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Thesis submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Civil Engineering

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April 28, 2011
Manassas, Virginia

Key Words: Natural Channel Stream Design, bankfull, urbanization, impervious area, channel enlargement
Abstract

It is well documented that urbanization changes the hydrology of watersheds (Hammer 1972; Booth 1991; Rose and Peters 2001). Increases in runoff volume and velocity from urbanization result in stream channel degradation (Hammer 1972; Henshaw and Booth 2000; Walsh et al. 2005; Leopold et al. 2005a; Poff et al. 2006). While stormwater management measures may be implemented to reduce the impact of stormwater runoff on streams, these practices do not reverse stream channel degradation that has already occurred. Stream restoration utilizing Natural Channel Stream Design (NCD) techniques is an effective way to reverse the effects of urbanization and return natural function to a stream. The design (bankfull) discharge for an NCD stream restoration project is the cornerstone of a restoration design. Existing methodologies for determining design discharges, such as hydrologic modeling and bankfull identification, have not worked well for NCD stream restoration projects in urban watersheds. The use of hydraulic geometry relationships serves as an alternative method for determining design discharge, but the required information is not generally available for urban Northern Virginia streams. However, rural regional curves developed for the Maryland piedmont, adjusted for watershed impervious area, provide a means to determine design discharges for urban stream restoration projects in Northern Virginia.
Acknowledgements

I would like to thank Dr. Tom Grizzard, my advisor and committee chair, as well as Dr. Adil Godrej and Dr. David Sample for their encouragement, guidance, and feedback. I am indebted to Mr. Mike Rolband, president of Wetland Studies and Solutions, Inc., for providing me with the opportunity to pursue my graduate degree and for allowing me to work on the Northern Virginia Stream Restoration project - a once in a lifetime work experience. Thank you to Mr. Frank Graziano whose engineering knowledge and mentoring has helped shape me as a professional. Additional thanks are due to the design team for the Northern Virginia Stream Restoration Bank, all of whom had a hand in the development and vetting of the method presented in this paper. Thank you to my family for their support throughout graduate school. Finally, all my thanks and love to my wife Kelly and daughter Nora who have given me their unconditional support, and shouldered the burden around our house, while I remained holed up in the basement drafting this thesis.
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1.0 Introduction

Between 1985 and 2008, the population of the Northern Virginia region (Arlington County, City of Alexandria, Fairfax County, Fauquier County, Loudoun County, and Prince William County) grew by 64% (U.S. Census Bureau 2010). With the population growth and associated development, impervious surfaces also increased; however, the difference in the pixel quality of aerial photography between the 1980’s and the present prevent the calculation of an exact rate of impervious area increase. Increased runoff from these surfaces has caused, and is continuing to cause, considerable damage to the region’s streams. In situ stream sediment, typically not of sufficient size to withstand the increased flow, is mobilized more frequently during storm events, resulting in excessive stream bed and bank erosion. As streams erode, they become increasingly disconnected from their floodplains; higher flows are contained in the stream channel, thereby exacerbating the erosional processes; pollutants are transported directly downstream; the quality of in-stream habitat is reduced; and, ultimately, infrastructure is compromised.

Stream restoration is a popular and effective method to reverse the physical damage done to streams by increases in impervious surfaces. Over one billion dollars per year is spent on stream restoration in the United States (Palmer and Allan 2006). Depending on the type and location of restoration practice (livestock exclusion fencing in a rural watershed versus channel realignment with bed reinforcement and structures in an urban watershed), project costs can range from approximately twenty-five dollars per linear foot to over one thousand dollars per linear foot of stream restored (Wetland Studies and Solutions, Inc. 2005). With the funds being invested in stream restoration projects, ensuring that stream restoration plans are designed and implemented properly is of the utmost importance, not only to those investing in them directly, but also to the populations (plant, wildlife, and human) who are to be the beneficiaries.

Urban stream restoration is a delicate and complicated process of reestablishing a balance between flow and sediment. A successful stream restoration design gives proper consideration to the various metrics that contribute to stream stability, such as flow, sediment transport, cross section dimensions, channel geometry, and revegetation. While all the aforementioned metrics
play a role in stream stability, flow is the cornerstone of the design, making its accurate
determination critical. This thesis will present a method for the determination of approximate
design discharges that account for the increased flow associated with urbanization for urban
stream restoration projects in Northern Virginia. The process by which this method was
developed offers a framework for the development of similar methods in other regions.
2.0 Literature Review

2.1 The Urban Watershed Problem

The ability of a stream to remain stable and maintain its shape is dependent on the flow and sediment load from upstream sources (Leopold 1994). A stable stream transports the supplied flow and sediment while maintaining its dimension, pattern, and profile without either aggrading or degrading (Rosgen 1994). Even a stream that is highly dynamic (e.g. eroding the outsides of meanders, depositing sediment on the inside of meanders, and shifting the location of its thalweg) may be considered stable if its morphologic characteristics, such as dimension, pattern, and profile, remain relatively constant over time (Shields et al. 2003).

Land use changes that alter the hydrologic character of a watershed, such as urbanization, negatively affect stream stability. As impervious cover increases, infiltration and evapotranspiration decrease, resulting in a greater volume of runoff that occurs at a greater frequency, while the reduced resistance of impervious cover results in increased runoff velocities (Hammer 1972; Booth 1991; Rose and Peters 2001). Figure 1, below, illustrates the shift from an undeveloped watershed with a relatively high percentage of infiltration and little runoff to an intensely developed watershed with relatively little infiltration and a high percentage of runoff (Federal Interagency Stream Restoration Working Group 1998). It is important to note that massive development is not needed to bring about these negative changes. Streams can begin to degrade, biologically and physically, with as little as ten percent impervious cover in a watershed (Wang et al. 2001; Center For Watershed Protection 2003; Booth 2005; Olivera and DeFFee 2007). Estimates for the increase in peak flow rates from urbanization range from 20% (Booth 1991) to 100% (Rose and Peters 2001). For a stream system that has evolved from an undeveloped condition, these alterations to the hydrograph are nearly always detrimental, resulting in stream channel enlargement through incision and widening (Hammer 1972; Henshaw and Booth 2000; Walsh et al. 2005; Leopold et al. 2005a; Poff et al. 2006). Hammer (1972) found that channel enlargement intensifies with the period of exposure to impervious surface runoff, with a stream reaching its maximum size at approximately 30 years post-development, while Caraco (2000) found that it could take between 50 and 75 years for the
maximum size to be achieved. Even if a stream has reached its maximum size, it may not be restabilized. It may take further decades for the stream system to restabilize, if it does so at all (Hammer 1972; Simon 1989; Henshaw and Booth 2000; Leopold et al. 2005a).

Figure 1. Evolution of runoff response with increasing urbanization (Federal Interagency Stream Restoration Working Group 1998)

Ironically, with urbanization, bankfull discharges occur more frequently (Leopold 1994), but the stream accesses its floodplain less due to the resulting stream degradation. A stream which overtopped its banks on average between the 1.5 and 2 – year pre-development storm event (Leopold 1994) may only access the floodplain in the largest of storm events in the post-development state. Where they were once able to access the floodplain to dissipate energy, these storm events are restricted to the stream channel, exacerbating channel erosion.

As a stream erodes and becomes incised, the stream bed elevation drops below the root zone of existing bank vegetation (essential in providing bank stability) further contributing to the erosive processes. Furthermore, the lowering of the stream bed, coupled with reduced groundwater recharge (Rose and Peters 2001), lowers the local groundwater table. This process
has a negative effect on the health of the riparian vegetation (Groffman, et al. 2003; Schilling et al. 2004). Disconnected from the floodplain, such incised channels serve as earthen conduits that efficiently transport pollutants such as nitrogen, phosphorous, and total suspended solids to downstream receiving waters. In addition, the excessive erosion from stream channel enlargement threatens infrastructure such as roads, bridges, culverts, and utilities. Figures 2 and 3 show a portion of the Colvin Run watershed in Reston, Virginia in both the pre- and post-development states. Between 1954 (Figure 2) and 2008 (Figure 3) imperviousness in this area increased from a negligible percentage to approximately thirty percent. Figure 4 shows a representative section of stream located downstream of the area depicted in Figures 2 and 3. The photo, taken in 2009, depicts the damage done to the stream from the development of the watershed.

Figure 2. Colvin Run watershed, pre-development (Photo used with permission of Wetland Studies and Solutions, Inc. 2011)

Figure 3. Colvin Run watershed, post-development (Photo used with permission of Wetland Studies and Solutions, Inc. 2011)
2.2 Solving the Urban Watershed Problem

2.2.1 Controlling Runoff

In order to restore balance to an existing urban stream network, and to prevent continual stream degradation, control of the volume and velocity of urban runoff is required, as well as the reversal of the stream degradation caused by urbanization. Over the past several decades, attempts have been made to control the volume and velocity of stormwater runoff through a variety of stormwater management practices. There are many examples of conventional stormwater practices that have been applied to commercial and residential developments. Wet retention and dry detention ponds are typical examples, among others. Unfortunately, many conventional stormwater management practices can actually increase stream degradation by increasing the duration of high flows, which cause more erosion (Booth 1991; Caraco 2000). Further study has shown that the calculations used in the designs of these ponds under-predicts the runoff volume these ponds will actually receive (Hancock et al. 2010). If designs are done with low predictions of runoff volume, an obvious consequence is that the practices may never actually perform to the intended design standard.
One approach to adequately controlling the increased runoff volume and velocity associated with development, would be to design stormwater management facilities that reduce the energy from post-development runoff to a value equal to or less than that of pre-development runoff energy. This may be accomplished by design practices that match the product of the volume of runoff and the peak flow rate for both pre and post-development conditions. Though not required, this is currently an option available to design engineers in Virginia (Code of Virginia, § 10.1-561 2010). Figure 5 compares a theoretical pre-development hydrograph to three different theoretical post-development hydrographs. One post-development hydrograph illustrates the increase peak discharge associated with a developed area with no stormwater management; a second illustrates the extended duration of the peak flow for a developed site with conventional stormwater management; and, a third illustrates the reduction in peak discharge for a developed site where the energy balance method was used to size the stormwater management facilities.

Figure 5. Comparison of pre-development hydrographs to post-development hydrographs (Chart used with permission of Wetland Studies and Solutions, Inc. 2011)
A newer stormwater management technique that has increasingly come into vogue over the past decade is Low Impact Development (LID). LID utilizes decentralized, small scale stormwater management techniques to mimic pre-development site hydrology and create a functional landscape to curb the effects of urbanization (Low Impact Development Center 2005). With LID, runoff volume control, peak runoff control, flow frequency/duration control, and water quality volume control (0.5 inches of runoff over the impervious surface) are achieved by routing stormwater through a network of detention and retention devices (Code of Virginia § 10.1-560 2010). When implemented properly, LID may be a promising solution to the problems associated with urban stormwater runoff (Petrey 2007). Figure 6 illustrates the performance of a LID system installed at Wetland Studies and Solutions, Inc. (WSSI) headquarters in Gainesville, Virginia during a measured storm event. The LID practices reduced the post-development storm flow well below those of pre-development conditions.

![Figure 6. Hydrograph comparing post-development peak flow routed through LID practices to pre-development peak flow and post-development no LID peak flow](image)
2.2.2 Stream Restoration

When properly designed and applied, conventional stormwater management practices and LID can reduce the volume and velocity of storm flows, but they cannot reverse bank erosion or restore natural function to a stream channel that has already been incised and disconnected from its floodplain. Traditional engineering practices such as the installation of riprap, concrete, and gabions may be used to stabilize eroding banks. However, they fall short of restoring natural function to the stream for two reasons. First, such practices do not address the problem of incision, because higher flows are kept within the channel and the pollutant loads continue to be transported downstream. In Virginia a stream channel stabilized with traditional engineering practices is required to contain the 10-year storm event (Virginia Administrative Code §4VAC50-30-40.19.2(b) 2010). Second, they do not provide any significant ecological value because a stream channel engineered with traditional practices lacks the variability in substrate, flow depth, and channel morphology that exists in a natural stream channel.

An alternative to traditional engineering practices is Natural Channel Design (NCD). As stated in the Code of Virginia, NCD is defined as the “utilization of engineering analysis and fluvial geomorphic processes to create, rehabilitate, restore, or stabilize an open conveyance system for the purpose of creating or recreating a stream that conveys its bankfull storm event within its banks and allows larger flows to access its bankfull bench and its floodplain” (Code of Virginia § 10.1-560 2010). Unlike conventional engineering practice, the goal of NCD is not simply the abatement of stream bank erosion or the maximization of channel conveyance, but to bring the flow and sediment of a stream system back into balance and return natural hydraulic function. NCD reduces in-stream storm flow velocities by resizing the stream channel dimensions such that a floodplain connection is reestablished, allowing large flow events to access, spread out, and slow down in the floodplain. Additionally, the reestablished floodplain connection helps reduce downstream pollution by improving nutrient and sediment uptake in the floodplain, increasing evapotranspiration, improving riparian habitat, and raising local ground water tables. Further, by reducing the flow depth and establishing a more stable channel geometry, excessive bank and bed erosion can be arrested. Studies have shown that restored streams may also have improved nitrogen processing (Kaushal et al. 2008; Craig et al. 2008).
Finally, the improved flow conditions within the stream channel, coupled with a restored channel geometry and improvements to the stream bank vegetative communities, may improve in-stream habitat (Sudduth and Meyer 2006; Walther and Whiles 2008).

NCD restoration projects are based on sizing the restored stream channel for the bankfull flow, which generally speaking, is the maximum flow a channel can convey before accessing its floodplain (Copeland et al. 2000). Bankfull flow is expressed as a quantity of water measured in terms of volume per unit time, such as cubic feet per second (cfs). In terms of NCD, the bankfull flow is generally taken to be equivalent to approximately the 1- to 2-year storm event, which bound the 1.5 year event proposed by Leopold (1994). As a watershed is developed and the runoff volume of each storm event increases, the frequency at which bankfull events occur has been found to increase. With NCD, the bankfull event is assumed to coincide with the effective discharge, which is the flow that transports the largest portion of sediment over the course of a year, and is also known as the channel-forming event.

Once a restoration practitioner has determined a design (bankfull) discharge, the size and shape of the restoration channel may be determined using a stable reference stream of similar character (Rosgen 1998; Hey 2006). Figure 7 shows examples of the essential planform geometry dimensions for developing a stream restoration plan. Figure 8 shows a similar example for riffle cross section dimensions.

Figure 7. Examples of planform dimensions (Sketch used with permission of Wetland Studies and Solutions, Inc. 2011)
Stream dimensions may be extrapolated from the reference reach to the restoration reach using appropriately selected dimensionless ratios. Dimensionless ratios exist for most key aspects of the stream channel, and include, but are not limited to, riffle width to mean riffle depth, riffle width to meander length, and valley slope to channel slope. Equations 1 and 2 provide an example of how width/depth ratio for the reference reach could be used to determine the bankfull mean depth for a restoration reach.

Reference Reach Width/Depth Ratio = \( \frac{W_{bkf-ref}}{d_{bkf-ref}} \)  \hspace{1cm} (1)

\[ = \frac{15.0}{1.2} \]
\[ = 12.5 \]

Where:
\( W_{bkf-ref} = \) Bankfull Width, Reference Reach, ft
\( d_{bkf-ref} = \) Bankfull Mean Depth, Reference Reach, ft

Assuming a proposed restoration reach has a design bankfull width of 20 feet, the design bankfull mean depth could then be computed as follows:

\[ d_{bkf-prop} = \frac{W_{bkf-prop}}{\left( \frac{W_{bkf-ref}}{d_{bkf-ref}} \right)} \] \hspace{1cm} (2)

\[ = \frac{20}{12.5} \]
\[ = 1.6 \text{ ft} \]

Where:
\( \frac{W_{bkf-ref}}{d_{bkf-ref}} = \) Width/Depth Ratio, Reference Reach
$W_{b kf-prop} = \text{Bankfull Width, Restoration Reach, ft}$

$d_{b kf-prop} = \text{Bankfull Mean Depth, Restoration Reach, ft}$

Table 1 summarizes the values presented in Equations 1 and 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference Reach</th>
<th>Restoration Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riffle Bankfull Width</td>
<td>$W_{b kf}$</td>
<td>10.0 ft</td>
</tr>
<tr>
<td>Riffle Bankfull Mean Depth</td>
<td>$d_{b kf}$</td>
<td>0.8 ft</td>
</tr>
<tr>
<td>Width/Depth Ratio</td>
<td>$W_{b kf}/d_{b kf}$</td>
<td>12.5</td>
</tr>
</tbody>
</table>

*Table 1. Summary of example width/depth ratio values*

Since the key dimensions of the restoration design are based on the design (bankfull) discharge, it follows that its proper selection is critical to the long term success of a stream restoration project.

### 2.3 Existing Methods for Determining Design Discharge

To develop a sound method for determining design discharge, it was first necessary to examine the utility of existing sizing methodologies, and to identify any issues associated with each method. Three sizing methodologies were selected for analysis: hydrologic modeling, bankfull identification, and regional curves.

#### 2.3.1 Hydrologic Modeling

Watershed models are powerful tools because they may be used to compute discharges at specific points in a watershed by either analyzing a particular synthetic storm event (i.e. NRCS, Type II, 24-Hour Storm) or a real-time rainfall event. The technology has advanced to the point where watershed modeling tools may be used to analyze the rainfall-runoff response of a large watershed under multiple precipitation scenarios almost instantaneously. While numerous modeling programs are available, the analysis presented here will be based on HEC-HMS Version 3.5, an Army Corps of Engineers model. HEC-HMS is a widely employed model in
stream restoration, and may be used to determine surface flow quantity in a watershed for either a single storm event or on a long term (continuous) basis.

Unfortunately, while programs such as HEC-HMS are powerful, user-friendly, and robust, they can provide the user with an unwarranted sense of accuracy in their predictions. Urban hydrology is an inexact science (Reese 2006), and model performance is only as good as the quality of the input data. For example, the calculation of travel time (i.e. the length of time it takes a drop of water to move through a watershed) is reliant on several subjective components. First, determining the drainage area for a stream restoration reach, which is a key component in determining discharge, is difficult in urban areas. Areas that have been developed do not necessarily follow natural drainage divides, and networks of storm sewers make the mapping of flow paths difficult. Further, pipe size, slope, and flow direction data are not always available. Finally, the, selection of roughness coefficients such as Manning’s n, used in calculating travel time, are subjective and may vary between designers for the same surface. Equation 3 and 4 show how travel time may be calculated for a piped section of a watershed using Manning’s equation.

\[ V_t = \frac{1.49 \times (D/4)^{2/3} S^{1/2}}{n} \]  

\[ T_t = \frac{(L/ V_t)}{60} \]

Where:

\[ V_t = \text{Velocity, ft/s} \]
\[ D = \text{Pipe Diameter, ft} \]
\[ S = \text{Slope, ft/ft} \]
\[ n = \text{Manning’s roughness coefficient} \]
\[ T_t = \text{Travel Time, min} \]
\[ L = \text{Flow Length, ft} \]
\[ V_t = \text{Velocity, ft/s} \]
Variations in the value of any of the aforementioned parameters will affect the travel time. A lower Manning’s roughness coefficient will increase the velocity through the pipe, reducing the travel time. A shorter travel time results in a higher discharge.

While HEC-HMS may be used in the analysis of real-time storm events, synthetic storms, are primarily used for design purposes. This is because there is usually a lack of site-specific rainfall data over an adequate length of time. In addition, local public facilities regulations often require the use of hydrologic modeling procedures that utilize synthetic storms to prove the adequacy of designs (Fairfax County Public Facilities Manual Section 6-0800 2001). However, the use of synthetic storms is problematic for bankfull flow determination for two reasons. First, while synthetic storm events exist for the 1-year and 2-year storm events, which bound the average bankfull storm, there is not a synthetic storm event for the bankfull storm event. Second, in the author’s experience, synthetic storms often do not accurately portray urban flow situations. For example, when an urban watershed in Fairfax County, Virginia, is modeled in HEC-HMS using the two-year 24-hour storm event (3.2” in 24 hours), the resulting discharge is typically in excess of the expected bankfull discharge. However, as shown in Table 2, a measured rainfall event in excess of 3.2 inches may not produce a bankfull flow, but a smaller event of short duration and high intensity may produce bankfull conditions. Table 2 compares two storm events and the resulting flow depths in a restored reach of stream in Reston, Virginia. At the location of the measurements, the watershed drains 439 acres and is 45% impervious. The bankfull depth of the restored stream was 3.0 feet. In accordance with the Fairfax County Public Facility Manual (PFM), Section 6, Plate 3-6 (2001), the Intensity-Duration-Frequency (IDF) Curve, both storms were just over a 2-year storm event. Only the second storm produced a bankfull event, even though Storm 1 produced more rainfall. This indicates that in urban watersheds the flow conditions may be more reliant on storm intensity as opposed to total rainfall depth and storm duration.

<table>
<thead>
<tr>
<th>Storm Event (Date)</th>
<th>Rain Total (in)</th>
<th>Storm Duration (hr)</th>
<th>Storm Intensity (in/hr)</th>
<th>Maximum Flow Depth (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1 (5/26/2009)</td>
<td>3.7</td>
<td>9.5</td>
<td>0.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Storm 2 (6/3/2009)</td>
<td>2.7</td>
<td>2.0</td>
<td>1.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 2. Measured storm event comparison
Models such as HEC-HMS provide users with a wide variety of input variables, but often lack clear guidance on how they should be applied. For example, HEC-HMS procedures lack guidance on how to select an appropriate control time (A. Miller, Watershed Concepts, personal communication 9/2010), which is the time step length for the modeled storm event. Steps may be selected that range from one minute to one day. Selection of a larger time step averages the peak flow over a longer time period, and results in a lower peak flow and a lower output flow rate. Table 3 compares the flow rates for two watersheds in Northern Virginia delineated by the author and modeled using HEC-HMS. Watershed 1 is approximately 863 acres with 38% impervious area, and Watershed 2 is approximately 765 acres with 37% impervious area. As may be seen in Table 3, changing the time step from one minute to ten minutes will result in a 27% decrease in flow rate for both of the studied watersheds. While reasonable assumptions may be made as to an appropriate time step for a given watershed and storm event, the lack of clear guidance leaves the user with a bit of uncertainty.

<table>
<thead>
<tr>
<th>Time Step (min)</th>
<th>Watershed 1</th>
<th>Watershed 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q (cfs)</td>
<td>Change in Q (%)</td>
</tr>
<tr>
<td>1</td>
<td>4,982</td>
<td>---</td>
</tr>
<tr>
<td>5</td>
<td>4,363</td>
<td>-12.4</td>
</tr>
<tr>
<td>10</td>
<td>3,631</td>
<td>-27.1</td>
</tr>
</tbody>
</table>

Table 3. Comparison of HEC-HMS time steps and resulting flow rates

Given the uncertainty associated with determining model input parameters, and the absence of an objectively determined storm event to model bankfull flow, models such as HEC-HMS may not provide a reliable platform on which to determine design discharges for urban stream restoration projects.

2.3.2 Bankfull Identification

Traditionally, the estimation of bankfull flow begins with the identification of the bankfull elevation in the field. Bankfull indicators may include the top of point bars (i.e. areas of sediment deposition on the inside of meanders), slope breaks on the stream bank, and/or changes in sedimentary or vegetative characteristics (Wolman 1955). Figure 9 is a typical riffle cross
section, and depicts bankfull stage at a break in slope and a change in sedimentary and vegetative characteristics.

Once a bankfull feature has been identified for a cross section representative of the stream reach in question, a cross section is then surveyed. The survey cross section data are then plotted and the bankfull area is computed. The resulting bankfull area, along with other input parameters, may be used in any number of uniform flow equations to give the bankfull flow.

While it is possible to determine a bankfull flow in this manner, the method has several shortcomings. First, natural variability makes the identification of bankfull in a stable stream difficult and dependent on the perspective of the observer (Williams 1978; Johnson and Heil 1996). Second, identification of bankfull in a disturbed reach is almost impossible because the stream cross section is in a state of flux. Since banks are typically highly eroded and incised in such cases, reliable bankfull indicators are sparse. In fact, any bankfull indicators that may be observed are more than likely from the former flow regime, thus adding considerable uncertainty to bankfull determination (Hey 2006; Copeland et al. 2000). If a stable reach is located upstream or downstream of the proposed restoration reach, bankfull could be identified in that reach and extrapolated to the project reach (Hey 2006). However, in many urban scenarios, as may be seen throughout Northern Virginia, a stable reach may not be present either upstream or downstream. USGS gauging station data may also be used to verify flow regimes, but many streams do not
have gauges and reduced matching funds from state and local agencies are forcing the USGS to shut down gauges (Schwartz 2006; M. Gurtz, USGS, personal communication, 4/11/2011). Since the field identification of bankfull under stable conditions is difficult, and the direct field identification of bankfull in a degraded urban stream is impossible, the method is not recommended for use in determining design flow for a degraded urban stream.

2.3.3 Regional Curves

When accurate identification of bankfull elevation in the field is not possible, the use of regional curves is recommended to aid in the determination of bankfull flow (Hey 2006). Regional curves are empirical relationships that relate hydraulic geometry of stream channels to discharge (Leopold and Maddock 1953). They operate on the premise that parameters such as width, depth, and discharge increase as simple power functions from upstream to downstream, as shown in Equations 5 through 8 (Leopold and Maddock 1953):

\[
\begin{align*}
    w &= aQ^b \\
    d &= cQ^f \\
    v &= kQ^m \\
    L &= pQ^j
\end{align*}
\]

Where;

- \( w \) = width
- \( d \) = mean depth
- \( v \) = mean velocity
- \( L \) = suspended-sediment load
- \( Q \) = discharge
- \( a, c, k, p, b, f, m, \) and \( j \) = numerical constants

Since the pioneering work of Leopold and Maddock, hydraulic geometry relationships have been developed for streams across the U.S. (United States Environmental Protection Agency 2010). In addition, they have been expanded to include relationships between drainage area and bankfull discharge, bankfull cross sectional area, bankfull width and bankfull depth (Harman, et al. 1999; McCandless and Everett 2002; Doll et al. 2002; Leopold et al. 2005a; Lotspeich 2009).
Regional curves used to select design parameters should be chosen from streams in the same hydrophysiographic province and of similar land use (i.e. rural versus urban) as the stream being restored. No curves currently exist specifically for urban Northern Virginia streams, however. Five regional curve studies from surrounding areas have been published: Virginia Piedmont (Lotspeich 2009), North Carolina Piedmont Rural (Harman et al. 1999), North Carolina Piedmont Urban (Doll et al. 2002), Eastern United States (Leopold et al. 2005b), and Maryland Piedmont (McCandless and Everett 2002). The available regional curves were plotted in Figure 10 using the equations presented in the respective studies, and analyzed to determine their utility in determining design discharges for urban streams in Northern Virginia. When plotted on the same chart the curves appear to show that with increasing drainage area and impervious area there is an increase in cross sectional area.

![Figure 10. Comparison of five published regional curves (McCandless and Everett 2002; Doll, et al. 2002; Harman, et al. 1999; Lotspeich 2009; Leopold et al. 2005b) ](image)

**2.3.3.1 Virginia Piedmont Regional Curves**

The United States Geological Survey (USGS) published regional curves for non-urban streams in the Piedmont physiographic province of Virginia (Lotspeich 2009). Streams used in
the survey were generally located in the southern portion of the state and had, on average, 3.9% of what the author termed Urban Area. Urban Area was not explicitly defined in the report, and impervious area was not given. For the purposes of this analysis, Urban Area has been assumed to contain 50% impervious area. Therefore, a watershed containing 3.9% Urban Area may be assumed to contain approximately 2.0% impervious surface. Since most of the study sites used in this regional curve study are located in the southern portion of Virginia, as shown in Figure 11, as well as the low impervious area percentage of the contributing watersheds, they are not directly applicable for use in Northern Virginia urban streams.

2.3.3.2 North Carolina Piedmont (Rural and Urban) Regional Curves

Two different, additional regional, curve studies of interest exist for the North Carolina Piedmont: one for rural streams (Harman et al. 1999) and one for urban (Doll et al. 2002).
Streams used in the urban study were primarily E-type streams, as defined by Rosgen (1994). A summary of the characteristics of the seven primary stream types as defined by Rosgen is shown in Table 4. As may be seen from the table, the E-Type streams are more sinuous than the other stream types with a high entrenchment ratio and a low width/depth ratio.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Stream Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Ent. Ratio (ER) (^1)</td>
<td>&lt;1.4</td>
</tr>
<tr>
<td>Sinuosity (k) (^2)</td>
<td>&lt;1.2</td>
</tr>
<tr>
<td>Width/Depth (W/D) (^3)</td>
<td>&lt;12</td>
</tr>
<tr>
<td>Slope (S) (^4)</td>
<td>0.04-0.99</td>
</tr>
</tbody>
</table>

\(^1\)ER = (Floodprone Width/Bankfull Width); Floodprone Width = Width at 2 x Maximum Bankfull Depth
\(^2\)k = Stream Length/Valley Length
\(^3\)W/D = Bankfull Width/Mean Bankfull Depth
\(^4\)S = Stream channel slope taken between two similar points along the thalweg (i.e. beginning of riffle to beginning of riffle).

Table 4. Summary of primary stream types, after Rosgen, 1994

The contributing watersheds to streams in the urban study contained, on average, 41% impervious area. With regards to the streams used in the rural study stream type was not identified, and the contributing watersheds contained less than 10% impervious area. While the impervious area in the urban study was similar to many watersheds in Northern Virginia, their distance from Northern Virginia reduces their local applicability.

2.3.3.3 Eastern United States Regional Curves

The Eastern United States Regional Curve data were presented in the reference curves section of the Reference Reach Field Book (Leopold et al. 2005b). Because no information was provided as to the origin of the study, morphologic character of the streams, or imperviousness of the contributing watersheds, too much uncertainty existed as to the direct applicability of these curves to Northern Virginia streams.

2.3.3.4 Maryland Piedmont Regional Curves

The United States Fish and Wildlife Service (USFWS) published a report on Maryland Piedmont Streams (McCandless and Everett 2002). As shown in Figure 11, the study streams
were in closer proximity to Northern Virginia than any of the other studies examined. Streams were primarily C-type, and the contributing watersheds contained less than 8% impervious area and were thus considered rural. Due to the close proximity and impervious area range, this study would appear to be directly applicable to rural streams in Northern Virginia, but the average impervious area was far too low to consider direct application to urban streams.
3.0 A Method for Determining Design Discharge

3.1 Selecting the Appropriate Regional Curve

Based on an examination of existing sizing methodologies as detailed above, it was concluded that design flows could not be confidently based on computer generate flows or field-identified bankfull features. It was concluded, however, that regional curves offer a solid platform on which to base design flows. The regional curves discussed in the previous section were analyzed because at quick glance they each held some promise with regard to their utility in determining design discharges for urban Northern Virginia streams. After reviewing each in more detail, it became evident that the rural Maryland curve was the most appropriate for use. While regional curves are available for the piedmont physiographic province of Virginia, the streams used to develop the regional curves for the piedmont region of Maryland are actually closer to Northern Virginia. They are also, of course, closer than the rural and urban North Carolina streams as well.

In addition, the author conducted a reference reach survey of stable streams in Northern Virginia. The data collected from the reference reach survey is currently used in the development of stream restoration designs for degraded streams in Northern Virginia by Wetland Studies and Solutions, Inc. (F. Graziano, Vice President – Engineering, Wetland Studies and Solutions, Inc., personal communication, April 11, 2011). The reference streams surveyed were similar to the streams in the Maryland study (primarily C-type). As noted previously, the urban North Carolina streams were primarily E-type streams and no information was given on the stream types of the rural North Carolina streams.

In many ways, the Maryland regional curves are well-suited for use in determining design discharge in Northern Virginia streams, but an acceptable method must be developed to adjust for the large differences in impervious area.

As has been well documented by others, urban streams experience more flow than watersheds of similar size in rural watersheds. Since the Maryland curves were developed in
rural watersheds, simply applying them to Northern Virginia streams would not be appropriate. As was previously stated, the average impervious area of the streams used in the Maryland study was 8%, and the impervious area for streams on which this method has been applied range from 20% to 50%. For this reason, the direct application of the Maryland regional curves to urban stream restoration projects would result in designs that were not of sufficient size to accommodate urban storm flows. The effect of the higher flows on cross sectional area is evident when the published rural regional curves are compared to the urban curves shown previously in Figure 10. As expected, when plotted on the same axes, the North Carolina Urban Curve (Doll et al. 2002), with an imperviousness of 41%, exhibited a much larger cross-section area for a given drainage area than either the rural Maryland (McCandless and Everett 2002) or Virginia (Lotspeich 2009) curves. Since the rural North Carolina curve represents a wide range of development conditions with watersheds up to 20% impervious, it is not surprising that it plots above the Maryland Curve (less than 8% watershed imperviousness). The Eastern U.S. curve (Leopold et al. 2005b) was disregarded in this comparison, as there were no data available on watershed characteristics.

One solution to reconciling the difference in impervious area between the rural Maryland regional curve and the urban watersheds in Northern Virginia lies in a report published by the Center for Watershed Protection (CWP) that details the impact of watershed development on channel enlargement (Caraco 2000). Based on the work of MacRae and DeAndrea (1999) and Brown and Claytor (2000), CWP developed a curve for predicting ultimate channel enlargement from percent impervious for streams in Maryland, Vermont, and Texas, as shown in Figure 12.
The product of the enlargement ratio, shown on the ordinate in Figure 12, and the cross sectional area of a rural stream is the approximate cross sectional area of an urban stream of equal watershed size based on the amount of impervious surface in the watershed of the urban stream.

The relationship of watershed imperviousness and enlargement ratio suggests a method to translate cross sections from regional curves developed in low imperviousness watersheds to more highly developed watersheds, such as are found in urban Northern Virginia streams. However, given the increased scatter in the data points for watersheds in excess of sixty percent impervious this enlargement ratio should only be applied in watersheds less than sixty percent impervious. An example may be developed from an urban stream in Northern Virginia with a watershed of 511 acres (0.8 mi²) and 45.5% impervious area. From the Maryland regional curve (Figure 10) it may be seen that a rural stream of this watershed size would have an approximate cross sectional area of 14.8 square feet. From the relationship proposed by Caraco (2000), and shown in Figure 12, it may be seen that the enlargement ratio for a watershed with 45.5% impervious area is 4.5. By applying the enlargement ratio to the rural cross sectional area, it may be determined that the cross sectional area for the urban stream should be 66.6 square feet. Equation 9 shows the drainage area to cross sectional area ratio from the rural Maryland regional

Figure 12. Urban enlargement curve (Caraco 2000, Figure used with permission of CWP)
Equation 10 shows how that relationship is adjusted using the enlargement ratio to convert from the rural to the urban cross sectional area using the example data from the preceding sentences. Figure 13 shows a comparison of the rural cross section to the urban cross section.

\[ A_{bkf} = (17.42DA^{0.73}) \]  

(9)

Where:

- \( A_{bkf} \) = Bankfull Cross Sectional Area, \( ft^2 \)
- \( DA \) = Reach Drainage Area, \( mi^2 \)

\[ A_{bkf-adj} = (17.42DA^{0.73}) \times ER \]  

(10)

\[ = (17.42(0.8)^{0.73}) \times 4.5 \]

\[ = 66.6 \, ft^2 \]

Where:

- \( A_{bkf-adj} \) = Bankfull Cross Sectional Area Adjusted For Impervious Area, \( ft^2 \)
- \( DA \) = Reach Drainage Area, \( mi^2 \)
- \( ER \) = Impervious Area Enlargement Ratio (from Figure 11)

**D.A. = 511ac (IA = 45.5%)**

**Figure 13. Comparison of rural cross section to cross section adjusted for impervious area (Sketch used with permission of Wetland Studies and Solutions, Inc. 2011)**

To test the validity of the method, an enlargement ratio based on the average impervious area of the urban North Carolina curve was applied to the rural Maryland curve to create a Maryland curve adjusted for urban conditions. The enlargement ratio was also applied to the
rural Virginia curve to create a Virginia curve adjusted for urban conditions to further determine if selecting the Maryland regional curves instead of the Virginia regional curves was correct. The adjusted Maryland and Virginia curves were then plotted against the urban North Carolina curve for comparison. The urban North Carolina curve was developed from streams with watersheds that averaged 41% impervious area, so, based on the CWP curve (Caraco 2000), an enlargement factor of 4.25 was applied to the drainage area to cross sectional area relationship from the rural Maryland regional curve as follows in Figure 14. When plotted together as shown in Figure 14, the urban North Carolina curve and adjusted Maryland curve plot in close agreement. The adjusted Virginia curve plots below both the urban North Carolina and the adjusted Maryland curves. Based on this information it was determined that the rural Maryland regional curve, adjusted for impervious area using the enlargement ratio would provide a cross section of adequate size to handle urban storm flows, whereas the cross sections sized based on the adjusted Virginia curve would be too small.

Figure 14. Adjusted Maryland and Virginia drainage area vs. cross section area regional curves compared to urban North Carolina regional curve.
3.2 Determining Design Discharge

The following procedure for determining a design discharge for urban stream restoration projects has been developed and is intended for use only in the piedmont physiographic province of Northern Virginia. Once a design reach has been identified, the watershed boundary may be determined using GIS topographic information as well as infrastructure data (roads, storm sewers, buildings, etc.). Impervious areas may then be determined using a combination of GIS information and high resolution aerial photography. In order to develop the design curve, the drainage areas from the design reach are applied to the rural Maryland regional curve which relates drainage area to cross sectional area. The resulting cross section areas may then be adjusted using the enlargement ratio (from Figure 12) for the associated impervious area. This calculation was also previously illustrated in Equation 9. Figure 15 shows a design curve developed for Snakeden Branch, an urban stream in Reston, Virginia. The design curve was developed for the upstream portion of the stream, from the headwaters to a point where the stream reaches slightly over 1 square mile (mi.)² in drainage area. The impervious area for the contributing watershed for this portion of the stream ranged from 25% to 50%. The 3 outlying data points in Figure 15 were from areas in the watershed with low impervious area.

![Figure 15. Comparison of the adjusted drainage area vs. cross sectional area regional curve for an urban Northern Virginia stream (Snakeden Branch) to published regional curves](image-url)
Once the adjusted cross sectional area is determined it is then converted to a flow rate using the cross sectional area to flow rate relationship from the Maryland regional curve as shown in Equation 11.

$$Q_{b_{k_{f-adj}}} = \left(\frac{A_{b_{k_{f-adj}}}}{0.28}\right)^{1/0.94}$$  \hspace{1cm} (11)

Where:

- $Q_{b_{k_{f-adj}}}$ = Bankfull Discharge Adjusted For Impervious Area
- $A_{b_{k_{f-adj}}}$ = Bankfull Cross Sectional Area Adjusted For Impervious Area

Figure 16 shows flow rates for Snakeden Branch calculated from the adjusted cross sectional area. The figure shows that the adjusted design curve for Snakeden Branch closely agrees with the North Carolina urban regional curve.

Figure 16. Comparison of adjusted drainage area vs. flow rate regional curve for an urban Northern Virginia stream (Snakeden Branch) to published regional curves
Once the conversion from cross sectional area to discharge is made, it is possible to size a proposed riffle cross section and subsequent channel dimensions, using the appropriate dimensionless ratios from reference reaches.
4.0 Discussion

Determining appropriate design flows for urban stream restoration projects is not a simple task. Available design methodologies must be evaluated for their respective strengths and weaknesses, and the most appropriate procedure selected for determining design flows in a given situation. To date, approximately ten miles of urban stream restoration projects in Northern Virginia, with watersheds ranging in impervious area from 20% – 50%, have been designed and restored using this method. While no statistical analysis has been performed to assess bankfull flows in the restored streams sized using this method, anecdotal evidence suggests that the method successfully predicts bankfull flows for urban streams in Northern Virginia. In all cases, the restored streams are overtopping their banks and accessing their floodplains more frequently than they were prior to restoration.

Following the restoration of streams in the Snakenden Branch watershed of Reston, Virginia, monitoring equipment was installed to develop data that would be helpful in determining the success of the project. The installed monitoring equipment included:

- Five water level loggers (WL16, Global Water Instrumentation, Inc.), which recorded data at five minute intervals;
- Two cameras (WSCA04, PlantCam powered by Wingscapes), installed in conjunction with two of the water level loggers, and configured to take photos at five minute intervals during daylight hours, and;
- Three tipping bucket rain gauges (TR-525L, Campbell Scientific), which provide a contact closure at precipitation increments of 0.01 inches. The rain gauges were connected to data loggers (CR200, Campbell Scientific) that recorded cumulative rainfall at fifteen minute intervals.

Plans had included development of stage-discharge relationships at each instrumented location, so as to begin recording a continuous flow record that would support the development of recurrence intervals for various storm flows. Unfortunately, the extremely flashy nature of the watershed has thus far prevented the measurement of discharge during any storm event since
construction. The level logger data do show that water surface elevations in the restored reach of Snakeden Branch reached or exceeded bankfull conditions several times over the course of a calendar year of 2009. While continuous data were not available prior to restoration, between 2004 and 2008, regular inspections by the author only resulted in a single observation of Snakeden Branch overtopping its banks. The overtopping in question occurred during a storm event that produced 9.4 inches of rain over a 24-hour period between June 25 and June 26, 2006. The event was determined to exceed the 100-year storm for Fairfax County, Virginia which is classified as 7.7 inches of rain over 24-hours (Virginia Department of Conservation and Recreation 1999). Figures 17 and 18 show a restored stream in the Snakeden Branch watershed before and during a storm event on June 28, 2010 where 0.83 inches of rain fell in 1.25 hours and the water surface elevation exceeded bankfull.

Post-restoration observations in the period from April 2008 to April 2011 show that, not only are the flows accessing the floodplain more frequently, but the channels are showing resistance to the experienced flows. Streams (some entering their third year post-construction) have remained stable and have not aggraded or degraded, suggesting that there is a restored balance between flow and sediment. It should be noted that other factors not discussed in this paper, such as stream geometry, size of the bed material, stream structures, and bank vegetation are also contributing to the improved stream stability.

Figure 17. Restored stream (tributary to Snakeden Branch) prior to a storm event (Photo used with permission of Wetland Studies and Solutions, Inc. 2011)
Figure 18. Water surface elevation exceeding bankfull during storm event in a restored stream (tributary to Snakeden Branch, same location as Figure 17) (Photo used with permission of Wetland Studies and Solutions, Inc. 2011)
5.0 Summary

Natural Channel Stream design projects are an effective way to restore streams damaged by increased runoff volume and velocity associated with urbanization. A restoration design is based on the design (bankfull) discharge, making the proper determination of the design discharge critical. The purpose of this thesis was to review existing methodologies, and to present a method, for the determination of approximate design discharges for urban stream restoration projects in Northern Virginia. From the work presented in this thesis the following can be concluded:

- Existing sizing methodologies do not adequately predict bankfull discharges for urban streams in Northern Virginia.

  - Output from hydrologic models is heavily dependent on the input parameters such as travel time and control time specifications. Variations in the input parameters result in variations in the computed discharges. Lack of guidance on how to properly choose input parameters such as control time make it difficult to determine if computed discharges are reasonable (Miller 2010). In addition, synthetic storms used to develop discharges do not adequately portray the urban rainfall runoff response, and do not exist for the bankfull storm event (i.e. 1- to 2-year storm event) used to size NCD restoration projects.

  - Field identification of bankfull is impossible in a degraded urban stream (Copeland et al. 2000; Hey 2006). Streams that are highly degraded lack reliable bankfull indicators such as slope breaks and changes in vegetative communities. In cases where bankfull indicators are found they are more than likely indicative of the pre-development flow regime. While bankfull could be extrapolated from stable reaches upstream or downstream of a reach proposed for restoration, more often than not these stable reaches do not exist.
Based on measurements taken in stable streams, **Regional curves** are a reliable tool for helping to determine a design discharge. A regional curve should be from the same hydrophysiographic province as the restoration reach. Unfortunately no regional curves exist for urban Northern Virginia streams.

- A design (bankfull) discharge for urban Northern Virginia stream restoration projects can be sufficiently determined through the use of adjusted rural Maryland regional curves. The drainage area to cross sectional area relationships from the rural Maryland regional curve can be adjusted using an impervious area to enlargement ratio curve presented by the CWP (Caraco 2000). The adjusted cross sectional areas are then converted to bankfull flow rates using a cross sectional area to discharge relationship from the Maryland regional curves.

- While observations tend to support the conclusion that the methodology is functioning well for Northern Virginia urban streams, caution should be exercised in application to streams outside of the region. Prior to implementing this method or one of similar design, a detailed analysis of existing methodologies should be undertaken as was done here. As previously noted, stable urban streams may exist in another region, making the development of localized regional curves possible, and adding a valuable option to existing sizing methodologies. Further, stable stream reaches may exist upstream or downstream of an impaired reach, making field identification and extrapolation of bankfull flows possible.

- The conclusion from this work is not that one particular sizing methodology should be used in determining bankfull discharge, but that whatever methodology is selected should be well-researched and applied to local conditions so as to reduce uncertainty.
6.0 Implications for the Future and Further Study

This thesis presents a reliable method to determine bankfull flows for urban stream restoration projects in Northern Virginia; however, it also suggests opportunities for future research.

There are opportunities to refine the enlargement ratio curve. As shown, the CWP curve (Caraco 2000) is a good tool for predicting channel enlargement in urban watersheds, but it was developed from a relatively small sample size. Additional study to increase the sample size could help to further refine the curve. As additional data are collected, it would be interesting to investigate how, or if, channel enlargement varies between stream type or by substrate type/size. For example, are there differences in the enlargement behavior between a stream in a sandy soil versus one in a clay soil?

There is a need for more real-time discharge measurements in the field. Once obtained, the field-measured flow data coupled with the continuous water level data could be used to develop rating curves to determine recurrence intervals of various flow events. Coupled with real-time rainfall data this information could be used to calibrate watershed models. These data could further be used to help develop specifications for selecting the appropriate control time (i.e. model time steps) in models such as HEC-HMS. Data from such small catchment flow monitoring could also be used to refine our understanding of the rainfall-runoff response in urban watersheds as well as help determine the recurrence interval of the design discharge.
Literature Cited


Low Impact Development Center. *Low Impact Development for Big Box Retailers.* Beltsville, Maryland: Low Impact Development Center, 2005.


Appendix A

Letters of Permission
Scott:

You have permission from myself and Wetland Studies and Solutions, Inc.

Mike

Michael S. Rolband, P.E., P.W.S., P.W.D., LEED(r) AP
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Please consider the environment before printing.

-----Original Message-----
From: srpetrey@vt.edu [mailto:srpetrey@vt.edu]
Sent: Monday, April 11, 2011 7:23 PM
To: Mike Rolband
Cc: Scott Petrey
Subject: Request Permission to Use Figures...

Mike

I am in the process of writing my thesis for a Master's of civil engineering at Virginia Tech. The subject of the thesis is determining design discharge for urban stream restoration projects. I would like to use the following figures:

-Pre- and Post-Development aerial photos of Colvin Run Watershed from the presentation Northern Virginia Stream Restoration Bank "Everything You Want To Know About Stream Restoration North of the Toll Road, Slide 19 (presented by Mike Rolband 3/27/2010).

-Cross Section comparison from the presentation Northern Virginia Stream Restoration Bank "Everything You Want To Know About Stream Restoration North of the Toll Road, Slide 49 (presented by Mike Rolband 3/27/2010).

--Storm comparison photos from the presentation Northern Virginia Stream Restoration Bank - Restoring Reston's Streams, Slide 35 (presented by Scott R. Petrey 10-7-2007).

Reference Reach example dimensions figure from the Northern Virginia Stream Restoration Bank, Colvin Run - Forest Edge South plan set, sheet 42 of 70.

Is it possible to get written permission to use these figures? Thank you in advance for considering my request.

Sincerely,
Scott Petrey
From: Greg Hoffmann <gph@cwp.org>
To: srpetrey@vt.edu
Cc: Kelly Petrey <kpetrey@wetlandstudies.com>
Subject: RE: Permission Request for use of Figure in Masters Thesis...

Scott,

The Center for Watershed Protection (CWP) grants permission for you to use Figure 5 from Article 19, Technical Note #115 from Watershed Protection Techniques in your masters thesis. We do require that it be cited as being from a CWP publication.

Feel free to contact me if you need further assistance.

Thank you,

Gregory Hoffmann, P.E.
Program Manager
Center for Watershed Protection
8390 Main St., 2nd Floor
Ellicott City, MD 21043

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From: Scott Petrey
Sent: Sunday, April 10, 2011 9:18 PM
To: dsc@cwp.org
Cc: srpetrey@vt.edu
Subject: Permission Request for use of Figure in Masters Thesis...

Ms. Caraco
My name is Scott Petrey and I am in the process of writing my thesis for a Master’s of civil engineering at Virginia Tech. The subject of the thesis is determining design discharge for urban stream restoration projects. I would like to use Figure 5 ("Ultimate" Channel Enlargement as a Function of Impervious Cover in Alluvial Streams in Maryland, Vermont, and Texas) in The Dynamics of Stream Channel Enlargement article (Article 19, Technical Note #115 from Watershed Protection Techniques 3(3): 729-734). Is it possible to get written permission to use this figure? If you are not the person I should be contacting, would you mind directing me to the person I should contact?

Thank you in advance for considering my request.

Sincerely,

Scott Petrey