Quantification of Streambed Hydraulic Conductivity in the Gwynns Falls Watershed and Surrounding Area

CUERE Technical Report 2009-002
June 2009

Peter Lapa-Lilly
Quantification of Streambed Hydraulic Conductivity in the Gwynns Falls Watershed and Surrounding Area

CUERE Technical Report 2009-002
June 2009

Peter Lapa-Lilly

University of Maryland, Baltimore County
Center for Urban Environmental Research and Education
1000 Hilltop Circle, Technology Research Center
Baltimore, Maryland 21250

This report is available as a downloadable pdf file from the internet at http://www.umbc.edu/cuere/BaltimoreWTB.

Please cite this publication as:

ON THE COVER
Gwynns Falls Trailhead # 2: July 17, 2008. Photograph by Peter Lapa-Lilly.
Table of Contents

Figures iv

Tables vi

Appendices vii

Acknowledgements viii

Abstract ix

1. Introduction 1

2. Study Area 2

2.1 Location 2

2.2 Land Use and Urbanization 2

2.3 Geology 2

2.4 Streambed Sediment 3

2.5 Streambed Slope and Channel Morphology 3

3. Methods 5

3.1 Sampling Design 5

3.2 Falling-Head Permeameter 6

3.3 Hydraulic Conductivity Determination 8

3.4 Stream Width and Streambed Thickness Measurements 10

3.5 Ancillary Data Collection 10

3.6 Data Analysis 12

4. Results 16
Table of Contents (continued)

5. Discussion 22
6. Concluding Remarks 24
7. References 25
**Figures**

**Figure 1.** Google Earth™ image depicting the Gwynns Falls watershed and subwatersheds (red), the surrounding domain (black), geology, and model hydrography (blue), in relation to Baltimore City, Baltimore County, and the network of major roads. Green and blue pins indicate planned locations at which measurements were to be taken within the Gwynns Falls watershed and the surrounding domain, respectively.

**Figure 2.** Examples of the scheme for site code naming.

**Figure 3.** Conceptual model of a falling head permeameter in use, with three of the parameters collected in the field labeled. Also shown is an actual image of a permeameter in use, after a ~20 cm decline in head from the initial level.

**Figure 4.** The permeameter shaft is pounded into the streambed using a small sledge hammer and a temporarily-attached protective steel flange.

**Figure 5.** Streambed thickness was measured using a slide-hammer, which was pounded into the bed material until further penetration was not possible. The transect tape was used to determine bankfull width, width of water, and the locations which are ¼, ½, and ¾ across the channel.

**Figure 6.** Well point-filter schematic and analysis, adapted from Hvorslev (1951).

**Figure 7.** Example data analysis spreadsheet, used to calculate hydraulic conductivity from permeameter field data. Plotted on the graph is the unrecovered head difference over time. The K value (highlighted in pink) has not yet been corrected for temperature, or averaged with other conductivity measurements from that site.

**Figure 8.** Map of site locations, including site label, watershed and study area boundaries, major streams, major geologic formations, and the Baltimore City border.

**Figure 9.** Five site locations within the Dead Run watershed.

**Figure 10.** Frequency distribution of bed thickness values measured in the field.

**Figure 11.** Frequency distribution of the logarithms of streambed hydraulic conductivity values.
Figures (continued)

Figure 12. Cumulative distribution function (CDF) of the logarithms of streambed hydraulic conductivity values, plotted against the theoretical log-normal CDF.

Figure 13. Plot of depth below streambed of the permeameter mesh outflow vs. calculated streambed hydraulic conductivity. Tests were not performed at varying depths in the streambed for any single measurement location.

Figure 14. Stream widths ranged from 40 cm to over 16 m. Shown here are: GF J: Winterbourne Rd at Morris Rd (left) and GF G: Ellicott Driveway at W Baltimore St (right).
Tables

Table 1. Data summary for the twenty eight sites within the surrounding model Domain. 18

Table 2. Data summary for the fourteen sites within the Gwynns Falls watershed. 19
## Appendices

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>Falling-head permeameter construction</td>
<td>26</td>
</tr>
<tr>
<td>Appendix B</td>
<td>Problems encountered in the field and possible solutions</td>
<td>32</td>
</tr>
<tr>
<td>Appendix C</td>
<td>Gwynns Falls individual site reports</td>
<td>37</td>
</tr>
<tr>
<td>Appendix D</td>
<td>Domain individual site reports</td>
<td>104</td>
</tr>
</tbody>
</table>
Acknowledgements

This material is based on work supported by the National Science Foundation under a REU supplement to grant EAR-0610009 and by NOAA under grant NA07OAR4170518. Work was completed for the Center for Urban Environmental Research and Education (CUERE). The author is grateful Claire Welty (CUERE, UMBC) for her support and advice, without which this study would not have been possible. Thanks are given to Robert J. Ryan (Temple University) for his assistance during the planning and analysis stages of this project, specifically for use of falling-head permeameter design specifications and of a template spreadsheet for field data analysis. Phil Larson, Christiane Runyan and Jeff Campbell (CUERE, UMBC) provided assistance with the planning and assembly of the permeameter equipment, while Tracy Kerchkof (CUERE, UMBC; now at EPA) supplied GIS data layers used in the selection of site locations. John Cataldi (UMBC) provided repairs to damaged hardware and insight into permeameter design alterations, in addition to construction of portions of the permeameters. Further thanks are given to Andrew Miller (UMBC) for his expertise regarding stream geomorphology and to Sarah Poole (CUERE, UMBC), who collaborated and provided assistance during the entire field campaign for this study.
Abstract

The objective of this work was to create a data set of streambed hydraulic conductivity values, along with bankfull width and streambed thickness, in order to calculate streambed conductance, which is an input parameter required by the USGS MODFLOW groundwater model. Hydraulic conductivity values of streambeds within and around the Gwynns Falls watershed were measured in-situ using a falling-head permeameter, at an average depth of 8.7 cm below the bed surface. More than 100 hydraulic conductivity measurements were performed at 42 sites during a three-week period in July and August of 2008. A variety of streams was sampled, including minor tributaries and several main stem branches. The study area spanned 603 km² along a gradient of urbanization from the highly developed downtown Baltimore region to the rural areas surrounding the upper Gwynns Falls.

Hydraulic conductivity was measured three times across the stream channel at each site and averaged to a single value. Results were corrected to a common water temperature of 20°C. The data were log-normally distributed, ranging from $1.41 \times 10^{-3}$ cm/sec to $5.62 \times 10^{-2}$ cm/sec with a mean value of $1.33 \times 10^{-2}$ cm/sec and a standard deviation of $9.10 \times 10^{-3}$ cm/sec. Average thickness of bed material above bedrock was found to be 33.0 cm, with a range of 8.20 to 90.1 cm and a standard deviation of 19.4 cm. A number of lessons were learned regarding the field techniques, which are also documented in this report.
1. Introduction

The purpose of this project was to measure streambed hydraulic conductivity values throughout the Gwynns Falls watershed as well as in the surrounding area, as dictated by the MODFLOW model domain set up for the UMBC/CUERE Urban Groundwater project. More specifically, the objective was to create a dataset of streambed hydraulic conductivity values, along with the bankfull width and streambed thickness, in order to calculate streambed conductance, which is an input parameter required by the MODFLOW model.

Hydraulic conductivity is the proportionality constant relating hydraulic gradient to specific discharge in Darcy's Law. It is a measure of how easily a fluid can move through a porous medium, and depends on the grain size distribution and packing of the material, as well as the properties of the fluid moving through the material; its dimensions are length per unit time (Freeze and Cherry 1979). Hydraulic conductivity values can be highly variable and often range over several orders of magnitude over a small length scale (order centimeters).

Streambed conductance is a mathematical model parameter defined as the hydraulic conductivity of the streambed multiplied by reach length and width and divided by streambed thickness (McDonald and Harbaugh 1988). Conductance indicates the ease of the movement of water between surface water and the subsurface. Streambed thickness is the depth of channel bed material overlying bedrock.

The report begins with a description of the study area, including the dominant land uses and delineation of the study area boundaries. The methods section details the sampling design, an overview of the design and construction of the falling-head permeameter equipment, and the field measurement procedure. Data analysis methods are described and include necessary adaptations to the procedure previously published in the literature. Results are presented using a number of statistical descriptions, and a discussion is provided to explain some of the apparent trends. Concluding remarks briefly address the potential application of this project’s dataset of hydraulic conductivity values to purposes beyond the MODFLOW model for which it was intended. Detailed appendices include the comprehensive design of the falling head permeameter, a collection of problems encountered in the field and their possible solutions, and individual site reports for every site visited, featuring field photography, satellite imagery, latitude/longitude, measured parameters and relevant statistics.
2. Study Area

2.1 Location

The primary focus of this project was on the Gwynns Falls watershed, located in Baltimore County and Baltimore City, Maryland and covering a total area of roughly 170 km² (Figure 1). The total length of above-ground streams within this area is roughly 184 km. The watershed encompasses the Gwynns Falls main stem and stretches from northwest (39.47510, -76.82833) to southeast (39.26870, -76.62742), where it empties into the Baltimore Harbor, which in turn flows to the Chesapeake Bay.

Also included in the study area was a surrounding ‘domain’ (Figure 1), the boundaries of which were defined for use in the MODFLOW hydrologic model. The domain was bounded primarily by the Patapsco River to the south and the west, the Jones Falls River and Goodwin Run to the east, and McGill Run, Board Run, and Western Run to the north. The domain completely surrounds the Gwynns Falls watershed, and covers an area of approximately 433 km². The majority of the 603 km² study area is within Baltimore County and Baltimore City, with a small portion of the domain reaching northwest into Carroll County.

2.2 Land Use and Urbanization

The Gwynns Falls spans a gradient of increasing urbanization, with the lower Gwynns Falls dominated by impervious land cover. Sub-watersheds within the city, such as Gwynns Run, now contain very few above-ground streams; i.e., the streams are mostly piped. The Gwynns Falls watershed also contains suburban areas, as well as forested and agricultural lands further to the northwest. Urban and developed lands account for 74% of the total area, compared to only 20% forest cover; total population of the watershed based on a 2000 census was 356,000 (Gwynns Falls Watershed 2008). The study area is traversed by several major roadways, including I-95, I-795, I-70, I-695 and I-83.

2.3 Geology

The study area is located primarily in the Maryland Piedmont, which extends from the base of the Blue Ridge Mountains in the northwest to the Coastal Plain lowlands in the southeast. The fall line crosses Baltimore City and separates the gently undulating hills of the Piedmont from the relatively flat Coastal Plain sediments.

Major geologic formations within the study area include: Baltimore Gabbro Complex, Relay Quartz Diorite, Ultramafic Rock (igneous); Baltimore Gneiss, Cockeysville Marble, Lower Pelitic Schist, Setters Formation, Wissahickon Formation (metamorphic or metasedimentary); Lowland Deposits, Potomac Group (sedimentary) (U.S. Geological Survey 2004). A map of the regional geology is displayed in Figure 1.
2.4 Streambed Sediment

McCandless and Everett (2002) measured median streambed particle size for 25 stream sites throughout the Maryland piedmont and found D50 values that ranged from 0.36 to 132.81 mm, with an average of 22.22 mm; most streambeds included in the study were predominantly gravel. Parent material and grain size of streambeds in the Maryland piedmont vary on local and regional scales. Sites visited during this study were typically a mix of sand and gravel, with several having large bedrock outcrops, boulders, or entirely silt beds. McCandless and Everett (2002) report that the majority of Maryland piedmont streams have banks made up primarily of sand (D50 = 0.36 to 1.13 mm).

2.5 Streambed Slope and Channel Morphology

Using a Digital Elevation Model (1 meter resolution), GIS analysis of roughly 100 kilometers of major streams within the Gwynns Falls watershed revealed the average streambed slope to be approximately 9.88 m/km (a 9.88 meter drop per kilometer traveled downstream). Subwatersheds were analyzed individually, yielding bed slope values ranging from 6.62 m/km in Scotts Level Run to 19.6 m/km in Maiden’s Choice. The largest of the subwatersheds, which follows the main stem Gwynns Falls river from its headwaters to its mouth, was found to have a relatively low 6.16 m/km gradient. A survey of 25 Maryland piedmont streams reported an average water surface slope of 0.0047, or 4.7 m/km (McCandless and Everett 2002). This report also indicates an average width to depth ratio of 15.1 and an average sinuosity index of 1.21.
Figure 1. Google Earth™ image depicting the Gwynns Falls watershed and subwatersheds (red), the surrounding domain (black), geology, and model hydrography (blue), in relation to Baltimore City, Baltimore County, and the network of major roads. Green and blue pins indicate planned locations at which measurements were to be taken within the Gwynns Falls watershed and the surrounding domain, respectively.
3. Methods

3.1 Sampling Design

One-hundred site locations for this study were planned and mapped using Google Earth satellite imagery and a number of overlays: the region’s underlying geology, MODFLOW model hydrography, road network, and the watershed and domain boundaries. A greater density of sites was planned for the Gwynns Falls watershed, which was of higher priority than the surrounding domain. Many of the sites coincided with Baltimore City and Baltimore County U.S. Geological Survey (USGS) stream gages, or were locations at which flow and stage were measured as part of a CUERE stream synoptic project in the spring of 2007. An increased density of sites was planned for the Dead Run subwatershed, which is an intensive study site for CUERE and Baltimore Ecosystem Study (BES) projects.

Every site planned was given a unique site code that (1) described whether the point was within the Gwynns Falls (GF) watershed or in the surrounding domain (Domain), (2) included a letter indicating the order in which the sites were chosen, and (3) listed the nearest major roadway intersection. Suffixes to the site codes were used to indicate whether a site was the location of a USGS stream gage and whether a site was within city limits, with a few sites meeting both criteria, but most meeting neither. Examples of the site codes used are shown in Figure 2.

![Figure 2. Examples of the scheme for site code naming.](image)

Sites were selected to provide a fairly even distribution of sampling locations throughout the Gwynns Falls and the domain. A further consideration was the estimated ease of access for each site, based on interpretation of satellite imagery and superposition of the road network on model hydrography. The final distribution of 100 planned sites is shown in Figure 1. Planning a high density of sites allowed for nearby back-up locations to be readily available in the field when a particular site was found to be inaccessible or otherwise infeasible.
3.2 Falling-Head Permeameter

Much of the preparatory work for this project involved the design, planning, and construction of two identical falling-head permeameters. The falling-head permeameter used in this study is a device for obtaining in-situ field data from which hydraulic conductivity of the streambed can be calculated. The permeameter allows a known amount of water to permeate into the streambed at a rate dictated by the changing hydraulic head in the permeameter reservoir, the hydraulic conductivity of the bed material, and the properties of the permeating water. Use of the device is preferable to other methods of estimating hydraulic conductivity, such as an analysis of the streambed’s grain size distribution, because it causes very little disturbance to the bed material and can be completed relatively quickly.

The permeameter design was adapted from that used by Ryan and Boufadel (2007 a), and consisted primarily of two components: a reservoir chamber and a shaft. The reservoir chamber was composed of a clear PVC tube attached to an end-cap housing a ball valve that could be opened and closed to control the outflow of water. The shaft of the permeameter consisted of a length of hollow iron pipe, an outflow region of drilled holes and fine mesh near the base, and a steel drive-point. A depiction of the falling-head permeameter in use is shown in Figure 3.

In the field, the permeameter shaft was inserted vertically into the streambed until the mesh outflow region was at a desired depth below the bed surface. The reservoir was then attached atop the shaft and filled with stream water to a known height. Once a valve was opened, the reservoir water drained downward through the permeameter shaft and past the sub-surface mesh outflow region, which was in contact on all sides with streambed material. The difference in head between the water level in the reservoir and the height of the stream surface drives the downward flow of water, while the porosity, grain sizes, and packing of the bed material limits the rate at which the water may permeate into the bed. Differences in calculated conductivity values due to variations in water density and viscosity were eliminated by measuring the temperature of the permeating water during each test and correcting all values to a common temperature. Hydraulic conductivity was calculated using the method of Hvorslev (1951), and is based on observations of reservoir water level height over time, which declines at a decreasing rate as the head difference is resolved.

Detailed specifications for the permeameters used in this study are found in Appendix A. Problems encountered during the use of the permeameters and other instruments in the field, and many possible solutions, are described in Appendix B.
Figure 3. Conceptual model of a falling head permeameter in use, with three of the parameters collected in the field labeled. Also shown is an actual image of a permeameter in use, after a ~20 cm decline in head from the initial level.
3.3 Hydraulic Conductivity Determination

Methods for obtaining a single hydraulic conductivity value using the portable falling-head permeameter were based on those used by Ryan and Boufadel (2007a). The completed permeameter included two separable sections: the shaft and the reservoir chamber, which were attached only while hydraulic conductivity tests were performed. A 1.27-cm threaded steel flange, small sledgehammer, stopwatch, thermometer, small bucket, and squeeze bottle containing clean tap water or deionized water were also required to carry out the procedure for an experimental run. Three tests were performed at most sites: at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ across the width of water, directly beneath a waterproof measuring tape that was stretched across the stream. Fewer tests were sometimes performed at sites with narrow streams or shallow beds. Prior to each test, the permeameter shaft was wetted with stream water, the mesh thoroughly rinsed using the squeeze bottle of clean water, and a steel flange hand-tightened onto the threads atop the shaft.

At each measurement location, the permeameter shaft, with the temporarily attached protective steel flange, was pounded into the streambed (Figure 4) until at least 7.5 cm of bed material was above the top of the mesh outflow region; the insertion depth was monitored using tape markings on the shaft. The flange provided a better striking surface for the sledgehammer and more evenly distributed the force, necessary for preserving the threads that connect the permeameter shaft to the ball valve.

Once the permeameter shaft was properly inserted into the bed, the steel flange was gently removed and Teflon tape was wrapped around the permeameter threads. The ball valve with attached reservoir chamber was then hand-tightened onto the threads. Removal of the flange and attachment of the reservoir chamber were done while holding the permeameter shaft in place to prevent disturbance of the streambed. With the ball valve closed, the reservoir was then filled with stream water to the 0 cm marking, near the top. At this point, temperature of the water in the reservoir, depth of the stream (at the shaft, parameter ‘$H$’ for data analysis) and the height from the streambed surface to the top of the water level in the full reservoir (parameter ‘$H_0$’ for data analysis) were measured and recorded. Insertion depth and the time of day were also recorded. To begin the test, a stopwatch was started and the permeameter’s ball valve was opened simultaneously, causing an immediate drop in water level within the reservoir. The falling water level (parameter ‘$h$’ for data analysis) was recorded using the permeameter’s 1 cm increment markings at pre-determined time intervals (Figure 3). The test continued until the water level fell to the 45 cm marking or until 20 minutes had elapsed. Total elapsed time and final water level were recorded.
Figure 4. The permeameter shaft is pounded into the streambed using a small sledgehammer and a temporarily attached protective steel flange.
3.4 Stream Width and Streambed Thickness Measurements

At each of the forty-two sites visited, a transect was set up across the stream channel, perpendicular to the direction of flow, using a 100-m measuring tape and two anchoring stakes. The tape readings at the right and left edges of water were recorded, and the width of water determined. The tape values corresponding to ¼, ½, and ¾ across the width of water were calculated and noted for later use. The bankfull width was then determined by recording the location at which the steeper banks leveled off to the flatter floodplain on each side of the stream. Transects were typically set up where the stream’s edges of water were well defined.

Streambed thickness was measured using a slide-hammer (AMS Thread-On Slide Hammer, Item # 77454) with an extension rod and a hardened steel tip. Three bed thickness measurements were recorded at each site: at ¼, ½ and ¾ across the width of water. At each measurement location, the assembled slide-hammer was pounded into the streambed, penetrating the bed material down to the underlying rock layer. Once bedrock was reached, the bed surface level was marked on the slide-hammer, and the slide-hammer was removed. Streambed thickness was determined by measuring from the tip of the hardened steel to the bed surface marking, using a meter stick. Penetration through saprolite made some measurements prone to error. Each measurement was performed about two feet downstream of the transect tape (Figure 5) so as not to disturb the bed material immediately beneath the tape, where the hydraulic conductivity tests were later performed. Bed thickness was measured prior to completing the hydraulic conductivity tests to ensure sufficient depth of material for operation of the falling-head permeameters, which require at least 14.5 cm of bed material. Multiple bed thickness values across a single transect were averaged to one value per site.

3.5 Ancillary Data Collection

GPS coordinates were collected on-site using a handheld GPS unit (Trimble GeoXT), along with photographs documenting the exact transect location and site conditions. Field notes containing any relevant information were recorded, including how best to approach the site, notes on the appearance of bed material, and descriptions of permeameter condition and operation before, during, and after the hydraulic conductivity tests. The date, operators, site code, arrival time, and departure time were recorded at the top of each data sheet, as well.
Figure 5. Streambed thickness was measured using a slide-hammer, which was pounded into the bed material until further penetration was not possible. The transect tape was used to determine bankfull width, width of water, and the locations which are ¼, ½, and ¾ across the channel.
### 3.6 Data Analysis

Hydraulic conductivity ($K$) values were calculated from collected field data using the method of Hvorslev (1951). Hvorslev’s method describes a well-point filter that drains a falling head of water into a sample of soil (Figure 6).

**Figure 6.** Well point-filter schematic and analysis, adapted from Hvorslev (1951).
The falling-head permeameter works under the same principles as the well point-filter, allowing a column of water to drain through a permeable section of pipe in the subsurface. In the field, the permeameter reservoir is elevated above the stream, creating a difference in head between the reservoir water and the stream surface. The difference in head drives the downward flow of water through the permeameter shaft and past the subsurface mesh outflow region. As water permeates into the bed, the reservoir empties and the difference in head declines.

By collecting periodic measurements of the declining water level in the reservoir, the ratio of the head difference at each point in time to the initial head difference can be plotted. The unrecovered head difference begins at a scaled value of 1 (100%) and declines as the test proceeds; these values are plotted on the vertical axis, using a logarithmic scale. The horizontal axis shows the time at which each water level reading was collected in the field, beginning with zero and ending with the final duration of the test. Fitting a linear trend line through the data points provides an equation for the calculation of Basic Time Lag ($T_0$), defined as the point at which the unrecovered head difference ratio is equal to 0.37:

$$T_0 = (0.37 - b) / m$$  \hspace{1cm} (1)

where $b$ is the $y$-intercept of the trend line and $m$ is the slope of the trend line. The extrapolated value for Basic Time Lag is an estimate of the number of seconds required for the head difference between the reservoir water level and the stream surface to fall to 37% of its initial value.

Each hydraulic conductivity test conducted in the field using a falling-head permeameter yielded a unique value for Basic Time Lag, from which the hydraulic conductivity of the streambed at that location could be calculated, using the formula:

$$K = \left[ d^2 \cdot \ln(L/D + (1 + (L/D)^2)^{1/2}) \right] / 8 \cdot L \cdot T_0$$  \hspace{1cm} (2)

where $d$ is the inner diameter of the reservoir chamber, $L$ is the length of the mesh outflow region, $D$ is the diameter of the mesh outflow region, and $T_0$ is the Basic Time Lag. Values for $d$, $L$, and $D$ are dimensions of the permeameter itself and do not change between tests. The two permeameters used during this study were created and measured to be identical in these three parameters.

An example data analysis spreadsheet, used to obtain an initial hydraulic conductivity value for each permeameter test performed, is shown in Figure 7.
Figure 7. Example data analysis spreadsheet, used to calculate hydraulic conductivity from permeameter field data. Plotted on the graph is the unrecovered head difference over time. The K value (highlighted in pink) has not yet been corrected for temperature, or averaged with other conductivity measurements from that site.
Using the methods described above, a value for hydraulic conductivity was obtained for every falling-head permeameter test performed. Multiple tests across a transect at a given site yielded multiple values for hydraulic conductivity; these values were averaged to a single representative hydraulic conductivity value. Readings of water temperature in the permeameter reservoir prior to each test were used to correct calculated hydraulic conductivity values to a common temperature of 20°C, using the formula:

\[ K_{20°C} = K \cdot (1.498 \cdot (e^{-T/28.8}) + 0.269) \]  

(3)

where \( K \) is the field measured hydraulic conductivity and \( T \) is the reservoir water temperature in degrees Celsius.

Multiple streambed thickness values across a transect were also averaged to one value per site, to be used as the representative bed thickness for that segment of reach.

All results were utilized for calculation of streambed conductance. Streambed conductance for a given stream segment was determined using the formula:

\[ C = K_{20°C} \cdot L \cdot W / M \]  

(4)

where \( K_{20°C} \) is the temperature corrected average hydraulic conductivity of the streambed, \( L \) is the length of reach (model hydrography segment) per the requirements of the ongoing MODFLOW work, \( W \) is the width of the stream, and \( M \) is the bed thickness (Fox 2007).
4. Results

Of the one-hundred sites planned, forty-two were visited over the course of the project. Twenty-eight sites were within the Gwynns Falls watershed, with fourteen in the surrounding domain. Ten sites coincide with USGS stream gage locations, ten sites are within Baltimore city limits, and ten different underlying geologic formations were covered. The final distribution of measurement locations is shown in Figure 8. The greatest density of measurements is located within the Dead Run subwatershed, in which 8 sites were visited, including 5 transects with 14 permeameter tests performed over an area of less than half a square kilometer (Figure 9).

Average thickness of bed material above bedrock was found to be 33.0 cm, with a range of 8.20 to 90.1 cm and a standard deviation of 19.4 cm. Bed thickness was measured at 40 sites, typically three times per site. The average standard deviation of intra-site bed thickness measurements was 7.44 cm.

Final values for streambed hydraulic conductivity ranged from $1.41 \times 10^{-3}$ cm/sec to $5.62 \times 10^{-2}$ cm/sec with a mean value of $1.33 \times 10^{-2}$ cm/sec and a standard deviation of $9.10 \times 10^{-3}$ cm/sec. The average standard deviation of intra-site conductivity measurements was $5.44 \times 10^{-3}$ cm/s. Tables 1 and 2 summarize the data for the Domain and Gwynns Falls sites, respectively. Appendices C and D include full descriptions of each site, including satellite and field imagery.
Figure 8. Map of site locations, including site label, watershed and study area boundaries, major streams, major geologic formations, and the Baltimore City border.
**Figure 9.** Five site locations within the Dead Run watershed.

**Table 1.** Data summary for the fourteen sites within the surrounding model Domain.

<table>
<thead>
<tr>
<th>Site</th>
<th>Average Hydraulic Conductivity, $K$ (cm/s) (20°C)</th>
<th>$\sigma K$ (cm/s)</th>
<th>Average Bed Thickness, $M$ (cm)</th>
<th>$\sigma M$ (cm)</th>
<th>Bankfull Width, $W$ (m)</th>
<th>Width of Water (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain A</td>
<td>2.05E-02</td>
<td>4.12E-03</td>
<td>14.5</td>
<td>1.48</td>
<td>5.38</td>
<td>4.90</td>
</tr>
<tr>
<td>Domain B</td>
<td>1.50E-02</td>
<td>5.95E-03</td>
<td>21.5</td>
<td>1.50</td>
<td>6.25</td>
<td>5.85</td>
</tr>
<tr>
<td>Domain D</td>
<td>1.58E-02</td>
<td>3.22E-03</td>
<td>15.5</td>
<td>2.67</td>
<td>6.30</td>
<td>3.30</td>
</tr>
<tr>
<td>Domain E</td>
<td>1.48E-02</td>
<td>1.74E-03</td>
<td>31.8</td>
<td>3.62</td>
<td>7.30</td>
<td>5.10</td>
</tr>
<tr>
<td>Domain G</td>
<td>1.20E-02</td>
<td>3.99E-03</td>
<td>37.5</td>
<td>6.87</td>
<td>5.25</td>
<td>3.56</td>
</tr>
<tr>
<td>Domain S</td>
<td>5.92E-03</td>
<td>2.03E-03</td>
<td>37.1</td>
<td>0.529</td>
<td>2.85</td>
<td>2.23</td>
</tr>
<tr>
<td>Domain U</td>
<td>6.70E-03</td>
<td>3.07E-03</td>
<td>78.7</td>
<td>39.5</td>
<td>3.75</td>
<td>2.01</td>
</tr>
<tr>
<td>Domain X</td>
<td>5.06E-03</td>
<td>2.83E-03</td>
<td>31.0</td>
<td>4.05</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td>Domain Z</td>
<td>3.85E-03</td>
<td>1.38E-03</td>
<td>17.9</td>
<td>3.63</td>
<td>4.39</td>
<td>3.64</td>
</tr>
<tr>
<td>Domain BB</td>
<td>1.51E-02</td>
<td>1.29E-02</td>
<td>26.0</td>
<td>6.06</td>
<td>5.18</td>
<td>4.41</td>
</tr>
<tr>
<td>Domain EE</td>
<td>6.40E-03</td>
<td>8.20</td>
<td>5.84</td>
<td>5.48</td>
<td>1.60</td>
<td>0.94</td>
</tr>
<tr>
<td>Domain II</td>
<td>1.08E-02</td>
<td>6.27E-03</td>
<td>22.7</td>
<td>5.80</td>
<td>8.06</td>
<td>5.09</td>
</tr>
<tr>
<td>Domain MM</td>
<td>1.18E-02</td>
<td>5.66E-03</td>
<td>22.5</td>
<td>11.3</td>
<td>8.95</td>
<td>7.19</td>
</tr>
<tr>
<td>Domain NN</td>
<td>5.86E-03</td>
<td>2.34E-03</td>
<td>59.2</td>
<td>6.58</td>
<td>2.63</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Table 2. Data summary for the twenty eight sites within the Gwynns Falls watershed.

<table>
<thead>
<tr>
<th>Site</th>
<th>Average Hydraulic Conductivity, $K$ (cm/s) (20°C)</th>
<th>$\sigma K$ (cm/s)</th>
<th>Average Bed Thickness, $M$ (cm)</th>
<th>$\sigma M$ (cm)</th>
<th>Bankfull Width, $W$ (m)</th>
<th>Width of Water (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF A</td>
<td>6.77E-03</td>
<td>9.57E-03</td>
<td>90.1</td>
<td>13.60</td>
<td>3.60</td>
<td>2.65</td>
</tr>
<tr>
<td>GF G</td>
<td>2.07E-02</td>
<td>1.24E-02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF H</td>
<td>1.52E-02</td>
<td>2.94E-03</td>
<td>12.3</td>
<td>3.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF J</td>
<td>1.41E-03</td>
<td></td>
<td>82.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF L</td>
<td>1.54E-02</td>
<td>1.09E-03</td>
<td>27.3</td>
<td>1.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF M</td>
<td>1.40E-02</td>
<td>1.88E-03</td>
<td>22.4</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF O</td>
<td>1.27E-02</td>
<td>5.59E-03</td>
<td>49.9</td>
<td>10.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF P</td>
<td>4.63E-03</td>
<td>1.45E-03</td>
<td>27.3</td>
<td>6.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF R</td>
<td>5.72E-03</td>
<td>4.71E-04</td>
<td>19.6</td>
<td>9.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF S</td>
<td>1.67E-02</td>
<td>9.10E-03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF U</td>
<td>1.27E-02</td>
<td>5.64E-03</td>
<td>35.0</td>
<td>10.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF V</td>
<td>1.47E-02</td>
<td>2.56E-03</td>
<td>22.2</td>
<td>2.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF AA</td>
<td>9.78E-03</td>
<td>4.05E-03</td>
<td>12.7</td>
<td>8.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF BB</td>
<td>1.84E-02</td>
<td>4.15E-03</td>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF CC</td>
<td>5.30E-03</td>
<td>2.21E-03</td>
<td>26.7</td>
<td>4.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF DD</td>
<td>1.36E-02</td>
<td>1.34E-03</td>
<td>29.7</td>
<td>1.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF EE</td>
<td>5.62E-02</td>
<td>1.72E-02</td>
<td>21.4</td>
<td>7.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF GG</td>
<td>2.34E-02</td>
<td>8.85E-03</td>
<td>10.7</td>
<td>3.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF II</td>
<td>1.38E-02</td>
<td>4.31E-03</td>
<td>31.7</td>
<td>17.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF JJ</td>
<td>1.27E-02</td>
<td>5.79E-03</td>
<td>37.0</td>
<td>7.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF NN</td>
<td>3.08E-02</td>
<td>3.90E-02</td>
<td>64.0</td>
<td>7.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF QQ</td>
<td>4.11E-03</td>
<td></td>
<td>41.0</td>
<td>9.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF RR</td>
<td>1.66E-02</td>
<td>9.34E-04</td>
<td>47.5</td>
<td>9.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF TT</td>
<td>1.51E-02</td>
<td>3.88E-03</td>
<td>40.2</td>
<td>2.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF UU</td>
<td>7.36E-03</td>
<td>2.10E-03</td>
<td>14.2</td>
<td>4.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF WW</td>
<td>7.28E-03</td>
<td>3.66E-03</td>
<td>46.3</td>
<td>11.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF YY</td>
<td>2.00E-02</td>
<td>2.81E-03</td>
<td>34.0</td>
<td>7.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF AAA</td>
<td>1.24E-02</td>
<td>3.71E-03</td>
<td>27.3</td>
<td>9.55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Frequency distributions of the streambed thickness and log-hydraulic conductivity values are provided in Figures 10 and 11, respectively. The hydraulic conductivity data appeared to be log-normally distributed according to the Kolmogorov-Smirnov test (Figure 12). Streambed hydraulic conductivity was measured at depth between 7.5 and 12.5 cm below the bed surface, with an average depth of 8.7 cm. No correlation was found between insertion depth and the calculated hydraulic conductivity of the streambed within this 7.5 to 12.5 cm range (Figure 13).
Figure 10. Frequency distribution of bed thickness values measured in the field.

Figure 11. Frequency distribution of the logarithms of streambed hydraulic conductivity values.
Figure 12. Cumulative distribution function (CDF) of the logarithms of streambed hydraulic conductivity values, plotted against the theoretical log-normal CDF.

Figure 13. Plot of depth below streambed of the permeameter mesh outflow vs. calculated streambed hydraulic conductivity. Tests were not performed at varying depths in the streambed for any single measurement location.
5. Discussion

Values for hydraulic conductivity obtained by the permeameters in this study are typical for clean sand or silty sand materials, based on the ranges given by Freeze and Cherry (1979). Results here are similar to those of Ryan and Boufadel (2007b), whose study of a single urban stream in the Piedmont in Pennsylvania yielded values ranging from $1.16 \times 10^{-4}$ cm/s to $1.78 \times 10^{-2}$ cm/s. Variation in conductivity measurements across a transect for a single site was less than the variation between sites.

The distribution of bed thickness measurements shown in Figure 11 indicates a moderate number of sites at which bed thickness was much greater than the average of 33.0 cm. Penetration through saprolite occurred at five sites (affecting 11 individual thickness measurements), at which the transition from streambed material to bedrock was poorly defined, causing an artificially high measurement of bed thickness. Adjustments were made to these measurements based on the amount of saprolite visible on the slide-hammer tip after removal from the bed. This adjustment was not always possible, and a total of six individual measurements were thrown out entirely. Variation in bed thickness measurements across a transect for a single site was much less than the variation between sites. Transects were typically set up in locations where it was thought there would be sufficient depth of bed material to perform hydraulic conductivity tests. This bias is likely to have caused an underrepresentation of low-end bed thickness values.

The forty-two sites visited included a variety of stream sizes and types. Stream widths ranged from $4.0 \times 10^{-1}$ m to $1.66 \times 10^1$ m (Figure 14). Forested, agricultural, residential, commercial, and industrial land uses were all represented in the areas immediately surrounding the sites. Ten different geological formations lie beneath the streambeds of the forty-two sites visited, including the Baltimore Gabbro Complex, Lower Pelitic Schist, and Baltimore Gneiss. While relationships between these factors and hydraulic conductivity were not explored in this study, inclusion of a variety of streams helped to ensure that the dataset is representative of the study area as a whole. Determination of spatial cross correlation and autocorrelation would require a more detailed study designed using a geostatistical approach (e.g., Goovaerts, 1997), with measurements carried out at nested spatial scales.
Figure 14. Stream widths ranged from 40 cm to over 16 m. Shown here are GF J: Winterbourne Rd at Morris Rd (left) and GF G: Ellicott Driveway at W Baltimore St (right).
6. Concluding Remarks

Future expansion of the dataset may allow for determination of spatial patterns in hydraulic conductivity as a function of stream position. Selection of site locations based on local watershed characteristics, rather than ease of access or evenness of spatial distribution, would be required to determine such trends. A potential influence on large-scale spatial patterns in streambed hydraulic conductivity may be the extent to which the surrounding land is built-up. The study area spans a gradient of urbanization from the rural areas surrounding the upper Gwynns Falls to the highly urban downtown Baltimore region, into which the Gwynns Falls extends. Spatial patterns of $K$ values are expected to be influenced by slope of the streambed, land use, position in watershed and the underlying geologic formation (Freeze and Cherry 1979).

Additional applications of the dataset may also include use of streambed hydraulic conductivity values to estimate hyporheic exchange, which directly affects chemical and biological cycling and transformations within a stream system (Ryan and Boufadel 2007 a). In this study, hydraulic conductivity was measured in the near-surface hyporheic zone (Ryan and Boufadel 2007 b), where exchange occurs most readily. Hydraulic conductivity of the streambed also affects the transport and fate of contaminants (Freeze and Cherry 1979), making this dataset potentially useful for analysis of stream pollutant loads, particularly within such an urban watershed.
References


Hvorslev, MJ. 1951. Time lag and soil permeability in groundwater observations; U.S. Army Corps. of Engineers, Waterways Experiment Station: Washington, DC, 1951. (Figure 18G)


