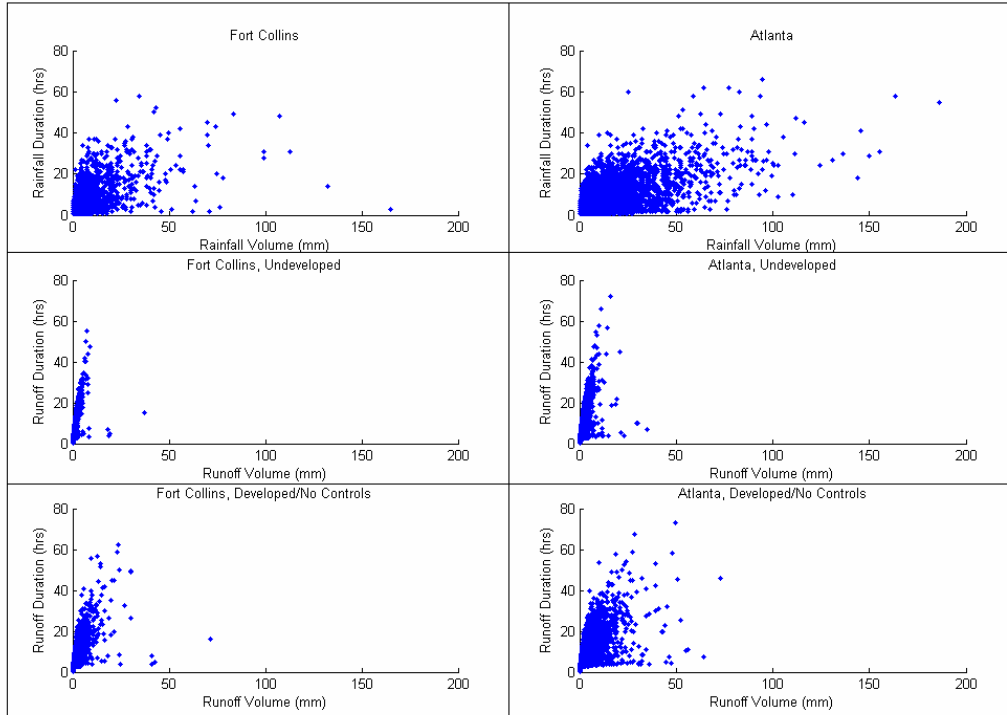
## REFERENCES

- American Society of Civil Engineers. 1998. Manual and Report on Engineering Practice No. 87. ASCE Reston, Virginia.
- Bledsoe, B.P. 2002. "Relationships of Stream Responses to Hydrologic Changes." In *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation*. Urbonas, B.R. (Ed.), American Society of Civil Engineers.
- Booth, D.B., Karr, J.R., Schauman, S., Konrad, C.P., Morley, S.A., Larson, M.G., and Burger, S.J. 2004. Reviving Urban Streams: Land Use, Hydrology, Biology, and Human Behavior. *Journal of the American Water Resources Association* **40** (5), 1351-1364.
- Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Henriksen J. 1998. Stream habitat analysis using the Instream Flow Incremental Methodology. *Information and Technology Report USGS/BRD-1998-0004*. US Geological Survey, Biological Research Division, Washington, DC.
- Bunn, S.E. and Arthington, A.H. 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* **30** (4), 492-507.
- Clausen, B. and Biggs, B.J.F. 2000. Flow Variables for Ecological Studies in Temperate Streams: Groupings Based on Covariance. *Journal of Hydrology* **237** (3-4), 184-197.
- City of Fort Collins – Water Utilities. 1997. Memorandum: Update to the Stormwater Drainage Design Criteria and Construction Standards. Memorandum to all manual owners. April 29, 1997.
- Cunnane, C. 1978. Unbiased plotting positions- a review. *Journal of Hydrology* **37**:205-222.
- Center for Watershed Protection (CWP). 2002. Is Impervious Cover Still Important? Section 1: A Review of Recent Urban Stream Research. [www.cwp.org/Impacts\\_Part1.PDF](http://www.cwp.org/Impacts_Part1.PDF). Ellicott City, MD.
- Gore, J.A., Layzer, J.B., and Mead, J. 2001. Macroinvertebrate Instream Flow Studies After 20 Years: a Role in Stream Management and Restoration. *Regulated Rivers- Research & Management* **17** (4-5), 527-542.
- Henriksen, J. A., Heasley, J., Kennen, J.G., and Niewsand, S. 2006. Users' Manual for the Hydroecological Integrity Assessment Process Software: U.S. Geological Survey, Biological Resources Discipline, Open File Report 2006-1093, 71 p.

- Huber, W.C. and R.E. Dickinson. 1988. *Storm Water Management Model User's Manual, Version 4*. Environmental Protection Agency. Athens, GA. EPA/600/3-88/001a.
- Jacobson, R.B., S.R. Femmer and R.A. McKenney. 2001. Land-use Changes and the Physical Habitat of Streams-A Review with Emphasis on Studies within the U.S. Geological Survey Federal-State Cooperative Program. U.S. Geological Survey, Circular 1175, 63.
- Kirby, C.W. 2003. Benthic Macroinvertebrate Response to Post-Development Stream Hydrology and Hydraulics. PhD Dissertation. George Mason Univ., Fairfax, VA. UMI Microform 3079343.
- Konrad, C.P. 2000. New Metrics to Characterize the Influence of Urban Development on Stream Flow Patterns. *The Washington Water Resource* **11**(4), 2-6.
- Konrad, C. P. and Booth, D. B. 2002. Hydrologic Trends Resulting from Urban Development in Western Washington Streams. U.S. Geological Survey Water-Resources Investigation Report, 02-4040. 40 pp.
- Milhous RT, Wegner DL, Waddle T. 1984. *User's Guide to the Physical Habitat Simulation System*. US Fish and Wildlife Service, FWS/OBS 81/43: Washington, DC.
- Nehrke, S.M. and L.A. Roesner. 2004. Effects of Design Practice for Flood Control and BMPs on the Flow Frequency Curve. *Journal of Water Resources Planning and Management*. ASCE. March/April Volume.
- Olden, J.D. and Poff, N.L. 2003. Redundancy and the Choice of Hydrologic Indices for Characterizing Streamflow Regimes. *River Research and Applications* **19** (2), 101-121.
- Oregon State University (OSU). 2001. EPA Storm water management model, <http://ccee.oregonstate.edu/swmm/>
- Poff, N.L. 1996. A Hydrogeography of Unregulated Streams in the United States and an Examination of Scale-dependence in some Hydrologic Descriptors. *Freshwater Biology* **36**:71-91.
- Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. 1997. The Natural Flow Regime. *Bioscience* **47** (11), 769-784.
- Poff, N.L. and Ward, J.V. 1989. Implications of Streamflow Variability and Predictability for Lotic Community Structure - a Regional-Analysis of Streamflow Patterns. *Canadian Journal of Fisheries and Aquatic Sciences* **46** (10), 1805-1818.
- Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology* **10**:1163-1174.
- Richter, B.D., Baumgartner, J.V., Wigington, R., and Braun, D.P. 1997. How Much Water Does a River Need? *Freshwater Biology* **37** (1), 231-249.

- Roesner, L.A. and B.P. Bledsoe. 2003. *Research Needs: Physical Effects of Wet Weather Flows on Aquatic Habitats*. WERF.
- Rohrer, C.A. 2004. Modeling the Effect of Stormwater Controls on Sediment Transport in an Urban Stream. Master's Thesis. Colorado State University, Fort Collins, CO.
- Scoggins, M. 2000. Effects of Hydrologic Variability on Biological Assessments in Streams in Austin, TX. City of Austin, Watershed Protection Department. NWQMC 2000 proceedings.
- Tharme, R.E. 2003. A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers. *River Research and Applications* **19** (5-6), 397-441.
- Urban Drainage and Flood Control District (UDFCD). 2001. Urban Storm Drainage Criteria Manual. Volumes 1 and 2. Denver, Colorado.
- Walsh, C.J. 2004. Protection of in-Stream Biota From Urban Impacts: Minimise Catchment Imperviousness or Improve Drainage Design? *Marine and Freshwater Research* **55** (3), 317-326.
- Walsch, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P. 2005. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. *Journal of the North American Benthological Society*. **24**(3):706-723.
- Water Environment Federation (WEF) and American Society of Civil Engineers (ASCE). 1998. *Urban Runoff Quality Management*. WEF manual of practice; no. 23. ASCE manual and report on engineering practice; 87.
- Waters, T.F. 1995. Sediment in Streams—Sources, Biological Effects, and Control. *American Fisheries Society Monograph* 7:251.

**APPENDIX A: RAINFALL AND RUNOFF VOLUMES FOR  
ATLANTA AND FORT COLLINS**



**Figure 16: Rainfall duration versus volume Ft. Collins and Atlanta**

**APPENDIX B: MATLAB M-FILES CODE FOR EACH  
METRIC**

## **T<sub>0.5yr</sub> (annualized) algorithm - written in Matlab © for 15-minute time-step resolution**

```
function [Tqh] = TQh(C,Qhalf,start,last,ph)
leap=0;
year=start;
column=1;

while year<last+1,
    if year<last+1,
        if ph==1,
            for i=1:35040,
                CC(i,column)=C(i+35040*3*leap+35136*leap,1);
            end
            ph=ph+1;
            column=column+1;
            year=year+1;

        end

        if year<last+1,
            if ph==2,
                for i=1:35040,
                    CC(i,column)=C(i+35040*3*leap+35040*(ph-1)+35136*leap,1);
                end
                ph=ph+1;
                column=column+1;
                year=year+1;

            end

            if year<last+1,
                if ph==3,
                    for i=1:35040,
                        CC(i,column)=C(i+35040*3*leap+35040*(ph-1)+35136*leap,1);
                    end
                    ph=ph+1;
                    column=column+1;
                    year=year+1;

                end

                if year<last+1,
                    if ph==4,
                        for i=1:35136,
                            CC(i,column)=C(i+35040*3*leap+35040*(ph-1)+35136*leap,1);
                        end
                        ph=1;
                        column=column+1;
                        year=year+1;

                    end
                end
            end
        end
    end
end
leap=leap+1;
```

```

end
year=start;
column=1;
while year<last+1,
    if year<last+1,
        for i=1:35136,

            if CC(i,column)>=Qhalf,
                D(i,column)=1;
            else,
                D(i,column)=0;
            end

        end
        column=column+1;
        year=year+1;
    end
Tqh_annual=(sum(D))*0.000028;
T=Tqh_annual';
Tqh(:,1)=prctile(T(:,1), [25 50 75]);

end

```

## **T<sub>Qmean</sub> algorithm - written in Matlab © for 15-minute time-step resolution**

```
function [Tqm] = TQmean_15(C,start,last,ph)
leap=0;
year=start;
column=1;

while year<last+1,
    if year<last+1,
        if ph==1,
            for i=1:35040,
                CC(i,column)=C(i+35040*3*leap+35136*leap,1);
            end
            ph=ph+1;
            column=column+1;
            year=year+1;

        end

        if year<last+1,
            if ph==2,
                for i=1:35040,
                    CC(i,column)=C(i+35040*3*leap+35040*(ph-1)+35136*leap,1);
                end
                ph=ph+1;
                column=column+1;
                year=year+1;

            end

            if year<last+1,
                if ph==3,
                    for i=1:35040,
                        CC(i,column)=C(i+35040*3*leap+35040*(ph-1)+35136*leap,1);
                    end
                    ph=ph+1;
                    column=column+1;
                    year=year+1;

                end

                if year<last+1,
                    if ph==4,
                        for i=1:35136,
                            CC(i,column)=C(i+35040*3*leap+35040*(ph-1)+35136*leap,1);
                        end
                        ph=1;
                        column=column+1;
                        year=year+1;

                    end

                    end

                    leap=leap+1;
```

```

end
year=start;
column=1;

while year<last+1,
    if year<last+1,

        M(1,column)=mean(CC(:,column));

    end
        column=column+1;
        year=year+1;
end
year=start;
column=1;

while year<last+1,
    if year<last+1,
        for i=1:35136,

            if CC(i,column)>=M(1,column),
                D(i,column)=1;
            else,
                D(i,column)=0;
            end

        end
        column=column+1;
        year=year+1;
    end

end
M;
Tqmean=(sum(D))*0.000028;
T=Tqmean';
Tqm(:,1)=prctile(T(:,1), [25 50 75]);

```

## **T<sub>Qmean</sub> (daily) algorithm - written in Matlab © for 1-day time-step resolution**

```
function [tqmD] = TQmean_day(A,start,last,ph)
%A is a continuous 15min flow record
nd=floor(size(A,1)/96);
B=zeros(96,nd);
q=size(B);
for i=1:nd,
    for j=1:96
        B(j,i)=A(j+96*(i-1),1);
    end
C(i,1)=mean(B(:,i));
end

leap=0;
year=start;
column=1;
while year<last+1,
    if year<last+1,
        if ph==1,
            for i=1:365,
                CC(i,column)=C(i+365*3*leap+366*leap,1);
            end
            ph=ph+1;
            column=column+1;
            year=year+1;

        end
        end

    if year<last+1,
        if ph==2,
            for i=1:365,
                CC(i,column)=C(i+365*3*leap+365*(ph-1)+366*leap,1);
            end
            ph=ph+1;
            column=column+1;
            year=year+1;

        end
        end

    if year<last+1,
        if ph==3,
            for i=1:365,
                CC(i,column)=C(i+365*3*leap+365*(ph-1)+366*leap,1);
            end
            ph=ph+1;
            column=column+1;
            year=year+1;

        end
        end

    if year<last+1,
        if ph==4,
```

```

        for i=1:366,
            CC(i,column)=C(i+365*3*leap+365*(ph-1)+366*leap,1);
        end
        ph=1;
        column=column+1;
        year=year+1;

    end
end
leap=leap+1;

end
year=start;
column=1;

while year<last+1,
    if year<last+1,

        M(1,column)=mean(CC(:,column));

    end
        column=column+1;
        year=year+1;
end
year=start;
column=1;

while year<last+1,
    if year<last+1,
        for i=1:366,

            if CC(i,column)>=M(1,column),
                D(i,column)=1;
            else,
                D(i,column)=0;
            end

        end
        column=column+1;
        year=year+1;
    end

end
M;
Y=(sum(D))/365.5;
annual_tqmD=Y';
tqmD(:,1)=prctile(annual_tqmD(:,1), [25 50 75]);

```

## Event-based metric algorithm - written in Matlab © to compute set of event-based metrics from a flow time series with a 15-minute time-step resolution

```

function [peak_flow] = storm_peak3_dur(flow)
threshold=0.106;
flow=flow-threshold;
flow_size=size(flow);
for i=1:flow_size(1,1)
    if flow(i,1)<0
        flow(i,1)=0;
    end
end
j=1;
for i=2:flow_size(1,1)
    if (flow(i-1,1)==0 && flow(i,1)>0 )
        start(j,1)=i;%records the start of an event
        j=j+1;
    end
end
j=1;
for i=1:flow_size(1,1)-1
    if (flow(i,1)>0 && flow(i+1,1)==0)
        finish(j,1)=i;
        j=j+1;
    end
end
k=1;
r=0;
for i=1:j-2

    if ((start(i+1,1)-finish(i,1))>=24)
        ti(k,1)=start(r+1,1);
        tf(k,1)=finish(i,1);
        k=k+1;
        r=i;
    end
end

peak_flow=zeros(k-1,11);
%start, end, t(Qp), duration, Qp, D, tp/td, Rn, Fn, Dpeak, Dpeak/D, V
peak_flow(:,1)=ti(:,1);
peak_flow(:,2)=tf(:,1);
peak_flow(:,5)=((tf(:,1))-(ti(:,1))+1);

for i=1:k-1

peak_flow(i,4)=(max(flow(peak_flow(i,1):peak_flow(i,2),1))+threshold);%
Qp

peak_flow(i,11)=(sum(flow(peak_flow(i,1):peak_flow(i,2),1))+threshold));
%V
end
for i=1:k-1
    for z=peak_flow(i,1):peak_flow(i,2)
        if flow(z,1)+threshold==peak_flow(i,4)

```

```

        peak_flow(i,3)=z;%t(Qp)
    end
end
end
t=0;
for i=1:k-1
    for z=peak_flow(i,1):peak_flow(i,2)
        if (flow(z,1)>=(0.75*(peak_flow(i,4) )-threshold))
            t=t+1;
        end
        peak_dur(i,1)=t;

    end
    t=0;
end

peak_flow(:,9)=peak_dur(:,1);%Dpeak
for l=1:k-1
    peak_flow(l,6)=(peak_flow(l,3)-peak_flow(l,1)+1);%tp
    peak_flow(l,7)=((peak_flow(l,4)-0.106)/(peak_flow(l,3)-
peak_flow(l,1)+1));%Rn
    peak_flow(l,8)=((0.106-peak_flow(l,4))/(peak_flow(l,2)-
peak_flow(l,3)+1));%Fn
    peak_flow(l,10)=(peak_flow(l,9)/peak_flow(l,5));%Dpeak/D
    peak_flow(l,12)=(peak_flow(l,3)-
peak_flow(l,1)+1)/peak_flow(l,5);%tp/D
end

peak_flow;
events(:,1)=prctile(peak_flow(:,4),[25 50 75])*0.028317;%Qp cms
events(:,2)=prctile(peak_flow(:,5),[25 50 75])*0.25;%D hrs
events(:,3)=prctile(peak_flow(:,7),[25 50 75])*0.1133;%Rn cms/hr
events(:,4)=-1*(prctile(peak_flow(:,8),[25 50 75]))*0.1133;%Fn cms/hr
events(:,5)=prctile(peak_flow(:,6),[25 50 75])*0.25;%tp hrs
events(:,6)=prctile(peak_flow(:,12),[25 50 75]);%tp/D
events(:,7)=prctile(peak_flow(:,11),[25 50 75])*0.2569;%V mm
events(:,8)=prctile(peak_flow(:,9),[25 50 75])*0.25;%Dpeak hrs
events(:,9)=prctile(peak_flow(:,10),[25 50 75]);%Dpeak/D

```

**APPENDIX C: NUMERICAL VALUES OF ALL METRIC  
MEDIAN AND INTERQUARTILE RANGES**

**Table 11: Numerical values of metric medians and IRs  $T_{Qmean}$  and  $T_{0.5yr}$**

| Atlanta $T_{qmean}$ (from 15min time-step) |       |       |       |          | Fraction of time |
|--|-------|-------|-------|----------|------------------|
| Percentile                                 | U     | D-NC  | D-OC  | D-OC/BMP | D-PS/BMP         |
| 25   | 0.047 | 0.049 | 0.129 | 0.166    | 0.166            |
| 50   | 0.050 | 0.053 | 0.137 | 0.178    | 0.178            |
| 75   | 0.054 | 0.056 | 0.146 | 0.186    | 0.186            |

| Atlanta $T_{qmean}$ (from daily time-step) |       |       |       |          | Fraction of time |
|--|-------|-------|-------|----------|------------------|
| Percentile                                 | U     | D-NC  | D-OC  | D-OC/BMP | D-PS/BMP         |
| 25   | 0.150 | 0.150 | 0.176 | 0.205    | 0.205            |
| 50   | 0.163 | 0.164 | 0.187 | 0.219    | 0.219            |
| 75   | 0.168 | 0.174 | 0.205 | 0.227    | 0.228            |

| Fort Collins $T_{qmean}$ (from 15min time-step) |       |       |       |          | Fraction of time |
|---|-------|-------|-------|----------|------------------|
| Percentile                                      | U     | D-NC  | D-OC  | D-OC/BMP | D-PS/BMP         |
| 25  | 0.033 | 0.027 | 0.083 | 0.101    | 0.099            |
| 50  | 0.041 | 0.032 | 0.093 | 0.112    | 0.112            |
| 75  | 0.069 | 0.038 | 0.104 | 0.128    | 0.129            |

| Fort Collins $T_{qmean}$ (from daily time-step) |       |       |       |          | Fraction of time |
|---|-------|-------|-------|----------|------------------|
| Percentile                                      | U     | D-NC  | D-OC  | D-OC/BMP | D-PS/BMP         |
| 25  | 0.090 | 0.074 | 0.094 | 0.112    | 0.112            |
| 50  | 0.104 | 0.088 | 0.114 | 0.129    | 0.130            |
| 75  | 0.130 | 0.098 | 0.124 | 0.149    | 0.145            |

| Fort Collins $T_{0.5yr}$ |          |          |          | Fraction of time |
|--------------------------|----------|----------|----------|------------------|
| Percentile               | U        | D-NC     | D-NC     | D-NC             |
|                          | 5%imp    | 30%imp   | 90%imp   |                  |
| 25                       | 8.40E-05 | 8.40E-05 | 8.40E-05 |                  |
| 50                       | 1.82E-04 | 1.54E-04 | 1.68E-04 |                  |
| 75                       | 3.36E-04 | 3.22E-04 | 2.94E-04 |                  |

| Fort Collins $T_{qmean}$ |          |          |          | Fraction of time |
|--------------------------|----------|----------|----------|------------------|
| Percentile               | U        | D-NC     | D-NC     | D-NC             |
|                          | 5%imp    | 30%imp   | 90%imp   |                  |
| 25                       | 3.28E-02 | 2.67E-02 | 2.76E-02 |                  |
| 50                       | 4.10E-02 | 3.21E-02 | 3.35E-02 |                  |
| 75                       | 6.92E-02 | 3.78E-02 | 3.86E-02 |                  |