

Topographic Models and Infiltration Rate Analysis: Evaluating Extent of Potential Groundwater  
Denitrification of Low-Relief Streams Draining Watersheds of the Atlantic Coastal Plain

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## ABSTRACT

Nitrate flux from agricultural watersheds via streams impairs coastal water quality on the Atlantic shoreline. On Virginia's Eastern Shore, low-relief gaining streams drain 54 small agricultural watersheds (80-1100 ha) that extend from the center of the Delmarva Peninsula to coastal lagoons and the Atlantic Ocean. Microbially mediated denitrification in subsurface water can dramatically reduce the amount of nitrate flowing from watersheds. Stage hydrographs were developed for four streams using continuous measurements of water-surface elevation in stilling wells, and median and maximum stage was identified. Putting together cross sections derived from hand measurements in the field at each stream, a topographic model of the stream bank, floodplain, and highlands was developed using GIS software. Stage record was combined with stream geometry to illustrate the areal extent that stream water inundates the floodplain following rain events. The increases in inundation area between median and high stage varied greatly among the streams, from a high of 1247% to a low of 46%. Some streams had significant reaches of dry channel over the year, and their water-covered areas increased the most with rain events. With new insights into stream access to floodplain areas during high-flow events, the potential for bank infiltration in riparian-zone sediments was explored. Infiltrometer measurements were collected in a manner that supported quantification of the comparative potential of surface-water input to the subsurface under different conditions, including location of stream, type of landscape, and vegetative cover of soil. The average hydraulic conductivity of the soils at each stream differed, but the hydraulic conductivities were on average 60% greater in the floodplain compared to in the stream bank, and vegetation cover had no significant effect. These results suggest that the floodplain, established by the topography, has the highest potential for infiltration and subsequent potential for denitrification.

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## Chapter 1: Introduction

### 1.1 Background

There are 54 small watersheds with low-order streams in the Virginia Delmarva Peninsula that flow eastward into coastal lagoons, contributing to potential degradation of coastal water quality (e.g., Denver et al., 2004; Mills et al., 2008). Draining predominantly agricultural land, these streams are subject to nutrient loading from fertilizer and animal waste applied to the land surface (Lowrance, 1992; Denver et al., 2004), and nitrate is a particular problem (Galloway et al., 2003). Dissolved nitrate infiltrates during rain events and, upon reaching the water table, travels with groundwater to emerge in the gaining streams of this area (Gu et al., 2007; Mills et al., 2008). In the subsurface, denitrification removes some biologically active nitrate under conditions of high organic matter content, low dissolved oxygen concentration, and sufficient residence time (Zarnetske et al., 2013; Flewelling et al., 2013). Ultimately, nitrate fluxes from watersheds to receiving coastal water predominantly by stream discharge (Sanford and Pope, 2013). The magnitude of nitrate flux via streams is very strongly related to the magnitude of water flux, and my research to date (Pickus et al., 2014) has focused on the problems of quantifying stream discharge (i.e., water flux).

In hopes of quantifying the nitrogen flux of some representative watersheds of the Delmarva Peninsula, I have been involved with the Mills-Herman research group in monitoring four streams (arranged from north to south): Bundick's Creek, Phillip's Creek, Cobb Mill Creek, and Tommy's Ditch. Pressure transducers suspended in previously installed stilling wells record continuous water-surface elevation that allowed for creation of stage hydrographs for each stream. Instantaneous discharge measurements made with a hand-held flow meter and

measurement of cross-sectional stream area have been taken and combined to create rating curves for each of the four streams. The rating curves were then applied to the stage record in order to obtain the discharge record that would eventually lead to quantification of nutrient flux.

Evaluation of the hydrographs indicated that at high-stage values the rating curve did not accurately relate stage to discharge (Pickus et al., 2014). Although other investigators have pointed to the problems of monitoring discharge in small, flashy streams during storm events (e.g., Linder and Miller, 2012; Vidon et al., 2009, Merwade et al., 2008), the details of why the rating curves cease to be useful at high-flow conditions vary from study to study. In our streams, the location of the stilling well was selected in order to have a stable and geometrically well-defined cross section at a culvert at which to monitor stream stage. We are never present in the field, however, at the recorded high-stage values, so we don't know the details of water distribution at high flow; yet, visual observation indicates the water occasionally leaves the stream channel, obviating our defined cross section that is the basis for the rating curve. The failure of the rating curves necessitates a different approach to understand and illustrate what is happening to water in these streams during high-flow storm events.

When stream elevation rises following a rain event, flow reversals occur in the streambed sediments turning the typically gaining streams into losing streams (Gu et al., 2008) such that stream water contributes to bank storage (Doble et al., 2012; Gu et al., 2012). This storage of water in the banks of the stream that is then released back to the stream as the water-surface elevation falls after peak storm flow passes by constitutes bank storage (Hornberger et al., 1998) and is of interest in a robust consideration of the fate of nutrients in small, flashy streams. The presence of different types of soil plays a role in determining the infiltration rates of this storm flow into the subsurface (Griffin et al., 2014). When water leaves the channel and spreads

laterally across the floodplain, infiltration into the unsaturated floodplain sediments contributes to temporary storage of water under conditions favorable for active biogeochemical transformations (Byrne et al., 2014).

Denitrification by biological processes in the subsurface of riparian areas has proven to be a significant aspect of nitrate reduction in streams (Vidon and Hill, 2004a, Harms et al., 2009). When microbially mediated denitrification occurs within floodplain soils, it is one of the main biological processes responsible for this riparian nitrogen uptake (Pinay et al., 2006). The topography of the landscape surrounding the stream and the hydraulic properties of the sediments within the riparian zone play important roles in governing the denitrification processes occurring there (Vidon and Hill, 2004b). Proximity of soils to the stream has been found to influence denitrification, with soils closer to the streams having higher rates of subsurface denitrification (Harms et al., 2008). The movement of water into the floodplain during storm events may then have a part in increasing the potential for denitrification in riparian zones.

## 1.2 Objectives

The goals of my research are (1) to assess the extent to which water flows onto the floodplain during high-flow events and (2) to estimate where and under what conditions the potential for infiltration into the subsurface is highest and where the highest level of denitrification may occur. Returning to the historical stage record, the extent to which water inundates the floodplain during storm events will be quantified. These results will inform our understanding of riparian denitrification associated with flood events and give information on how to manage high-nitrogen streams to promote riparian denitrification to its fullest extent.

## **Chapter 2: Methods**

### 2.1 Field Site Description

The Virginia Eastern Shore Peninsula is located east of the Chesapeake Bay that separates it from mainland Virginia and is in the Coastal Plain physiographic province. There is a drainage divide running north-south along the center of the peninsula, with water draining either west into the Chesapeake Bay or east into coastal lagoons along the margin of the Atlantic Ocean. Small, low-order streams drain 54 watersheds along the eastern side of the peninsula. Four streams were studied for this project, chosen because they span the length of the Virginia part of the peninsula and have been locations of past studies. In order from the northernmost to southernmost, the streams are Bundick's Creek, Phillip's Creek, Cobb Mill Creek, and Tommy's Ditch (Figure 1). They all drain watersheds predominated by cropland that is routinely planted in a rotation of different crops. The streams are all very small, incised streams. The specific study location along each stream was chosen due to its proximity to an already installed stilling well, allowing for the application of continuous stage and discharge data to any work done on the stream reach.



Figure 1. Map of the Eastern Shore of Virginia showing location of study sites.

## 2.2 Overview of Research Methods

This project has three main parts. In one part, continuous stage records were developed at each stream using pressure transducers installed in stilling wells. The stage measurements were organized into water years, and the median and maximum stage of each stream was calculated. In the second part, three-dimensional topographic models of the four streams were made. The models illustrate the morphology of each stream, including location of bank and floodplain, and the extent of water inundation across the land surface under different stream-flow conditions. In the last part, hydraulic conductivity was calculated using infiltration measurements in the floodplain and stream bank, on the north and south sides of the stream, and in vegetated and non-vegetated ground conditions.

### 2.2.1. Water-Surface Elevation Record

Solinst<sup>®</sup> pressure transducers installed in stilling wells collected continuous data on a ten- or six-minute interval. The record was downloaded periodically and, using Solinst<sup>®</sup> Levellogger Pro software, the pressure data were compensated for barometric pressure to give water depth in the stilling well. Some of these values are measurements of the water table when the stream is dry. At the time of each transducer download, a water-level meter was used to make a depth-to-water (DTW) measurement from the top of the stilling well to the water surface in the stilling well. The height of the top of the stilling well was documented and known (pers. commun., Aaron Mills), allowing the DTW measurement to act as an elevation starting point for the beginning of each downloaded record.

The different periods of record, separated by download dates, were organized into water years using Microsoft<sup>®</sup> Office Excel. Stage hydrographs were completed for each stream for water years 2008-2013. The median and maximum water-surface elevation for each water year was calculated from this record. If stage was measured to be at a level below the elevation of the streambed, we concluded there was no water in the channel. When maximum and median were calculated, all stream stages that resulted in no water in the channel were excluded from the calculations. The lowest surveyed streambed elevation (Methods 2.2.2) was subtracted from the median and maximum water-surface elevation to give a median and maximum stream depth. The water-surface elevation record from 2010 was used for the remainder of this project.

## 2.2.2 Elevation Profile and GIS-Generated Topographic Model

A self-leveling rotary laser level with a tripod, a stadia rod, a laser detector with a clamp to attach to the stadia rod, a measuring tape, string, and stakes were used to characterize stream cross sections. Stakes were driven into the ground and a string was tied off parallel to the stream, far enough to the side of the stream to extend fully into the flattened plain next to the stream. This string served as the starting point for one end of the cross sections. The measuring tape was then unwound and stretched taut perpendicular to both the stream and the initial string set up. The measuring tape acted as a transect along which an elevation profile was taken across the floodplain, into the stream bank and stream, and continued on to the other side of the floodplain. The self-leveling rotary laser level was set up on the tripod to create a datum at an elevation high enough to capture all elevation data.

Measurements were taken using the stadia rod and laser detector along the measuring tape line. The measurements were taken noting how far along the transect the point was ( $X$ ) and the distance from the ground surface to the laser-level datum ( $Z$ ). Regular intervals of one meter in  $X$  were used until the elevation began to change more rapidly when smaller intervals were used. The measuring tape was moved farther downstream from the culvert by about 2 meters each time, keeping it perpendicular to the initial side string. Four more elevation profiles were made leading to a total of five profiles for each stream.

The height of the top of the stilling well at each location was taken to serve as a reference point between the laser-level transect measurements and the long-term stage measurements made in the stilling well. This reference point allowed the two data sets to be combined and represented together in one topographic model.

The data were entered into an Excel file with the Y column representing how far from the culvert the elevation profile was, X representing how far along the elevation profile from the initial string the measurement was, and Z representing the distance from the ground to the laser-level datum. The highest Z measurement was calculated to get the lowest stream elevation measured which was then subtracted from each Z measurement. The result was the lowest Z coordinate being zero and the rest of the coordinates being positive values based off the zero level when mapped in ESRI ArcScene.

ESRI GIS ArcScene 10.2 was used to generate 3D visualizations of the stream morphology. Data were imported using the “add data” feature. The add XYZ data feature was employed to add the vertical Z class of data and all of the data were projected in a 3D field. These points were exported as a shapefile to be edited using GIS analyst tools. The shapefiles were opened in ArcScene and using the “create TIN” tool under the 3D Analyst Tools in the ArcToolbox, interpolated surface layers for each of the stream models were created. These surfaces are not georeferenced, because they were used only to illustrate the land and water-surface elevations for each stream.

The minimum, median, and maximum surface-water elevation data from the stage records for Water Year 2010 for each stream was applied to the modeled stream topography. The reference measurements of the top of the stilling wells were employed to convert the different surface-water elevations to the same scale as the topographic models. This correction was done by subtracting the water-surface elevation from the known height of the stilling well. This value was added to the measured distance between the top of the stilling well and the laser-level datum, giving the distance from the datum to the water-surface elevation. This value was then subtracted from the minimum measured streambed value so it would be on the same scale as

the topographic model. This correction was done for the median and maximum water-surface elevations. Default elevation contours were created using the “Create Contour” feature in the surface layer Toolbar. The initial elevation contours were projected on the models and then manually edited to show the level of water inundation under median and maximum water-surface elevations. The area of the landscape being inundated by water in the stream reach under study for median and maximum water-surface elevations was quantified using the “Measure Polygon” tool in ArcScene.

### 2.2.3 Hydraulic Conductivity and Infiltration Potential

Cumulative infiltration rates of the land areas occasionally subject to inundation surrounding each stream were measured. Measurements were made in each of several classes: north and south sides of the stream, stream bank and floodplain, and vegetated and non-vegetated soil. Three measurements were made in each class at each stream, resulting in 96 infiltration measurements. The vegetation class was based on observation on whether there was vegetation growing at the point of infiltration or not. The location classes were based on the topographic models to see if the location was in the floodplain or the stream bank. Some areas of the stream bank or floodplain were not uniformly flat and it was necessary to cut out a small flat shelf in the bank in order to perform the infiltration tests.

A mini-disk infiltrometer was used to make cumulative infiltration measurements. The methods for this hydraulic conductivity calculation were adapted from The University of Virginia Hydrology Laboratory Manual (Eshelman et al., 2011) and from Zhang (1997). The mini-disk infiltrometer was filled with water to a known depth. The suction on the infiltrometer was set to -2 for each of the measurements and it was placed on the soil being measured. The

depth of water in the infiltrometer was tracked along with time. The cumulative infiltration was graphed versus the square root of the infiltration time. Using a quadratic fit of infiltration depth versus the square root of time, a parameter ( $C_1$ ) necessary for calculating hydraulic conductivity was produced (Figure 2) using

$$I = C_1 t + C_2 \sqrt{t} \quad (1)$$

where  $I$  is cumulative infiltration (cm),  $t$  is time (s),  $C_1$  ( $\text{cm s}^{-1}$ ) is related to hydraulic conductivity, and  $C_2$  ( $\text{cm s}^{-1/2}$ ) is related to soil sorptivity. A two-term equation that describes water flow into the soil due to gravity and capillary forces was employed to calculate hydraulic conductivity

$$K = C_1 / A \quad (2)$$

where  $K$  is hydraulic conductivity,  $C_1$  is related to hydraulic conductivity and is calculated using Equation 1, and  $A$  is a van Genuchten parameter determined by the soil type and given in a table (Eshelman et al., 2011). The soil type was determined using the texture-by-feel analysis. At each stream a soil texture was determined, and each stream's soil was categorized as sandy clay loam.

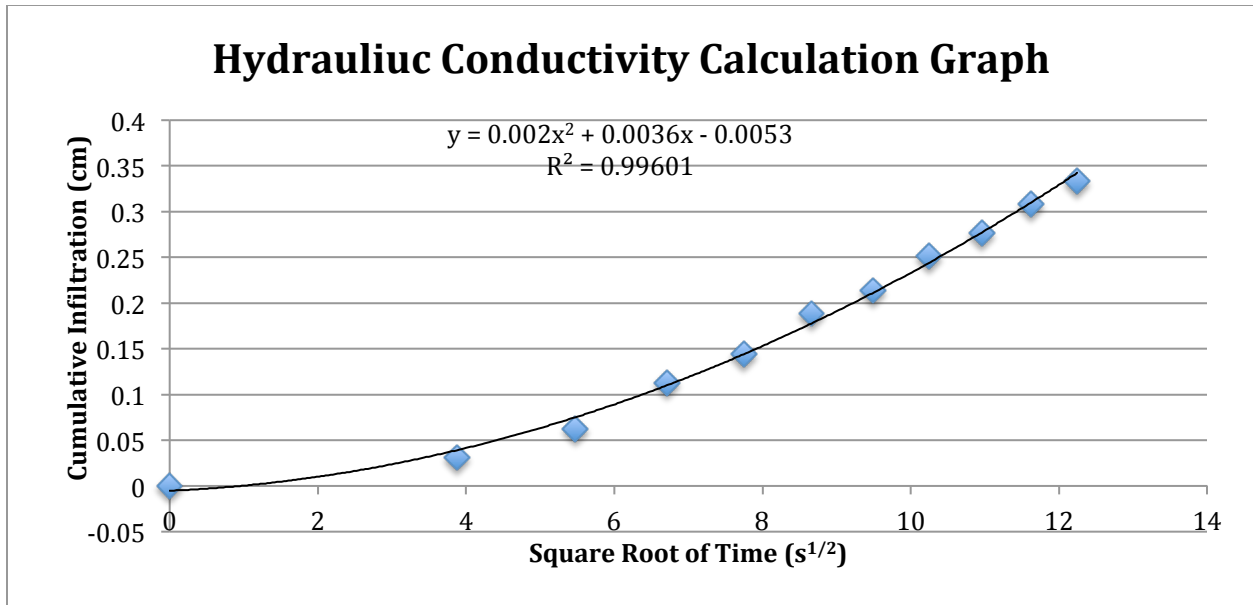


Figure 2. The quadratic fit equation based on the cumulative infiltration versus the square root of time. The equation gives the first parameter necessary to calculate the hydraulic conductivity for each section of soil sampled.

The calculated hydraulic conductivities were entered into an Excel sheet so they could be entered into SAS<sup>®</sup> 9.4 for statistical analysis. Four testable independent variables were identified: stream, vegetation, landscape, and bank side. The dependent variable was hydraulic conductivity. Analysis of variance (ANOVA) was determined as the appropriate test to determine significance of the independent variables. Seven of the calculated hydraulic conductivities were negative, so these values were entered into SAS as missing data points. Using the Brown Forsythe test, homogeneity of variance within each independent variable in the project was tested to make sure they met the requirements necessary for ANOVA testing. The stream variable failed this requirement, so the hydraulic conductivity was transformed using a log<sub>10</sub> scale. The Brown-Forsythe test was rerun using the log<sub>10</sub> transformed data resulting in all independent variables passing the test for homogeneity of variance. The statistical analysis was run twice, once as a full ANOVA design with all independent variables included and once as a

reduced ANOVA design not including the bank-side variable (Table 1). A test to determine significance of the bank-side variable, a log likelihood ratio test, was used to determine if the bank-side variable had any effect on the model. The test proved the bank-side effect to be insignificant, so the reduced ANOVA design was used to test the null hypothesis that the means of each variable will not differ.

Table 1. ANOVA design and variable breakdown.

ANOVA design	Type of Variable							
	Main Variable 1 Stream	Main Variable 2 Landscape	Main Variable 3 Vegetation	Variable 4 Bank Side	Interaction 1 Stream*Bank	Interaction 2 Stream*Vegetation	Interaction 3 Bank*Vegetation	Interaction 4 Stream*Bank*Vegetation
Model I (Reduced)	Fixed	Fixed	Fixed	N/A	Fixed	Fixed	Fixed	Fixed
Mixed Model (Full)	Fixed	Fixed	Fixed	Random	Fixed	Fixed	Fixed	Fixed

## Chapter 3: Results

### 3.1 Stage Hydrographs

The stage hydrographs (Figures 3-6) show the water-surface elevation of each stream over the course of Water Year 2010. The median stage is plotted as the dotted red line, the maximum stage is plotted as the dotted blue line, and the elevation of the lowest point of the streambed is plotted as the dotted brown line. Bundick's Creek (Figure 3) and Phillip's Creek (Figure 4) were both found to be dry for large portions of the year, so the median water-surface elevation for these streams was calculated using only the stage data when there was water in the streambed. Cobb Mill Creek (Figure 5) and Tommy's Ditch (Figure 6) were not found to be dry for any portions of the year, so the median water-surface elevation for these streams at all times also represents the median water-surface elevation for all times that there was water in the streambed.

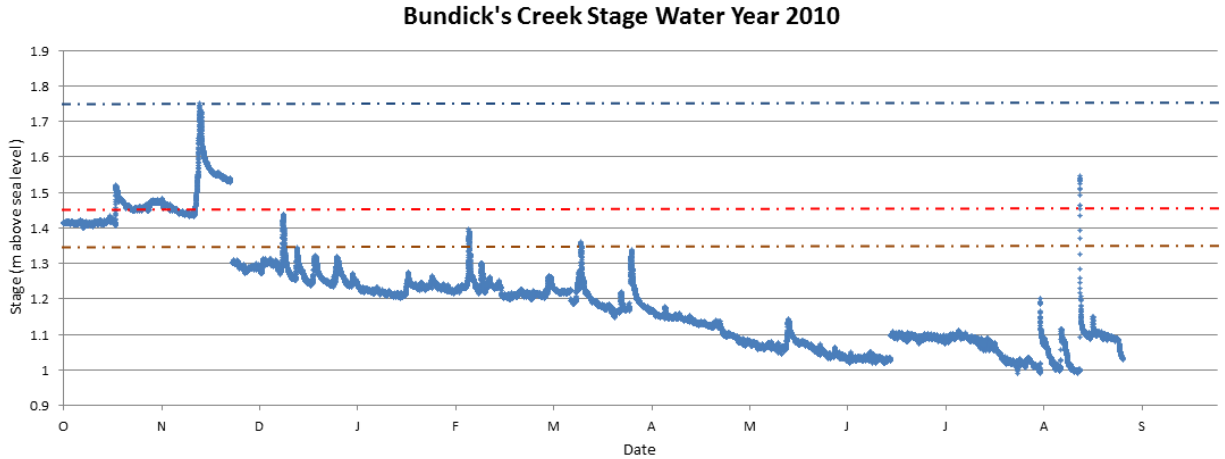


Figure 3. Stage hydrograph of Bundick's Creek for Water Year 2010. The blue line shows the maximum stage, the red line shows the median stage when there was water in the channel, and the brown line shows the elevation of the streambed.

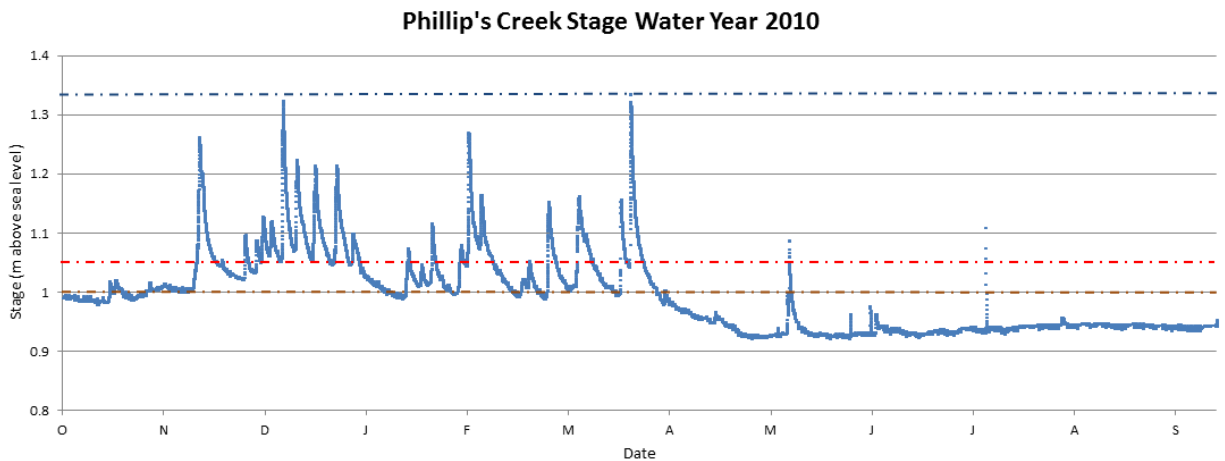


Figure 4. Stage hydrograph of Phillip's Creek for Water Year 2010. The blue line shows the maximum stage, the red line shows the median stage when there was water in the channel, and the brown line shows the elevation of the streambed.

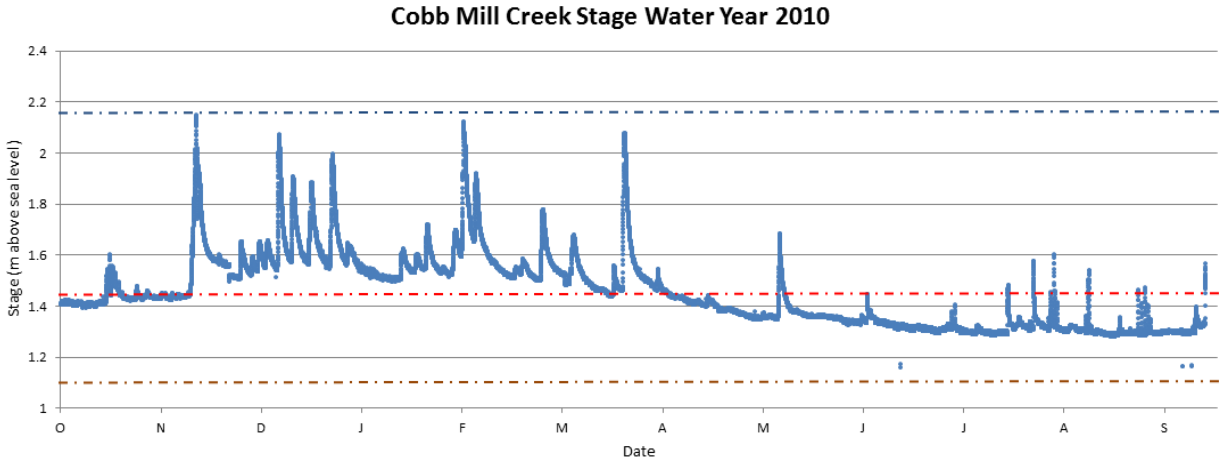


Figure 5. Stage hydrograph of Cobb Mill Creek for Water Year 2010. The blue line shows the maximum stage, the red line shows the median stage, and the brown line shows the elevation of the streambed.

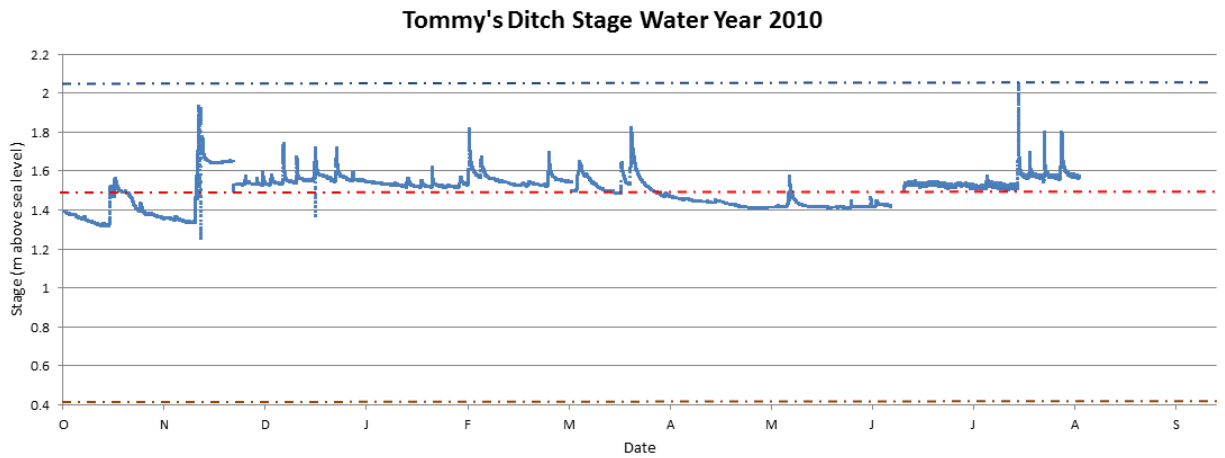


Figure 6. Stage hydrograph of Tommy's Ditch for Water Year 2010. The blue line shows the maximum stage, the red line shows the median stage, and the brown line shows the elevation of the streambed.

There are apparent discontinuities in the stage record. One can clearly be seen in the middle of November in the Bundick's Creek hydrograph (Figure 3). These apparent offsets in what should actually be contiguous measurements occur due to drift over time in the pressure recorded by the transducers. This drift was corrected back to the absolute elevation each time the transducer was downloaded and the hand-measured DTW measurement was used as the initial stage value for that period of record, leading to what appear to be jumps in the record.

All of the stage records show the majority of the high-stage events occurring in the first half of the water year, with one high-stage event occurring at the end of the water year. The timing of high-flow conditions in Water Year 2010 is clearly linked to the annual precipitation record (Appendix, Figure A3) in which the frequency of storms was much higher in the first half of the water year, and the largest storm of record that year was in November. This distribution of storms explains the general behavior of stream stage being higher in the first half of the water year followed by an overall trend of decline after that.

The streams differ in their relative elevation from sea level (Table 2). Each stream also holds different depths of water in its channel (Table 2). Tommy's Ditch has the highest median stream depth of 1.09 m, followed by Cobb Mill Creek with an average depth of 0.28 m (Table 2). Bundick's Creek and Phillip's Creek both have very shallow average depths of less than 10 cm (Table 2). Tommy's Ditch has the highest maximum stream depth of 1.61 m, again followed by Cobb Mill Creek (Table 2). The difference between median and maximum stage for each stream provides an indication of how extensively water leaves the defined channel during storm events. The stream with the most floodplain inundation during large storm events is Cobb Mill Creek (Table 2). These differences between median and maximum stage are relatively smaller among

the streams than are the differences between median and maximum stream depths, but these measures of all four streams fell within the same order of magnitude.

Table 2. The minimum streambed elevation, median stage, maximum stage, median stream depth, maximum stream depth, and the difference between median and maximum stage for each stream. The elevations and stages are expressed relative to mean sea level.

Stream	Minimum Streambed Elevation (m)	Median Stage (m)	Maximum Stage (m)	Median Stream Depth (m)	Maximum Stream Depth (m)	$\Delta$ Median Stage and Maximum Stage (m)
Bundick's Creek	1.36	1.45	1.75	0.09	0.39	0.30
Phillip's Creek	1.01	1.05	1.34	0.04	0.33	0.29
Cobb Mill Creek	1.15	1.43	2.15	0.28	1.00	0.72
Tommy's Ditch	0.44	1.53	2.05	1.09	1.61	0.52

### 3.2 Topographic Models

The topographic models (Figures 7-10) show two important aspects of the study streams. First, the extent of the stream bank and floodplain for each stream is illustrated in the topographic models. Second, the topography is the basis for showing the extent of water inundation into the floodplain during storm events. For the purposes of this study, explicit definitions of what is meant by stream bank and floodplain depend upon the history of water access to those areas. Herein, the stream bank for each model is defined as the area of the model that was inundated by water at a median water-surface elevation and is illustrated in dark blue in the models. The floodplain for each model is defined as the area of the model that was inundated

by water at the maximum water-surface elevation and is illustrated in light blue in the models.

The highlands for each model are defined as the area around the stream that was never inundated with water and are shown as brown in the models.

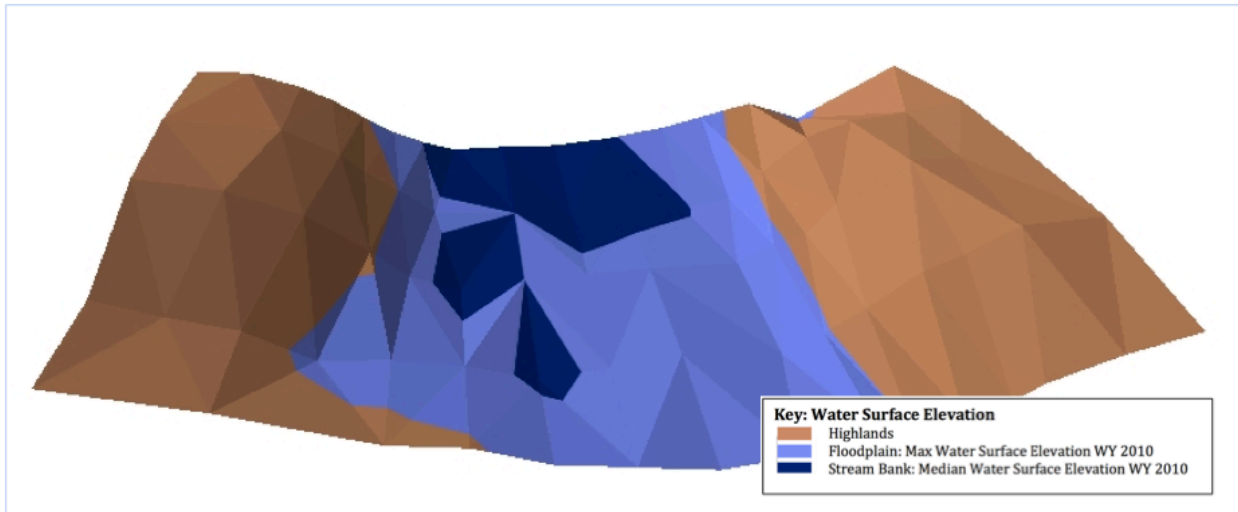


Figure 7. Topographic model of Bundick's Creek showing the water-surface elevations of different water level conditions.

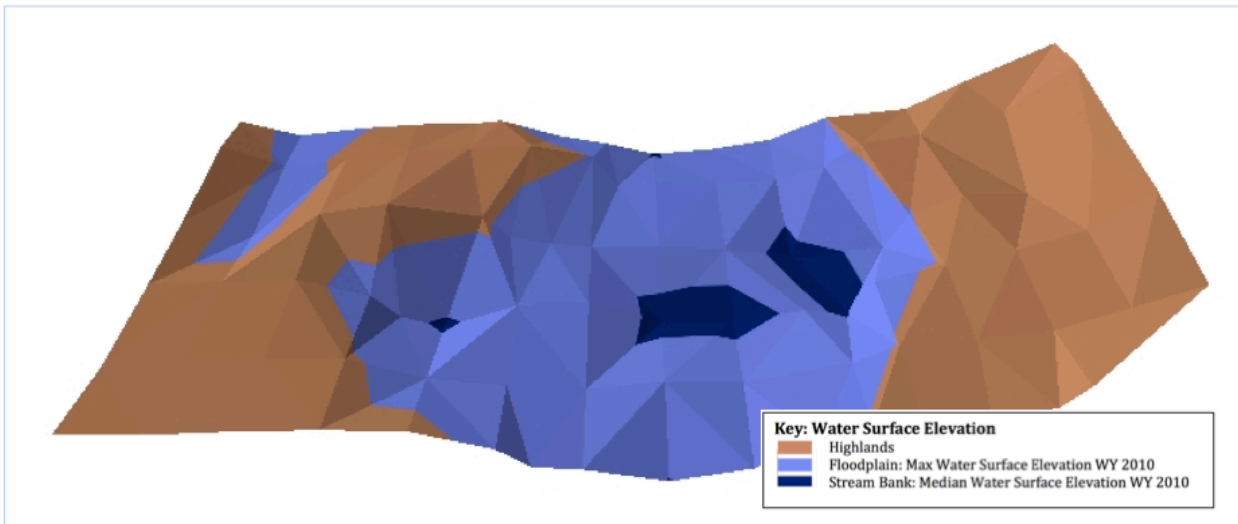


Figure 8. Topographic model of Phillip's Creek showing the water-surface elevations of different water level conditions.

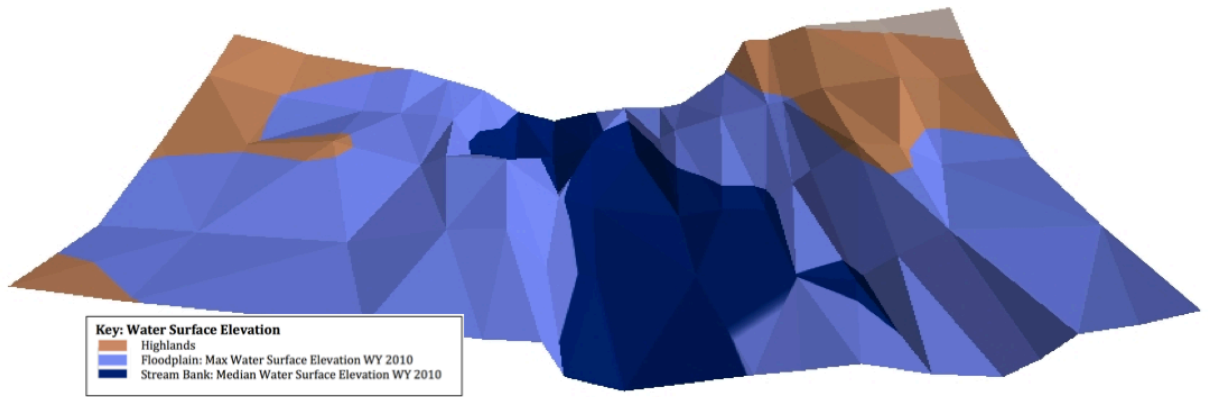


Figure 9. Topographic model of Cobb Mill Creek showing the water-surface elevation of different water level conditions.

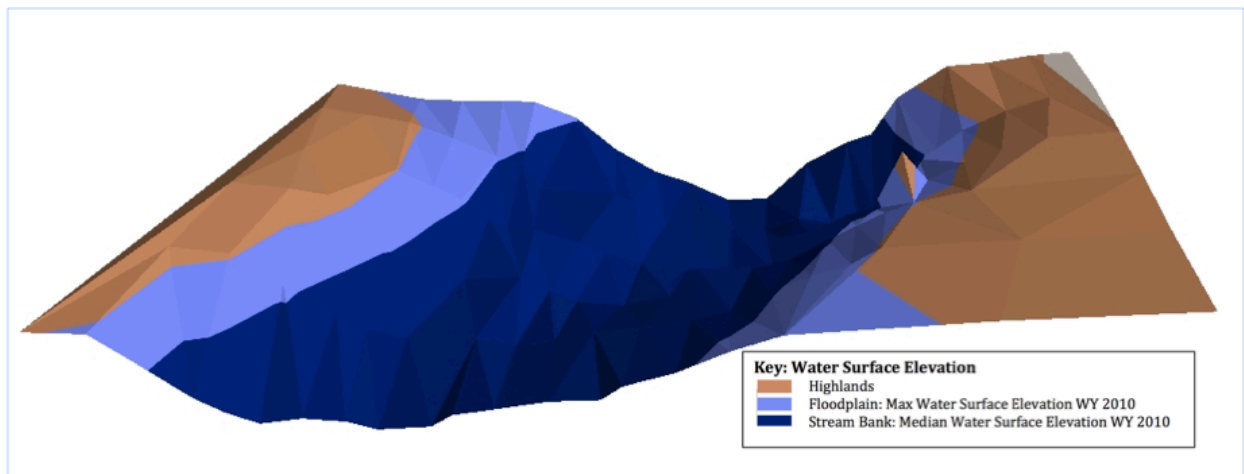


Figure 10. Topographic model of Tommy's Ditch showing the water-surface elevation of different water level conditions.

When the water-surface elevations were projected onto the topographic models, each stream was found to have very different areal extents of inundation. At Tommy’s Ditch (Figure 10), the floodplain appears to better follow the path of the stream, expanding comparatively little between median and maximum water-surface elevations. At Bundick’s Creek (Figure 7), Phillip’s Creek (Figure 8), and Cobb Mill Creek (Figure 9), the floodplain appears to extend out much farther away from the stream bank, inundating a larger portion of land. When the increases in inundation areas are quantified, the range of values is very large (Table 3). Bundick’s Creek has the most extreme increase in inundation area between median and maximum stream stage, increasing in surface area by 1247% (Table 3). The length of the reach of each model is not uniform, so a comparison of the absolute increase in inundation does not explain the increase comparatively.

Table 3. Extent of model inundation of the stream bank under median water-surface elevation and of the floodplain under maximum water-surface elevation.

Stream	Model Inundation of the Stream Bank (m <sup>2</sup> )	Model Inundation of the Floodplain (m <sup>2</sup> )	Percent Change
Bundick's Creek	1.9	25.6	1247%
Phillip's Creek	10.7	40.1	275%
Cobb Mill Creek	24.2	94.1	289%
Tommy's Ditch	34	49.5	46%

The models of the two southern streams, Cobb Mill Creek (Figure 5) and Tommy’s Ditch (Figure 6), both show continuous above-ground water flow throughout Water Year 2010. The models of the two northern streams, Bundick’s Creek (Figure 3) and Phillip’s Creek (Figure 4), both show discontinuous above-ground flow, implying significant reaches of dry channel during portions of the year. The continuous stage record implies there is groundwater movement through the subsurface under the dry parts of the stream bank. Looking at the barometrically

corrected transducer records for each stream for Water Year 2010, Cobb Mill Creek and Tommy's Ditch held a water-surface elevation above the lowest point of the streambed for the entire year, Bundick's Creek only had water in its streambed for 21.3% of the year, and Phillip's Creek only had water in its streambed for 33.0% of the year. The small, disconnected patches of inundated stream bank in Bundick's Creek (Figure 3) and Phillip's Creek (Figure 4) coupled with the large extent of inundated flood plain under high-stage conditions demonstrate that both of these streams are very susceptible to flashy stormflow.

### 3.3 Infiltration Rate Analysis

Using analysis of variance (ANOVA) statistical analysis, the only independent variables found to be significant to a 95% confidence level were the stream variable and landscape variable. The null hypothesis for the stream variable stated that there would be no significant difference between the mean of the hydraulic conductivities measured at each stream. The P-value for the stream variable was less than 0.05 so the null hypothesis was rejected, indicating that the variable has a significant effect on hydraulic conductivity (Table 4). The null hypothesis for the landscape variable stated that there would be no significant difference between the mean hydraulic conductivity of measurements made in the stream bank and in the floodplain. The P-value for the bank effect was less than 0.05 so the null hypothesis was rejected, indicating that the variable has a significant effect on hydraulic conductivity (Table 4). The other independent variables did not prove to have any significant effect on calculated hydraulic conductivity. The vegetation variable, looking at the difference between vegetated and nonvegetated soils, was the only fixed independent variable where the null hypothesis, that there was no significant effect,

was accepted. All of the interactions between the different variables proved to have no significant effect on the calculated hydraulic conductivity.

Table 4. The number of degrees of freedom within each effect (Num DF), the number of degrees of freedom for the total measurements (Den DF), the F-Value, and the P-Value for each independent variable.

<b>Tests of Fixed Variables</b>				
Variable	Num DF	Den DF	F-Value	P-Value
Stream	3	73	4.00	0.0108
Vegetation	1	73	0.29	0.5907
Landscape	1	73	5.99	0.0168
Stream*Vegetation	3	73	0.77	0.5150
Stream*Landscape	3	73	0.85	0.4704
Vegetation*Landscape	1	73	0.60	0.4397
Stream*Vegetation*Landscape	3	73	0.76	0.5229

The mean hydraulic conductivities measured within the different classes of variables give insight into which streams have stream banks and floodplains with the highest average hydraulic conductivity (Table 5). Cobb Mill Creek has the soil with the highest hydraulic conductivity, being almost double the rest of the streams. In order of decreasing values after Cobb Mill are Bundick’s Creek then Phillip’s Creek and Tommy’s Creek. Overall, the hydraulic conductivity of the soil in the floodplain is on average 60% greater than the average hydraulic conductivity in the bank (Table 5).

Table 5. The mean hydraulic conductivity broken down by different variables. The variables are given both as log10 transformed data on which the analysis was performed and as the back-transformed data in the original units of m/s<sup>2</sup>.

<b>Means of Significant Variables</b>				
Variable	Stream	Landscape	Log10 K	K (m/s <sup>2</sup> )
Stream	Bundick's Creek		-5.72	1.89E-06
Stream	Cobb Mill Creek		-5.40	3.95E-06
Stream	Phillip's Creek		-5.76	1.73E-06
Stream	Tommy's Creek		-5.82	1.50E-06
Landscape		Bank	-5.78	1.62E-06
Landscape		Floodplain	-5.56	2.72E-06

## Chapter 4: Discussion

### 4.1 Floodplain Inundation

Selection of Water Year 2010 for analysis was based upon its having the most complete stage records of recent years. At various times, transducer failure or vandalism led to significant gaps in the time series of stage data. Looking at past precipitation records (Appendix A, Figures A1-A5), however, it is clear that Water Year 2010 had larger precipitation events than the rest of 2008-2012. These large precipitation events implies that the flashy streams under investigation may have been even more susceptible to inundation of the floodplain soils than in other drier years. Considering the stage hydrographs (Figures 3-6) and topographic models (Figures 7-10), it is apparent that high-flow events cause inundation of the floodplain of each of the study streams. The streams varied in the extent of inundation, though. Notably, Bundick's Creek increased in surface area by 1247% and Phillip's Creek and Cobb Mill Creek increased in surface area by just under 300% (Table 3).

The different extents of inundation are a result of the detailed and contrasting topography among the streams. The steep banks immediately adjacent to the stream channel at Tommy's Ditch (Figure 10) account for it having the smallest percent increase in inundated area under high flow (Table 3). Comparatively, the reaches of Bundick's Creek (Figure 7), Phillip's Creek (Figure 8), and Cobb Mill Creek (Figure 9) studied here all of have much gentler sloping land immediately adjacent to the stream channel and are therefore much more susceptible to inundation.

The difference in median stage and maximum stage can be used to assess the magnitude of the effect of a storm event in increasing the stage for each stream. By looking at the difference

between median stage and maximum stage, the base flow is excluded and the storm-event flow is focused on. Base flow may contribute a significant portion of discharge to a stream (Bedient and Huber, 2002). In the four study streams, base flow is very different, so removing it from the analysis allows for a better comparison of the effect of storm event flow alone. Unlike the widely varying inundation area increase, all of the streams have a stage increase on the same order of magnitude (Table 2). This similarity in stage increase during storm events shows that the precipitation affects each stream in a similar way, implying that topography plays the largest role in determining inundation area. This conclusion about topography's effect coupled with the high annual precipitation of the 2010 Water Year studied here has interesting implications. With a decrease in annual precipitation, the extent of floodplain inundation would decrease much more at Tommy's Ditch despite its higher water stage. The effect of a decrease in precipitation would have much less of an effect on the shallower streams despite their significantly smaller median stream stage. The extent of inundation of the floodplain of these low-order streams draining the Atlantic Coastal Plain is mostly determined by the slope of the floodplain, with median stage and the amount of time streams have water in the channel not playing a large role. Other studies have shown similar results, with topography being an important aspect of flood modeling (Merwade et al., 2008).

The slope of the floodplain also affects the discharge of a stream. Past studies attempting to quantify the discharge of these streams ran into difficulty when the rating curves failed (Pickus et al., 2014). These rating curves were built by applying a power trendline to hand stage and discharge measurements. A lack of data on discharge and stage under high-flow conditions results in the rating curves failing to accurately predict discharge from stage (Pickus et al., 2014; Merwade et al., 2008). This failure is a result of the presumed geometry used to calculate

discharge not accurately representing the actual geometry when water left the bank and spread across the floodplain. The models and floodplain inundation findings show that the slope of the floodplain at each stream is different from the stream bank and streambed, and more detailed geometric measurements may be required to better calculate discharge. A certain known stage elevation where the rating curve fails may also help in the calculation of more accurate discharge records.

#### 4.2 Potential Denitrification

The calculated hydraulic conductivities under the different soil conditions and the new characterization of inundation areas during storms give insight into where potential for infiltration is highest, and, thus, where the potential for subsurface riparian denitrification may also be highest. Topography affects the hydrology of riparian zones and, in turn, can alter their denitrification efficiency (Vidon and Hill, 2004a). Changes in water level affect denitrification by altering the duration of aerobic and anaerobic conditions (Pinay et al., 2007). The hydraulic conductivity of the subsurface also has an effect, with regions of low hydraulic conductivity disallowing some infiltration and diverting water out of the riparian zone and decreasing the effectiveness of nitrate removal (Vidon and Hill, 2004a). The floodplain was determined to have a 60% higher hydraulic conductivity than the stream bank, meaning upon inundation the floodplain becomes an important site for potential denitrification. Studies have also found that floodplains characterized by short flooding followed by periods of drying out can become hot spots for nitrogen transformation (Shrestha et al., 2014). This high potential for denitrification is particularly important for streams that periodically flood and go dry, such as Bundick's Creek

and Phillip's Creek in this study, because they have a larger increase in inundated floodplain in storm events than the other streams. With the larger increase in inundated areas, these two streams may have a higher potential for infiltration and, thus, denitrification during high-flow events than streams that have continuous water in the channel and spread out less extensively.

The presence of vegetation was found to have no significant effect on hydraulic conductivity of soils in this study. This lack of significance is interesting because the presence of root systems and other soil disturbances caused by vegetation seemed likely to play a role in increasing the hydraulic conductivity of soils (Niemeyer et al., 2014). There are important implications on potential denitrification in terms of infiltration due to the insignificance found in this variable. The results of this study suggest that planting crops or other vegetation on floodplains would not have an effect on their hydraulic conductivity and therefore would not change the amount of water entering the subsurface where there is potential for denitrification. The interaction of plant roots and subsurface flow has been found to be important for denitrification, though (Hill, 1996), and is still a factor for potential denitrification, just not hydraulic conductivity. There was also no significance of any of the interactions of the measured variables, implying that the vegetation and landscape have no importance on each other when determining hydraulic conductivity.

#### 4.3 Recommendations for Future Work

To expand this work, many more streams should be surveyed. More streams draining the 54 watersheds of the Virginia Eastern Shore could be surveyed to better understand the morphologies of similar streams. Increasing the study area would substantiate my results and

either reinforce their validity or show contrasting conditions in the same area. The four streams in my study all had soils with different hydraulic conductivities, varying median and maximum stream stages, and varying floodplain slopes. Observing more streams on the Virginia Eastern Shore could allow more insight into the effect of slope and hydraulic conductivity on riparian denitrification. More infiltration measurement should also be made, allowing for a better estimation of the overall hydraulic conductivities. For instance, the insignificance of the presence of vegetation on hydraulic conductivity surprised me. It would be interesting to see if the effect of vegetation became significant with more infiltration measurements or at different streams draining the Eastern Shore.

Other logical next steps building on this research include looking more closely at other variables that affect subsurface riparian denitrification on low-order streams draining the Atlantic Coastal Plain. Making the slope of the floodplain a more direct focus of the study could result in a better understanding of storm-event denitrification. This closer focus could include comparing the infiltration rates between more streams with similar morphologies to Tommy's Ditch and other streams like Phillip's Creek with more gently sloping floodplains. Past research has suggested that confining layers at shallow depths increase the potential for denitrification in the riparian subsurface (Hill, 1996). Hydraulic conductivity could also be measured at different depths of the streambed and floodplain to assess the existence and potential contribution to denitrification that these confining layers may have on these Atlantic coastal streams.

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# Appendix A: Annual Precipitation Records, 2008-2012

## WY 2008 Daily Precipitation

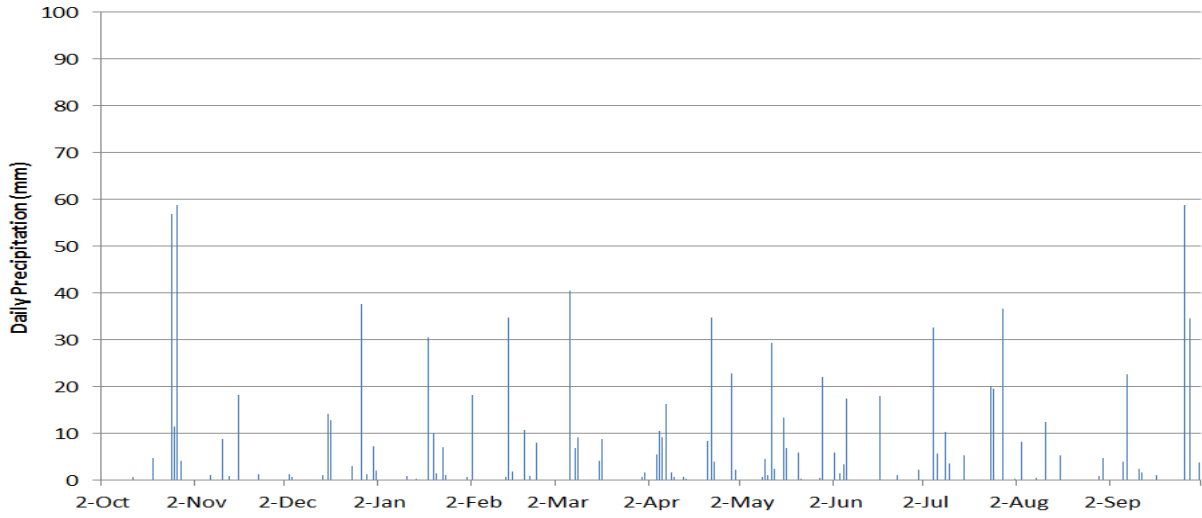


Figure A1. Daily precipitation for Water Year 2008.

## WY 2009 Daily Precipitation

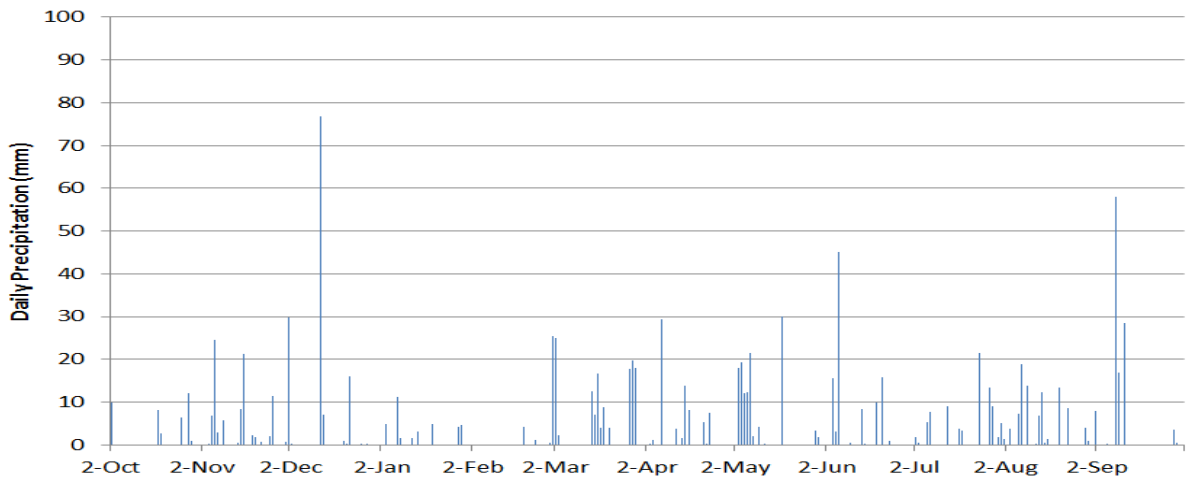


Figure A2. Daily precipitation for Water Year 2009.

### WY 2010 Daily Precipitation

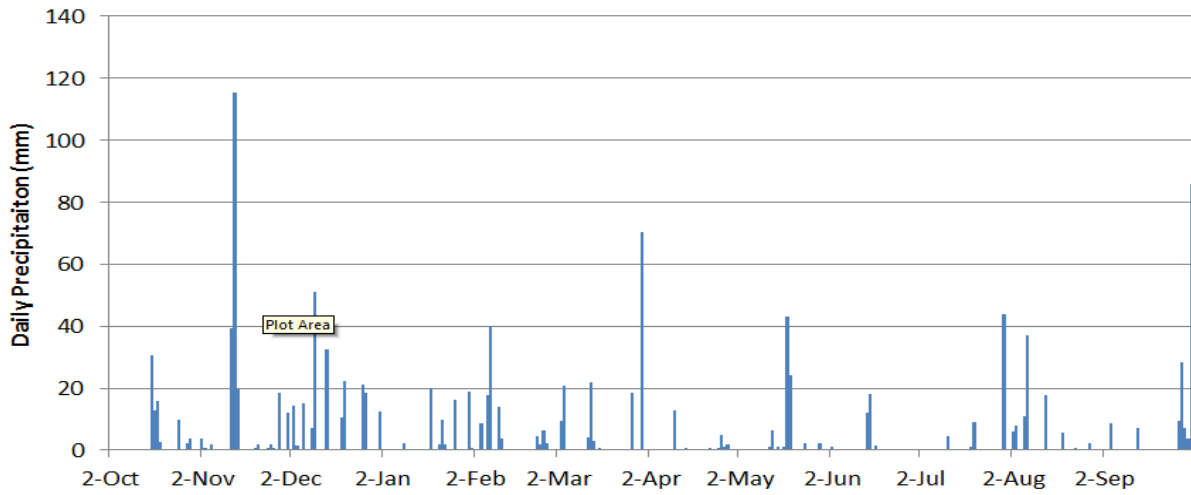


Figure A3. Daily precipitation for Water Year 2010.

### WY 2011 Daily Precipitation

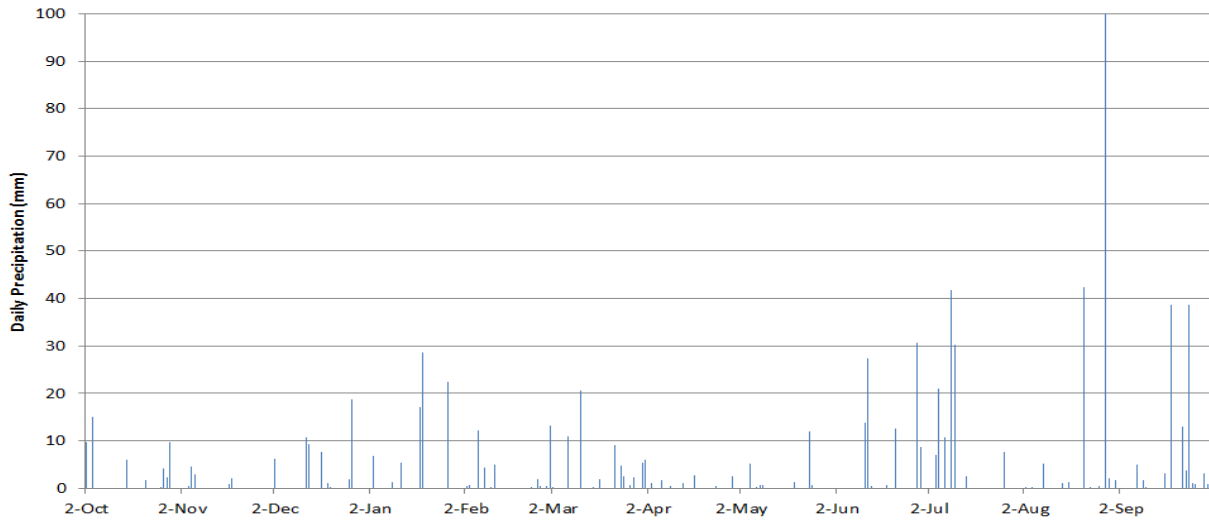


Figure A4. Daily precipitation for Water Year 2011.

### WY 2012 Daily Precipitation

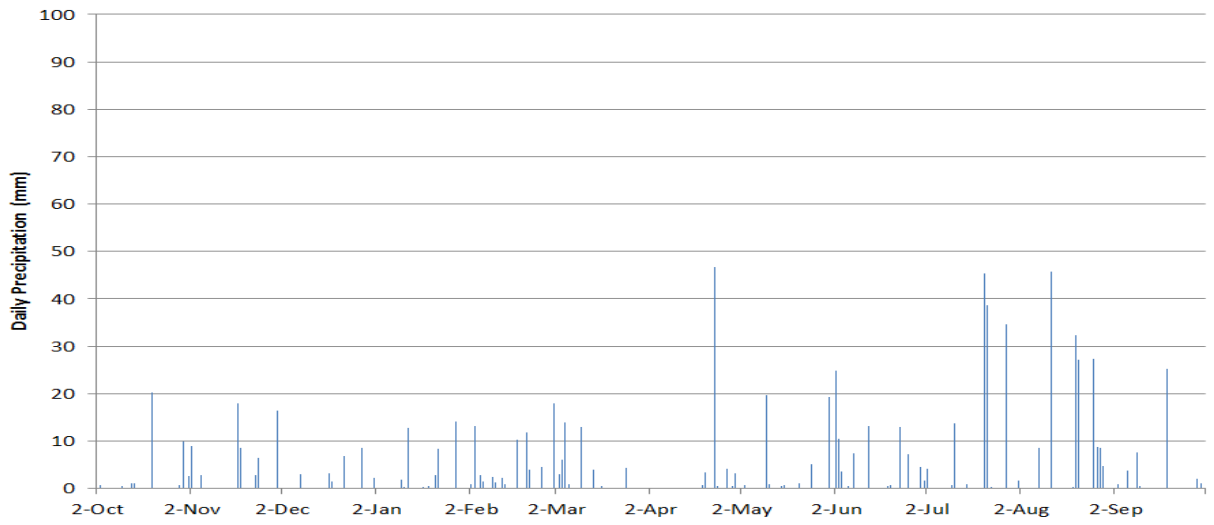


Figure A5. Daily precipitation for Water Year 2012.