EVALUATING THE CONTRIBUTION OF GROUNDWATER TO WETLAND WATER BUDGETS, CENTRAL PIEDMONT, VIRGINIA

by

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ABSTRACT

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In the Piedmont region of Virginia, development pressures are increasing the demand for mitigation wetlands but appropriate construction sites are relatively scarce due to local topography and geology. Many existing water budget models used for planned mitigation sites exhibit considerable error when estimating groundwater fluxes, particularly for historical years that lack hydraulic head data. This difficulty has led many planners to neglect or underestimate the contribution of groundwater to wetland water budgets, resulting in mitigation sites that fail to create the appropriate hydrology for the desired vegetation community. However, reliable estimations of groundwater input contributing to wetland water budgets can be generated by coupling models that reconstruct historic hydrographs (e.g. Effective Monthly Recharge (W_{em}) model) with mass balance water budget models that account for soil storage (e.g. WetBud, development in progress). Using these models to simulate years that represent a range of hydrologic conditions (e.g. wet, normal, and dry years) can provide planners with critical information regarding the contribution of specific water budget inputs such as groundwater input.

Two case studies of natural toe-slope wetlands located in the central Piedmont of Virginia demonstrate the W_{em} is effective in predicting monthly head elevations for wells in Piedmont hillslope and toe-slope landscape positions (NSE > 0.84). Predicted head levels for wet, normal, and dry years were used in the calculation of groundwater input using Darcy's Law. Monthly water budgets generated using the WetBud Basic Scenario tool for two wet, two normal, and two dry years at each wetland reveal that groundwater input accounts for approximately 20% of total water budget inputs on any given year, regardless of total precipitation. However, seasonal variations in the relative contribution of groundwater to water budget inputs suggest that local floodplain morphology is the major factor influencing hydrology at each site. Overall, this study demonstrates that when coupled with the Effective Monthly Recharge (W_{em}) model, the WetBud Basic Scenario tool provides a practical platform that can be used to reliably predict the contribution of groundwater to wetland water budgets for years that lack observed water level data.

ACKNOWLEDGEMENTS

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INTRODUCTION

Overview of the Study Area

A proper understanding of site hydrology is the main design factor that will determine the success of a constructed wetland (Davis, 2009). In the Piedmont region of Virginia, development pressures are increasing the demand for mitigation wetlands but appropriate construction sites are relatively scarce due to local topography and geology. Many existing water budget models used for planned mitigation sites exhibit considerable error when estimating groundwater fluxes, particularly for historical years that lack hydraulic head data. This difficulty has led many planners to neglect or underestimate the contribution of groundwater to wetland water budgets, resulting in mitigation sites that fail to create the appropriate hydrology for the desired vegetation community. In addition, the recent geomorphic history of Piedmont valley bottoms may cause marked variations in the abundance of groundwater in those settings (Richardson, 1982). Therefore, this study attempted to assess the groundwater availability in a toe-slope/valley bottom setting overlying a common bedrock type by constructing monitoring well transects and assessing the stratigraphy and permeability. The data will be used to calibrate and verify the Wetland Water Budget model (WetBud) (under construction) and calculate water budgets for two wetlands on Piedmont floodplains for years that represent a range of hydrologic conditions.

Background and Previous Studies

The complex geologic history and morphology of the extensive Piedmont Physiographic Province has resulted in valley bottom settings with hydrology that supports many wetland ecosystems. The abundance of broad valley bottoms and their associated hydrology makes them desirable locations to construct mitigation wetlands. A lack of understanding of the many factors govern the hydrology of these valley bottom wetland systems has resulted in many failed attempts to construct viable mitigation wetlands in the Piedmont. However, the success of these wetlands may be improved with the development of more sophisticated yet practical water budget modeling tools that reliably predict the response of these wetlands to a range of hydrologic conditions.

Geologic History of the Piedmont Physiographic Province

The Piedmont Physiographic Province is the largest physiographic province in Virginia, extending from north to south across the entire state, bounded on the east by the Fall Zone, which separates it from the Coastal Plain Province to the east, and on the west by the Blue Ridge Province (Figure 1). The Piedmont is characterized by gently rolling hills with moderate relief (Markewich et al., 1990). The surface of the uplands is mantled by thick saprolite developed over bedrock terranes consisting of igneous and metamorphic rocks of Proterozoic to Paleozoic age. These terranes are punctuated by a series of sedimentary basins that formed lowlands as a result of continental rifting that was initiated approximately 200 mya during the breakup of the supercontinent Pangaea (Whittecar et al., 2013). Following the breakup of Pangaea, this landscape endured repeated and progressive episodes of deep crustal erosion due to isostatic uplift (Poag and Sevon, 1989; Pazzaglia, 2000) leading to the extensive stream networks that now flow into several large river systems (Sherwood et al., 2010).

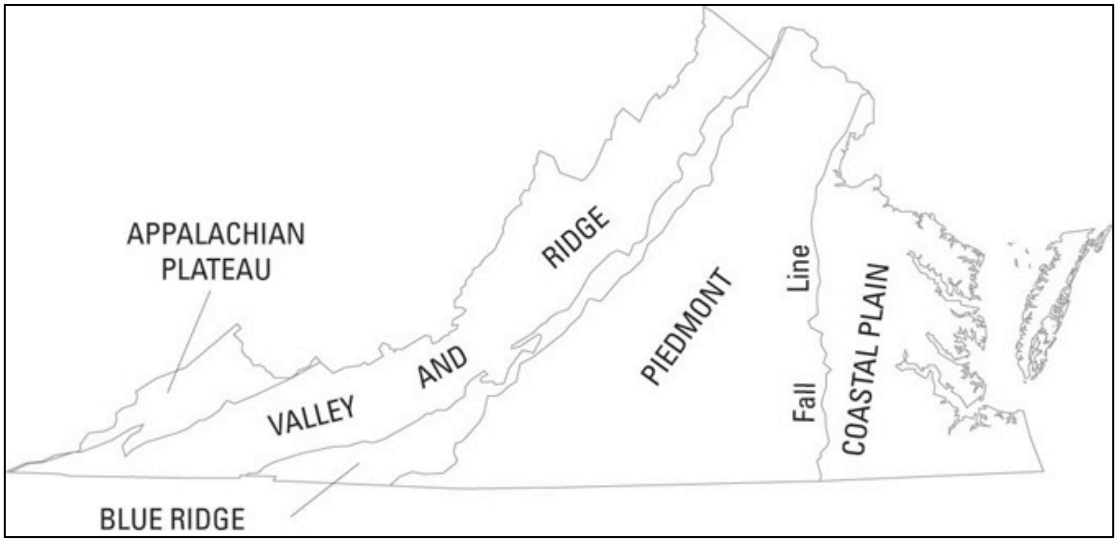


Figure 1. Physiographic Provinces of Virginia. (from William & Mary Department of Geology. http://web.wm.edu/geology/virginia/)

Piedmont Wetland Hydrology and Morphology

In the Piedmont, groundwater in the hillside seeps towards the valley bottom through a wedge-shaped mantle of weathered regolith which focuses groundwater into toe-slopes at valley edges (Figure 2). Water usually seeps downhill slowly through saprolite and colluvium, but can pass quickly through megapores formed in those materials (Ruan and Illangasekare, 1998). Toe-slopes may be steep if eroded by a migrating stream channel but elsewhere gently-sloped sediment aprons abound. These relatively permeable wedges contain slope debris and small alluvial fans washed from the hillside (Whittecar et al., 2013). At most toe-slope settings, water flow is upwards during much of the year, and shallow water tables fluctuate little. Thus the present understanding of hillside and valley bottom hydrology in the Piedmont leads one to expect that much of the water that infiltrates into saprolite and colluvium beneath the valley sides should seep out at toe-slope springs before soaking back into the floodplain or terrace, or pass through a toe-slope apron as it moves downhill towards the stream channel.

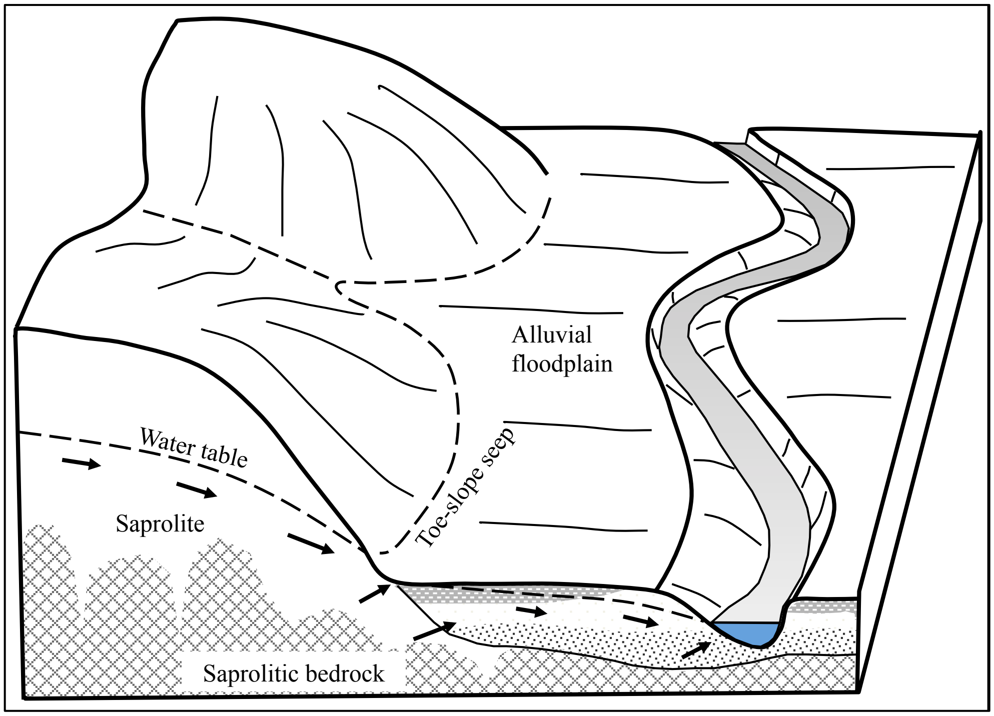


Figure 2. Schematic of Piedmont valley bottom hydrology. Arrows represent general direction of groundwater movement.

The main factors that affect the occurrence and distribution of groundwater across Piedmont floodplain wetlands are thickness and lithology of sediments combined with degree of stream incision. Prior to European settlement (pre-1730) these floodplains were characterized as having a relatively thin layer of fine-grained overbank sediments above a thin bed of basal sand and gravel deposited by a migrating stream surrounded by extensive vegetated wetlands. Recent studies (e.g. Jacobson and Coleman, 1986; Walter and Merritts, 2008; Schenk and Hupp, 2009) have determined that widespread post-settlement land-use changes have drastically influenced Piedmont floodplain morphology and hence, wetland hydrology. During the period between 1730 to approximately 1930 widespread deforestation and agricultural practices caused increased runoff and sediment yields to streams, which was coupled with extensive damming of streams for water power needed to supply local mills (Walter and Merritts, 2008). This combination of activities resulted in the deposition of thick sequences of fine-grained sediment on floodplains and in millpond reservoirs upstream of dams. Over the last century many of these dams have been abandoned and breached by their streams, causing streams to become deeply incised into the millpond sediments. The deep incision of these streams and their position relative to their new floodplain surface has several implications for wetland hydrology. In many cases the depth of stream incision has resulted in abandoned valley flat terraces with wetlands that no longer receive overbank flow inputs (Walter and Merritts, 2008). In addition, large macropore networks may develop in the silt-rich deposits and result in water losses due to seepage that are difficult to quantify (Bevin and Germann, 1982).

Although the occurrence of wetlands in these valley bottoms is commonly restricted to valley edges where groundwater rises to the surface along toe-slope seeps, their distribution in these settings cannot necessarily be attributed to the interpretation of their morphology. In certain instances, these wetlands extend far out into the valley flat where toe-slope seepage is not evident, suggesting that lithology and microtopography are major factors governing wetland hydrology in these settings. However, given their position in the landscape, little to no input from overbank flow, and the possibility of excessive seepage losses from macropores, groundwater inputs may be a major source of hydrology for valley bottom wetlands (Winston, 1996). Therefore, a proper understanding of groundwater hydrology is essential when attempting to interpret or recreate (e.g. for mitigation) any aspect of these wetland systems.

Mitigation Wetlands

Inaccurate assessments of water sources prior to wetland construction may produce low success rates, success being judged by meeting target goals of wetness-controlled vegetation communities. In the Commonwealth of Virginia low success rates are commonly attributed to being "too wet" or "too dry" to support the intended biological community and are largely a result of poor water budget planning (Whittecar and Daniels, 1999). Failure due to being "too wet" is frequently observed in wetlands designed to rely heavily on groundwater, where design redundancies have intentionally introduced more groundwater than necessary (Pierce, 1993 and Garbisch, 1994). Because groundwater inputs are difficult to estimate without extensive field data, a common practice is to design wetlands that eliminate or neglect any groundwater exchange in the system. This goal can be achieved by constructing wetlands that rely on a perched water table, created through subsoil compaction and an impermeable clay lining. By treating the wetland as a level pool in which surface water outflow is regulated by an outlet structure the water budget components can be easily quantified. However, wetlands designed in this manner become vulnerable during extended periods of drought and may fail because they are "too dry" (Brown and Veneman, 2001).

Wetland Water Budget Modeling and Model Assessment

The success or failure of a mitigation wetland in any setting will largely depend on the effectiveness of the chosen water budget method to predict water levels for the wetland for a variety of climatic conditions. When attempting to determine wetland water budgets it is important to understand the limitations of the variables estimated and applications of the chosen water budget method. In general, the basic equation for a wetland water budget has an accepted formulation (Pierce, 1993):

$$\mathrm{P} + \mathrm{SWI} + \mathrm{GWI} = \mathrm{ET} + \mathrm{SWO} + \mathrm{GWO} + \Delta\mathrm{S}, \qquad (1)$$

Where: P = precipitation
SWI = surface water inflow

GWI = groundwater inflow
ET = evapotranspiration
SWO = surface water outflow
GWO = groundwater outflow
ΔS = change in storage

Precipitation is the major input in most wetland water budgets and although it is easily measured, local precipitation may vary widely over small distances, particularly during convective storms systems generated during summer months. Thus, close proximity of a measurement to the site is critical.

Surface water inflow and outflow occur as both overland and channelized flow. Volumes of channelized flow entering or leaving the site can be easily constrained with knowledge of channel geometry and average flow velocity (Pierce, 1993). Non-channelized sheet flow directly contributing to the site during rain events can be estimated using a variety of methods. However, non-channelized sheet flow has been shown to be a source of considerable error when balancing water budget equations (Arnold et al., 2001). A common method used to estimate surface runoff is the Soil Conservation Service (SCS) runoff curve number method, which depends on soil type, antecedent soil moisture, and land cover conditions combined with drainage basin size (Kent, 1973).

In some cases groundwater input may accounts for a large portion of water budget inputs (e.g. Gilvear et al., 1993; Arnold et al., 2001) and act as a major driver of wetland hydrology. Estimations of groundwater input and output require knowledge of subsurface geometry, lithology, and hydraulic head data. Due to the relatively large requirement of data needed to estimate these components they are often overlooked or erroneously approximated, resulting in a poorly constrained water budget and failure to establish appropriate site hydrology (Winston, 1996).

Evapotranspiration is the combined loss of water to the atmosphere from direct evaporation and transpiration by plants. It is the second largest term in the water budget equation and thus accurate estimations of this parameter are critical to all water budget studies (Sanford and Selnick, 2012). The evaporation component can be accurately predicted with meteorological data but the transpiration component can be difficult to estimate because of variable rates of transpiration within the plant community (Pierce, 1993). Methods do exist to directly quantify rates of actual evapotranspiration (e.g. White, 1932) but it is more practical to estimate potential evapotranspiration (PET), a theoretical calculation based on meteorological data. A major assumption of these calculations is that a water source is always available. Two equations commonly used to estimate PET are the FAO-56 Penman-Monteith equation (Jensen et al., 1990) and the Thornthwaite (1948) equation. The Penman-Monteith method estimates daily PET for a grass reference crop. Although this equation was developed for a grass reference crop it is frequently applied to a variety of settings and proven to be a suitable estimate of PET for many types of vegetation due to the high resolution of the input parameters involved (e.g. solar radiation, wind speed, relative humidity) (Chaubey and Ward, 2006). The Thornthwaite method uses mean monthly air temperature to estimate PET on a monthly basis. Because mean monthly air temperature records exist for most locations this method is desirable for areas that lack the high resolution solar and weather data required for the Penman equation. The Thornthwaite equation is recommended by Pierce (1993) for calculating PET for wetland water budgets; however, many studies have found that model predictions for water levels in wetlands match observed water level trends more closely when using the Penman equation (e.g. Gloe, 2011; Harder et al., 2007; Jensen et al., 1990).

Complete wetland water budget studies usually take one of two approaches to quantify the fluxes in and out of the wetland: simple mass-balance of the water budget equation using a box model, or advanced three-dimensional numerical models (e.g. MODFLOW). The latter approach is usually designed to model flow dynamics within the wetland system with a number of internal (e.g. drainage ditches, soil compaction) or external complexities (e.g. land use changes in the surrounding watershed, storm events) that can change and affect the occurrence or distribution of water within the system. This type of model requires detailed knowledge of all physical parameters (e.g. stratigraphy, hydraulic conductivity, porosity, etc.) contributing to site hydrology. Many studies in the past have successfully reproduced observed water table dynamics using this approach (e.g. Winston, 1996; Gerla, 1999; Bradley, 2002) and predicted water budgets for historical years. Although this type of model can be effective at producing wetland water budgets, the extensive parameterization of variables needed for calibration of modeling software is often complicated and make this method somewhat impractical for simple planning purposes.

Simple mass-balance water budgets determine volumetric fluxes in and out of the wetland by treating the wetland as a box with a known volume and are calculated with minimal data regarding subsurface characteristics (e.g. stratigraphy, lithology). This approach is ideal for planning purposes because it reduces the total number of parameters involved. Using this approach, Favero et al. (2007) found groundwater seepage to be the term that most influences water budget error. A similar study performed by Chaubey and Ward (2006) found that large discrepancies in water budget calculations also reside in evapotranspiration values and that the accuracy of estimates for groundwater input is directly related to the frequency at which measurements are taken. Calculations regarding these two parameters are problematic because in most cases they are estimated rather than directly measured. Estimations of groundwater input can be especially difficult during historical years that lack hydraulic head data needed in the calculation. As a result of the difficulty associated with estimating groundwater fluxes many design plans choose to completely ignore this component in the water budget equation by assuming it is either negligible or abundant in supply, thus placing the most emphasis on efforts to manage the remaining factors.

One way to address problems associated with estimating groundwater input for years without hydraulic head data is to utilize existing water level prediction models to predict heads needed to establish the hydraulic gradient in the Darcy's Law calculation of groundwater discharge. The Effective Monthly Recharge (W_{em}) model developed by Whittecar and Lawrence (1999) generates synthetic hydrographs for water levels in wells using historical weather data. Whittecar et al. (in review) improved this model by evaluating different methods used to calculate evapotranspiration and validated this procedure for wetlands in coastal plain settings where sandy lithologies dominate. However, the effectiveness of this model has not been tested for Piedmont settings where fine-grained lithologies make up the majority of regolith.

The W_{em} requires a series of five steps to run and calibrate the model. Step one requires the measurement of head levels at the beginning of each month for the calibration period. Whittecar et al. (in review) recommend that during the calibration process one should exclude readings taken from wells at the beginning of each month that have experienced significant recent rainfall.

Step two includes gathering data for monthly totals for precipitation, potential evapotranspiration (PET), and interception. PET values are calculated using the FAO-56 Penman-Monteith equation (Jensen, 1999) to estimate evapotranspiration. Monthly values for interception are chosen based on results from Dunne and Leopold (1978), where they describe the gross annual percentage of rain intercepted by different plant groups. For watersheds that are entirely forested, the percentage of rainfall lost to interception depends on the forest mix; where the respective percentages of coniferous and deciduous combined make a total of 100%. For example, watersheds composed entirely of coniferous forest will have an interception value of 27% throughout the entire year due to the absence of leaf-off months. Entirely deciduous watersheds will have 13% during leaf-on months and 5% during leaf-off months. Leaf-off months are December, January, February, and March.

Step three is the calculation of the W_{em} time series. First monthly recharge (W_{mo}) is calculated for every month of the calibration period. Monthly recharge (W_{mo}) is calculated using the following equation:

$$W_{mo} = P_{mo} - (P_{mo} \times I_{mo}) - ET_{mo}, \qquad (2)$$

where: W_{mo} = monthly recharge

P_{mo} = total monthly precipitation (cm)

I_{mo} = interception (percentage of rainfall that fails to reach the ground, expressed as a decimal)

ET_{mo} = total monthly evapotranspiration (cm)

Next, using the W_{mo} values, effective monthly recharge (W_{em}) is calculated, which is a time-weighted sum of recharge from a certain number of months prior to each month W_{em} is calculated for. The following equation is used to determine effective monthly recharge:

$$W_{em} = \sum_{a=1}^{n} W_{mo} \times D^{a-1}, \tag{3}$$

where: W_{em} = effective monthly recharge (cm)
n = number of prior months (1 through 18)
D = decay factor (between 0.99 and 0.55 at intervals of 0.05)

Step four is the calibration process. For each time series using a given n and D, linear regression is used to plot values of W_{em} *vs.* observed monthly head to generate a correlation coefficient (R^2). Correlation coefficients of each regression are then recorded in an R^2 matrix to determine which n and D combination generates the best correlation between W_{em} and observed head.

The final step uses the standard equation of the line that produces the best correlation coefficient in step four to estimate head elevations for each month by using the W_{em} value as 'x' in the regression equation.

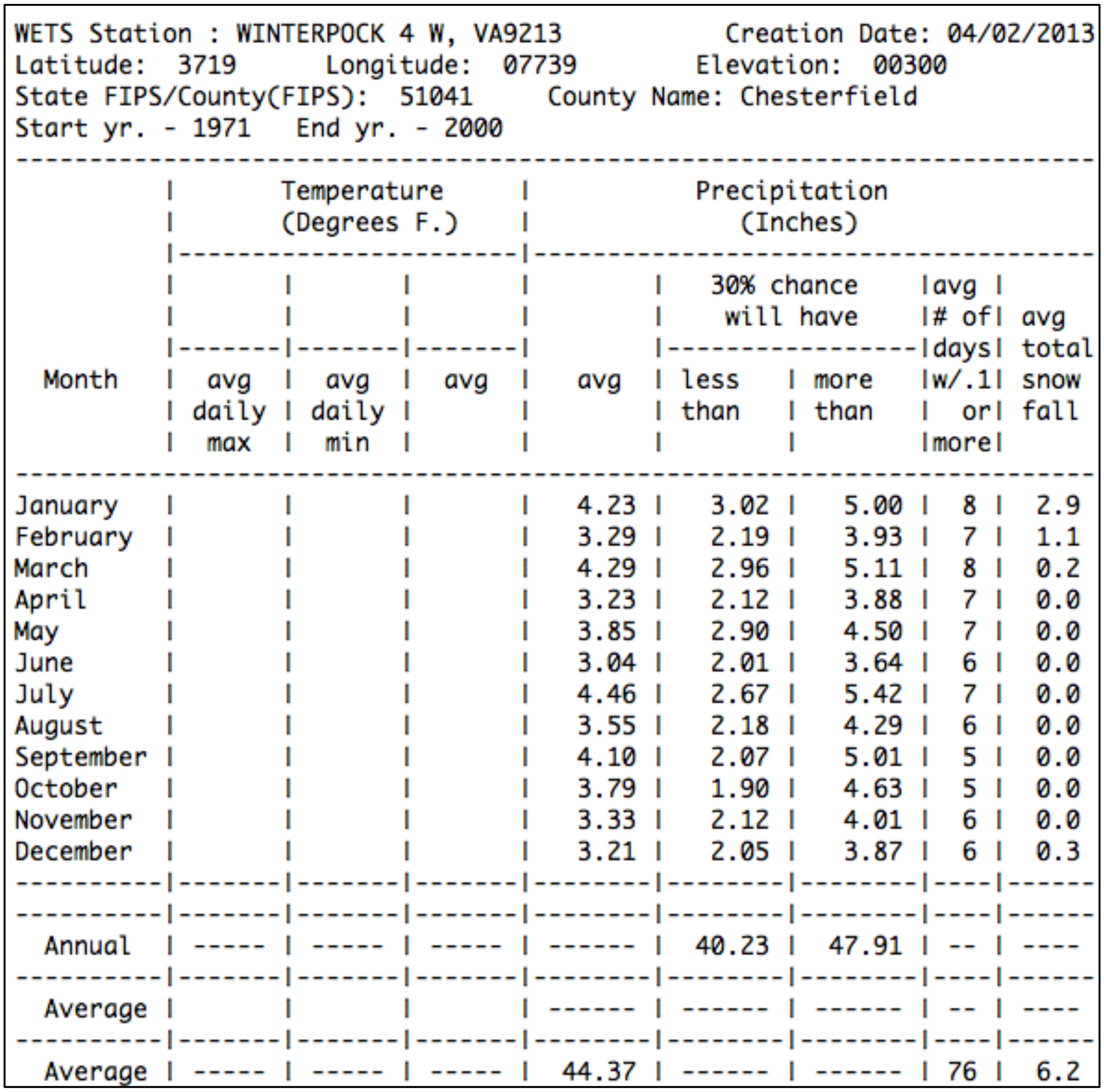
In order to have confidence in predictions for past or future wetland behavior it is necessary to quantify the ability of the model to reproduce observed data. This assessment can be achieved by using a method developed by Nash and Sutcliffe (1970) to calculate model efficiency. The Nash-Sutcliffe efficiency parameter values range from $-\infty$ to 1, where a value of 1 indicates a perfect match of modeled and observed data. A value of 0 indicates that model output is as accurate as the mean of observed data. Efficiency values less than 0 indicate that the mean of the observed values is a better predictor than model output.

If the W_{em} method can be proven effective for lithologies at a given site, it is possible to predict water levels at those sites for past years during periods before the wells were constructed. With these head estimates, one can generate the hydraulic gradients needed to calculate groundwater discharge with Darcy's Law.

Pierce (1993) recommends that when preparing a water budget for a planned wetland one should develop a quantitative estimate for all significant water inputs and outputs on a monthly basis and that calculations should include years that represent a range of hydrologic conditions (e.g. typical wet, normal, and dry years). This approach is prudent because wetlands exhibit marked seasonal fluctuations that strictly govern the resident vegetation community (Cole et al., 1997). In addition, a monthly water budget approach is ideal because water budget studies that use annual aggregation of water budget components mask periods of water surplus or drought that ultimately determine the fate of wetland plants (Winter, 1988).

Choosing years that represent a range of hydrologic conditions can be accomplished by referring to WETS tables developed by the National Resources Conservation Service (NRCS). The objective of a WETS table is to define normal ranges of monthly and yearly precipitation for a given geographic area over a representative time period (e.g. last 30 years) (WETS, 1995). In reference to the WETS table example shown in Figure 3, wet, normal, and dry year splits are as follows: Wet months or years are those that have a precipitation total greater than the "30% chance will have more than" total in column seven. Dry months or years are those that have a precipitation total less than the "30% chance will have less than" total in column six. Normal months or years are those with precipitation totals that fall in the range between wet and dry. For example, a dry year for this location would have an annual precipitation total less than 40.23 inches and a wet year would have an annual precipitation total greater than 47.91 inches.

WETS tables are practical for determining years that represent a range of hydrologic conditions; however, these classifications have no regard for the distribution of precipitation throughout a given year. For the purpose of wetland mitigation planning, hydrologic conditions during the beginning of the growing season are especially critical to early succession in wetland vegetation communities. Therefore, years selected to represent a range of hydrologic conditions should also be representative of those conditions during the growing season. McLeod (2013) outlined a supplemental procedure to determine if wet, normal, and dry years selected based on the WETS table splits also have those respective hydrologic conditions during the spring months (e.g. March –June). As opposed to designating years as wet, normal, and dry based on total annual precipitation, choosing years that meet the corresponding spring criteria more appropriately represent the range of hydrologic conditions for the critical months affecting wetland vegetation communities and thus are most suitable for water budget planning purposes.



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WETS Station : WINTERPOCK 4 W, VA9213         Creation Date: 04/02/2013
Latitude:  3719      Longitude:  07739       Elevation:  00300
State FIPS/County(FIPS):  51041     County Name: Chesterfield
Start yr. - 1971   End yr. - 2000
-----------------------------------------------------------------------
          |       Temperature      |            Precipitation
          |       (Degrees F.)     |              (Inches)
          |-----------------------|--------------------------------------
          |       |       |       |        |   30% chance    |avg |
          |       |       |       |        |   will have     |# of| avg
          |-------|-------|-------|        |-----------------|days| total
  Month   |  avg  |  avg  |  avg  |   avg  | less    | more  |w/.1| snow
          | daily | daily |       |        | than    | than  |  or| fall
          |  max  |  min  |       |        |         |       |more|
-----------------------------------------------------------------------
January   |       |       |       |   4.23 |   3.02 |   5.00 |  8 |  2.9
February  |       |       |       |   3.29 |   2.19 |   3.93 |  7 |  1.1
March     |       |       |       |   4.29 |   2.96 |   5.11 |  8 |  0.2
April     |       |       |       |   3.23 |   2.12 |   3.88 |  7 |  0.0
May       |       |       |       |   3.85 |   2.90 |   4.50 |  7 |  0.0
June      |       |       |       |   3.04 |   2.01 |   3.64 |  6 |  0.0
July      |       |       |       |   4.46 |   2.67 |   5.42 |  7 |  0.0
August    |       |       |       |   3.55 |   2.18 |   4.29 |  6 |  0.0
September |       |       |       |   4.10 |   2.07 |   5.01 |  5 |  0.0
October   |       |       |       |   3.79 |   1.90 |   4.63 |  5 |  0.0
November  |       |       |       |   3.33 |   2.12 |   4.01 |  6 |  0.0
December  |       |       |       |   3.21 |   2.05 |   3.87 |  6 |  0.3
----------|-------|-------|-------|--------|--------|--------|----|------
----------|-------|-------|-------|--------|--------|--------|----|------
  Annual  | ----- | ----- | ----- | ------ |  40.23 |  47.91 | -- | ----
----------|-------|-------|-------|--------|--------|--------|----|------
  Average |       |       |       | ------ | ------ | ------ | -- | ----
----------|-------|-------|-------|--------|--------|--------|----|------
  Average | ----- | ----- | ----- |  44.37 | ------ | ------ | 76 |  6.2
```

Figure 3. WETS table example. Note monthly and yearly splits (columns 4-6) used to determine wet, normal, and dry months and years.

Description of Study Sites

Two study sites located in the central Piedmont of Virginia, Pocahontas State Park (PSP) and Powhatan Wildlife Management Area (PWMA), were selected for this study (Figure 4). These sites were chosen because they overlie common bedrock types (e.g. granite and gneiss) and their valley bottoms share morphologies (e.g. toe-slopes, broad valleys, and deeply incised streams) commonly found throughout the Virginia Piedmont. In addition, these sites represent natural analogs for many present and future wetland mitigation sites.

Pocahontas State Park is located within the Beach Quadrangle in Chesterfield, VA (Figure 5). The study site is a small freshwater, forested wetland on the floodplain of a small, unnamed perennial stream. In the immediate vicinity of the study site the floodplain is approximately 35 m wide. From bank to bank, the stream channel is approximately 1.5 m wide with a bank height of approximately 1.0 m. Physical evidence of overbank flow at this site is rare, suggesting occurrences are rare and restricted to extreme rainfall events in the local watershed of less than 2.5 km^2. Mostly forested with young pine and mature hardwoods, the upland surrounding the site consists of gently to moderately sloping hills with a maximum local relief of approximately 30 m. The Petersburg Granite underlies the regolith in this area (Virginia Division of Mineral Resources, 1993). Mean annual precipitation for this location is 113 cm.

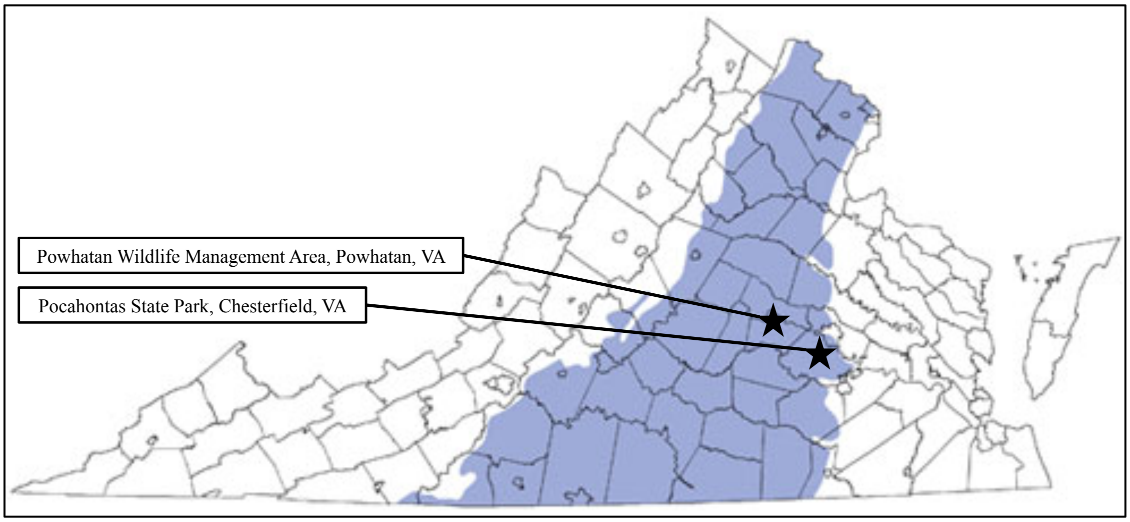


Figure 4. Virginia county map showing study site locations and Piedmont Physiographic Province. (Image modified from vabci.org)

Powhatan Wildlife Management Area (PWMA) is located within the Powhatan and Trenholm Quadrangles in the center of Powhatan County, VA (Figure 6), approximately 40 km west-northwest of Pocahontas State Park. The study site is a freshwater, forested wetland on the floodplain of Sallee Creek, a deeply incised perennial stream that drains the surrounding uplands. Lack of evidence for overbank flow such as debris rack lines following extreme rain events suggest Sallee Creek is hydraulically disconnected from its floodplain and does not experience overbank flow. From bank to bank, Salle Creek is approximately 15 m wide with a bank height of approximately 2.5 m. In the immediate vicinity of the study area the width of the floodplain is approximately 60 m. Land cover in the approximately 25 km^2 local watershed is primarily mature pine and upland hardwoods, with a small portion being fallow fields maintained for habitat enhancement on the wildlife management area. Terrain in this area consists of rolling hills with slopes that vary from relatively steep to gentle, with a maximum local relief of approximately 45 m. Biotite gneiss underlies regolith in the immediate area of the study site (Virginia Division of Mineral Resources, 1993). Mean annual precipitation for this location is approximately 108 cm.

Goal and Objectives

The research hypothesis for this study is that a modified version of the Pierce (1993) approach used to determine wetland water budgets is an effective method to generate water budgets in natural and created wetlands that rely on groundwater as a source of hydrology. The overall goal of this research is to enhance mitigation wetland design and planning efforts by determining the significance of groundwater contributing to natural wetland water budgets in the Virginia Piedmont. To achieve this goal it was necessary to complete the following objectives:

1. Characterize the distribution of surficial materials in Piedmont valley bottoms and their hydrogeologic properties.
2. Determine if predictive models (e.g. Effective Monthly Recharge (W_{em}) model developed by Whittecar and Lawrence (1999) and Whittecar et al. (in review)) developed for Coastal Plain can be effective in Piedmont settings.
3. In each study area evaluate water budgets developed for typical wet, normal, and dry years based on the past 30 years of precipitation data.

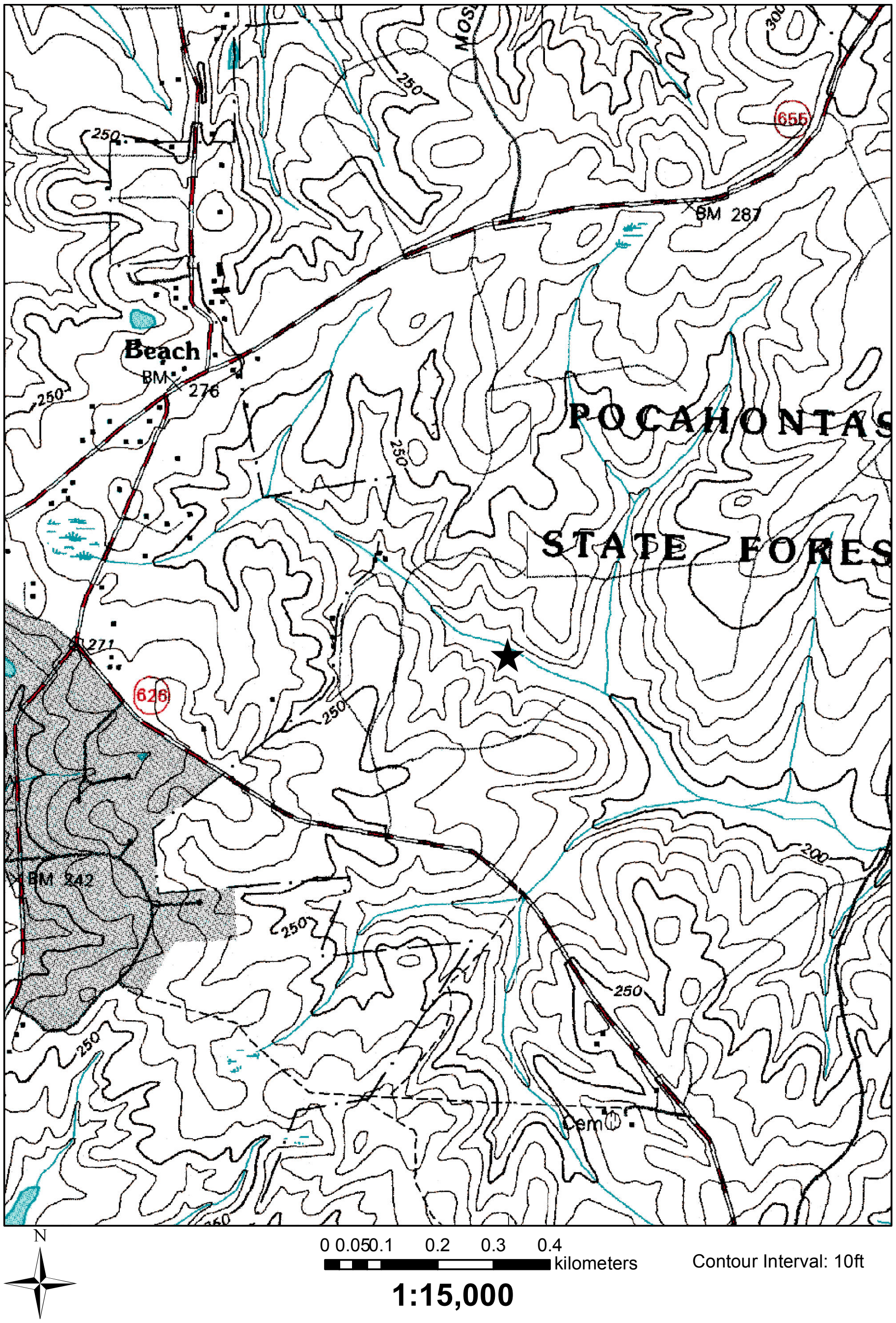


Figure 5. Topographic map of immediate area surrounding Pocahontas State Park study site (black star). PSP study site coordinates (decimal degrees)- Latitude: 37.349, Longitude: -77.584. (Image formatted from USGS 7.5' Beach Quadrangle, 1994)

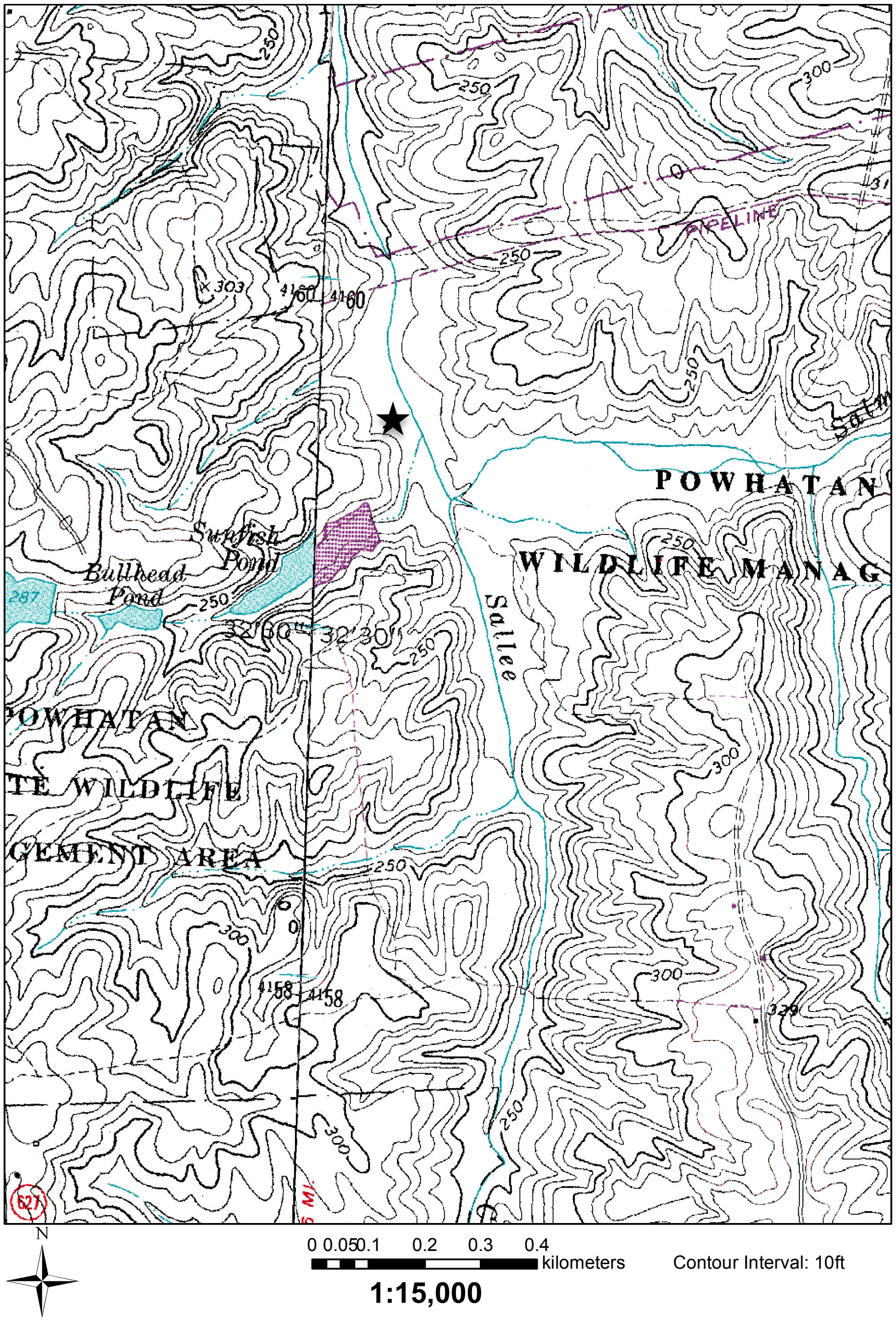


Figure 6. Topographic map of immediate area surrounding Powhatan WMA study site (black star). Powhatan WMA study site coordinates (decimal degrees)- Latitude: 37.546, Longitude: -77.998. (Image formatted from USGS 7.5' Powhatan (1987) and Trenholm (1979) Quadrangles)

CHAPTER 2

METHODS

This research project required four main procedures. The first involved collecting data regarding lithology and stratigraphy. The second involved setting up a network of wells at each site to collect hydrologic data. The third used the wells to gather data regarding the hydraulic properties of the sediments, which would later be used as setup parameters for wetland water budget models. The final procedure used data gathered from all of the former tasks to develop wetland water budget models. Ultimately, the data gathered from these methods would lead to a comprehensive understanding of Piedmont wetland stratigraphy, hydrology, and the significance of groundwater in each respective wetland water budget.

Lithology of Valley Bottom Deposits

Three transects, one at PSP and two at PWMA, were chosen for lithologic and stratigraphic evaluation. Two transects were selected at PWMA to characterize the two major toe-slope settings contributing groundwater to the wetland in the broad valley bottom at this site. Overall, the three transects are thought to represent the most common toe-slope morphologies found in the Virginia Piedmont. Hand-auger data and ground-penetrating radar surveys were used to determine the lithology and geometry of the valley bottom deposits. Following data collection and processing, a stratigraphic cross-section was created for each transect. Stratigraphic contacts were inferred in locations where data were not retrieved.

Auger Hole Transects

A total of fifteen auger holes were logged, six at PSP and nine at PWMA. Three transects of auger holes, one at PSP (A-A', Figure 7) and two at PWMA (B-B' and C-C', Figure 8), were taken roughly perpendicular to the stream channel from hillside to stream. Each hole was drilled using a 7.5 cm diameter, open-bucket hand-auger. In instances where non-cohesive sediments were encountered (e.g. saturated coarse sand), a closed-bucket auger was used to retrieve samples. Auger penetration depths ranged from 1.0 - 3.5 m. Auger holes were terminated when saprolite was encountered, when sediment was not cohesive enough for retrieval, or when the auger was refused. Upon retrieval, lithologic descriptions were recorded and each sample was placed in an open core tube and photographed. The depth of each distinct layer in the profile was recorded to the nearest 2 cm. Textural classifications were made based on the feel method (Brady and Weil, 2008). Auger hole logs are reported in Appendix A.

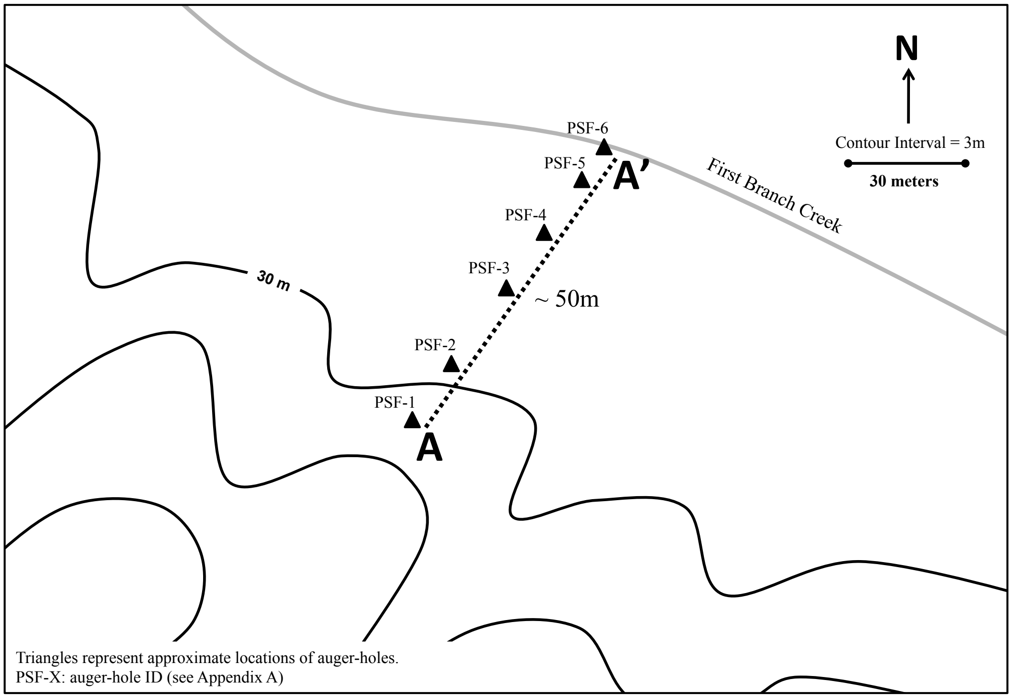


Figure 7. Map view of Pocahontas State Park (PSP) study site auger holes. Contours based on USGS 7.5'-series Beach, VA Quadrangle (1994). Dashed line represents approximate length of ground-penetrating radar (GPR) transect A-A'.

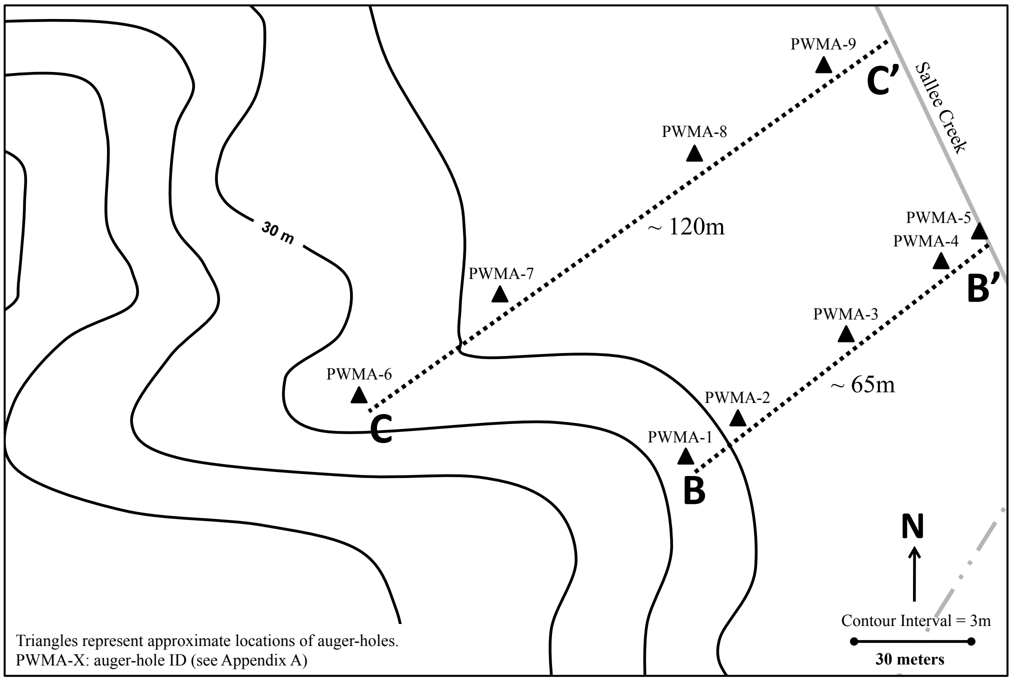


Figure 8. Map view of Powhatan WMA study site auger holes. Contours based on USGS 7.5'-series Powhatan, VA Quadrangle (1987). Dashed lines represent approximate lengths of ground-penetrating radar (GPR) transects B-B' and C'-C'.

Ground-penetrating Radar (GPR) Data Collection and Processing

Ground-penetrating radar (GPR) is useful for identifying horizontal stratigraphic contacts and how they vary across a given transect. Data from GPR surveys conducted at each study site served as a supplement to auger hole data used to determine the geometry of the valley bottom deposits. The objective of these surveys was to determine the lateral continuity and overall thickness (e.g. depth to sediment-saprolite interface) of these deposits. These surveys enable us to further constrain the boundaries of these deposits, which is necessary when constructing water budget models. The data were collected using a PulseEkko 100 GPR system in common-offset acquisition mode (Figure 9). Antenna frequency (100 MHz), step size (0.5 m), antenna spacing (1.0 m), and number of stacks per trace (4) were chosen based on recommendations in Sensors and Software Survey Design (1992) regarding target depth and host material. These settings provide an optimal balance between spatial resolution, depth of penetration, and signal-to-noise ratio in the survey environment. Additional set up parameters can be found in Appendix B.

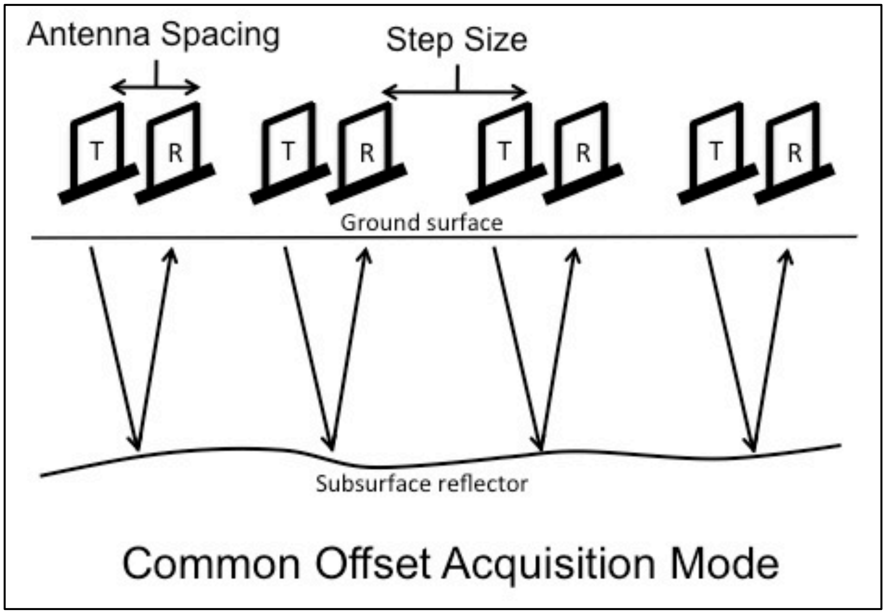


Figure 9. Common offset acquisition mode using ground-penetrating radar. T = transmitter. R = receiver. (Modified from Sensors and Software, 1992)

A total of three transects were surveyed, one at PSP (Figure 7) and two at PWMA (Figure 8). Each transect was designed to coincide with auger hole and monitoring well transects in place at each site.

GPR data processing included the application of a 'dewow' filter, additional trace stacking to reduce noise, assigning an appropriate electromagnetic wave velocity for the materials encountered, and applying topographic correction using topographic survey data (Appendix B). 'Dewow' is a high-pass filter that suppresses the high-amplitude, low frequency 'wow' that interferes with the high frequency signal of the actual reflectors (Sensors and Software, 1998). This standard filtering practice enhanced the clarity of the output image. Additional trace stacking used the average of the surrounding traces to produce a smoother image with less noise. Assigning an appropriate electromagnetic-velocity to the profile is necessary to produce an accurate estimation of depth for a particular reflector in a profile. The velocity of 0.06 m/ns was assigned for each profile based on the average velocities of common geologic materials at 80-120 MHz from Neal (2004). Topographic correction was applied to produce a profile that depicts the topography traversed during data collection. These processing techniques were applied to the datasets to improve the signal-to-noise ratio in the data and to facilitate accurate lithologic interpretation. After processing the GPR data, the interpretations were compared with auger hole logs to validate the stratigraphic correlations.

Hydrologic Investigations

A series of monitoring wells and piezometers were installed along transects at each site to gather data regarding the hydrology of each wetland. The data collection period was 16 months (May 2011-August 2012) at PSP and 13 months (August 2011-August 2012) at PWMA. The data gathered during this investigation were necessary to observe seasonal trends, identify zones of recharge and discharge, quantify groundwater inflow and outflow, and calibrate groundwater models.

Water Level Data Collection

A total of three transects of monitoring wells and piezometers were installed, one transect (A-A') at PSP (Figure 10) and two transects (B-B' and C-C') at PWMA (Figure 11). Transect A-A' at PSF and B-B' at PWMA were constructed from upland to stream across toe-slope seeps adjacent to steep hillsides. Transect C-C' at PWMA, located approximately 80 m north of and parallel to B-B', was constructed across a sediment apron intersecting the valley bottom at the base of a shallow swale in the hillside. Monitoring wells were installed in four positions along each transect: hillslope, toe-slope, mid-floodplain, and edge of stream bank. In addition, two piezometers were installed in each position, with the exception of the dry edge location in transects at PWMA, where only monitoring wells were installed. A total of twelve wells were installed along transect A-A' and ten wells total in B-B' and C-C'. Data gathered from monitoring wells allowed us to observe water table gradients and fluctuations. Piezometers installed adjacent to monitoring wells demonstrated the presence and gradient of vertical groundwater flow. All monitoring wells and piezometers were constructed using the standard installation procedure from Sprecher (2008) (Figure 12). Upon completion of well construction, relative elevation for the top of each well casing was determined to the nearest centimeter using laser-level surveying equipment.

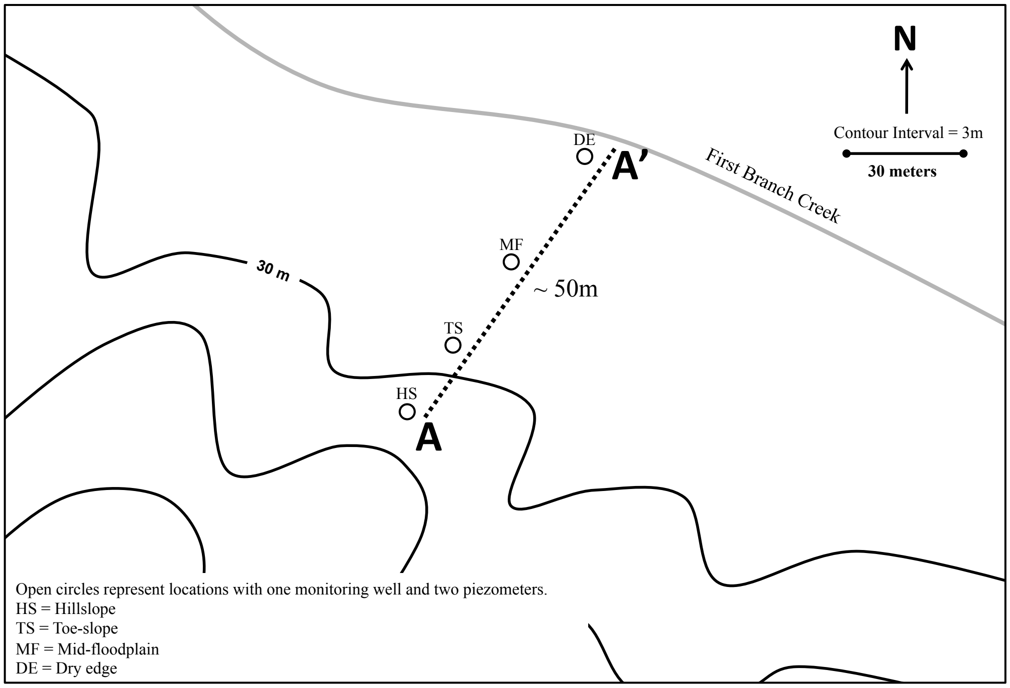


Figure 10. Map view of Pocahontas State Park well locations. Contours based on USGS 7.5'-series Beach, VA Quadrangle (1994). Dotted line represents approximate length of transect A-A'.

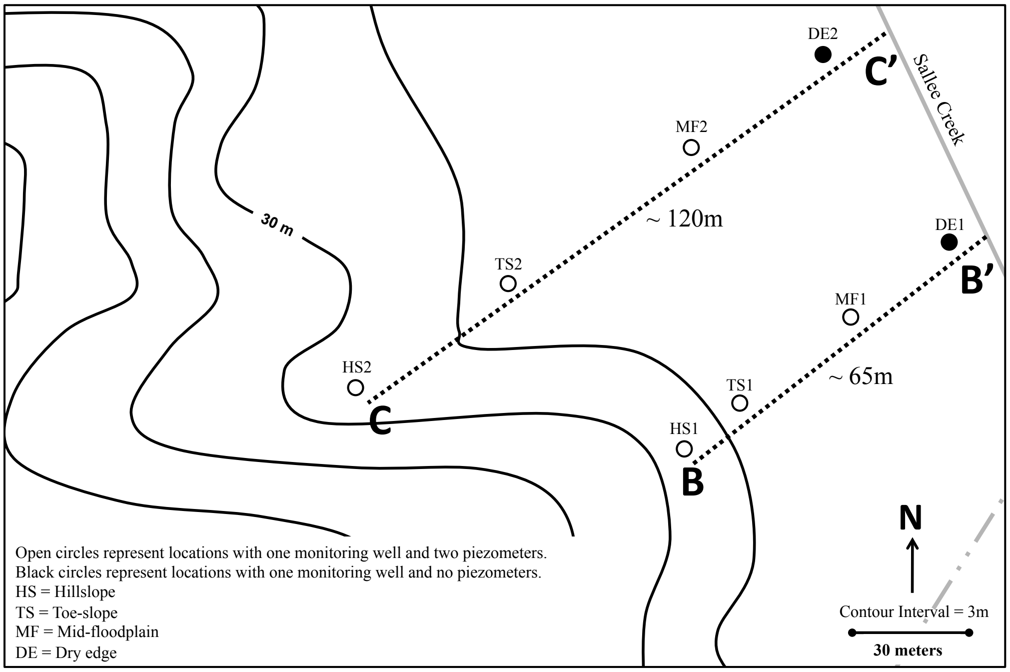


Figure 11. Map view of Powhatan WMA well locations. Contours based on USGS 7.5'-series Powhatan, VA Quadrangle (1987). Dotted lines represent approximate lengths of transects B-B' and C-C'.

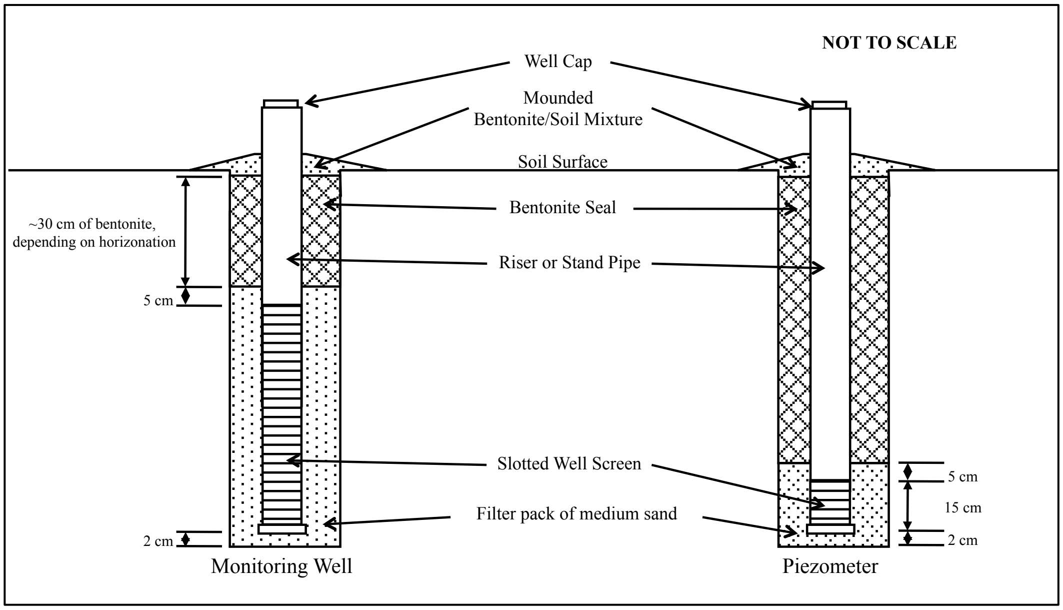


Figure 12. Standard installation for monitoring wells and piezometers. (Modified from Sprecher, 2008)

Solinst Model 3001 Leveloggers were used to record water levels and water table fluctuations that occurred in response to precipitation events and diurnal cycles caused by evapotranspiration. Leveloggers were deployed in hillslope and toe-slope monitoring wells at both sites plus the mid-floodplain monitoring wells at PWMA (total n = 8). Each device was suspended several centimeters above the bottom of the well with Kevlar cable (Figure 13) and recorded water levels hourly. The loggers recorded absolute pressure measured in meters. In order to compensate for changes in barometric pressure and to avoid time lag in the compensation, a Solinst Barologger Edge pressure transducer was deployed in a dry well approximately 1.5 m deep at each site (Figure 13). The Barologgers use pressure algorithms based on air rather than water pressure, which results in better accuracy during compensation. Barologgers suspended above water levels in shallow water wells (as recommended by Solinst) are susceptible to near surface temperature fluctuations, which may compromise the Barologger data by causing erroneous pressure readings (McLaughlin and Cohen, 2011). Therefore, by suspending the Barologger in a dry well at a sufficient depth to avoid these erroneous readings we achieved better accuracy during compensation. Levelogger data was barometrically compensated using Solinst Version 4.0 Levelogger Software Data Compensation Wizard, which automatically produces compensated data files using synchronized data files from the Barologger and Levelogger.

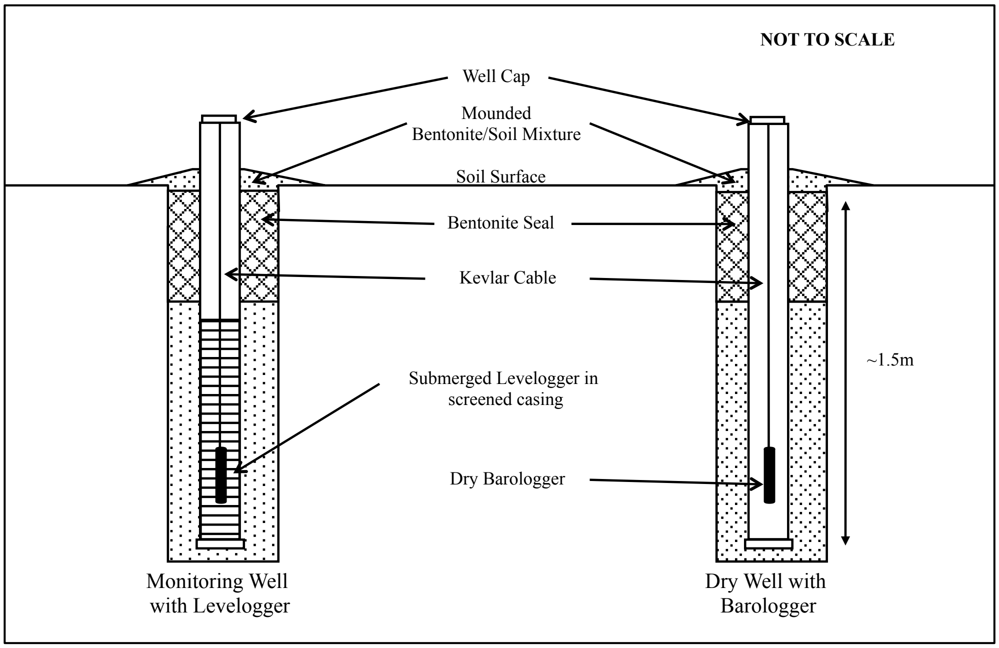


Figure 13. Levelogger and Barologger positions in wells. One dry well containing a Barologger was installed at each site.

Water levels were measured by hand in all monitoring wells (n = 12) and piezometers (n = 20) at the beginning of every month using a Slope Indicator Co. water level meter (±0.01 ft). Monthly depth-to-water measurements were used to determine water table profiles throughout the monitoring period. Piezometer data were used to identify zones of recharge and discharge and the vertical gradient associated with each landscape position. In addition, these measurements were used to calibrate the Leveloggers in the selected monitoring wells.

Hydraulic Properties of Sediments

Two common field methods were used to estimate the hydraulic conductivity and specific yield of the regolith at each site. Hydraulic conductivity (K) values were needed to quantify groundwater input and output. Estimations of specific yield (S_y) were needed as input parameters for wetland water budget models as well as model calibration.

Slug Tests

Hydraulic conductivity (K) was measured in saprolite, alluvial, and colluvial sediments using slug tests in seven piezometers total. Each piezometer was bailed rapidly and allowed to recover as water-level data was collected at 1-second intervals using a Solinst Model 3001 Levelogger submerged in the well. Hydraulic conductivity was calculated using the following version of the Hvorslev (1951) method developed by Demir and Narasimhan (1994):

$$K = S_f \frac{\ln(h_1/h_2)}{t_2 - t_1}, \qquad (4)$$

where: K = hydraulic conductivity (m/sec)

S_f = shape factor (unitless)

h_1 = head (m) after initial displacement at $t_1 = 0$ (sec)

h_2 = head (m) at t_2 (sec)

The shape factor (S_f) is determined by dividing the cross-sectional area of the well pipe by the steady-state shape factor:

$$S_f = \frac{A_{stp}}{S_{fss}}, \qquad (5)$$

where: A_{stp} = cross-sectional area of standpipe (m^2)

S_{fss} = steady-state shape factor (unitless)

The steady-state shape factor (S_{fss}) is determined using the equation developed by Hvorslev (1951) for cases with a finite screen length and takes the form:

$$S_{fss} = \frac{2\pi L}{\ln\left[\frac{L}{D} + \left(1 + \left(\frac{L}{D}\right)^2\right)^{1/2}\right]}, \qquad (6)$$

where: L = length of gravel pack zone (m)

D = borehole diameter (m)

All piezometers were constructed in the same manner (L = 0.30 m and D = 0.075 m) and shared the same S_f of 0.0049 for all K calculations.

Estimation of Specific Yield

Continuous water level data along with rainfall storm event data were used to estimate drainable porosity, which is similar to specific yield (Harder et al., 2007). These estimates were based on the following equation developed by Williams (1978):

$$n_d = (P_e/\Delta WT) \times 100, \qquad (7)$$

where: n_d = drainable porosity (expressed as a percentage)

P_e = precipitation event total

ΔWT = rise in water table

Williams (1978) suggest that these events should only correspond to instances where the water table rises within the top 1.0 m of the soil and that the water table response should be less than one day. In order to ensure accuracy of response times, only isolated precipitation events were chosen for the analysis. The objective of this analysis was to determine if the values for calculated for specific yield are in agreement with those selected in the sensitivity analyses during model calibration.

Wetland Water Budget Modeling

Wetland water budgets were determined for each site using the ‘Basic Scenario’ tool in WetBud, a water budgeting package (further development in progress) that allows planners/designers to estimate water budgets for constructed wetlands. The ‘Basic Scenario’ tool utilizes a modified version of the Integrated Pierce methodology, which is the current standard for designing, modeling, and constructing mitigation wetlands. Typically, this modeling approach is designed for constructed wetlands that rely on a perched water table, created through subsoil compaction and clay lining, thus neglecting any interaction with groundwater surrounding the system. Groundwater is neglected in this design practice because groundwater fluxes are difficult to estimate without extensive field data; thus the current practice seeks to eliminate or neglect any groundwater exchange in the system. To model a system designed in this manner, Pierce

(1993) recommended calculating a monthly water budget for wet, normal, and dry years utilizing precipitation data from the previous 30 years. The Integrated Pierce methodology was modified in WetBud to account for groundwater exchange within the system and specific yield of the soil, both of which affect water levels below the surface. This modified approach was used to determine the contribution of groundwater to wetland water budgets in natural wetland systems on a monthly and yearly basis. Accounting for the specific yield of the soil allows the model to more accurately predict water levels below the soil surface in the wetland by converting the simple model mass balance values (e.g. cm of standing water above the ground surface) into head values (e.g. water level relative to ground surface).

By treating the wetland as a level pool, six terms are factored into the wetland water budget equation: surface inflow (runoff), groundwater inflow, precipitation, evapotranspiration, surface outflow, and groundwater outflow (Figure 14).

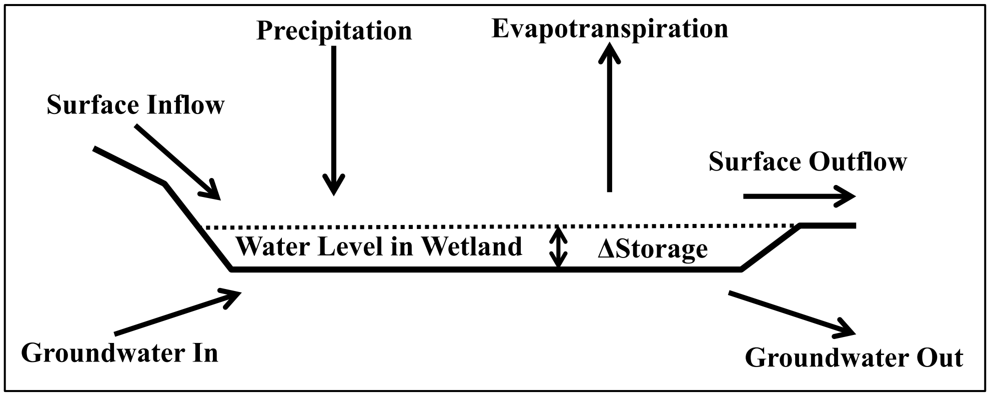


Figure 14. Simplified version of the wetland water budget. Inputs and outputs using the modified version of the Integrated Pierce approach are shown.

Mass balance water levels are converted to head levels, either above or below the ground surface, by accounting for soil storage (specific yield) based on the following criteria (generated by the WetBud development team):

First, the initial fill value (water level elevation relative to ground surface) is converted to a mass balance value. The criterion used for conversion depends on the water level relative to ground surface and are as follows:

$$if\ Elev(t) < 0, \qquad then\ IN_{tot} = Elev(t) * F_{soil}$$

$$if\ Elev(t) > 0, \qquad then\ IN_{tot} = Elev(t) *\ F_{srfc}$$

where: Elev(t) = initial water elevation relative to surface (cm) (ground surface = 0)

IN_{tot} = initial mass balance water level value (cm)

F_{soil} = soil storage factor (specific yield)

F_{srfc} = surface storage factor (equals 1 for open water; set to 0.98 to account for vegetation in standing water)

The mass balance sum of all water budget inputs and outputs is then added to IN_{tot}. The total mass balance is then converted to the new water level relative to ground surface (Elev (t+1)) by dividing the total mass balance by the soil storage factor or surface storage factor, which depends on the initial water level-to-mass balance conversion. The following example applies to a change in water level when the water level is above the ground surface:

F_{srfc} = 0.98

Elev(t) = 7.47 cm

ΔW = -2.44 cm (sum of all inputs and outputs)

IN_{tot} = 7.47 cm * 0.98 = 7.3206 cm

Total mass balance = 7.3206 cm + (-0.244 cm) = 7.0706 cm

Total mass balance to Elev(t+1) = 7.0706 / 0.98 = 7.22 cm

Daily precipitation data for the Pocahontas State Park study site were obtained from NCRS climate data station Winterpock 4 W, VA US, located approximately 6.40 km (3.97 mi) WSW of the study site. Daily precipitation data for the Powhatan Wildlife Management Area study site was obtained from NCRS climate data station Powhatan, VA US, located approximately 10.46 km (6.50 mi) ESE of the study site.

Surface water inflow from side-slope catchment areas was determined by WetBud, which uses Soil Conservation Service (SCS) Curve Number method for determining surface inputs into a wetland. The curve number is an empirical parameter that is integral for predicting runoff from the catchment draining into the wetland. This number is based on physical characteristics of the catchment area of the wetland, including soil type, antecedent moisture conditions, and land cover. Curve numbers were generated using the WinTR-55 Small Watershed Hydrology program (Roberts et al., 2009). Inputs needed for curve number generation were approximate acreages of total area for direct surface runoff, land cover type, and hydrologic soil groups. Acreages of total area for direct surface runoff and land cover type were determined using aerial images and topographic maps. Acreages for hydrologic soil groups were determined using soil maps obtained from Web Soil Survey (2012). See Table 1 below for WinTR-55 inputs used for curve number generation. Surface water outflow from the modeled site was determined by establishing a "weir height," which allows surface water to escape the model when water levels are above the prescribed height. Weir heights assigned for PSP and PWMA were 0.0 cm and 2.54 cm, respectively, and were based on average observed depth of water above the surface during times when water was at or above the surface.

TABLE 1. WinTR-55 INPUTS USED TO DETERMINE CURVE NUMBER (CN)

		Hydrologic Soil Group (acres)					
Site ID	Cover Type/ Condition	A	B	C	D	Area contributing runoff (acres)	CN
PSP	Woods/Good	-	5.75	-	0.25	6.00	56
PWMA	Woods/Good	-	12.00	-	2.00	14.00	58

Groundwater input and output were quantified using the following form of Darcy's Law:

$$Q = KA\frac{h_1 - h_2}{L}, \qquad (8)$$

where: Q = groundwater discharge (m^3/sec)
K = hydraulic conductivity (m/sec)
A = cross-sectional area (m^2)
h_1 = head elevation in up-gradient well (m)
h_2 = head elevation in down-gradient well or at L (m)

L = distance between h_1 and h_2

Groundwater discharge, Q, was then converted into a rate (e.g. m/month) by dividing Q by the wetland surface area. Relative water level elevations in hillslope and toe-slope wells were used to establish the hydraulic gradient for groundwater entering the site. For PWMA, the average of groundwater input for calculated for transects B-B' and C-C' was used as input for the model. For groundwater output, the hydraulic gradient was taken as that between the relative water level elevations in the dry edge wells and the adjacent stream. Monthly stream levels were estimated from photographs and notes taken during site visits. Hydraulic conductivity, K, values calculated from slug tests in the materials pertaining to each segment were used in the calculations. For PWMA, the average of K values calculated for HSDP B-B' and HSDP C-C' was used. Hydraulic conductivity values for wells screened in materials that were not tested were chosen based on values found in the literature.

To estimate groundwater input for wet, normal, and dry years that fell outside of the monitoring period, the Effective Monthly Recharge (W_{em}) model developed by Whittecar and others (2013) was used to predict head levels hillslope and toe-slope wells, which were then used to establish the hydraulic gradient in Darcy's Law. Using this method to predict water levels for these years required calibration and validation of the W_{em} for the observation period. Groundwater output for years that fell outside of the monitoring period was entered as a constant value, which was the average of calculated groundwater output during the 13-month monitoring period (8/1/11-8/31/12).

Evapotranspiration was calculated using the FAO-56 Penman-Monteith method (Jensen, 1990). Due to a lack of high-resolution weather data necessary for this calculation in the immediate area of each study site, temperature, wind speed, and solar radiation data were gathered from the National Solar Radiation Database for the Richmond International Airport and applied for both sites, which fall within a 40-mile radius of the weather station.

Surface water outflow was determined by establishing a weir height during model setup. When the wetland is 'full', the water level is reported at the weir elevation above surface. If the predicted water level is below the weir height, then the model output is that of the calculated water level. Since neither of the study sites contained an actual weir, weir heights for each site were defined as the average depth of surface water in the toe-slope location during the 13-month monitoring period.

Model Calibration

The model was calibrated for each site over a 13-month period from 8/1/11-8/31/12, where observed water level data in toe-slope monitoring wells was compared to model output. At PWMA, the observed water level used for calibration was taken as the average of both toe-slope monitoring wells. A sensitivity analysis over a range of values for specific yield was used for model calibration. This parameter was selected because virtually all other input parameters were observed or calculated with well-established methods. Although specific yield was estimated for select locations at each site using well data, these estimations do not represent average specific yield values for the entire stratigraphic package underlying each wetland and should not be treated as such. Model fit was evaluated using the Nash-Sutcliffe Model Efficiency test (Nash and Sutcliffe, 1970).

Simple Model Runs

Following model calibration the model was used to predict monthly water budgets for two typical wet, normal, and dry years at each site. Wet, normal, and dry years were determined for each site using historical precipitation data in WETS tables developed by the NRCS for the 30-year interval between 1980 and 2010 and by applying the wet, normal, dry spring criteria explained by McLeod (2013). Monthly water budgets and seasonal trends were then compared. In this analysis, an emphasis was placed on the respective contribution of groundwater relative to total water budget inputs during wet, normal, and dry years.

CHAPTER 3

RESULTS

Lithology of Valley Bottom Deposits

Interpretations of stratigraphy at each site were made based on cross-sections created from auger-hole data. Inferences made regarding stratigraphic continuity were supported by GPR profiles made for each transect.

Auger Hole Transects

The geometry and lithology of valley bottom sediments at PSP were determined using data gathered from the six auger holes and are illustrated in Figure 15. Transect A-A' at PSP had a total length of 40 m. In the valley bottom, maximum thickness of sediment above saprolite was approximately 2.20 m, observed in the location of PSP-4. Coarse angular sand and basal gravels lay atop saprolite and were laterally continuous across the valley bottom. The combined thickness of these units ranged from a featheredge at PSP-2 to 0.64 m beneath PSP-4 and PSP-5. Basal sand and gravel was overlain by dense sandy clay and silty clay that extended to the surface, except between PSP-2 and PSP-3 where a thin bed of sand sat above the dense clay. A thin layer of organic muck was present at the surface between these two boreholes and its extent was roughly coincident with the sand bed beneath it. In the streambed, a thin layer of coarse sub-angular sand was underlain by approximately 0.60 m of fine silty clay.

The geometry and lithology of regolith at PWMA was constrained using auger hole data from two transects. Figure 16 illustrates the stratigraphy underlying transect B-B', which had a total length of 65 m. Five holes were augered along this transect. The saprolite surface drops steeply between PWMA-1 and PWMA-2, suggesting sediments extending farther out from the hillside into the valley may be considerably thicker than illustrated in the cross-section. PWMA-2 was the only hole augered in the valley at this site to reach saprolite, suggesting a minimum thickness of valley fill at this site of 2.94 m. The saprolite encountered in PWMA-2 was tightly foliated and contained large (4 cm) clasts of unweathered quartz. Very poorly sorted, sub-angular basal sand and gravel was laterally continuous across this transect except in the interval between PWMA-2 and PWMA-3, where it became interbedded within poorly sorted sandy clay at depths between 1.83 and 2.79 m. Lying atop the basal sand and gravel were thick beds of sandy silt and clay that extended from toe-slope to stream bank. A notable feature of these fine-grained beds was an abundance of macropores, which were observed in the stream bank of Sallee Creek. A thin layer of brown, organic-rich medium sand interrupts the fine-grained beds above and below it. This sand bed is laterally continuous across the entire transect at a depth of approximately 0.75 m. In the bed of Sallee Creek, a thin layer of coarse angular sand was underlain by approximately 2.00 m of silty clay, which became interbedded with coarse angular sand with increasing depth just above its contact with coarse sand and gravel below.

Figure 17 illustrates the stratigraphy underlying transect C-C', which had a total length of 120 m. Four holes were augered along this transect. Unlike the other transects which begin on relatively steep hillslope, this transects begins upslope in a shallow swale on the hillside at the head of a colluvial wedge/sediment apron that spreads out into the valley. In PWMA-6, a thin layer of brown, organic-rich medium sand, which lies atop feldspar-rich gneissic saprolite, underlies a thin layer of sandy clay. Above the clay lies thick, sandy colluvium. The sand bed in PWMA-6 is relatively homogenous and laterally continuous across the entire transect at a depth of approximately 0.50 m. This sand bed is likely the continuation of the sand bed found in transect B-B'. Above and below this sand bed lay relatively thick, heterogeneous beds of sandy silt and clay. Macropores were observed in these units outcropping in the stream bank and those below the water table were visibly draining those beds of water.

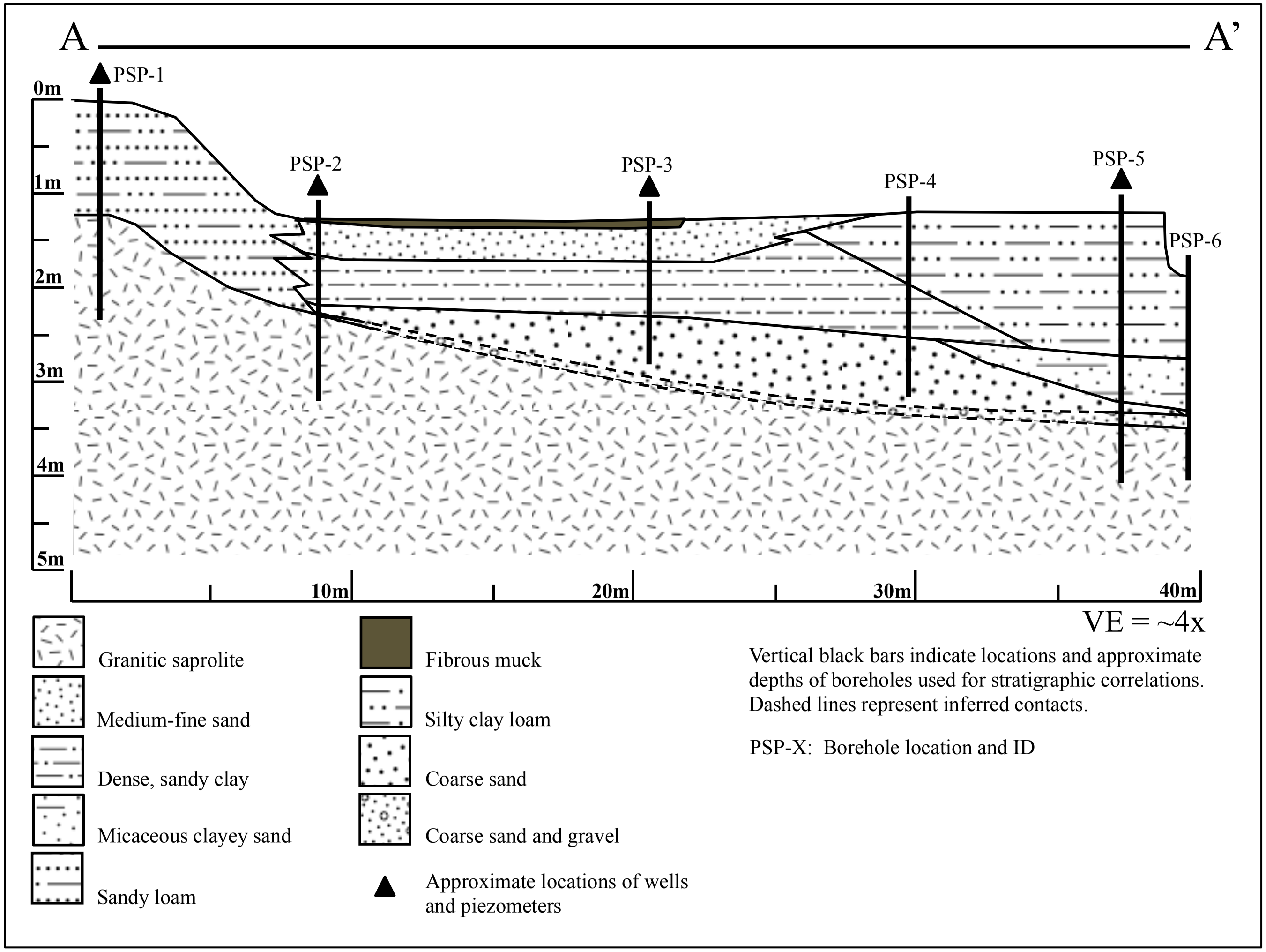


Figure 15. Generalized stratigraphic cross-section: transect A-A’ at Pocahontas State Park.

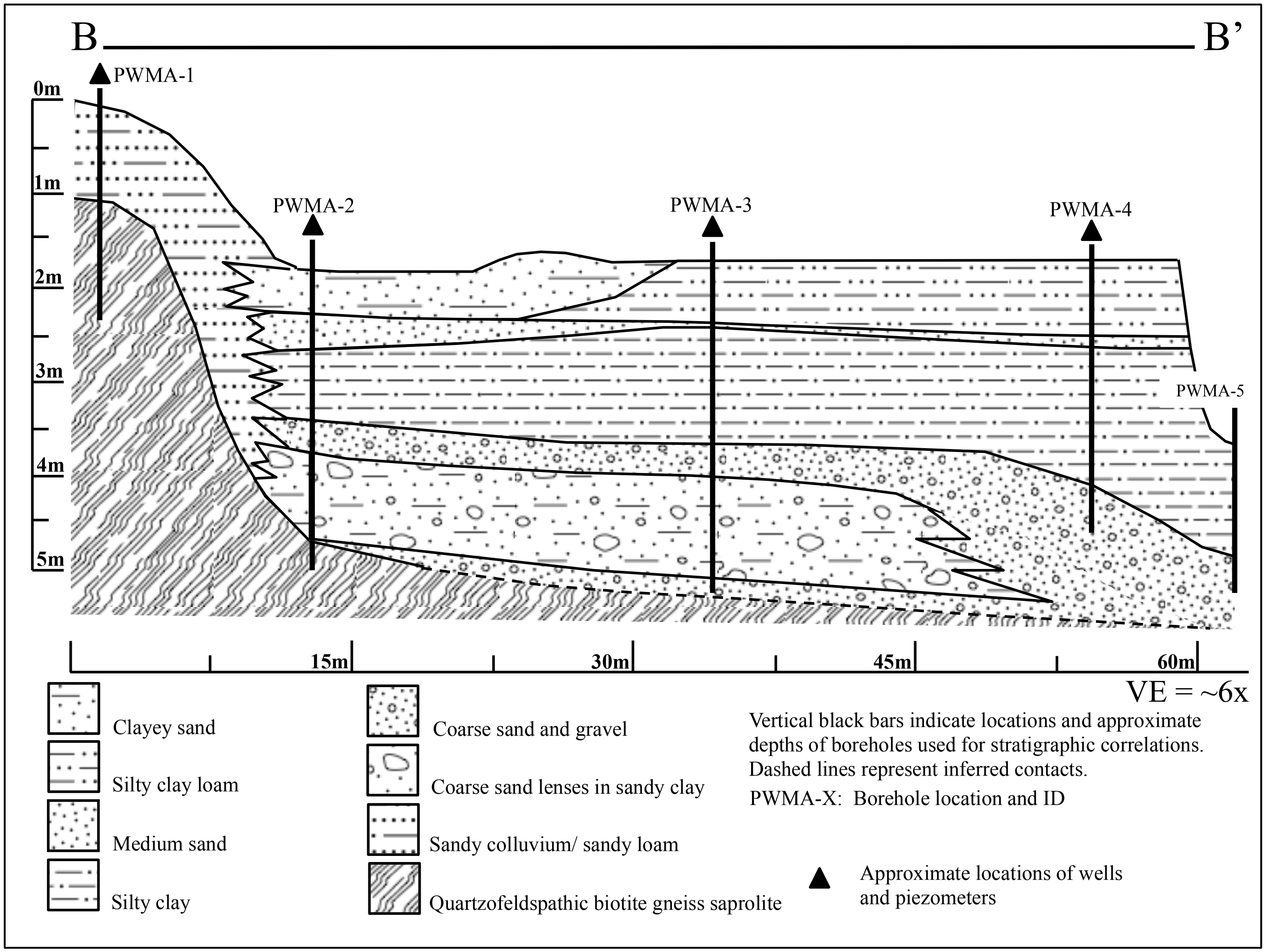


Figure 16. Generalized stratigraphic cross-section: transect B-B’ at Powhatan WMA.

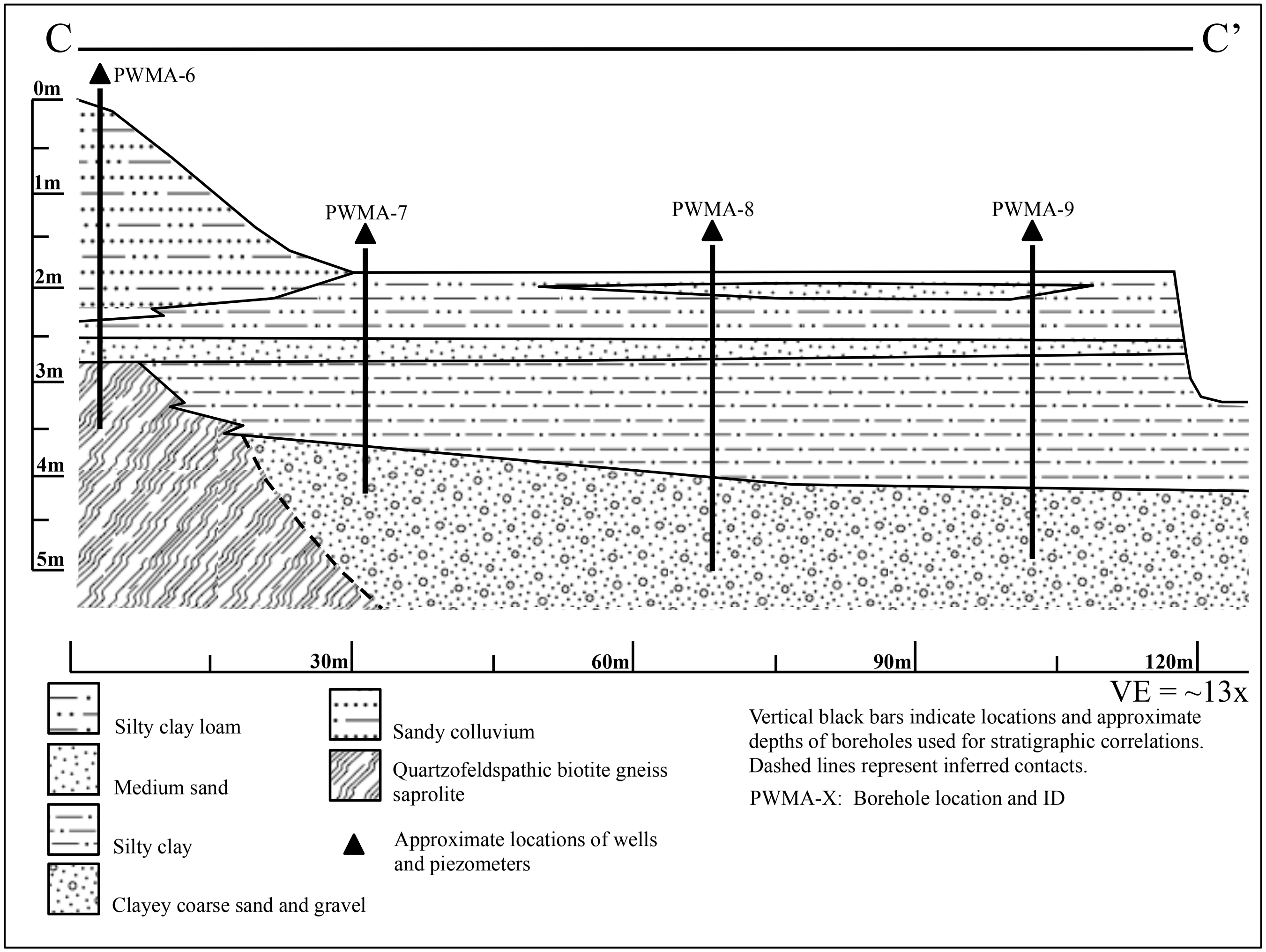
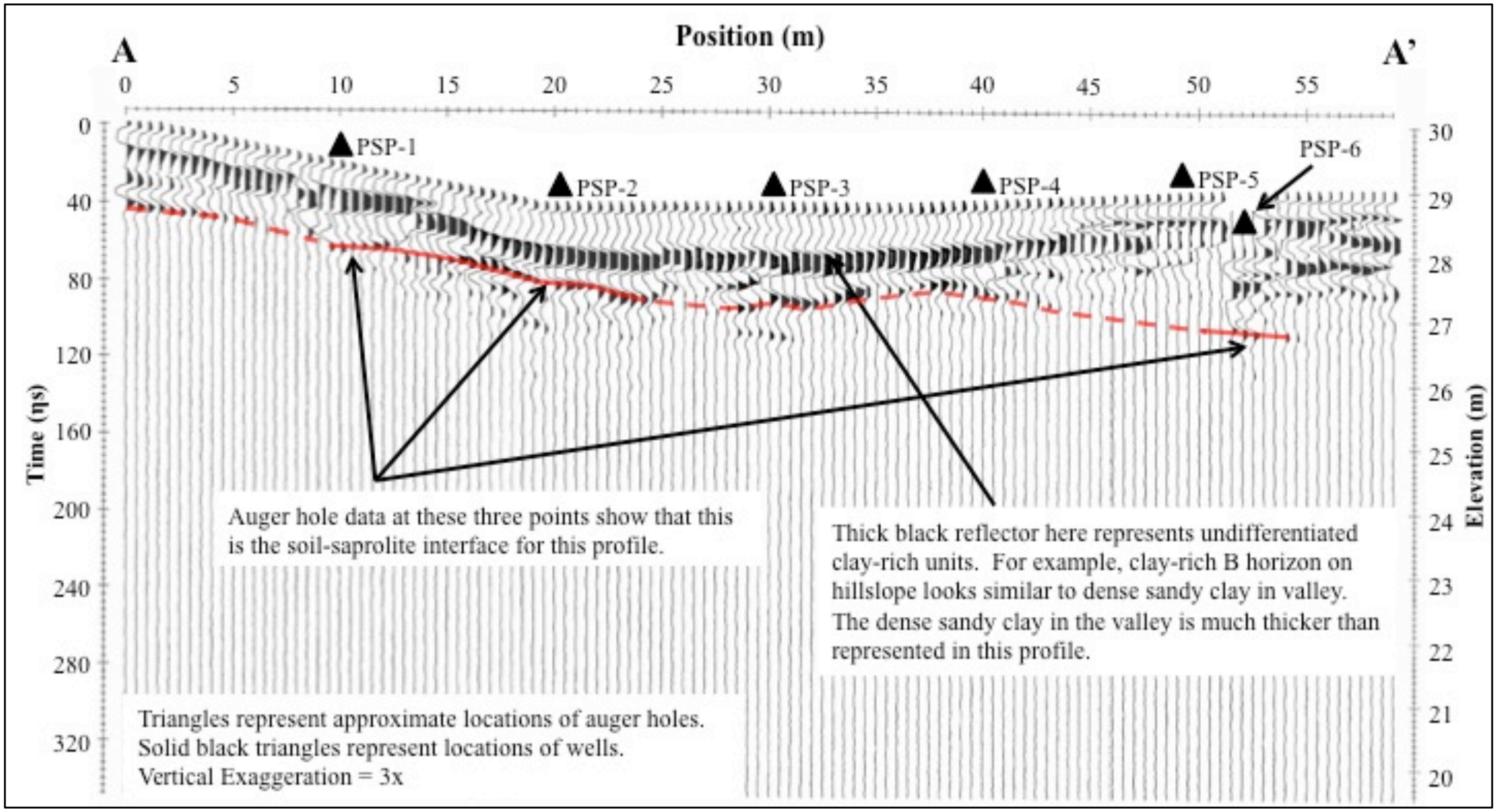


Figure 17. Generalized stratigraphic cross-section: transect C-C’ at Powhatan WMA.

Ground-penetrating Radar Profiles

GPR data were collected in January 2012 from three transects corresponding with the auger-hole transects. GPR transect lengths for PSP (A-A'), PWMA (B-B'), and PWMA (C-C') were 59 m, 86 m, and 98.5 m, respectively. The GPR profiles generated for each transect illustrate the gross structure of the subsurface and generally agree with stratigraphic cross-sections produced from auger hole data. In addition, the GPR data support the assumption that beds are laterally continuous across the valley bottom. The soil-saprolite interface was not evident beneath the valley bottom sediments in the profiles generated for PWMA, which is likely due to the soil-saprolite interface lying at depths greater that the depth of reach intended for the survey design (approximately 3-4 m). To reach depths greater than 4 meters a lower antenna frequency (e.g. 50 MHz) would have been required, however, resolution would have been compromised and thin beds would have become indistinguishable. Clay-rich sediments found at depth at PWMA may have also contributed to insufficient signal penetration due to signal attenuation.

The GPR profile of transect A-A' at PSP (Figure 18) shows agreement with the auger hole data regarding the soil-saprolite interface at the hillslope and toe-slope locations. However, the soil-saprolite contact on the profile is unclear in locations PSP-3 through PSP-6. This contact may actually be represented on the profile in the location of PSP-4 but auger hole data are insufficient to confirm this notion. The absence of this contact beneath the dry edge and streambed locations is likely due to the considerable thickness of a micaceous clayey sand unit, which resulted in increased attenuation of the signal. The three major units between the toe-slope and stream are only separated by one major contact on the GPR profile. The thick, black layer in Figure 18 likely represents the most clay-rich units from position 0 to 40 at depths between 0.50 and 1.10 m. Between positions 20 and 40, however, this clay-rich unit is actually much closer to the surface than the GPR profile suggests and appears to be lumped together with the overlying sand bed.



Auger hole data at these three points show that this is the soil-saprolite interface for this profile.

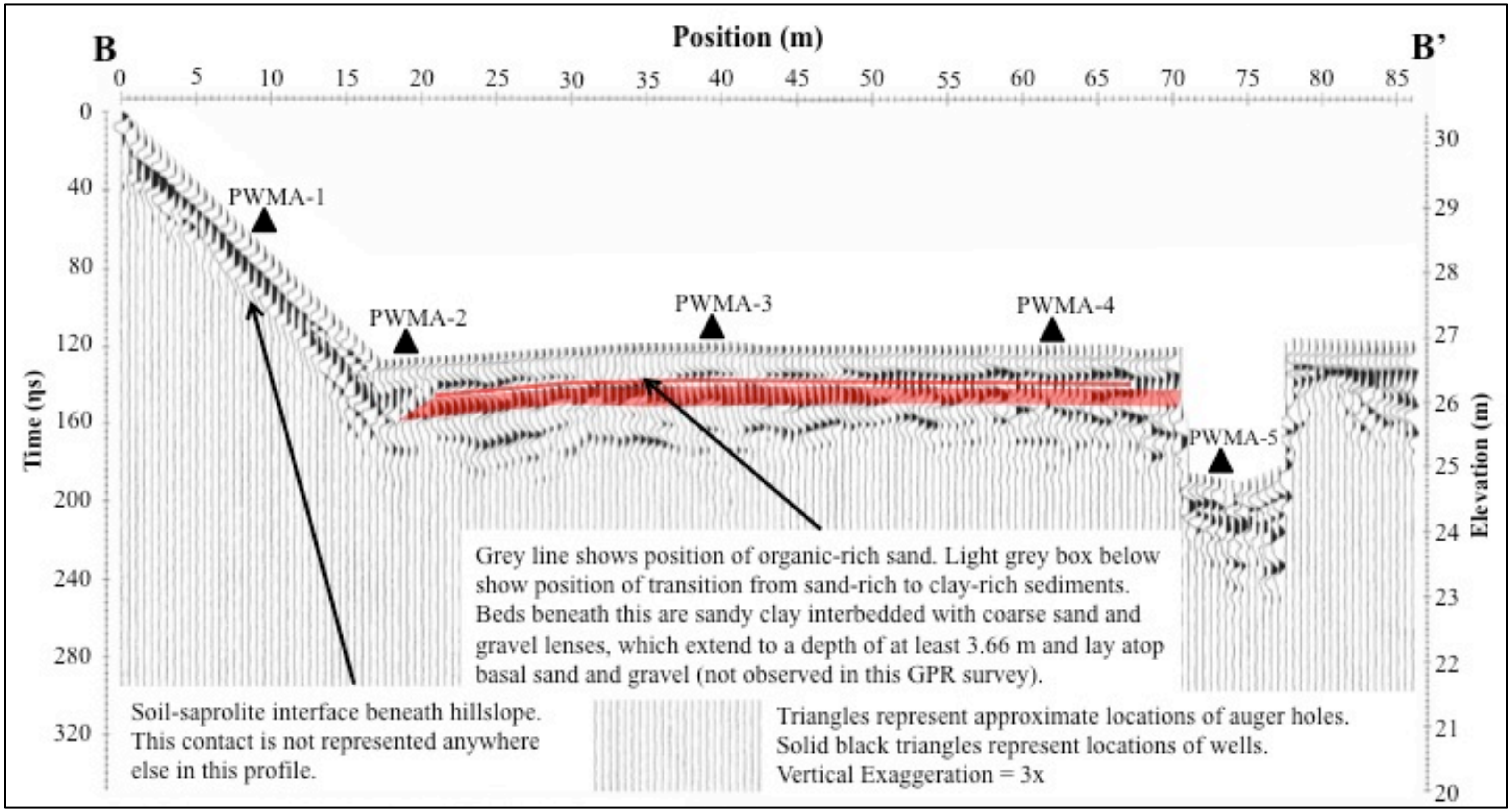
Thick black reflector here represents undifferentiated clay-rich units. For example, clay-rich B horizon on hillslope looks similar to dense sandy clay in valley. The dense sandy clay in the valley is much thicker than represented in this profile.

Triangles represent approximate locations of auger holes.
Solid black triangles represent locations of wells.
Vertical Exaggeration = 3x

Figure 18. GPR profile for transect A-A' at Pocahontas State Park. Solid and dashed gray lines indicate confirmed and inferred position of soil saprolite interface, respectively.

Transect B-B’ at PWMA contained the most lithologic variability of the three transects surveyed and auger hole data showed fair agreement with depths to known reflectors on the GPR profile (Figure 19). Auger hole data regarding the saprolite surface in the location of the PWMA-1 (position 10) agree with the GPR profile, however, this contact is absent throughout the remainder of the profile. The signal is terminated beyond approximately 1.50 m depth from surface across the entire profile past position 17. Auger hole data show that valley bottom stratigraphy extends well beyond this depth to at least 3.50 m. The relatively planar surface of signal termination suggests that the antenna frequency was insufficient for the survey environment rather than signal attenuation due to clay-rich sediments. Above the depth of signal loss there are several somewhat distinct reflectors that are consistent with auger hole data. The reflectors are laterally continuous across the profile until position 60, where all reflectors become very diffuse. The first of the reflectors is a laterally continuous silt-rich bed that extends from the surface to depths ranging from 0.5 to 0.70 m. Beneath the silt, a thin bed of organic-rich sand appears on the profile as a thin, discontinuous white band. Underlying the thin sand bed is a diffuse transition from sand-rich to clay-rich sediment between approximately 0.5 and 1.0 m depth. This transition is represented on the profile by a diffuse, thick black band extending across the profile. Below this depth, the silty clay-rich sediments are interbedded with sand as depth increases. These are represented as diffuse beds at the base of the profile. Auger hole data show these beds extend at least 0.30 m beyond the depth of signal loss to a depth of 1.80 m, where a bed of coarse sand briefly interrupts them before extending to a depth of at least 3.66 m at position 10.

The GPR profile for transect C-C’ at PWMA was the longest of the three transects surveyed (Figure 20) at 98.5 m, however, this survey did not reach the stream bank due to equipment failure. This transect differs from the other two in that it traverses a colluvial wedge that begins upslope in a swale between two hillsides. The depth to the soil-saprolite interface was not evident anywhere in the profile and much like the GPR profile for B-B’, the signal is terminated along a roughly planar surface at a depth of approximately 1.20 m across the profile past position 32. The concave-up surface of this reflector that first appears at position 24 suggests a distinct lithologic transition from hillslope to valley bottom and is roughly coincident with the contact of silty clay with basal sand and gravel shown in auger hole data. The GPR profile suggests the silty clay is laterally extensive across the valley bottom with a continuous thickness of roughly 0.75 m until it tapers to a featheredge at position 24. Above this unit, a relatively thick continuous black reflector appears across the entire profile. This reflector likely represents undifferentiated units nearest the surface that are thin and very heterogeneous, making no distinction between colluvium and sandy beds in the valley bottom. In addition, the uppermost reflector in the profile shows little variability in thickness across the profile and no distinction between hillslope and valley bottom sediment is observable.

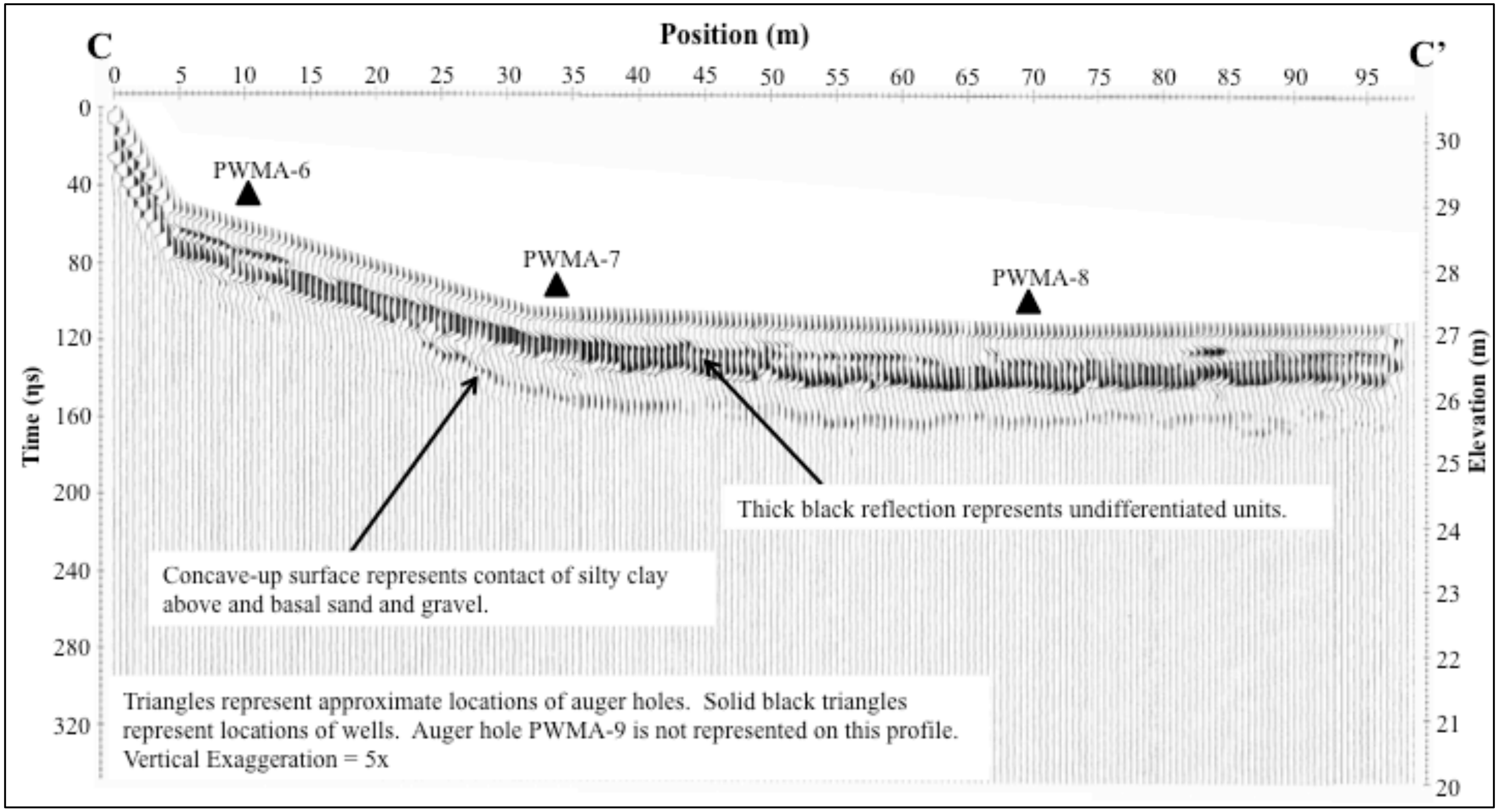


Grey line shows position of organic-rich sand. Light grey box below show position of transition from sand-rich to clay-rich sediments. Beds beneath this are sandy clay interbedded with coarse sand and gravel lenses, which extend to a depth of at least 3.66 m and lay atop basal sand and gravel (not observed in this GPR survey).

Soil-saprolite interface beneath hillslope. This contact is not represented anywhere else in this profile.

Triangles represent approximate locations of auger holes. Solid black triangles represent locations of wells. Vertical Exaggeration = 3x

Figure 19. GPR profile for transect B-B' at Powhatan WMA.



Thick black reflection represents undifferentiated units.

Concave-up surface represents contact of silty clay above and basal sand and gravel.

Triangles represent approximate locations of auger holes. Solid black triangles represent locations of wells. Auger hole PWMA-9 is not represented on this profile. Vertical Exaggeration = 5x

Figure 20. GPR profile for transect C-C’ at Powhatan WMA.

Hydrologic Investigations

Water level data in monitoring wells and piezometers show seasonal water table dynamics and the spatial and temporal distribution of recharge and discharge zones at each site. For clarity, results for each site are reported separately.

Water Level Data Collection

Hydrographs generated from hourly water level data collected from May 2011 to July 2012 in hillslope and toe-slope monitoring wells along transect A-A' at Pocahontas State Park reveal several aspects of the hydrology of this system (Figure 21). During the winter months the water level in the toe-slope remains relatively stable and shows a weak response to precipitation events. These characteristics suggest that surface water is efficiently removed following precipitation events and that during times that lack precipitation water levels are sustained by groundwater rising to the surface. The largest hydraulic gradients occur during these months, which result in larger volumes of groundwater being discharged at the toe-slope, adding support to this presumption. Although a significant source of surface inflow is not evident at this site, it may also contribute to the sustained water levels in this position. The relative stability of water levels during the winter months seen in both wells on the hydrograph in Figure 21 can also be attributed to a lack of significant water withdrawal due to evapotranspiration. During the summer months when water withdrawal due to evapotranspiration is at its maximum, the diurnal fluctuations recorded in each well are similar, suggesting similar transpiration rates of vegetation in the uplands and in the valley bottom. Monthly water level measurements taken at the beginning of each month in all wells in the valley bottom at PSP show a range of approximately 0.70 m. However, continuous water level measurements in the toe-slope well show a range of 1.13 m. An additional 0.40 m of water level drawdown was observed in the toe-slope well data following the monthly water level measurement on July 2, 2012. It is likely that the mid-floodplain and dry edge wells experienced this drawdown as well, thus the overall range in water level in the valley bottom wells will be taken as the 1.13 m seen in the toe-slope well. Across this transect a low flow gradient from toe-slope to stream exists for the majority of the monitoring period. During the summer of 2011, March 2012, and August 2012 the flow gradient was reversed. Although no water level data was recorded in the adjacent stream,

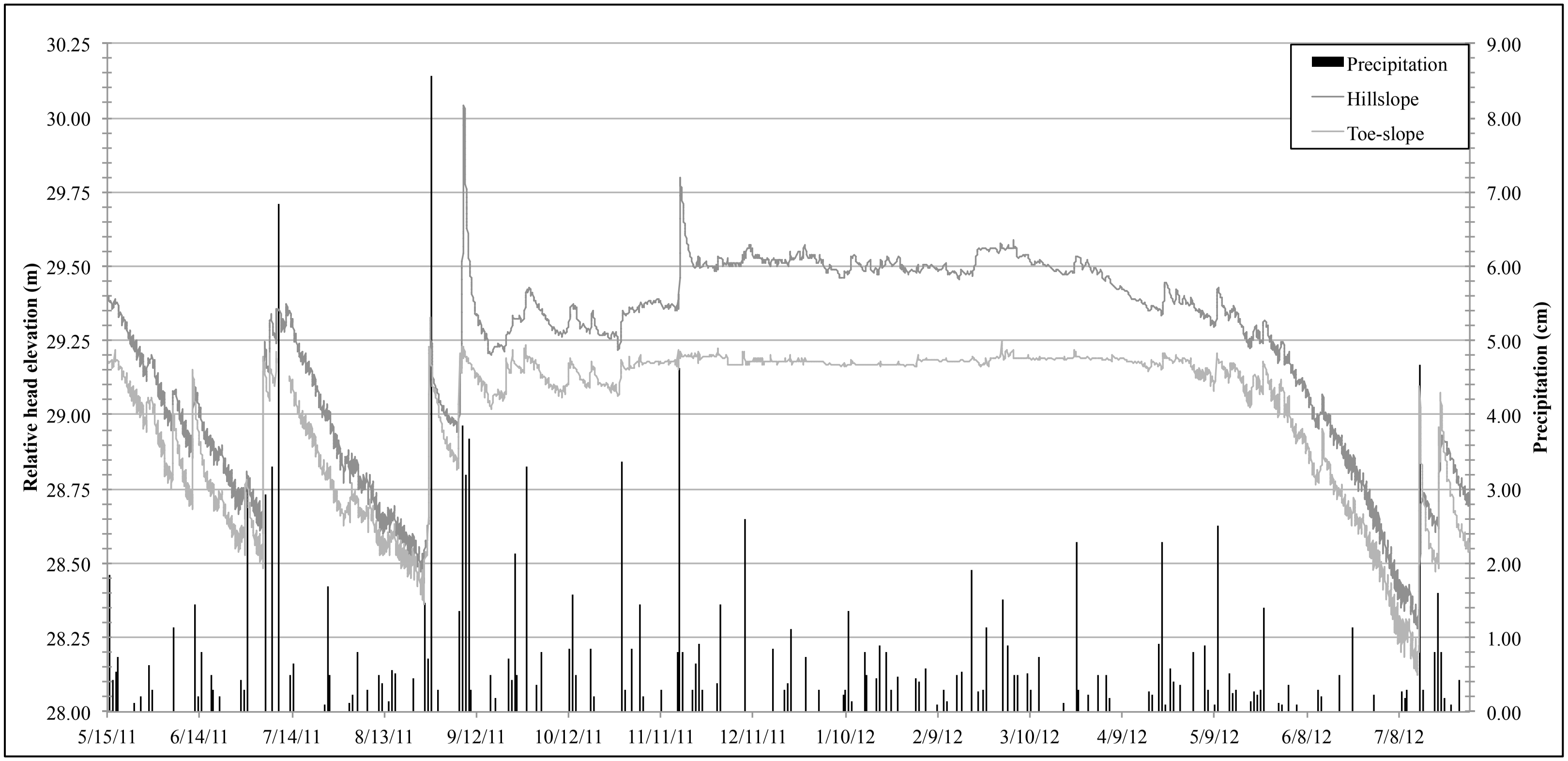


Figure 21. Pocahontas State Park 15-month relative head elevation hydrograph for hillslope and toe-slope monitoring wells. Hydrographs for each well were generated from hourly data points. Vertical bars represent daily total precipitation.

it is likely these reversals were brief and due to higher than usual streamflow. A summary of monthly water level measurements taken in monitoring wells along transect A-A' is shown in Table 2. Summaries of water level ranges for continuous data corresponding to the hydrographs in Figure 21, monthly depth-to-water measurements, and relative head elevations for wells along this transect are reported in Appendix C.

TABLE 2. MONTHLY WATER LEVEL SUMMARY: PSP TRANSECT A-A'

Well location	Water level relative to surface (m)			
	Avg.	Max	Min.	Range
Hillslope	-1.26	-0.44	-2.20	1.00
Toe-slope	-0.20	0.05	-1.08	0.69
Mid-floodplain	-0.27	0.02	-0.72	0.70
Dry edge	-0.53	-0.26	-0.97	0.71

Depths and locations of piezometer nests along transect A-A' at PSP are illustrated in Figure 22. A summary of monthly vertical flow gradients is presented in Table 3. Flow was upward in the hillslope and toe-slope positions for all months during the monitoring period, indicating that these two landscape positions act as perpetual groundwater discharge zones. In the mid-floodplain position an upward gradient was present only during summer months but served as a recharge zone for the remainder of the year. Piezometer data in the dry edge position show that in most months groundwater is being discharged to the adjacent stream. See Appendix C for monthly depth-to-water values in all piezometers.

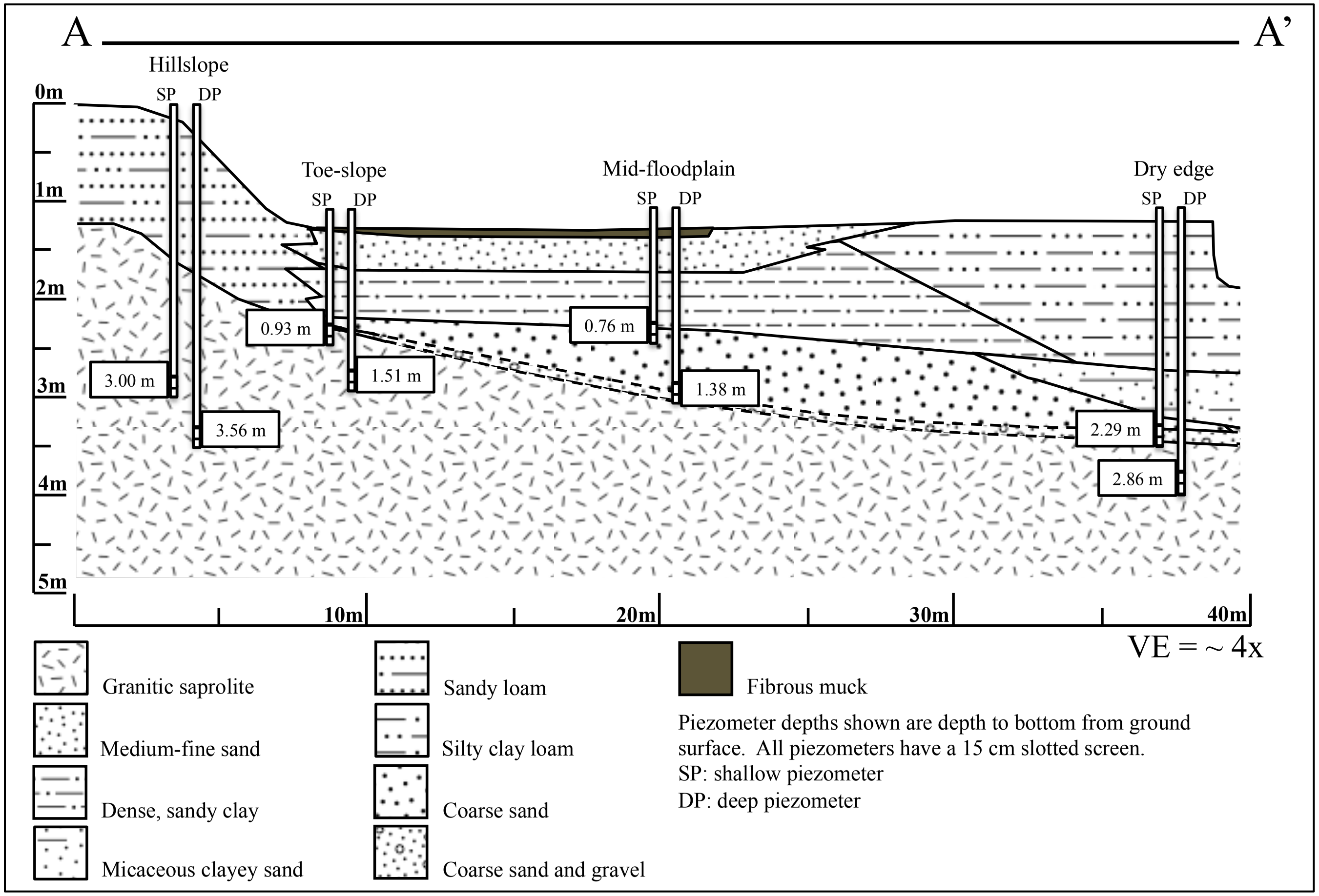


Figure 22. Cross-section showing piezometers at Pocahontas State Park study site transect A-A’.

TABLE 3. MONTHLY PIEZOMETER GRADIENTS: PSP TRANSECT A-A’

Mo./Yr.	Hillslope	Toe-slope	Mid-floodplain	Dry Edge
May-11	0.11	0.03	-0.11	-0.16
Jun-11	0.23	0.02	0.15	0.04
Jul-11	0.18	0.02	≥0.24*	0.00
Aug-11	0.16	0.10	0.23	-0.05
Sep-11	0.02	0.02	-0.05	0.02
Oct-11	0.18	0.05	-0.60	0.05
Nov-11	0.05	0.03	-0.06	0.54
Dec-11	0.64	0.09	-0.06	0.04
Jan-12	0.05	0.07	-0.10	0.04
Feb-12	0.11	0.07	-0.08	0.18
Mar-12	0.05	0.10	-0.53	0.02
Apr-12	0.14	0.00	-0.18	0.04
May-12	0.11	0.01	-0.16	0.02
Jun-12	-	-	-	-
Jul-12	0.05	0.02	0.03	0.02
Aug-12	0.07	0.07	0.02	0.00

Note: Negative values (gray cells) represent a downward vertical gradient. Dashes indicate months with no data.
*Shallow piezometer was dry, thus this value represents the minimum vertical gradient.

In both transects at PWMA, hourly data were collected from August 2011 to July 2012 in hillslope and toe-slope monitoring wells and from January 2012 to August 2012 in mid-floodplain monitoring wells. Characteristics of hydrographs created from these data reveal several aspects of the hydrology of the two transects at this site, which have different hillslope and toe-slope morphologies. To reiterate, transect B-B’ was constructed from a steep upland hillside to stream edge. Transect C-C’ is located approximately 80 m north of and parallel to B-B’ and was constructed across a sediment apron intersecting the valley bottom at the base of a shallow swale in the hillside. Seepage is evident at the toe-slope of the sediment apron where it meets the valley bottom. There are several notable features seen in the hydrograph of monitoring well data in transect B-B’ (Figure 23). During times when the water level is below the surface the hydrographs of the toe-slope and mid-floodplain wells are flashy in response to precipitation events, suggesting these sediments are highly permeable. The flashiness of the toe-slope hydrograph during times when surface water is present suggests considerable surface flow is being diverted to this area following precipitation events. In general, vegetation communities in the hillside and valley bottom along this transect are alike, so it is surmised that the differences in diurnal fluctuations caused by evapotranspiration are caused by differences in lithology, which regulate the amount of water accessible to plants in the root zone. The hydrograph in Figure 23 also reveals that, in contrast to that observed in transect A-A' at PSP, the hydraulic gradient between the hillslope and toe-slope wells along this transect is the smaller during the winter months than in the summer months. A summary of the continuous water level data shown in Figure 23 is reported in Appendix C. Along transect B-B' the range of water table fluctuations varied between wells located in the valley bottom. The dry edge well had the smallest range of 0.55 m and experienced the greatest depth-to-water from the surface, at 1.30 m. The largest range was 0.94 m, observed in the mid-floodplain well. The water level range observed in the toe-slope was 0.88 m and the greatest depth to water was 0.71 m. A summary of monthly water level measurements for this transect is seen in Table 4. All monthly water level measurements are reported in Appendix C.

TABLE 4. MONTHLY WATER LEVEL SUMMARY: PWMA TRANSECT B-B'

Well Location	Water level relative to surface (m)			
	Avg.	Max	Min.	Range
Hillslope	-1.55	-1.26	-2.01	0.75
Toe-slope	-0.15	0.17	-0.71	0.88
Mid-floodplain	-0.69	-0.33	-1.27	0.94
Dry edge	-0.95	-0.75	-1.30	0.55

Note: Dry edge well data only represents period from February 2012-August 2012.

Depths and locations of piezometer nests along transect B-B' at PWMA are illustrated in Figure 24. A downward gradient was present for all months in the hillslope location. With the exception of November 2011 in the toe-slope location, all months in the toe-slope and mid-floodplain location had upward gradients, indicating that these are discharge zones. The perpetual upward gradient observed in the mid-floodplain location was unexpected and demonstrates that discharge zones can extend many meters out into the floodplain. It must be noted that the piezometers in the mid-floodplain along this transect are screened in the base of the valley fill at depths greater than 2.0 m and that the

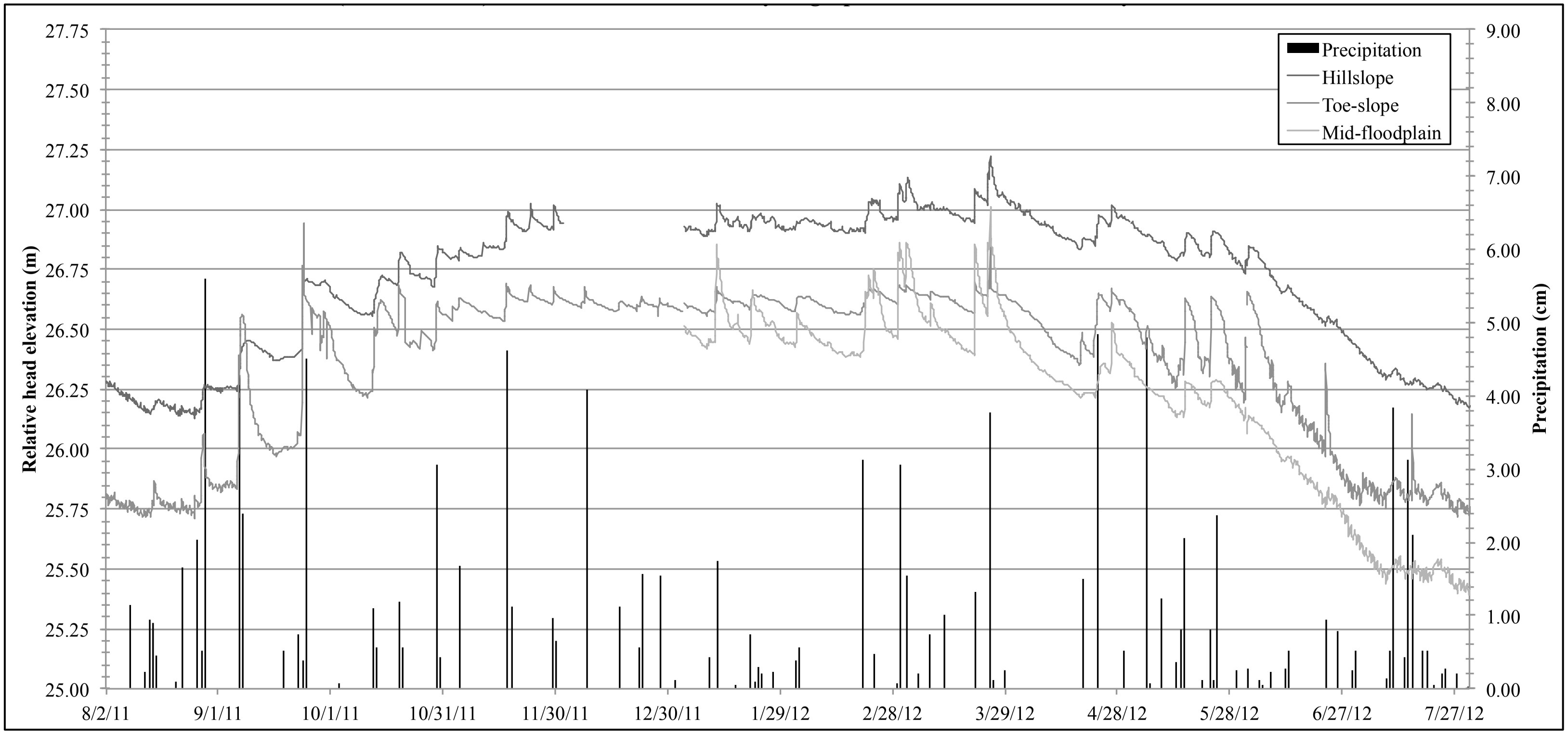


Figure 23. Powhatan WMA transect B-B’ 12-month relative head elevation hydrograph. Hydrographs were generated from hourly data collected in monitoring wells.

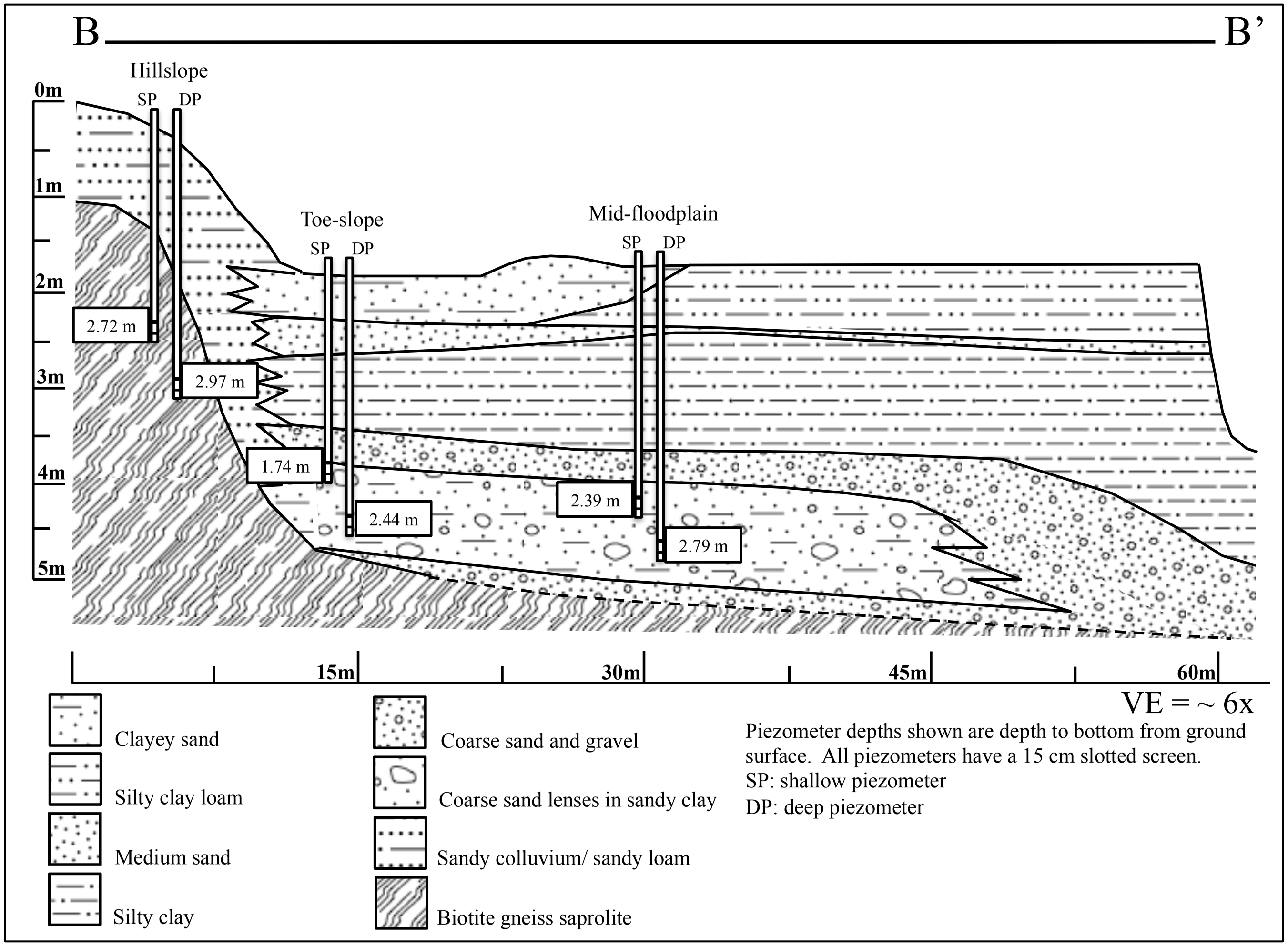


Figure 24. Cross-section showing piezometers at Powhatan WMA study site transect B-B’.

upward gradient observed in this location may not be present in shallower depths. A summary of monthly vertical flow gradients is presented in Table 5.

TABLE 5. MONTHLY PIEZOMETER GRADIENTS: PWMA TRANSECT B-B’

Mo./Yr.	Hillslope	Toe-slope	Mid-floodplain
Aug-11	-	0.19	-
Sep-11	-0.16	0.17	1.03
Oct-11	-0.12	0.00	0.33
Nov-11	-0.12	-0.24	0.15
Dec-11	-0.36	-	0.13
Jan-12	-0.32	0.01	0.30
Feb-12	-0.04	0.03	0.07
Mar-12	-0.20	0.00	0.25
Apr-12	-0.04	0.06	0.50
May-12	-0.04	0.06	0.45
Jun-12	-	0.10	-
Jul-12	-0.04	0.21	1.10
Aug-12	-0.04	0.19	1.20

Note: Negative values (gray cells) represent a downward vertical gradient. Dashes indicate months with no data.

A hydrograph of continuous water level data gathered in wells along transect C-C’ is shown in Figure 25. The hydrograph of the hillslope swale monitoring well exhibits features inherent to its position in the landscape, which is a natural discharge point where flowlines converge. The flashiness of the hydrograph suggests groundwater is rapidly delivered to this location following precipitation events. However, the magnitude of these peaks and the duration of the decline following them are greatly diminished during the summer months when plants are actively transpiring. Although it is evident that during summer months excess groundwater being delivered to the hillslope swale location is being taken up by transpiration, the hydraulic gradient remains stable between the hillslope swale and toe-slope. Over the same time period, the stable hydraulic gradient between these two wells is in contrast to the increasing hydraulic gradient seen in transect B-B’ and the decreasing gradient in transect A-A’. The stable gradient observed in transect C-C’ is likely being sustained by a steady source of groundwater. Diurnal fluctuations caused by evapotranspiration are similar in all three hydrographs shown in Figure 25. The diurnal fluctuations observed in the toe-slope and mid-floodplain well are smaller than those observed in transect B-B’, suggesting the mostly shrub-scrub vegetation surrounding this transect withdraws less water than the larger, more densely spaced hardwoods and few small plants around transect B-B’. A summary of the continuous data used to generate the hydrograph in Figure 25 is reported in Appendix C. Monthly water level measurements and piezometer data gathered along transect C-C’ support interpretations of the hydrograph and add additional insight into the factors affecting the hydrology at this site. The range of water levels for wells in the valley bottom was smallest at the toe-slope and largest at the dry edge, at 0.66 m and 0.93 m, respectively. Similar to that observed in transect B-B’, the lowest water level was recorded in the dry edge well, at 1.33 m below surface. The lowest water level in the mid-floodplain well along this transect was approximately 0.5 m shallower than that observed in the mid-floodplain well in transect B-B’, which supports the notion that evapotranspiration is greater in transect B-B’. A summary of monthly water level measurements taken along transect C-C’ is reported in Table 6.

TABLE 6. MONTHLY WATER LEVEL SUMMARY: PWMA TRANSECT C-C’

Well location	Water level relative to surface (m)			
	Avg.	Max	Min.	Range
Hillslope swale	-1.39	-0.57	-1.99	1.42
Toe-slope	-0.24	0.00	-0.66	0.66
Mid-floodplain	-0.24	0.00	-0.76	0.76
Dry edge	-0.76	-0.40	-1.33	0.93

Note: Dry edge well data only represents period from February 2012-August 2012.

Depths and location of piezometer nests along transect C-C’ at PWMA are illustrated in Figure 26. Supporting the hydrograph interpretation regarding zones of groundwater discharge, the hillslope swale and toe-slope experienced an upward gradient during all months of the observation period. In contrast to the mid-floodplain position in transect B-B’ but similar to that in transect A-A’ at PSP, the mid-floodplain in transect C-C’ behaved as a recharge zone for most months and as a discharge zone during summer months. A summary of monthly vertical flow gradients is presented in Table 7. Monthly water level measurements for all piezometers PWMA are reported in Appendix C.

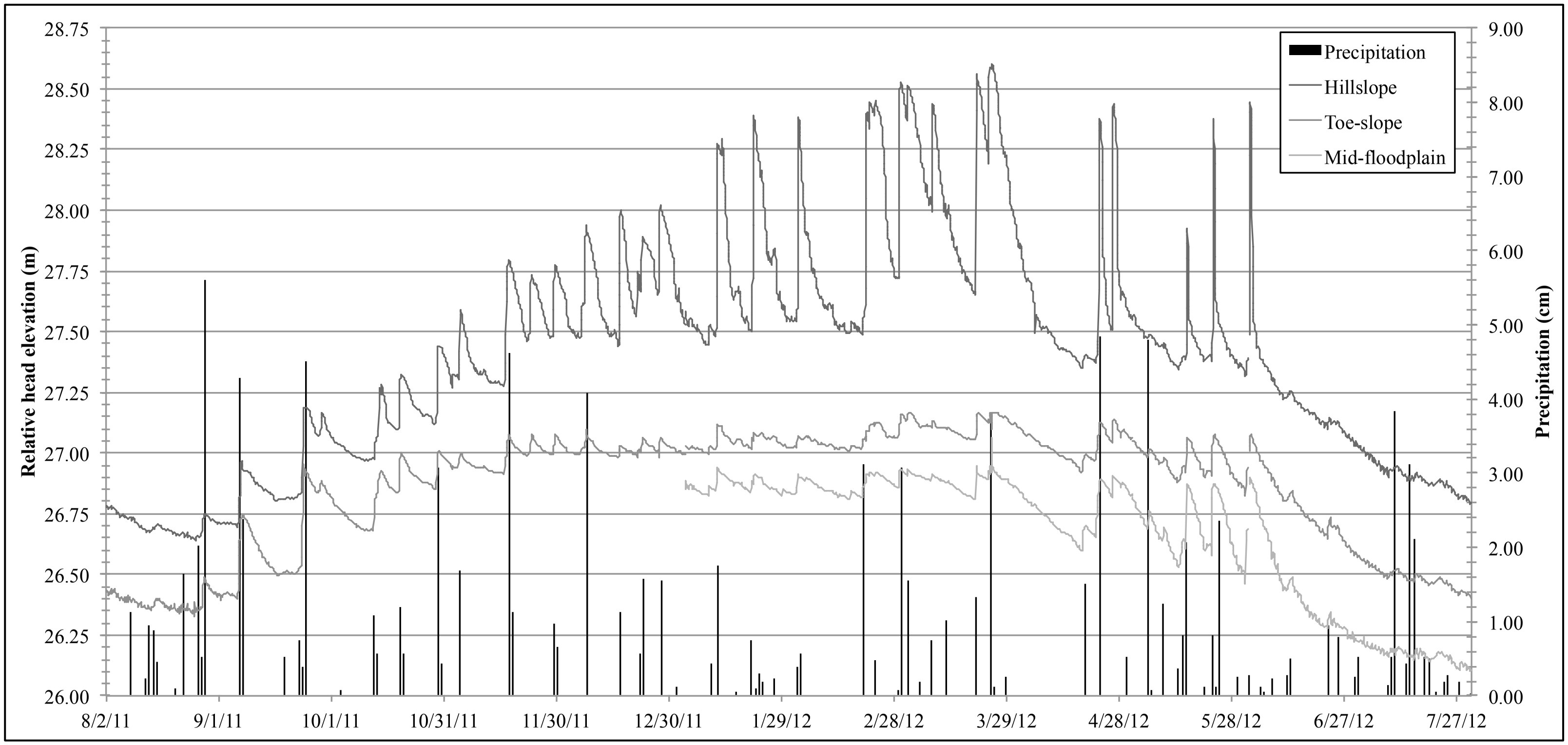
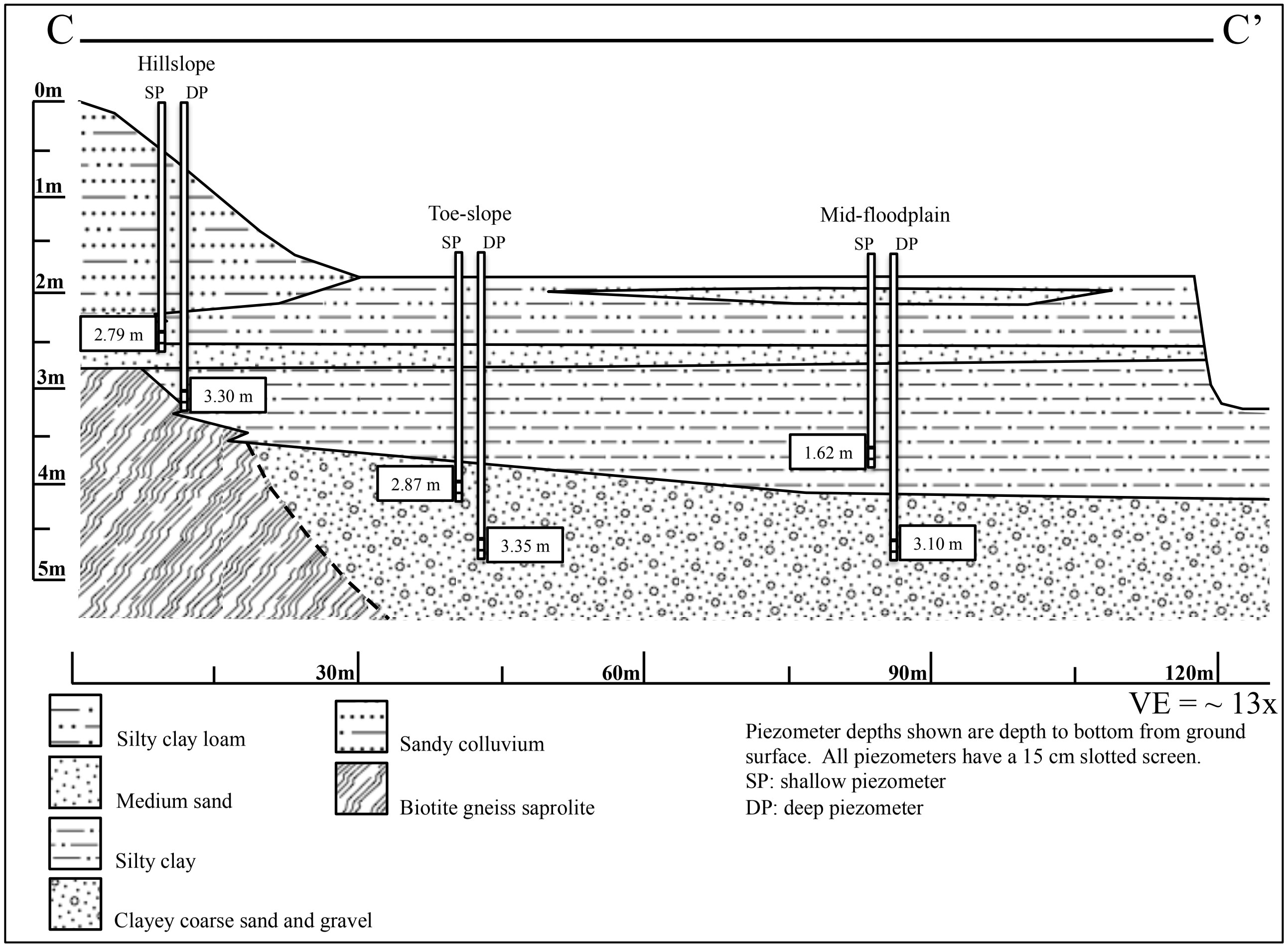


Figure 25. Powhatan WMA transect C-C’ 12-month relative head elevation hydrograph. Hydrographs were generated from hourly data collected in monitoring wells.

TABLE 7. MONTHLY PIEZOMETER GRADIENTS: PWMA TRANSECT C-C’

Mo./Yr.	Hillslope swale	Toe-slope	Mid-floodplain
Aug-11	-	-	-
Sep-11	0.14	0.48	0.09
Oct-11	0.10	1.06	-0.03
Nov-11	0.12	0.15	-0.08
Dec-11	0.29	0.06	-0.03
Jan-12	0.22	0.04	-0.02
Feb-12	0.43	0.08	-0.02
Mar-12	0.76	0.29	0.00
Apr-12	0.20	0.15	0.03
May-12	0.14	0.10	-0.03
Jun-12	-	0.42	-
Jul-12	0.06	0.17	0.18
Aug-12	0.06	0.06	0.14

Note: Negative values (gray cells) represent a downward vertical gradient. Dashes indicate months with no data.



Piezometer depths shown are depth to bottom from ground surface. All piezometers have a 15 cm slotted screen.
SP: shallow piezometer
DP: deep piezometer

Figure 26. Cross-section showing piezometers at Powhatan WMA study site transect C-C'.

Hydraulic Properties of Sediments

Hydraulic conductivity (K) values were needed to quantify groundwater input and output using Darcy's Law. Estimations of specific yield were needed as input parameters for wetland water budget models as well as model calibration.

Slug Tests

Seven piezometers were used to determine K via slug tests, two at PSP and five at PWMA. At PSP, tests were conducted in saprolite derived from the Petersburg Granite and gravelly coarse sand. At PWMA, tests were conducted in saprolite derived from biotite gneiss, coarse sand and gravel, a colluvium/saprolite mix, clayey fine sand with coarse sand lenses, and clayey, very coarse sand and gravel.

Results of the slug tests, which were conducted between May 2012 and July 2012, are reported in Tables 8 and 9. The average K calculated for each material represents the average of three successive trials in the well tested. In two wells, MFDP1 and HSDP2 at PWMA, three trials were not completed due to erroneous logger data that was compromised by barometric pressure changes during the second and third trial. Although at least three trials were desired to make a conclusion about K values using slug tests, the values for these units reported in Tables 8 and 9 agree with values found in the literature for similar materials (Table 10). Slug test data are reported in Appendix D.

TABLE 8. SLUG TEST RESULTS: PSP TRANSECT A-A'

Well ID	Material Type	Trial 1 K (m/sec)	Trial 2 K (m/sec)	Trial 3 K (m/sec)	Avg. K (m/sec)
HSDP	Granitic saprolite	6.66×10^{-7}	1.78×10^{-6}	2.82×10^{-6}	2.30×10^{-6}
TSSP	Coarse sand and gravel	2.66×10^{-5}	1.21×10^{-5}	5.94×10^{-6}	1.49×10^{-5}

Note: K-hydraulic conductivity; HS-hillslope; TS-toe-slope; DP-deep piezometer; SP-shallow piezometer.

TABLE 9. SLUG TEST RESULTS: PWMA

Well ID	Material Type	Trial 1 K (m/sec)	Trial 2 K (m/sec)	Trial 3 K (m/sec)	Avg. K (m/sec)
HSDPB	Biotite gneiss saprolite	1.61×10^{-5}	1.69×10^{-5}	1.71×10^{-5}	1.67×10^{-5}
TSDPB	Coarse sand and gravel	1.00×10^{-5}	1.47×10^{-5}	1.46×10^{-5}	1.31×10^{-5}
MFDPB	Clayey fine sand with coarse sand lenses	1.46×10^{-7}	5.26×10^{-7}	-	3.36×10^{-7}
HSDPC	Colluvium/saprolite mix	2.30×10^{-8}	-	-	2.30×10^{-8}
TSDPC	Clayey very coarse sand and gravel	1.38×10^{-7}	3.33×10^{-7}	3.90×10^{-7}	2.87×10^{-7}

Note: K-hydraulic conductivity; HS-hillslope; TS-toe-slope; MF-mid-floodplain; DP-deep piezometer; SP-shallow piezometer; B-transect B-B'; C-transect C-C'.

TABLE 10. HYDRAULIC CONDUCTIVITY (K) VALUES IN PUBLISHED LITERATURE

Material Type	K (m/sec)	Author(s)
Mica-schist saprolite	7.5×10^{-7}	Vepraskas et al. (1991)
Grandodiorite saprolite	7.4×10^{-5}	Crossley (2004)
Biotite granite saprolite	4.0×10^{-6}	Dewandel et al. (2006)
Felsic gneiss saprolite	1.0×10^{-6}	Shoeneberger and Amoozegar (1990)
Coarse sand and gravel	$10^{-3} – 10^{-5}$	Fetter (2001)
Silty sand	$10^{-6} – 10^{-9}$	Fetter (2001)
Clay	$10^{-8} – 10^{-11}$	Fetter (2001)

The differences in hydraulic conductivity between the saprolites may reflect differences in structural and petrologic characteristics of each parent rock. The saprolite at PSP is derived from the Petersburg Granite, which at this location is a homogenous, equigranular, coarse-grained nonfoliated rock that has roughly equal percentages of quartz, feldspar, and biotite (evidenced by auger hole data and visual observation of nearby core stone). Auger hole data show that this rock has weathered uniformly to produce a homogeneous saprolite. The hydraulic conductivity values for this unit are in close agreement with data found in the literature for saprolite derived from similar parent rock (e.g. Dewandel et al., 2006, Crossley, 2004). Hydraulic conductivity values calculated from bail tests in the two piezometers screened in gneissic saprolite at PWMA illustrate how heterogeneity in the parent rock can strongly influence local groundwater flow. The bail test performed in HSDPB had a conductivity three orders of magnitude greater than that in HSDPC. Although tightly foliated, the saprolite in HSDPB contains many large, unweathered clasts of quartz, the voids around which likely provide preferential flowpaths for groundwater. The same saprolite tested in HSDPC was dense and rich in clayey, weathered feldspars, which clearly inhibited flow at this location.

The respective hydraulic conductivities of saprolite have implications for how groundwater is delivered from the uplands to the wetland at each site. If the homogeneity of the saprolite at PSF persists in the surrounding hillside, one can assume that groundwater being delivered to the wetland at this site will be relatively uniform across the toe-slope. At PWMA, where considerable heterogeneity exists in the saprolite, it is possible that groundwater being discharged along toe-slopes may vary widely depending on local water table gradients induced by spatial variations in hydraulic conductivity.

Hydraulic conductivity values also varied widely for the materials tested in the toe-slope piezometers at PWMA. In TSDPB the coarse sand and gravel was two orders of magnitude larger than the clayey coarse sand and gravel in TSDPC, which is evidence that the clay content in TSDPC was sufficient to significantly inhibit the hydraulic conductivity in that location.

Estimation of Specific Yield

Continuous water level data for eight monitoring wells, two at PSP and six at PWMA, were used to estimate specific yield (S_y) of aquifers. This analysis was performed using data from monitoring wells screened in heterogeneous sediments, thus the results reflect the dominant lithology over the interval screened.

The dominant lithologies in the hillslope and toe-slope monitoring wells at PSP were clayey sandy loam derived from granitic saprolite and dense sandy clay, respectively. Over the five rainfall events used in the analysis at this site, results were fairly consistent in both wells tested at PSP with a maximum range of 8% between trials, recorded in the hillslope well. Average S_y values for each well, 10% for hillslope and 5% for toe-slope, are in agreement with values for similar materials as reported in the compilation by Johnson (1967). Results are reported in Table 11.

TABLE 11. SPECIFIC YIELD RESULTS: PSP TRANSECT A-A’

		Hillslope		Toe-slope	
Date	ppt (cm)	ΔWT (cm)	S_y (%)	ΔWT (cm)	n_d (%)
6/4/11	1.14	8	14	25	5
6/11/11	1.45	25	6	47	3
7/14/12	4.67	36	13	87	5
7/20/12	1.6	24	7	45	4
10/18/11	0.86	7	12	9	10
		Avg.	10	Avg.	5
		Overall avg.		7.5	

Note: ppt-precipitation; ΔWT-change in water level; S_y-specific yield.

Wells screened in sediments in four different landscape positions were tested at PWMA, hillslope, hillslope swale, toe-slope, and mid-floodplain. The number of rainfall events used for each well varied slightly due to limited data and few isolated storm events during the monitoring period. The dominant lithologies for hillslope B-B’ and C-C’ were sandy loam derived from biotite gneiss and clayey sandy loam, respectively. The high specific yield of 30% reported for hillslope B-B’ likely reflects the presence of many unweathered quartz clasts present within the soil matrix and resembles values found for much coarser lithologies in Johnson (1967). Results for hillslope C-C’, with an average specific yield of 9%, reflect the high clay content within the soil profile, typical of hillslope colluvium overlying saprolite (Pavich and Obermeier, 1985). The sediment in the location of toe-slope wells was dominated by fine to medium sand. Averages for these specific yields were approximately 30%, which closely resemble results for similar lithologies in Johnson (1967). Specific yield values calculated for the two wells in the mid-floodplain positions reflect distinct differences in dominant lithology over interval screened. Although the sediment in the vicinity of both wells was mostly sandy clay, the profile of mid-floodplain C-C’ was punctuated by a roughly 30 cm interval of fine-medium sand, which should yield a larger specific yield for this well. Results are shown in Table 12.

TABLE 12. SPECIFIC YIELD RESULTS: PWMA

Transect B-B’		Hillslope		Toe-slope		Mid-floodplain	
Date	ppt (cm)	ΔWT (cm)	S_y (%)	ΔWT (cm)	S_y (%)	ΔWT (cm)	S_y (%)
10/19/11	4.62	11	42	18	26	-	-
11/4/11	1.63	5	33	6	27	-	-
11/29/11	4.09	11	37	6	68	-	-
12/8/11	1.12	-	-	7	16	-	-
1/12/12	1.55	12	13	10	16	42	4
3/1/12	3.12	10	31	8	39	36	9
3/21/12	3.15	13	24	13	24	46	7
		Avg.	30	Avg.	31	Avg.	6

Transect C-C’		Hillslope swale		Toe-slope		Mid-floodplain	
Date	ppt (cm)	ΔWT (cm)	S_y (%)	ΔWT (cm)	S_y (%)	ΔWT (cm)	S_y (%)
10/19/11	4.62	18	26	12	39	-	-
11/4/11	1.63	27	6	5	33	-	-
11/29/11	4.09	27	15	8	51	-	-
12/8/11	1.12	31	4	6	19	-	-
1/12/12	1.55	75	2	9	17	14	11
3/1/12	3.12	78	4	7	45	-	-
3/21/12	3.15	91	3	11	29	14	23
		Avg.	9	Avg.	33	Avg.	17
	Overall avg. for both transects				20		

Note: ppt-precipitation; ΔWT-change in water level; S_y-specific yield.

Wetland Water Budget Modeling

Development of wetland water budgets for each site consisted of five steps. The first step was calibration of the Effective Monthly Recharge (W_{em}) model. The next step was choosing years that represent the range of hydrologic conditions experienced at each site. These years were selected based on the procedure described by McLeod (2013). Two wet, two normal, and two dry years were selected for each site to determine if there was variability between years that met the same wetness criteria. The W_{em} model was then run for each of the selected years to estimate monthly head elevations for hillslope and toe-slope wells at each site, which were then used to establish the hydraulic gradient in the Darcy’s Law calculation of groundwater discharge. After monthly estimations of groundwater inputs were made, the WetBud simple model was used to determine complete monthly water budgets for the selected years at each site.

Effective Monthly Recharge Model (W_{em}) Calibration

For the W_{em} calibration period, sixteen months for PSP (May 2011 – August 2012) and thirteen months for PWMA (August 2011 – August 2012), observed monthly head levels for hillslope and toe-slope wells at both sites were used. Whittecar et al. (in review) recommend that during the calibration process one should exclude readings taken from wells at the beginning of each month that have experienced significant recent rainfall. Due to a limited number of data points in our study, all monthly head measurements were included, regardless of significant recent rainfall. Choosing to filter the data as recommended by Whittecar et al. (in review) would result in a sample size too small to complete the objectives of this analysis. Precipitation data were gathered from weather stations closest to each respective site (see methods section). Potential evapotranspiration (PET) values were calculated by WetBud, which uses the FAO-Penman-Monteith method of estimating PET. Monthly values for interception were chosen based on results from Dunne and Leopold (1978), where they describe the gross annual percentage of rain intercepted by different plant groups during leaf-on and leaf-off months. Leaf-off months are December, January, February, and March. An approximation of the forest mix for each site was based on analysis of aerial imagery. See Table 13 below for interception values used for each site.

TABLE 13. INTERCEPTION VALUES

Site ID	%Deciduous	%Coniferous	Interception (%) Leaf on	Interception (%) Leaf off
PSP	20	80	30	15
PWMA	75	25	17	10

Note: Interception values based on Dunne and Leopold (1978).

Results of the effective monthly recharge model calibration were consistent for wells at each respective site. Calibration period results for each well used in the analysis are reported in Table 14. Predicted heads closely matched observed heads, with low average monthly absolute errors (< 10 cm), and high Nash-Sutcliffe Efficiency values (> 0.84) suggest the model does a reasonable job at predicting head elevation for hillslope and toe-slope wells in these landscape settings. Hydrographs of predicted and observed head elevations are shown in Figures 27-32. Effective Monthly Recharge (W_{em}) Model output data for the calibration period can be found in Appendix F.

TABLE 14. RESULTS OF EFFECTIVE MONTHLY RECHARGE CALIBRATION

Well ID	N	D	R^2	Avg. AE (cm)	NSE	Equation of Line
PSF HS (A-A’)	15	0.85	0.93	7.0	0.93	Y = 0.0335x + 29.9180
PSF TS (A-A’)	9	0.80	0.86	8.0	0.86	Y = 0.0275x + 29.4102
PWMA HS (B-B’)	12	0.85	0.92	7.0	0.92	Y = 0.0471x + 27.1850
PWMA TS (B-B’)	14	0.80	0.88	10	0.88	Y = 0.0496x + 26.7710
PWMA HS (C-C’)	7	0.90	0.84	14	0.84	Y = 0.0432x + 27.7600
PWMA TS (C-C’)	12	0.85	0.91	6.0	0.91	Y = 0.0418x + 27.2660

Note: N-and-D combinations are those that generated the highest correlation coefficient when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. HS-hillslope; TS-toeslope; N-number of months prior; D-decay factor; NSE-Nash-Sutcliffe efficiency; Avg. AE-average monthly absolute error for observed and predicted heads for calibration period.

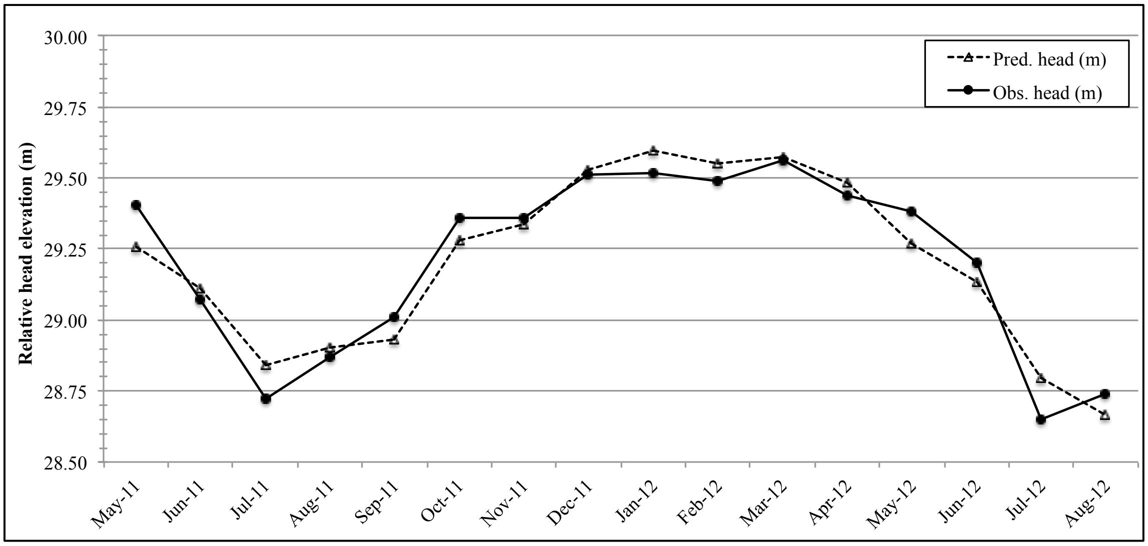


Figure 27. Effective Monthly Recharge (W_{em}) model calibration period predicted (Pred. head) and observed (Obs. head) head elevation hydrograph for Pocahontas State Park hillslope A-A'. N-and-D combinations are those that generated the highest correlation coefficient (R^2) when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. Nash-Sutcliffe Efficiency (NSE) test results for modeled and observed heads.

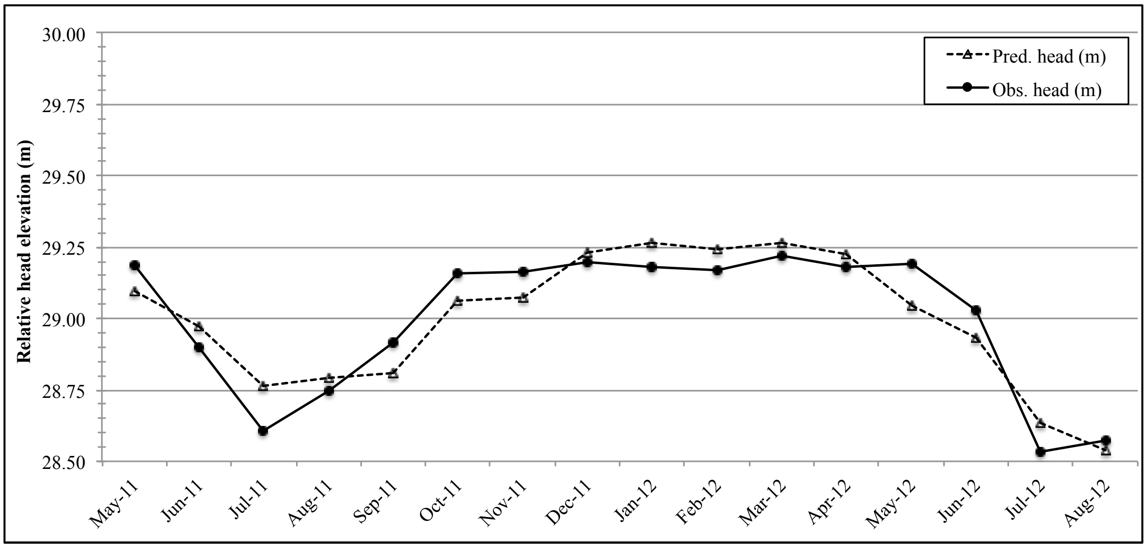


Figure 28. Effective Monthly Recharge (W_{em}) model calibration period predicted (Pred. head) and observed (Obs. head) head elevation hydrograph for Pocahontas State Park toe-slope A-A'. N-and-D combinations are those that generated the highest correlation coefficient (R^2) when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. Nash-Sutcliffe Efficiency (NSE) test results for modeled and observed heads.

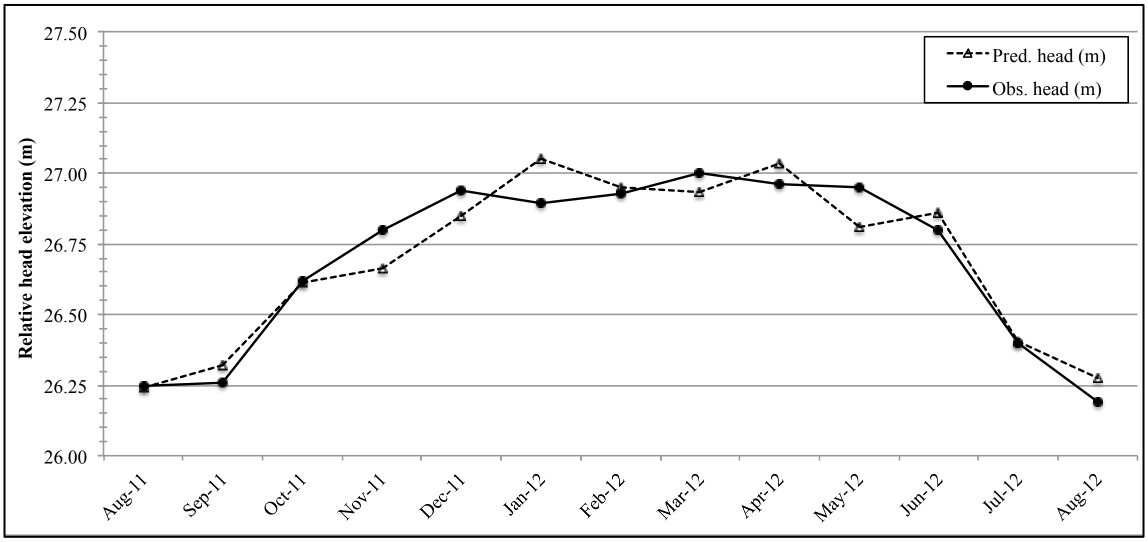


Figure 29. Effective Monthly Recharge (W_{em}) model calibration period predicted (Pred. head) and observed (Obs. head) head elevation hydrograph for Powhatan WMA hillslope B-B'. N-and-D combinations are those that generated the highest correlation coefficient (R^2) when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. Nash-Sutcliffe Efficiency (NSE) test results for modeled and observed heads.

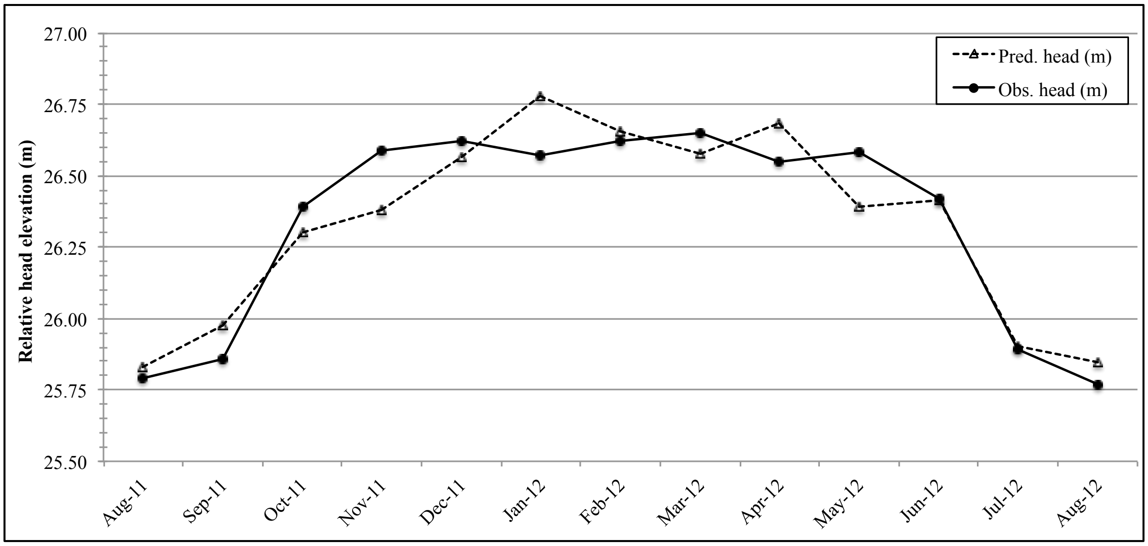


Figure 30. Effective Monthly Recharge (W_{em}) model calibration period predicted (Pred. head) and observed (Obs. head) head elevation hydrograph for Powhatan WMA toe-slope B-B'. N-and-D combinations are those that generated the highest correlation coefficient (R^2) when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. Nash-Sutcliffe Efficiency (NSE) test results for modeled and observed heads.

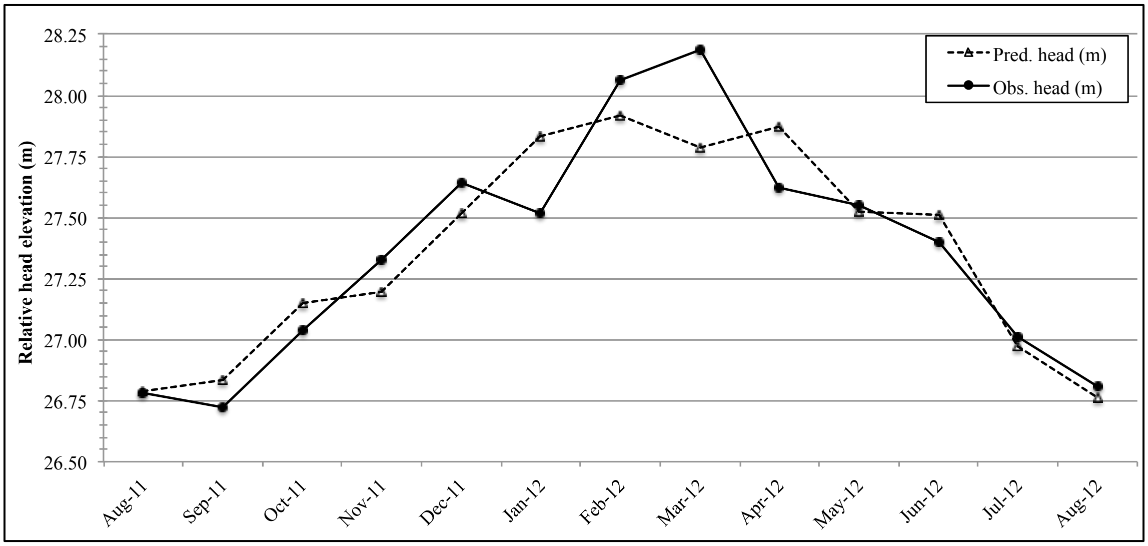


Figure 31. Effective Monthly Recharge (W_{em}) model calibration period predicted (Pred. head) and observed (Obs. head) head elevation hydrograph for Powhatan WMA hillslope C-C'. N-and-D combinations are those that generated the highest correlation coefficient (R^2) when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. Nash-Sutcliffe Efficiency (NSE) test results for modeled and observed heads.

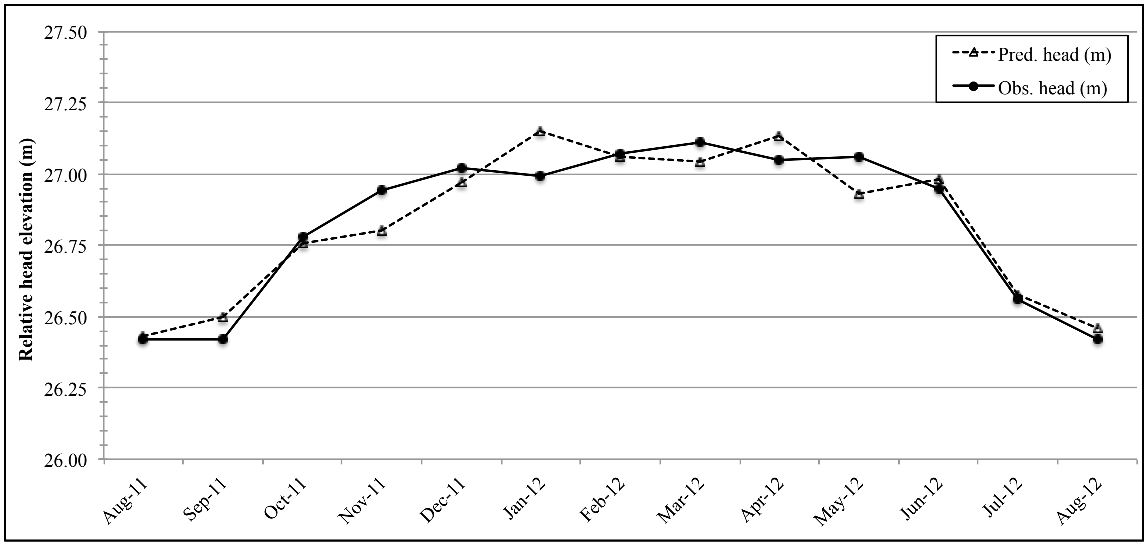


Figure 32. Effective Monthly Recharge (W_{em}) model calibration period predicted (Pred. head) and observed (Obs. head) head elevation hydrograph for Powhatan WMA toe-slope C-C'. N-and-D combinations are those that generated the highest correlation coefficient (R^2) when plotting effective monthly recharge (W_{em}) vs. observed monthly head for each well. Equations shown are the standard equation of the best-fit line used to generate predicted heads. Nash-Sutcliffe Efficiency (NSE) test results for modeled and observed heads.

The results of the W_{em} calibration reveal biases manifested on a seasonal basis at both sites. These seasonal biases can partially be explained by physical attributes (e.g. landscape position) of each well used for the calibration. During winter and summer months the W_{em} model tends to over-predict head levels. During winter months at toe-slopes water levels are commonly at or above the ground surface, upon which water is able to leave the site as surface flow. The W_{em} model does not account for surface flow leaving the site and does not establish an upper boundary for the elevation to which the water table can rise, thus resulting in an over-predicted head elevation for wells in toe-slope locations. The result of over-prediction during winter months in hillslope wells has likely developed because this model presumes the water table increases linearly and through time is partially controlled by a steady rate of groundwater outflow (Whittecar et al., in review). However, in most cases during these months there is an increase in the lateral gradient of the water table surface and thus increase in the rate of groundwater being discharged at toe-slopes, which causes the model to over-predict the amount of water being stored in the hillside. Over-predictions during summer months were not as pervasive as those during winter months and thus are likely a result of inaccuracies in weather data regarding the timing and magnitude of precipitation and temperature fluctuations between the study site and the weather station. Under-predictions were the most common during transitional months (e.g. spring and fall) but were not necessarily restricted to the months specified for those seasons. During transitional months at PSP the under-predicted error decreases as the fall leaf-off phase progresses and increases as the spring leaf-on phase begins, with similar trends being reflected in the wells at PWMA. Naturally, interception values during these months will be in transition and the results for these months reflect these trends. The associated under-predicted head values for these transitional months suggest that interception values assigned to these months are in excess of what is naturally occurring and should be reevaluated during future modeling approaches.

Overall, the results of the Effective Monthly Recharge (W_{em}) model demonstrate that it is an effective method to predict water levels for hillslope and toe-slope wells in Piedmont landscapes and should reliably predict water levels for historic years without water level data.

Wet, Normal, and Dry Year Selection

Wet, normal, and dry years for each site were selected from the range between 1980 and 2012. The initial grouping of wet, normal, and dry years was based on annual precipitation totals in the WETS table corresponding to each site. These WETS tables are located in Appendix E. The most appropriate years were then determined using the procedure outlined by McLeod (2013). The years selected for each site are reported in Table 15.

TABLE 15. YEARS SELECTED FOR WATER BUDGET ANALYSES

	PSP	PWMA
Wet	1983, 1984	1993, 2003
Normal	1999, 2000	1983, 2002
Dry	1991, 2012	1980, 2007

Groundwater Input and Output

Monthly groundwater input was calculated for the observation period from August 2011 to August 2012 and for the chosen wet, normal, and dry years at each site. For both sites, monthly groundwater input and output was calculated as a depth, which was obtained by dividing groundwater discharge by the wetland surface area. Monthly groundwater input calculated for the observation period for both sites are reported in Table 16. Due to a much larger cross-sectional area in the groundwater discharge calculation for PWMA and differences in local precipitation totals, the magnitudes of groundwater input at each site are not comparable. However, their respective trends throughout the year were slightly different. In contrast to the decrease in groundwater input during the summer at PSP, groundwater input at PWMA increased during the summer. These contrasting annual trends were also reflected in groundwater inputs for wet, normal, and dry years (Figures 33 and 34). The contrasting trends are a reflection of the ability of each respective wetland to store water at the surface. At PWMA, surface water ponding during the winter months causes a decrease in the hydraulic gradient between the toe-slope and the adjacent hillside. The wetland at PSP lacks the ability to store surface water and as water storage increases in the adjacent hillside so does the hydraulic gradient. This trend at PSP also suggests recharge in the hillside occurs at faster rate than discharge at the toe-slope. Relative magnitudes and contributions of groundwater discharge to water budget inputs for wet, normal, and dry years are discussed in the next section. Predicted head elevations from the W_{em} for wet, normal, and dry years for each site are reported in Appendix F. All variables included in groundwater input and output calculations for all years selected are reported in Appendix G.

TABLE 16. OBSERVED MONTHLY GROUNDWATER INPUT

Mo./Yr.	PWMA (cm)	PSP (cm)
Aug-11	3.93	0.44
Sep-11	2.54	1.24
Oct-11	2.55	1.19
Nov-11	3.13	1.66
Dec-11	3.88	2.29
Jan-12	3.96	2.17
Feb-12	4.03	2.03
Mar-12	5.16	2.10
Apr-12	4.25	1.39
May-12	4.31	1.15
Jun-12	4.47	0.90
Jul-12	4.54	0.60
Aug-12	3.86	1.32
Avg.	3.89	1.35

Note: Groundwater input values for PWMA represent the average of monthly groundwater input calculated for transects B-B’ and C-C’.

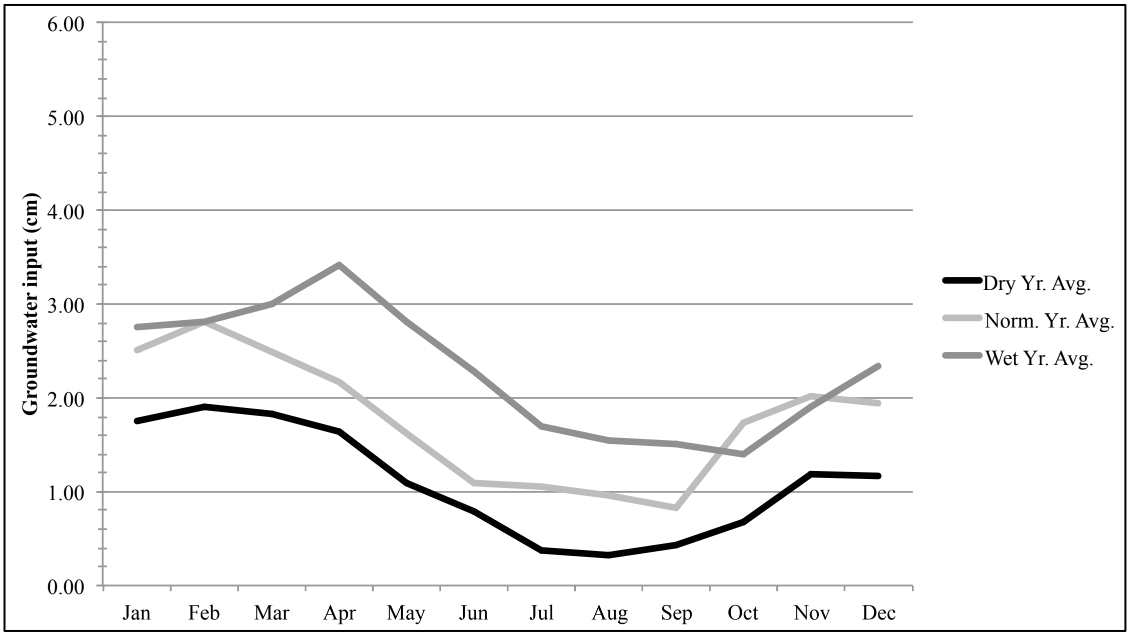


Figure 33. Average monthly groundwater input for wet, normal, and dry years selected for analysis at Pocahontas State Park study site.

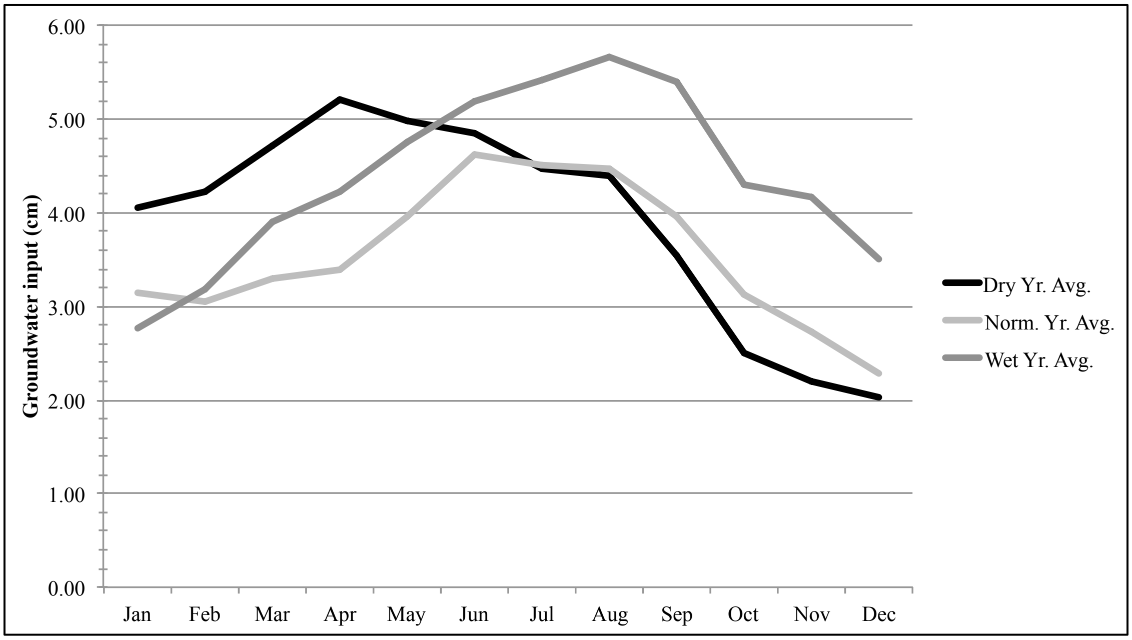


Figure 34. Average monthly groundwater input for wet, normal, and dry years selected for analysis at Powhatan WMA study site.

Monthly Wetland Water Budgets

Monthly wetland water budgets were developed for the 13-month (August 2011-August 2012) calibration period and for the selected wet, normal, and dry years at each site using the WetBud Basic model. The model was calibrated for each site by performing a sensitivity analysis of specific yield. Specific yield values used in the analysis ranged from 0.10 to 0.50. For PSP and PWMA, specific yield values of 0.45 (NSE = 0.88) and 0.15 (NSE = 0.89) produced the best fit between predicted and observed water levels, respectively, and were the values used for all further model runs at each site. Predicted water levels and Nash-Sutcliffe Efficiency values for all sensitivity runs are reported in Appendix H.

Predicted water levels closely matched observed head levels for each site (Figures 35 and 36). Overestimations of depth-to-water were most common. In general, the larger errors were more common during fall and spring months for both sites. The average of monthly absolute errors during the calibration period for PSP and PWMA were 7 cm and 9 cm, respectively. The largest absolute error for PSP was an underestimate of 17 cm, occurring during May 2012. Likewise, at PWMA the largest error was an underestimate of 25 cm during June 2012. Similar to the errors seen in the Effective Monthly Recharge (W_{em}) model, it is likely that many can be attributed to inaccuracies in weather data that differ from the conditions experienced at the site. It is also possible for errors in the predicted water levels to be an artifact of errors in the W_{em}, which was used in the process of estimating groundwater inputs. Overall, even the largest errors in predicted water levels at both sites were minimal, thus confidence can be placed in model predictions for years that lack water level data.

At both sites predicted monthly water levels showed considerable variability between years that met the same wetness criteria (Figures 37 and 38). At PSP, dry years had similar trends throughout the year. Likewise, trends for both normal years were nearly identical at PWMA. Based on the observation period at each site, the overall ranges for all years simulated at both sites appear to be within an expected range of water levels. At PWMA, the greatest range in water level was 264 cm during dry year 1980. From the period between 1980 and 2012, 1980 and 2003 received the lowest and highest total annual precipitation in Powhatan, VA, respectively. Thus these simulations

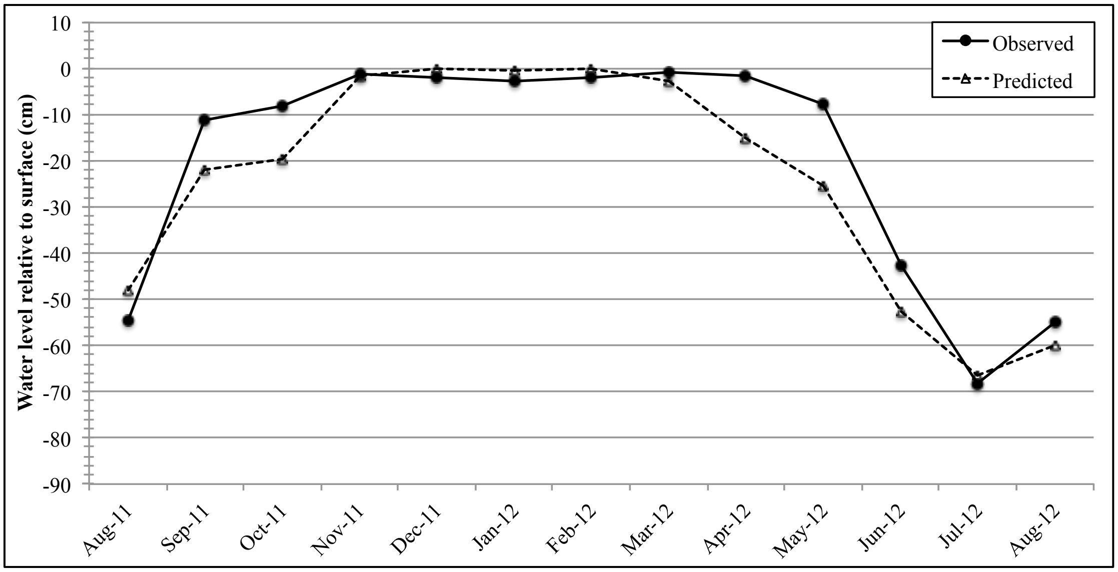


Figure 35. Predicted and observed water level for Pocahontas State Park WetBud basic model calibration period.

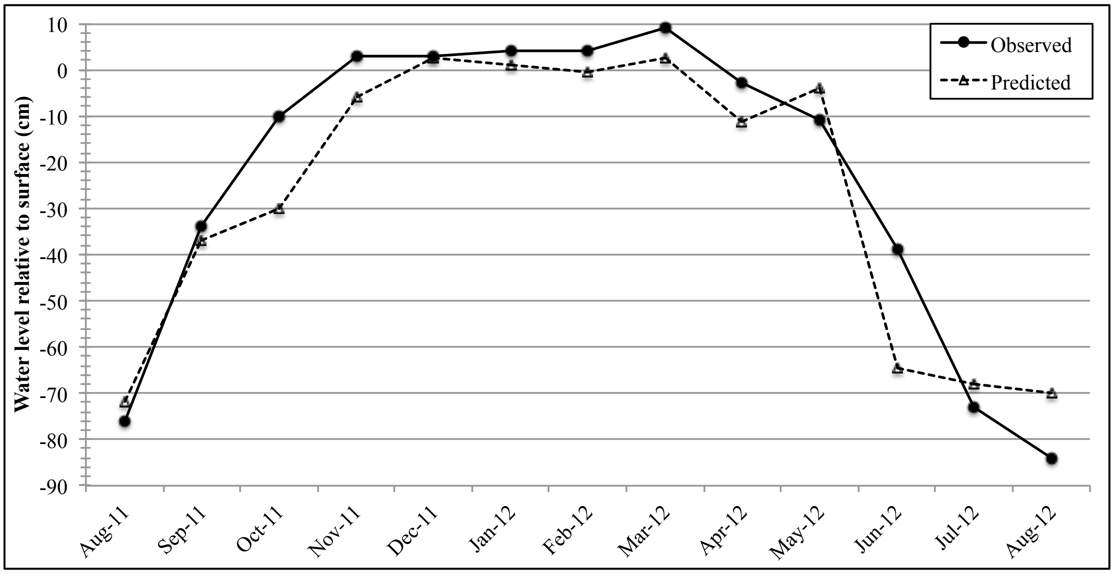


Figure 36. Predicted and observed water level for Powhatan WMA WetBud basic model calibration period.

represent endpoints in the range of conditions experienced at this wetland. In contrast, the driest year on record at PSP was 2012 and the predicted water table range was approximately 60 cm, much closer to that seen during wet year 1983 and normal year 1999. Dry year 1991 at PSP, the median of dry years over the same period of record, experienced the largest range in water level, at 90 cm. During the spring months there were marked differences in the rate of water table decline between like years at PSP, whereas at PWMA the rates of water table decline are roughly similar for all but the wettest year.

At each site monthly water budget inputs were analyzed to determine the relative contribution of groundwater on annual and seasonal bases. At PSP, the contribution of groundwater to annual water budget inputs was very similar for all years. During normal and dry years at PSP, the average total annual contribution of groundwater to water budget inputs was 13.5%. During wet years at PSP, the average total annual contribution of groundwater was 16.5%. Overall, the data suggest that regardless of yearly precipitation totals at PSP the contribution of groundwater to water budget inputs will be approximately 15.0%. Annual water budget inputs and their respective percentages for the years analyzed at PSP are reported in Tables 17 and 18. At PWMA, average groundwater inputs accounted for 21.5%, 30.5%, and 38.0% for wet, normal, and dry years, respectively. The larger contribution of groundwater during dry years at PWMA is in contrast to that seen at PSP. Annual water budget inputs and their respective percentages for the years analyzed at PWMA are reported in Tables 19 and 20.

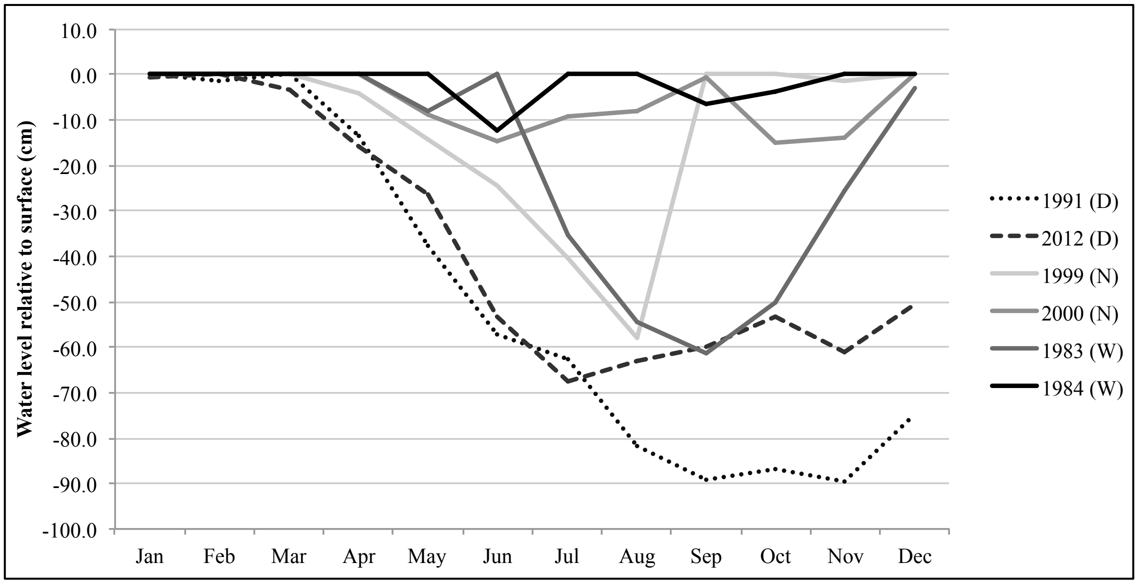


Figure 37. Predicted average monthly water levels for wet (W), normal (N), and dry (D) years at Pocahontas State Park study site. Note: scale on y-axis is much less than y-axis shown in Figure 38.

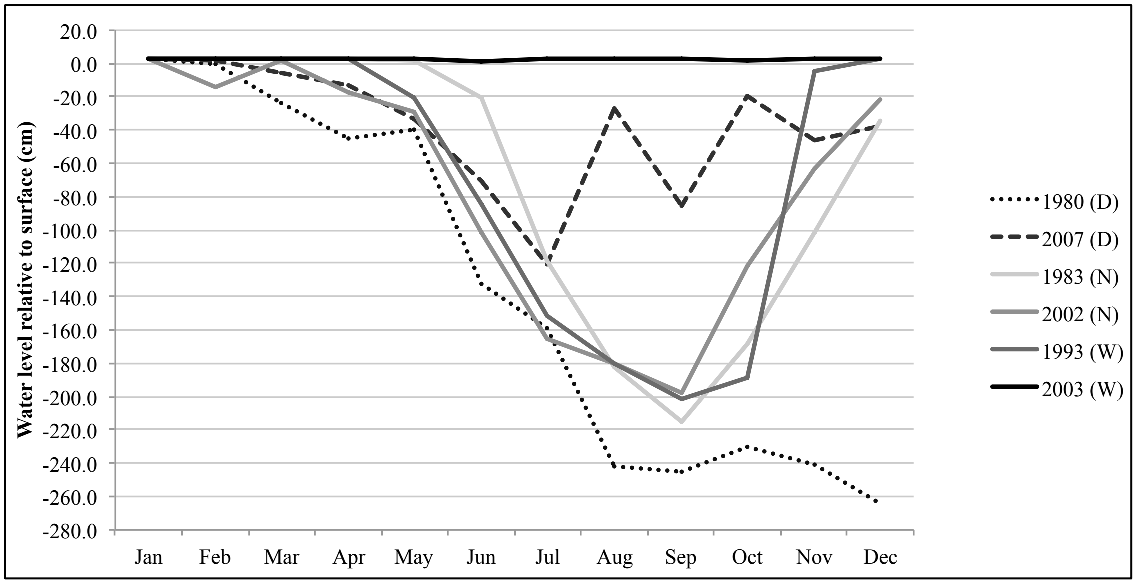


Figure 38. Predicted average monthly water levels for wet (W), normal (N), and dry (D) years at Powhatan WMA study site. Note: scale on y-axis is much greater than y-axis shown Figure 37.

TABLE 17. TOTAL ANNUAL WATER BUDGET INPUTS AT PSP

Year	GW input (cm)	Precipitation (cm)	Runoff (cm)	Total (cm)
1991 (Dry)	11.6	92.5	3.9	108.0
2012 (Dry)	14.8	77	1.4	93.2
1999 (Normal)	20.3	118.4	65.1	203.8
2000 (Normal)	22.1	105.3	4.4	131.8
1983 (Wet)	24.2	124.5	27.7	176.4
1984 (Wet)	30.8	124.7	9.4	164.9

TABLE 18. PERCENTAGE OF ANNUAL WATER BUDGET INPUTS AT PSP

Year	GW input (%)	Precipitation (%)	Runoff (%)	Total (%)
1991 (Dry)	11	86	3	100
2012 (Dry)	16	83	1	100
1999 (Normal)	10	58	32	100
2000 (Normal)	17	80	3	100
1983 (Wet)	14	70	16	100
1984 (Wet)	19	75	6	100

TABLE 19. TOTAL ANNUAL WATER BUDGET INPUTS AT PWMA

Year	GW input (cm)	Precipitation (cm)	Runoff (cm)	Total (cm)
1980 (Dry)	54.2	69.0	2.5	125.7
2007 (Dry)	52.4	91	18.2	161.6
1983 (Normal)	50.7	108.6	4.6	163.9
2002 (Normal)	46.1	106.8	1.7	154.6
1993 (Wet)	49.4	124.9	24.4	198.7
2003 (Wet)	44.8	173.4	34.1	252.3

TABLE 20. PERCENTAGE OF ANNUAL WATER BUDGET INPUTS AT PWMA

Year	GW input (%)	Precipitation (%)	Runoff (%)	Total (%)
1980 (Dry)	43	55	2	100
2007 (Dry)	33	56	11	100
1983 (Normal)	31	66	3	100
2002 (Normal)	30	69	1	100
1993 (Wet)	25	63	12	100
2003 (Wet)	18	69	13	100

The seasonal contribution of groundwater to water budget inputs was analyzed to determine if it plays a larger role during the spring and summer months that are most critical for wetland vegetation. At PSP, results of the seasonal analyses were similar to the annual totals regarding groundwater input, where its seasonal contribution to water budget inputs was comparable between wet, normal, and dry years, where it accounted for roughly 20% during winter, spring, and fall (Figure 39). However, during dry and normal year summer months groundwater only accounted for an average of 9% (Figure 39). Due to lower input from precipitation and runoff during these months it was expected that groundwater input would account for a larger portion of total inputs, however, due to the decrease in groundwater input during these months this did not occur. Results of the seasonal analyses at PSP are reported in Table 21. Complete monthly water budgets for all years analyzed at PSP are reported in Appendix I.

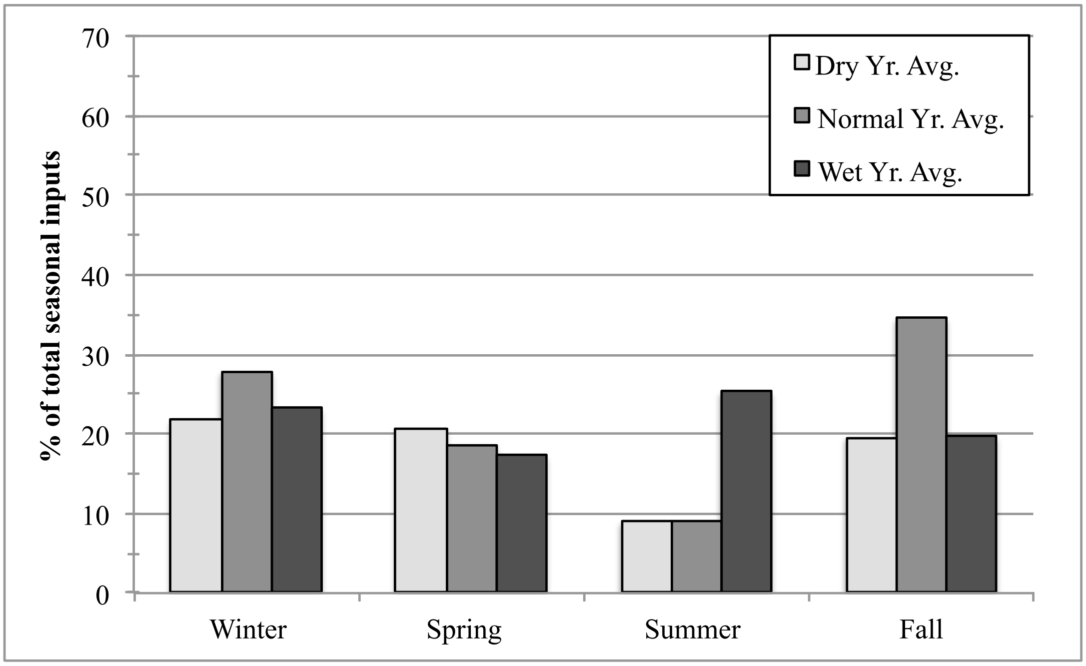


Figure 39. Pocahontas State Park average seasonal contribution of groundwater input.

TABLE 21. SEASONAL AVERAGE GROUNDWATER CONTRIBUTION TO WATER BUDGET INPUTS FOR WET, NORMAL, AND DRY YEARS AT PSP

Year	Winter (%)	Spring (%)	Summer (%)	Fall (%)
1991 (D)	18	22	5	9
2012 (D)	25	19	13	31
1999 (N)	31	21	7	23
2000 (N)	24	17	11	46
1983 (W)	22	18	31	8
1984 (W)	25	17	20	31
Dry Yr. Avg.	22	21	9	20
Norm. Yr. Avg.	28	19	9	35
Wet Yr. Avg.	23	17	25	20

Note: percentages represent the average percentage of monthly groundwater input contributing to water budget inputs for each season. Winter months are December-February, spring months are March-May, summer months are June-August, and fall months are September-November. D-dry year; N-normal year; W-wet year.

Seasonal trends for the range of years at PWMA were in contrast to those seen at PSP. During drier years at PWMA, groundwater input accounts for up to 40% of water budget inputs during spring and up to 46% during summer (Figure 40). During spring months, dry groundwater input for dry years accounted for an average of 15% more than normal years and 20% more than wet years (Figure 40). During summer months, groundwater input accounted for 46% during dry years and 48% during normal years, compared to 33% during wet years, which is a result of result of greater precipitation and surface runoff entering the site during wetter years (Figure 40). As shown in Table 22, the relatively large and sustained contribution of groundwater to water budget inputs throughout the year is a reflection of monthly groundwater input trends, which increase during the summer months at this site. These results suggest groundwater input plays a critical role in maintaining wetland hydrology at this site during dry years and through the drier months of spring and summer. Complete monthly water budgets for all years analyzed at PWMA are reported in Appendix I.

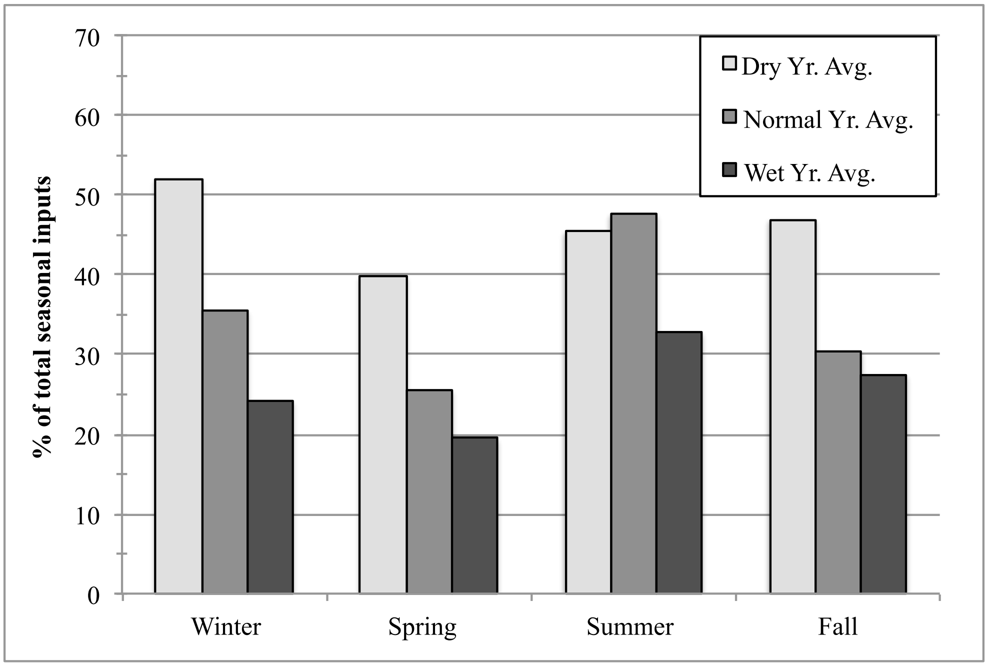


Figure 40. Powhatan WMA average seasonal contribution of groundwater input.

TABLE 22. SEASONAL AVERAGE GROUNDWATER CONTRIBUTION TO WATER BUDGET INPUTS FOR WET, NORMAL, AND DRY YEARS AT PWMA

Year	Winter (%)	Spring (%)	Summer (%)	Fall (%)
1980 (D)	64	44	61	39
2007 (D)	40	36	30	55
1983 (N)	32	22	55	36
2002 (N)	39	29	40	25
1993 (W)	23	20	45	32
2003 (W)	25	19	21	23
Dry Yr. Avg.	52	40	46	47
Norm. Yr. Avg.	36	26	48	31
Wet Yr. Avg.	24	20	33	28

Note: percentages represent the average percentage of monthly groundwater input contributing to water budget inputs for each season. Winter months are December-February, spring months are March-May, summer months are June-August, and fall months are September-November. D-dry year; N-normal year; W-wet year.

CHAPTER 4

DISCUSSION AND CONCLUSIONS

This study reveals that local floodplain morphology is the major factor influencing hydrology at the two sites. The influence of these factors becomes evident when looking at the annual trend of groundwater entering each site. Differences in these trends are illustrated in Figure 41, which shows the average annual trend of groundwater input at each site for an equally scaled cross-section across which groundwater input has been calculated. When equally scaled, we see that the annual trend of groundwater input is more stable at PWMA and in contrast to PSP, groundwater input increases during the spring and summer months. This trend occurs at PWMA because the thick package of floodplain sediment and the lack of connectivity with the adjacent stream allows for a steepening hydraulic gradient during the spring and summer months, causing groundwater inputs to remain stable when water levels in the floodplain decline.

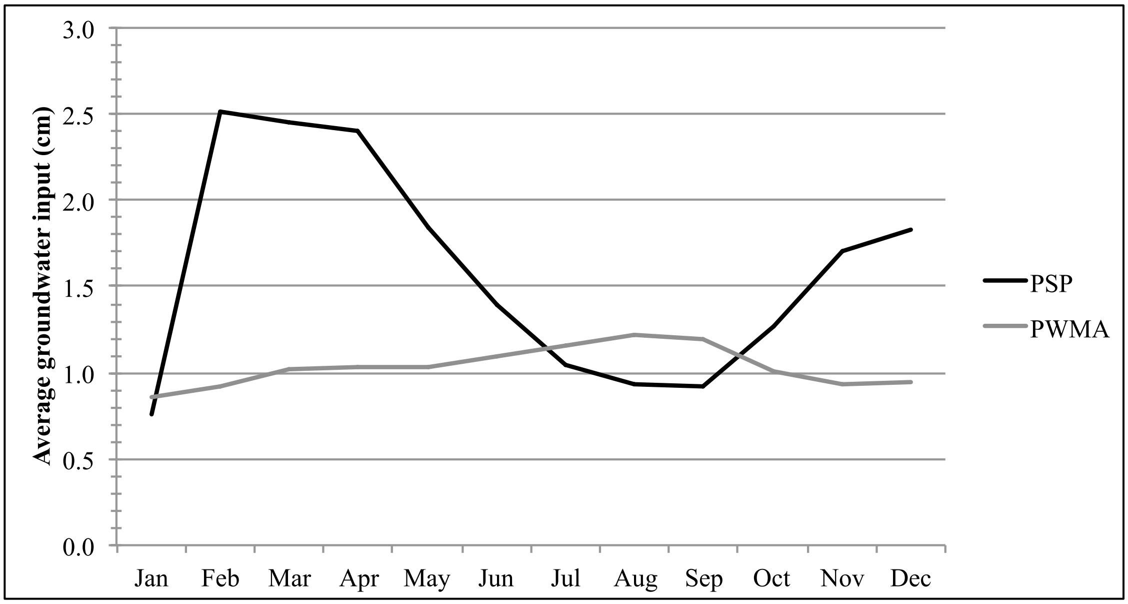


Figure 41. Average groundwater input for equal-scaled cross-section at each site. Average monthly groundwater input was calculated monthly for all years included in the analyses at each site. PSP = Pocahontas State Park. PWMA = Powhatan WMA.

The respective morphology of each site is also reflected in the range of fluctuation in annual water levels. The water table surface was relatively flat across the floodplain at PSP, suggesting the adjacent stream limits the amount of groundwater output throughout the year. Expectedly, at PWMA the depth to the water table surface increases with distance from the toe-slope due to the lack of hydraulic connectivity with the adjacent stream, which results in more groundwater lost as discharge to the stream. In addition, macropores in the heterogeneous sediments at PWMA may be causing water levels to drop more rapidly closer to the stream edge. The relatively flat water table surface across the floodplain at PSP makes this type of morphology more suitable for simple water budget models, which assume the wetland is a flat level pool and cannot predict spatial differences in water levels. In contrast, considerable uncertainty exists when using a simple model for sites similar to PWMA that exhibit highly variable water levels from toe-slope to stream.

Overall, the Effective Monthly Recharge (W_{em}) model was effective for predicting water levels for wells in Piedmont hillslope and toe-slope landscape positions. However, the largest and most common errors in water level predictions were made during fall and spring months. This model could be improved by determining interception values for these transitional leaf-on and leaf-off months. In addition, future studies should test the versatility of the W_{em} to predict water levels in wells extending farther out into the floodplain. If proven effective for wells located in positions out across the floodplain, water level predictions for these positions could be used to supplement water level predictions made by simple box models that are calibrated using observed water levels in the toe-slope.

The WetBud basic model was calibrated using observed toe-slope water levels at each site and performed well during the observation period at both sites. Although a fair degree of confidence can be placed in model runs for the years that lacked observed water level data, there are several assumptions that should be noted. The WetBud basic model did not account for topography of the surrounding landscape or micro-topography within the wetland, which control the amount of runoff entering the site during large rain events and the distribution and amount of surface flow entering and leaving the site, respectively. Because of these assumptions considerable uncertainty exists regarding surface flow parameters and their contribution to the water budgets for each wetland. In addition, due to the difficulty estimating monthly groundwater outflow this parameter was assigned a constant value for yearly simulations at both sites. Assigning a constant value may be more appropriate for sites such as PSP where the water table gradient fluctuates little from month-to-month and is at least partially controlled by water level in the adjacent stream. In contrast, seasonal fluctuations in water table gradients at PWMA cause the greater variation in the rate of groundwater outflow, which introduces a source of error by assigning a constant rate of groundwater outflow. The error associated with this parameter will be evaluated during further development of the WetBud program.

With conscious regard to the possible sources of error, results of the wetland water budgets have provided important insight into the range of conditions expected in these Piedmont wetlands. Wet, normal, and dry years were selected based on specific criteria designed to eliminate years that do not appropriately represent the hydrologic conditions their annual precipitation totals imply. One goal of this selection procedure was to enhance prediction capabilities by establishing a baseline for water levels that occur at a given site during these years. In most cases, the range of predicted water levels for any given wet, normal, or dry year at the two sites included in this study were highly variable, making it difficult to definitively ascertain what water levels were ‘normal’ or ‘dry’. The variability of results for years that fell in the same wetness category demonstrated the importance of multi-year, monthly water budget analyses. In addition, this type of analysis should not be used to establish ‘typical’ water levels for a given wet, normal, or dry year but rather use these years to determine the overall range of water levels one can expect during a range of hydrologic conditions.

For the range of years analyzed at each site, groundwater contributed a substantial portion of water budget inputs and the consistent results suggest that this contribution can be readily predicted. At PSP, groundwater contributed approximately 20% to annual water budget inputs regardless of annual precipitation totals. The relative contribution of groundwater to seasonal water budgets was consistent for the range of years as well. At PWMA, consistent trends between years in the same wetness category suggest these predictions are reliable as well. On average, groundwater contributed roughly 10% more to annual inputs than years in the next wettest category, where during dry years the average annual groundwater input contributed approximately 40% as opposed to 30% during normal years. For most years at PWMA, seasonal groundwater contributions were greater during drier months.

One notable feature of predicted water levels for the range of years analyzed at PWMA was that only small differences were seen in water levels during spring months. These results are encouraging for planning purposes because these months are most critical for early succession in wetland plants. However, the water levels rapidly declined during the spring months for dry years at PSP, which has implications for plant mortality early in the growing season. The ability of these models to accurately predict water levels during these spring months is critical for mitigation planning, the success of which is largely dictated by rates of plant mortality. Furthermore, recovery of water table following dry years with exceptionally dry winters is crucial to the next spring. In 3 out of 4 dry year simulations, water levels shows slow or no recovery heading into the next year. Should dry conditions persist for the next several months, wetland plants could experience severe stress during the following spring. This type of scenario could easily go unnoticed if the following year fails to meet the wet, normal, dry spring criterion associated with the annual precipitation total. In the event that this situation occurs it is recommended that the water budget analysis should be extended through the following year.

Several conclusions regarding Piedmont valley bottom wetland water budgets have been drawn from this study and should be taken into consideration for all further analyses in these systems. Lithology and morphology exert a major influence on site hydrology and water budget studies should be constructed based on observed data regarding these parameters rather than generalizations made for any particular region. When coupled with the Effective Monthly Recharge (W_{em}) model, the WetBud basic model provides a practical platform that can be used to reliably predict the contribution of groundwater to wetland water budgets for years that lack observed water level data or for years in the future. Furthermore, at least two years falling in wet, normal, and dry wetness categories should be included in water budget analyses to ensure the range of expected conditions and variability within those conditions is accounted for.

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APPENDIX A

WELL COMPLETION REPORTS AND AUGER-HOLE LOGS

Well Completion Report

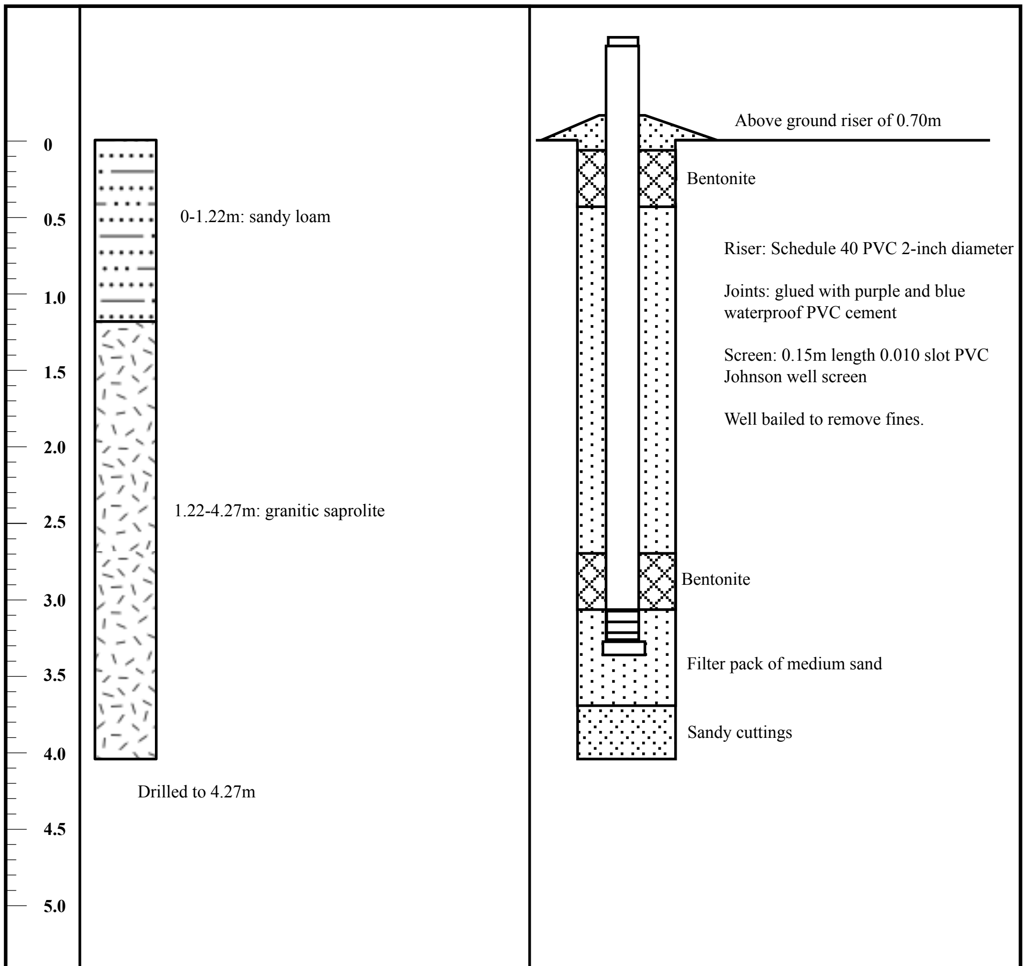
Project: Pocahontas State Park
Location: Hillslope

Well Name: HSDP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 31.18m above datum

Construction Date: 3/5/11

Scale (m) **Borehole Information** **Well Construction Information**



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old
Dominion University, Norfolk, Virginia

Well Completion Report

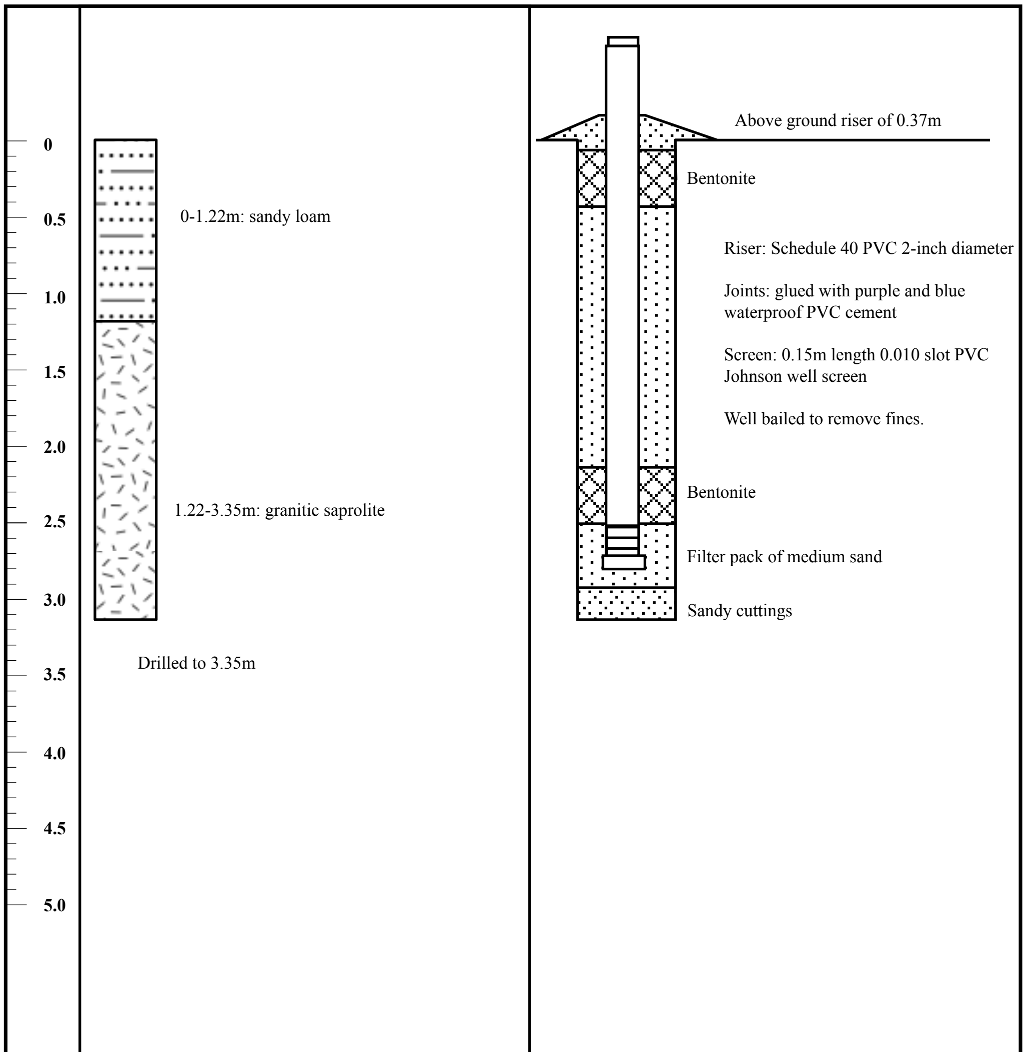
Project: Pocahontas State Park
Location: Hillslope

Well Name: HSSP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 30.85m above datum

Construction Date: 3/5/11

Scale (m) **Borehole Information** **Well Construction Information**



Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old
Dominion University, Norfolk, Virginia

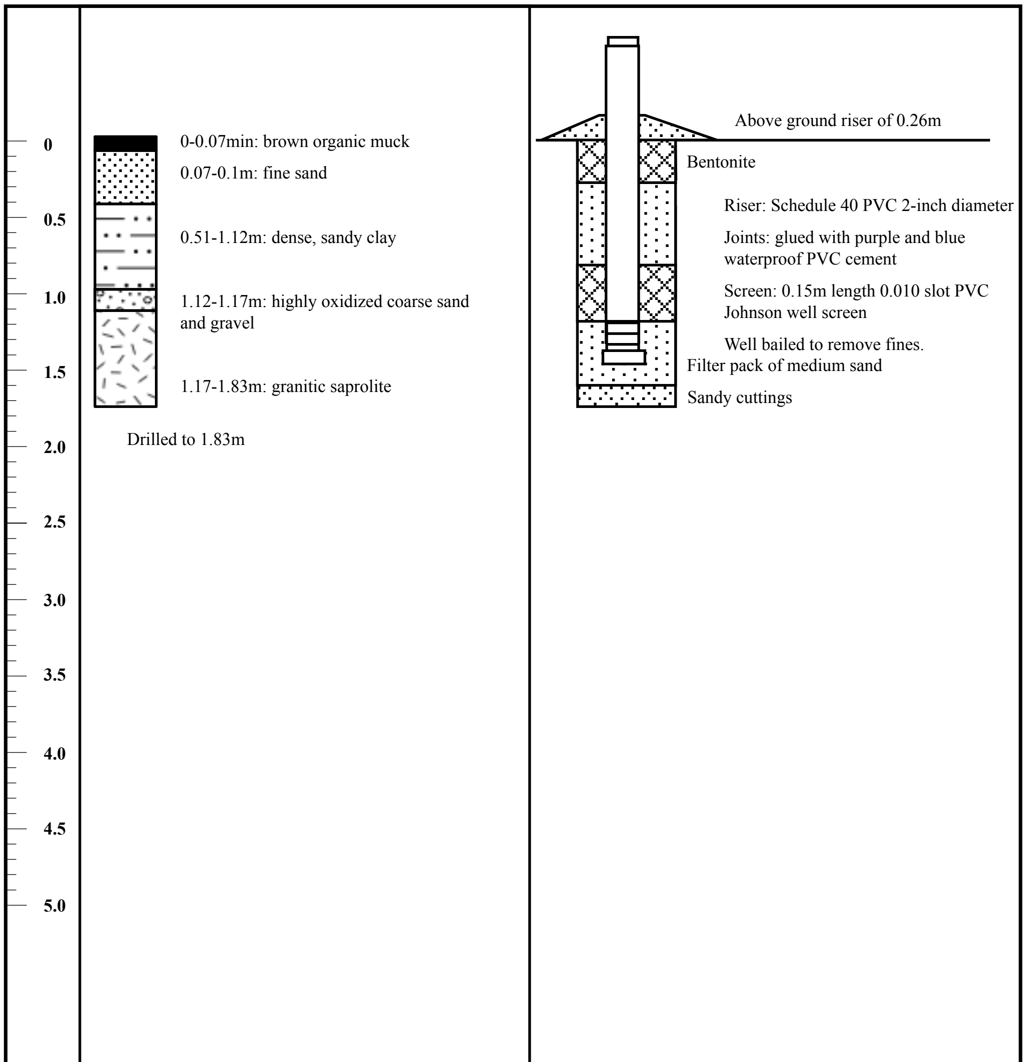
Well Completion Report

Project: Pocahontas State Park
Location: Toeslope

Well Name: TSDP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.46m above datum

Construction Date: 3/5/11



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old
Dominion University, Norfolk, Virginia

Well Completion Report

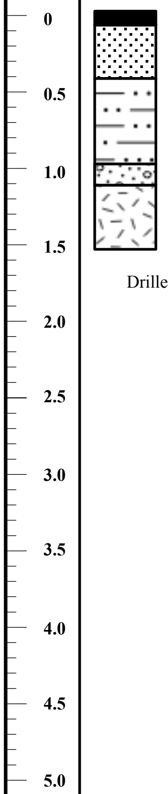
Project: Pocahontas State Park
Location: Toeslope

Well Name: TSSP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.43m above datum

Construction Date: 3/5/11

Scale (m) Borehole Information



0-0.07min: brown organic muck

0.07-0.1m: fine sand

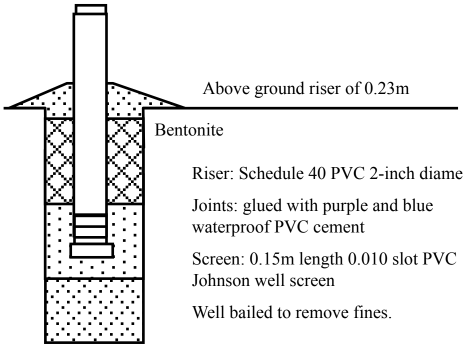
0.51-1.12m: dense, sandy clay

1.12-1.17m: highly oxidized coarse sand and gravel

1.17-1.52m: granitic saprolite

Drilled to 1.52m

Well Construction Information



Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Pocahontas State Park
Location: Middle of floodplain

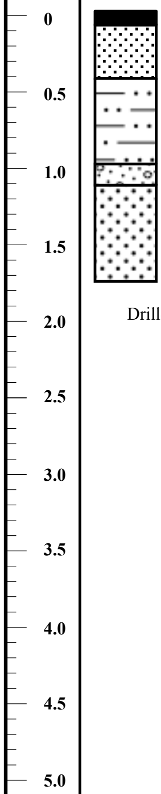
Well Name: MFMW
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.48m above datum

Construction Date: 3/5/11

Scale (m) **Borehole Information** **Well Construction Information**

Borehole ID: PSP-3



0-0.07m: brown organic muck

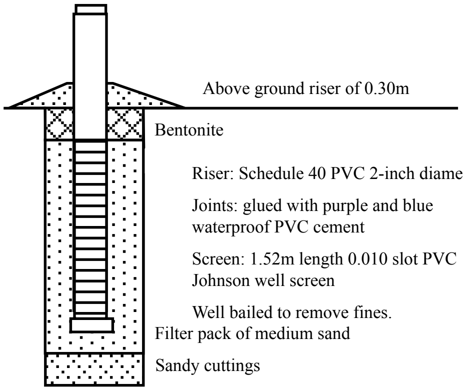
0.07-1.12m: fine sand

0.51-1.12m: dense, sandy clay

1.12-1.17m: highly oxidized coarse sand and gravel

1.17-1.83m: medium to coarse sand

Drilled to 1.83m



Above ground riser of 0.30m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 1.52m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

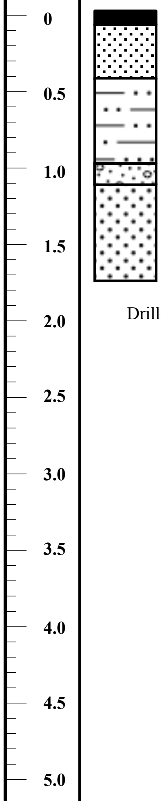
Project: Pocahontas State Park
Location: Middle of floodplain

Well Name: MFDP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.56m above datum

Construction Date: 3/5/11

Scale (m) **Borehole Information**



0-0.07m: brown organic muck

0.07-1.12m: fine sand

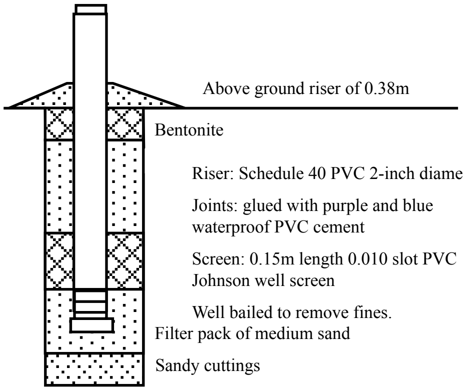
0.51-1.12m: dense, sandy clay

1.12-1.17m: highly oxidized coarse sand and gravel

1.17-1.83m: medium to coarse sand

Drilled to 1.83m

Well Construction Information



Above ground riser of 0.38m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

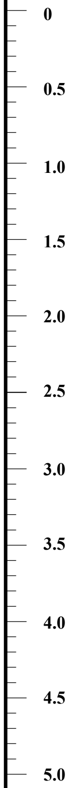
Well Completion Report

Project: Pocahontas State Park
Location: Between mid-floodplain and dry edge next to stream
Top of auger hole elevation: 29.18

Well Name: no well in this location
Augered by: K Dobbs
Auger hole Date: 3/5/11

Scale (m) **Borehole Information** **Well Construction Information**

Borehole ID: PSP-4



0-0.75m: silty loam

0.75-1.60m: dense, sandy clay

1.60-2.00m: highly oxidized coarse sand and gravel

Drilled to 2.00m

Report Approved by:_______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Pocahontas State Park
Location: Dry edge next to stream

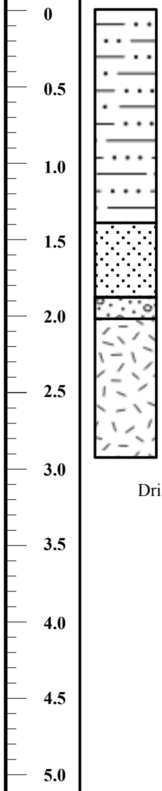
Well Name: DEMW
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.88m above datum

Construction Date: 3/5/11

Scale (m) Borehole Information

Borehole ID: PSP-5



0-1.52m: silty clay loam

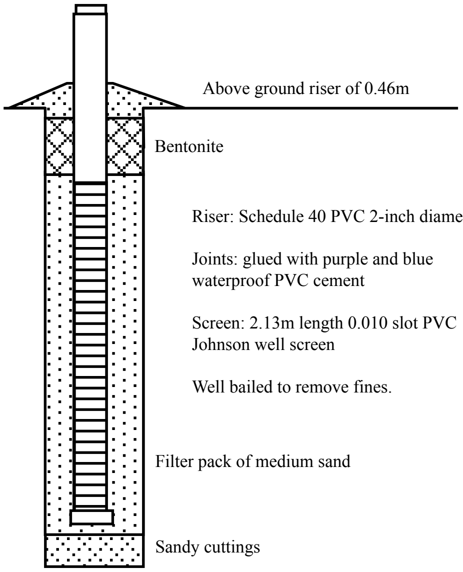
1.52-2.11m: micaceous clayey medium sand

2.11-2.16m: highly oxidized coarse sand and gravel

2.16-3.05m: granitic saprolite

Drilled to 3.05m

Well Construction Information



Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 2.13m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

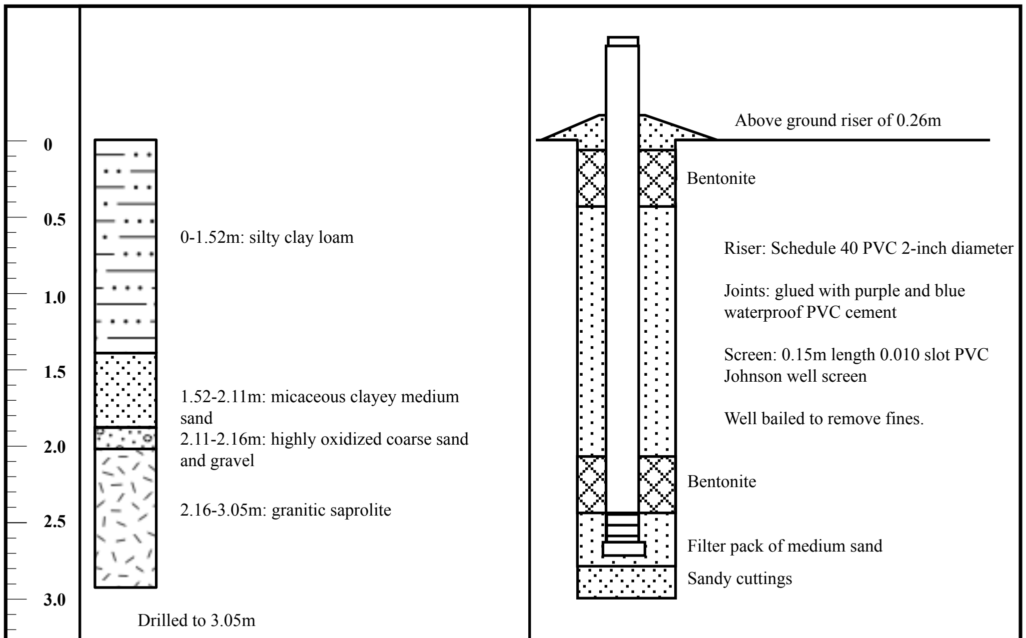
Project: Pocahontas State Park
Location: Dry edge next to stream

Well Name: DEDP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.68m above datum

Construction Date: 3/5/11

Scale (m) **Borehole Information** **Well Construction Information**



0-1.52m: silty clay loam

1.52-2.11m: micaceous clayey medium sand

2.11-2.16m: highly oxidized coarse sand and gravel

2.16-3.05m: granitic saprolite

Drilled to 3.05m

Above ground riser of 0.26m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Bentonite

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

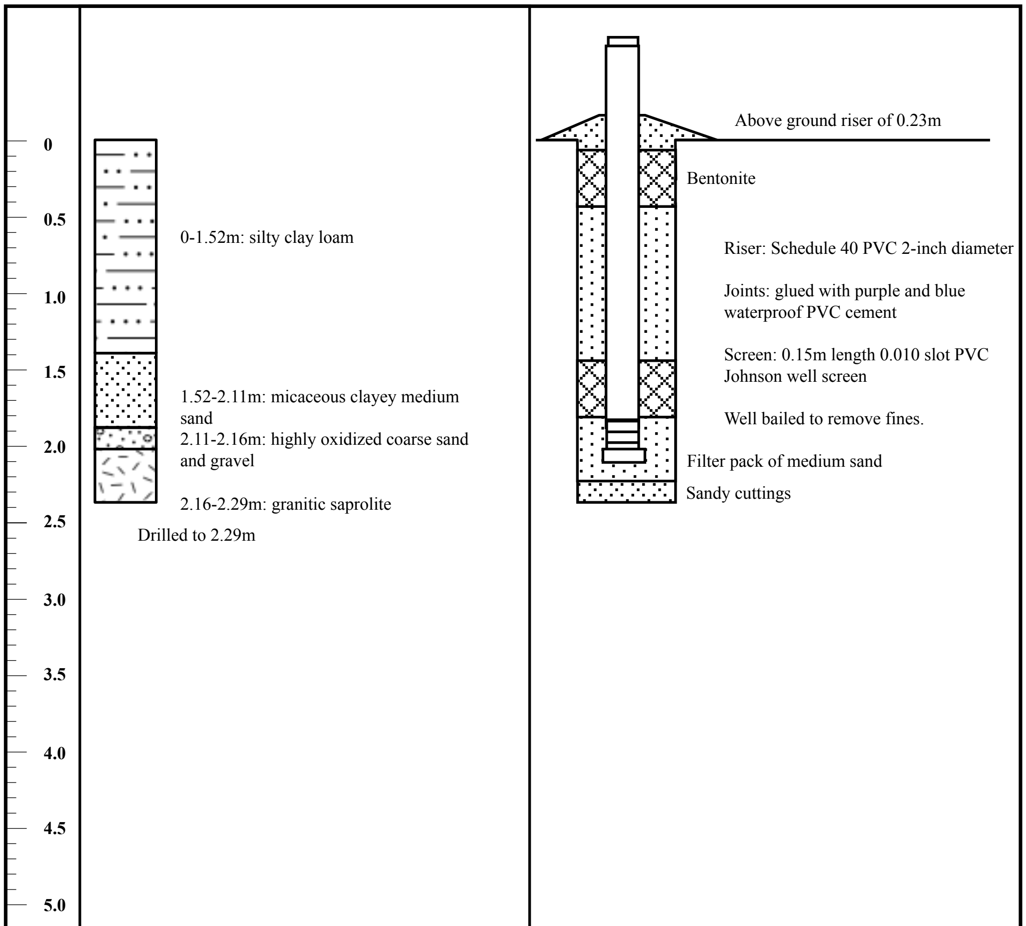
Project: Pocahontas State Park
Location: Dry edge next to stream

Well Name: DESP
Constructed by: K Dobbs and H Walden

Top of casing elevation: 29.65m above datum

Construction Date: 3/5/11

Scale (m) **Borehole Information** **Well Construction Information**



0-1.52m: silty clay loam

1.52-2.11m: micaceous clayey medium sand

2.11-2.16m: highly oxidized coarse sand and gravel

2.16-2.29m: granitic saprolite

Drilled to 2.29m

Above ground riser of 0.23m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old
Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area

Location: Transect B-B' hillslope

Top of casing elevation: 28.32m above datum

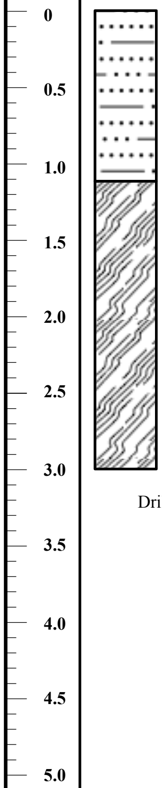
Well Name: HSMW1

Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**

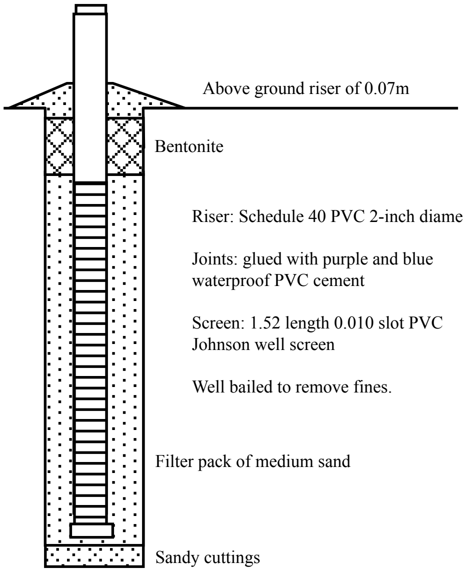
Borehole ID: PWMA-1



0-1.22m: sandy loam

1.22-3.05m: gneissic saprolite

Drilled to 3.05m



Above ground riser of 0.07m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 1.52 length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

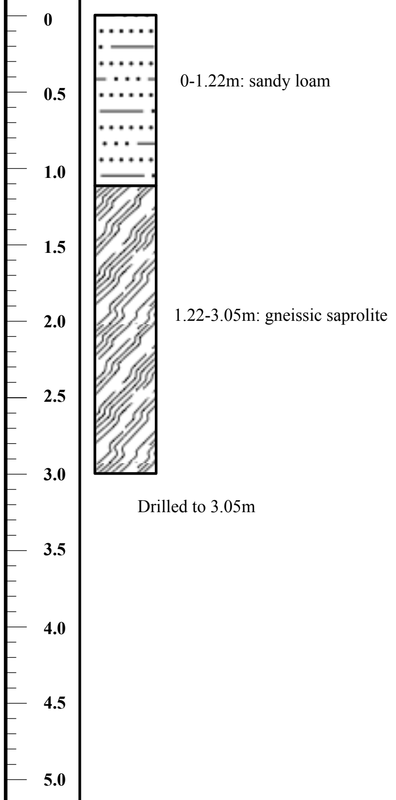
Project: Powhatan Wildlife Management Area
Location: Transect B-B' hillslope

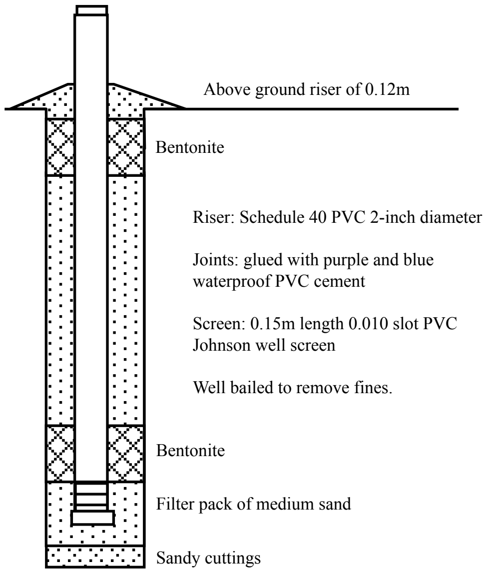
Top of casing elevation: 28.36m above datum

Well Name: HSDP1
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**





Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

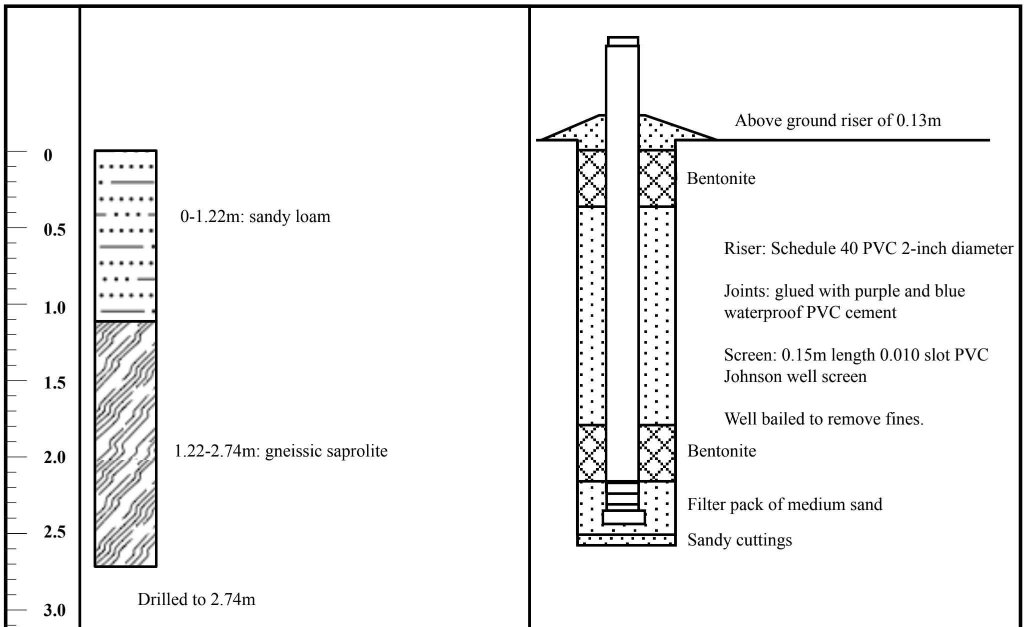
Project: Powhatan Wildlife Management Area
Location: Transect B-B’ hillslope

Top of casing elevation: 28.37m above datum

Well Name: HSSP1
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

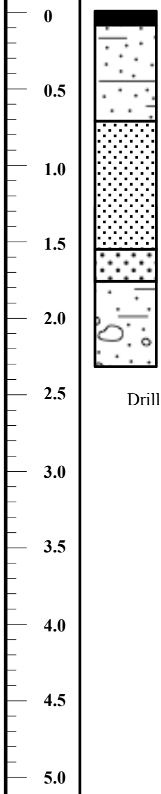
Project: Powhatan Wildlife Management Area
Location: Transect B-B’ toe-slope

Top of casing elevation: 26.71m above datum

Well Name: TSDP1
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) — Borehole Information



0-0.05m: brown organics

0.05-0.76m: clayey medium sand

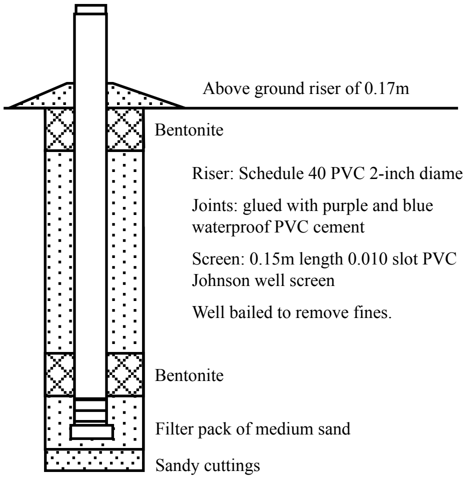
0.76-1.68m: clayey fine sand

1.68-1.83m: coarse sand

1.83-2.44m: Lenses of coarse angular sand in clayey fine sand

Drilled to 2.44m

Well Construction Information



Above ground riser of 0.17m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Bentonite

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

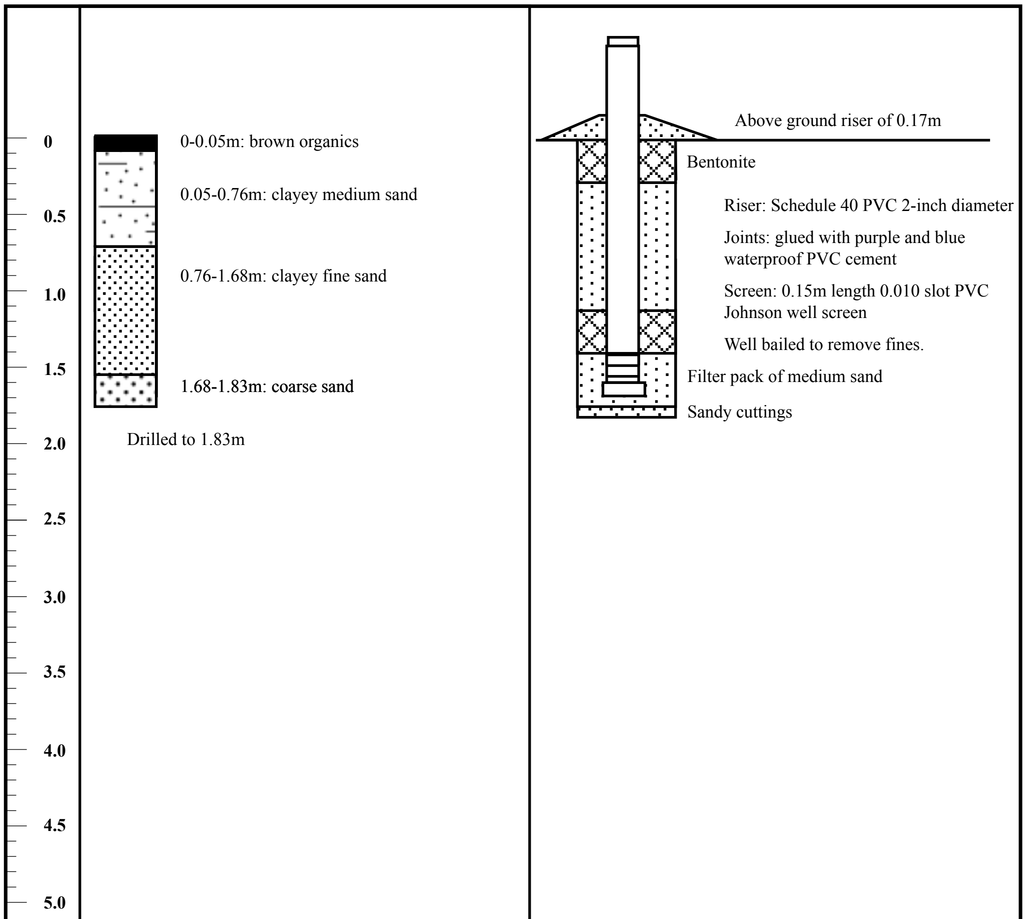
Project: Powhatan Wildlife Management Area
Location: Transect B-B’ toe-slope

Top of casing elevation: 26.69m above datum

Well Name: TSSP1
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect B-B’ mid-floodplain

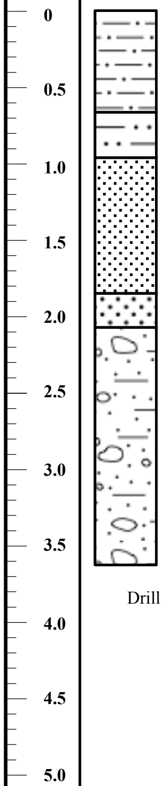
Top of casing elevation: 27.08m above datum

Well Name: MWMF1
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information**

Borehole ID: PWMA-3



0-0.71m: silty loam

0.71-1.02m: sandy clay

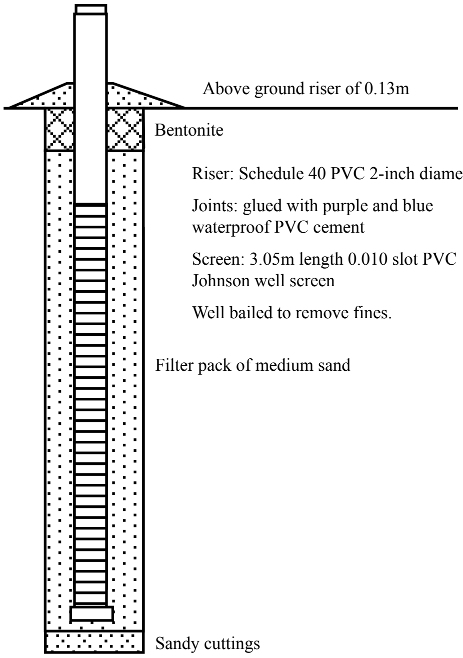
1.02-1.88m: clayey fine sand

1.88-2.11m: coarse sand

2.11-3.66m: Lenses of coarse angular sand in clayey fine sand

Drilled to 3.66m

Well Construction Information



Above ground riser of 0.13m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 3.05m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area

Location: Transect B-B’ mid-floodplain

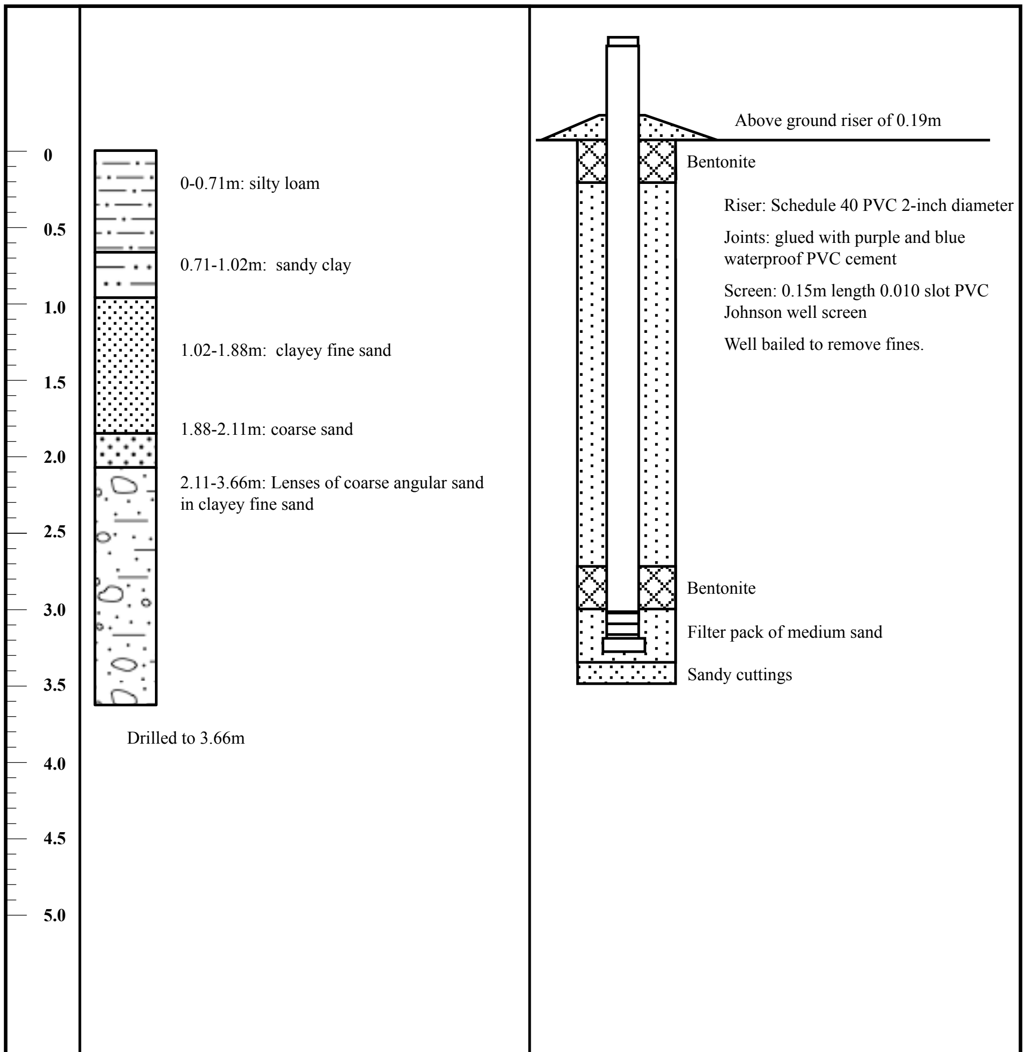
Top of casing elevation: 27.09m above datum

Well Name: MFDP1

Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

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Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect B-B’ approx. 5 m from stream bank

Well Name: DEMW1
Constructed by: K Dobbs

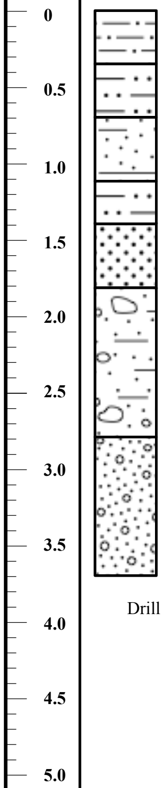
Top of casing elevation: 27.26m above datum

Construction Date: 1/14/12

Scale (m) Borehole Information

Well Construction Information

Borehole ID: PWMA-4



0-0.41m: silty loam

0.41-0.76m: sandy clay

0.76-1.19m: clayey fine sand becomes sandier with depth

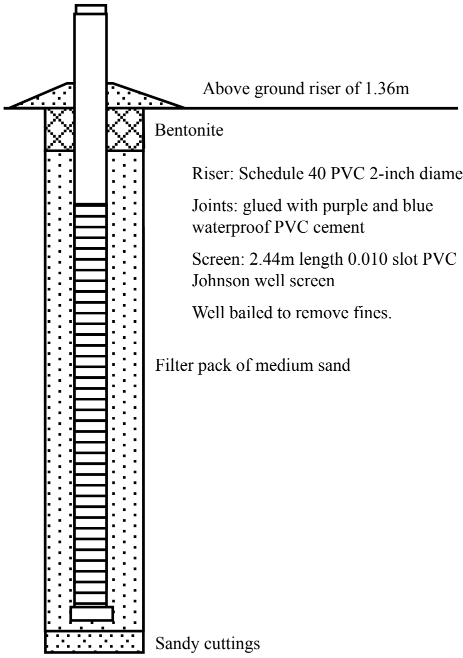
1.19-1.52m: very dense sandy clay becomes sandier with depth

1.52-1.91m: very coarse sand

1.91-3.05m: very dense clay with some coarse sand and gravel in matrix (likely same unit as that listed as 60-96” in MF1 boreholes), unit coarsens with depth

3.05-3.66m: very coarse sand and sub-rounded/sub-angular gravel

Drilled to 3.66m



Above ground riser of 1.36m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 2.44m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

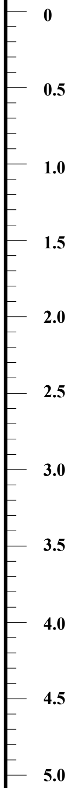
Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

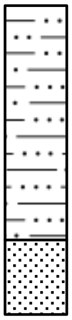
Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Sallee Creek stream bed
Well Name: no well in this location
Constructed by: K Dobbs

Elevation: 24.94m
Construction Date: 1/14/12

Scale (m)	**Borehole Information**	**Well Construction Information**
	Borehole ID: PWMA-5	





0-1.52m: sandy clay

1.52-2.0m: fine sand coarsens with depth to medium-coarse sand

Drilled to 2.0m

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

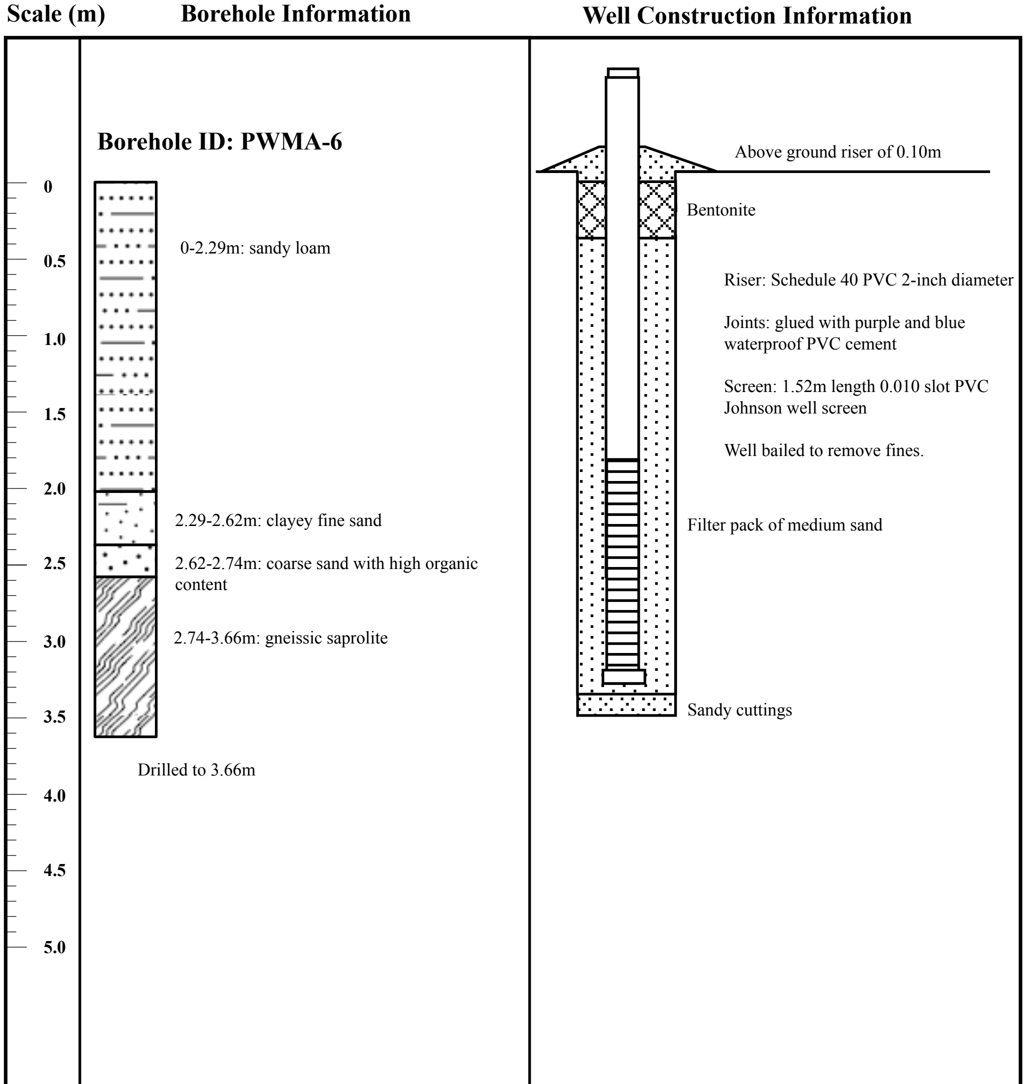
Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect C-C' hillslope swale

Top of casing elevation: 28.81m above datum

Well Name: HSMW2
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area

Location: Transect C-C' hillslope swale

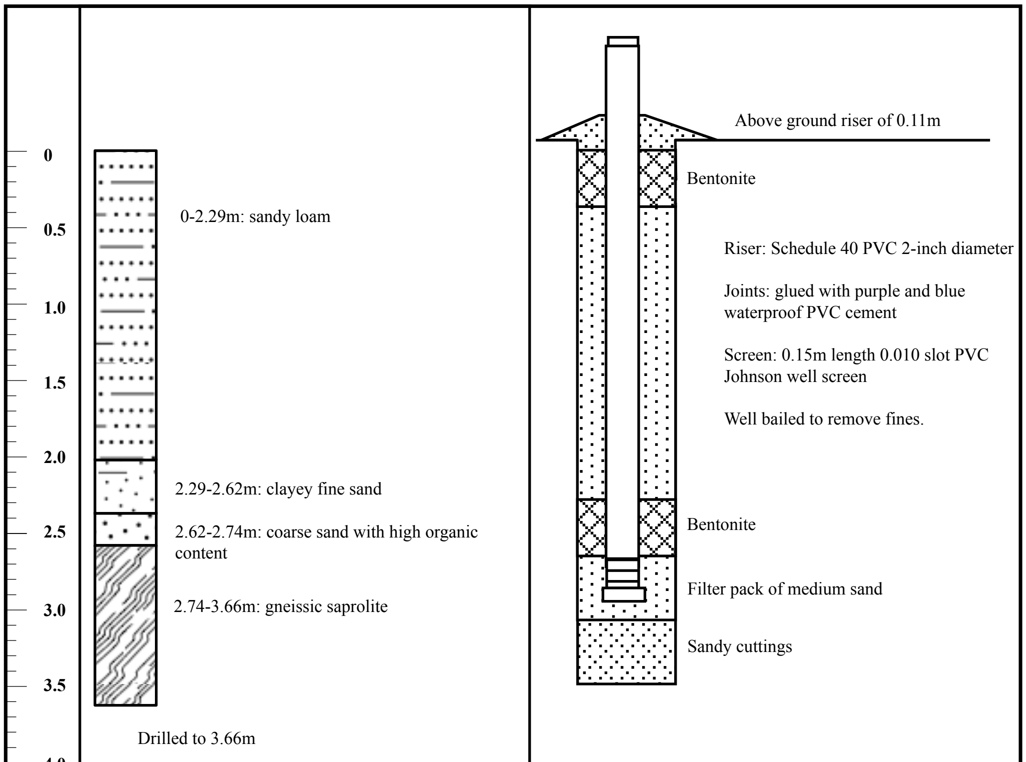
Top of casing elevation: 28.82m above datum

Well Name: HSDP2

Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**



Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect C-C' toe-slope

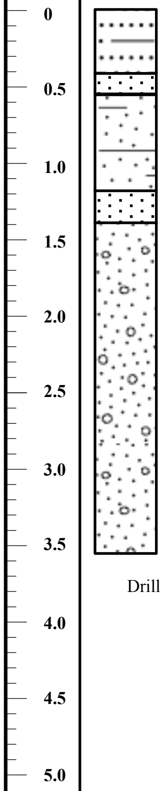
Top of casing elevation: 27.16m above datum

Well Name: TSMW2
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**

Borehole ID: PWMA-7



0-0.56m: sandy loam

0.56-0.61m: brown organic-rich medium sand

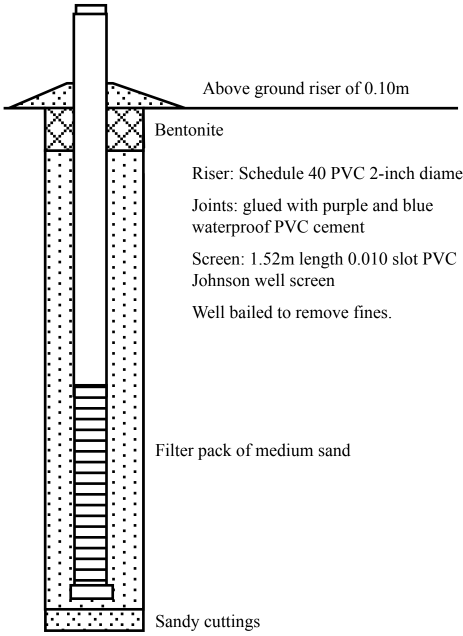
0.61-1.22m: sandy clay

1.22-1.52m: clayey sand with coarse pebbles at base

1.52-2.08m: **reduced** coarse sub-round/sub-angular sand and gravel

2.08-3.51m: highly **oxidized** coarse sub-round/sub-angular sand and gravel

Drilled to 3.51m



Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 1.52m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Report Approved by:______________________

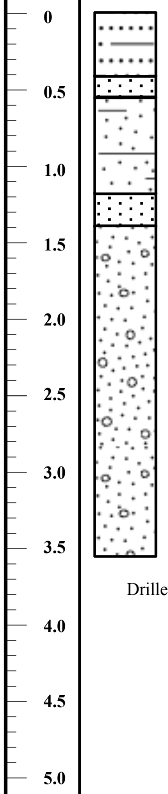
Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect C-C’ toe-slope
Top of casing elevation: 27.19m above datum

Well Name: TSDP2
Constructed by: K Dobbs M Richardson and W Myers
Construction Date: 7/1/11

Scale (m) **Borehole Information**



0-0.56m: sandy loam

0.56-0.61m: brown organic-rich medium sand

0.61-1.22m: sandy clay

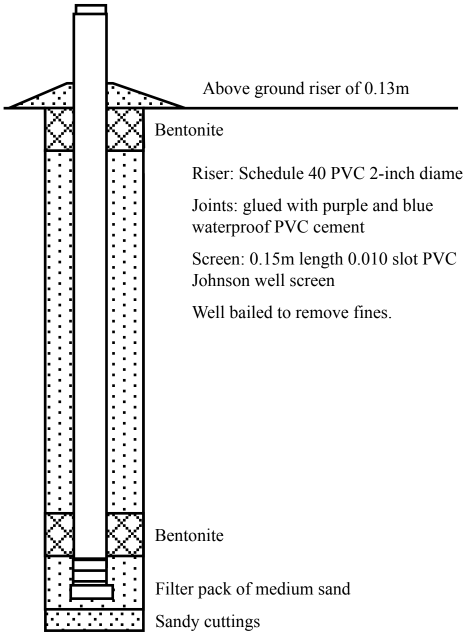
1.22-1.52m: clayey sand with coarse pebbles at base

1.52-2.08m: **reduced** coarse sub-round/sub-angular sand and gravel

2.08-3.51m: highly **oxidized** coarse sub-round/sub-angular sand and gravel

Drilled to 3.51m

Well Construction Information



Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

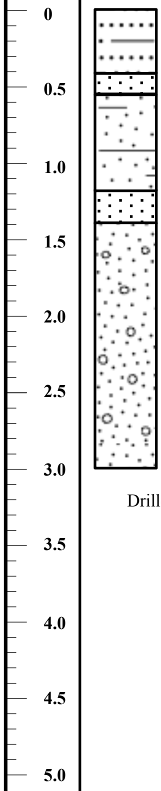
Project: Powhatan Wildlife Management Area
Location: Transect C-C' toe-slope

Top of casing elevation: 27.09m above datum

Well Name: TSSP2
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) Borehole Information



0-0.56m: sandy loam

0.56-0.61m: brown organic-rich medium sand

0.61-1.22m: sandy clay

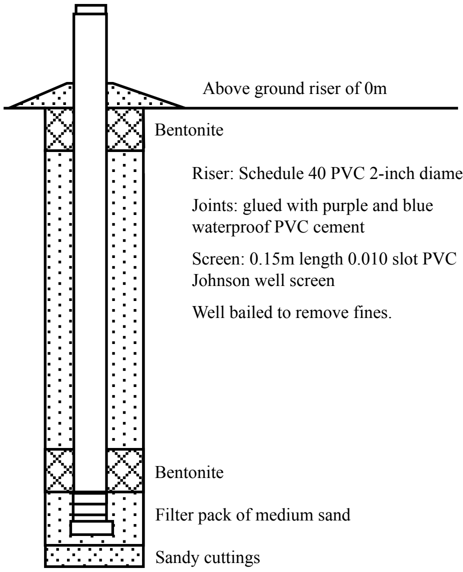
1.22-1.52m: clayey sand with coarse pebbles at base

1.52-2.08m: **reduced** coarse sub-round/sub-angular sand and gravel

2.08-3.05m: highly **oxidized** coarse sub-round/sub-angular sand and gravel

Drilled to 3.05m

Well Construction Information



Above ground riser of 0m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Bentonite

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

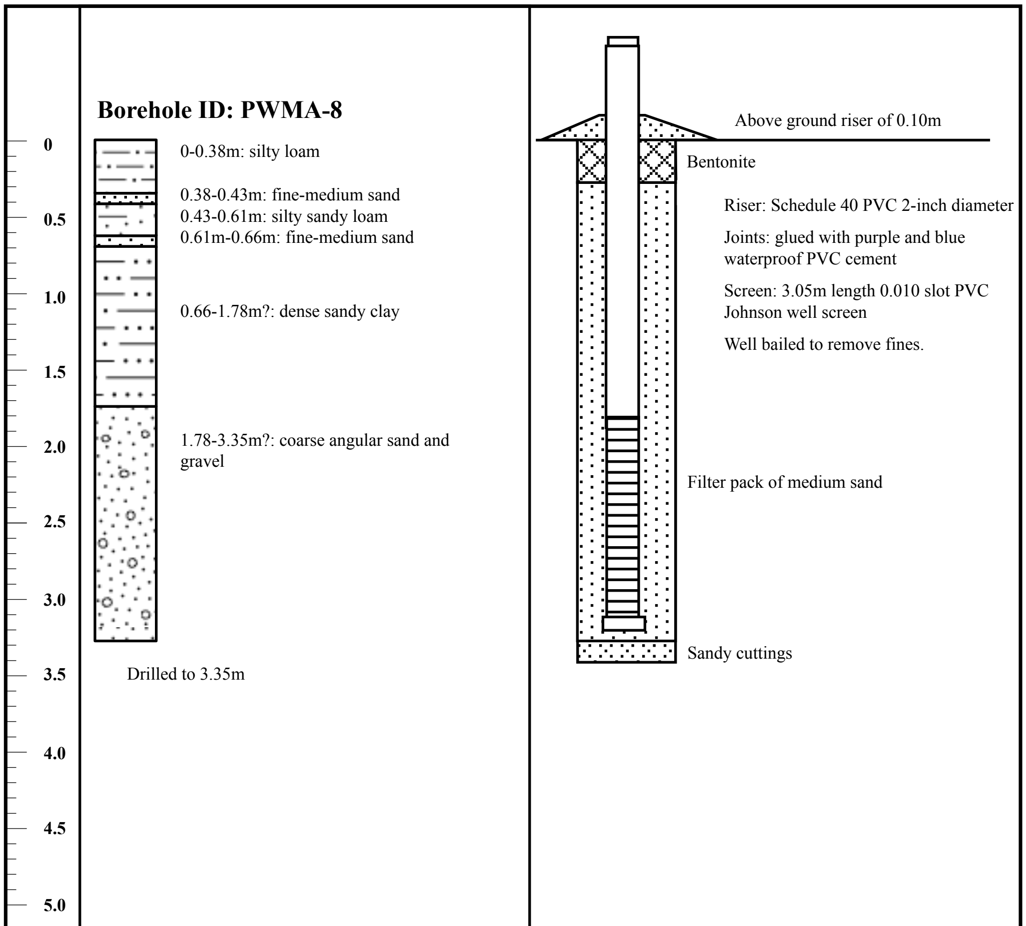
Project: Powhatan Wildlife Management Area
Location: Transect C-C’ mid-floodplain

Top of casing elevation: 27.00m above datum

Well Name: MFMW2
Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) **Borehole Information** **Well Construction Information**



Borehole ID: PWMA-8

0-0.38m: silty loam
0.38-0.43m: fine-medium sand
0.43-0.61m: silty sandy loam
0.61m-0.66m: fine-medium sand
0.66-1.78m?: dense sandy clay
1.78-3.35m?: coarse angular sand and gravel

Drilled to 3.35m

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 3.05m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

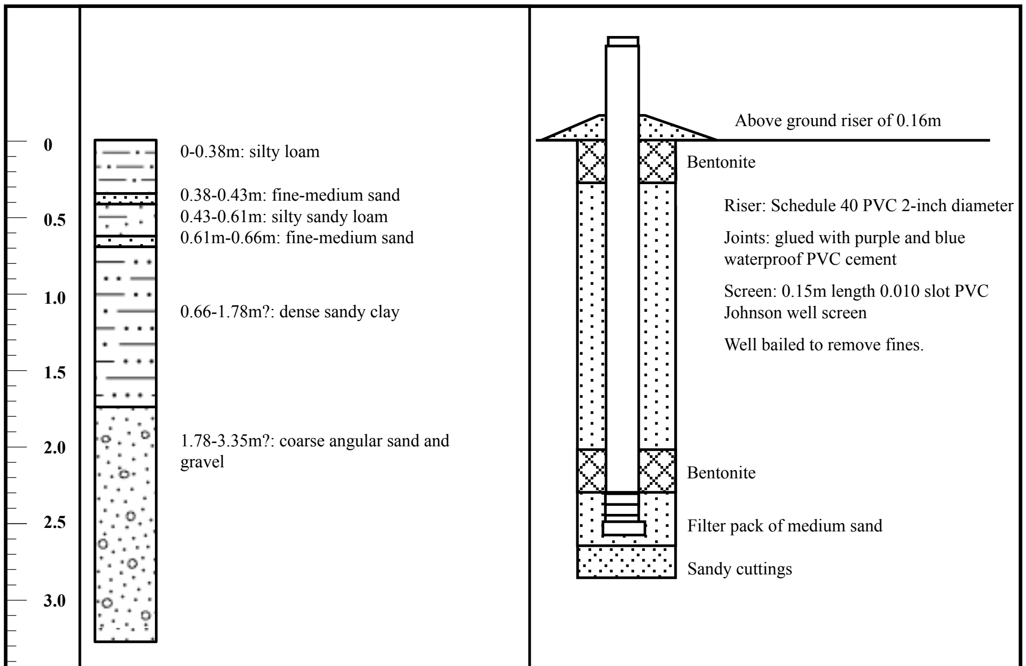
Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect C-C’ mid-floodplain
Top of casing elevation: 27.06m above datum

Well Name: MFDP2
Constructed by: K Dobbs M Richardson and W Myers
Construction Date: 7/1/11



0-0.38m: silty loam
0.38-0.43m: fine-medium sand
0.43-0.61m: silty sandy loam
0.61m-0.66m: fine-medium sand
0.66-1.78m?: dense sandy clay
1.78-3.35m?: coarse angular sand and gravel
Drilled to 3.35m

Above ground riser of 0.16m
Bentonite
Riser: Schedule 40 PVC 2-inch diameter
Joints: glued with purple and blue waterproof PVC cement
Screen: 0.15m length 0.010 slot PVC Johnson well screen
Well bailed to remove fines.
Bentonite
Filter pack of medium sand
Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area

Location: Transect C-C’ mid-floodplain

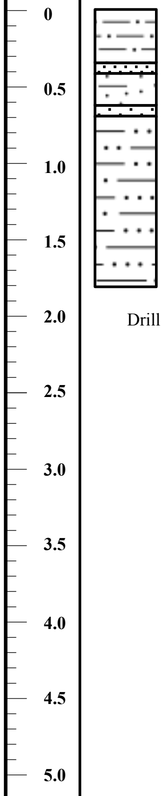
Top of casing elevation: 27.04m above datum

Well Name: MFSP2

Constructed by: K Dobbs M Richardson and W Myers

Construction Date: 7/1/11

Scale (m) Borehole Information



0-0.38m: silty loam

0.38-0.43m: fine-medium sand

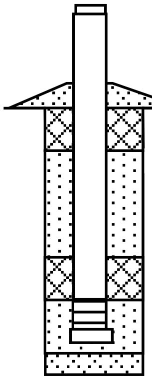
0.43-0.61m: silty sandy loam

0.61m-0.66m: fine-medium sand

0.66-1.83m?: dense sandy clay

Drilled to 1.83m

Well Construction Information



Above ground riser of 0.14m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 0.15m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

Well Completion Report

Project: Powhatan Wildlife Management Area
Location: Transect C-C’ 15m from stream bank

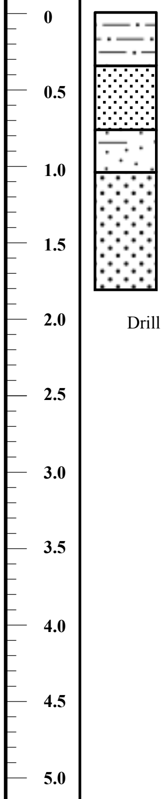
Well Name: DEMW2
Constructed by: K Dobbs

Top of casing elevation: 27.10m above datum

Construction Date: 1/14/12

Scale (m) **Borehole Information** **Well Construction Information**

Borehole ID: PWMA-9



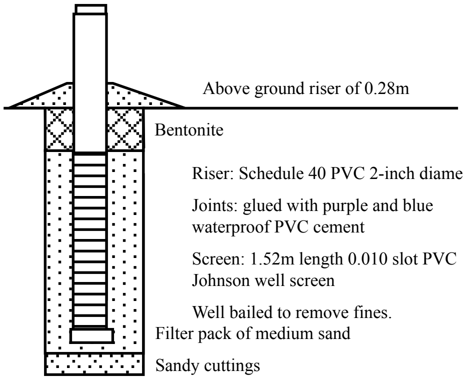
0-0.38m: silty loam

0.38-0.76m: fine-medium sand

0.76-1.09m: silty clay

1.09-1.83m: medium sand coarsens downward to very coarse sand

Drilled to 1.83m



Above ground riser of 0.28m

Bentonite

Riser: Schedule 40 PVC 2-inch diameter

Joints: glued with purple and blue waterproof PVC cement

Screen: 1.52m length 0.010 slot PVC Johnson well screen

Well bailed to remove fines.

Filter pack of medium sand

Sandy cuttings

Report Approved by:______________________

Department of Ocean Earth and Atmospheric Sciences Old Dominion University, Norfolk, Virginia

APPENDIX B

GPR SETUP PARAMETERS

GPR Survey 1 – PSP Transect (A-A') Setup parameters

PulseEKKO Data Sheet

DATA FILE #1 PARAMETERS:

```
        Data file = C:\EKKO42\POCA1COR.hd

        23/08/102
        NUMBER OF TRACES  = 119
        NUMBER OF PTS/TRC = 640
        TIMEZERO AT POINT = 46
        TOTAL TIME WINDOW = 512
        STARTING POSITION = 0.0000
        FINAL POSITION = 59.0000
        STEP SIZE USED = 0.5000
        POSITION UNITS = meters
        NOMINAL FREQUENCY = 100.00
        ANTENNA SEPARATION = 1.0000
        PULSER VOLTAGE (V) = 400
        NUMBER OF STACKS = 4
        SURVEY MODE = Reflection
        COLLECTED BY PE100 – CON: 971111 RX: 971023
                                  TX: 980603 ANT: ??
        SOURCE DATA FILE = C:\EKKO42\poca1
        ELEVATION DATA ENTERED: MAX = 31.09   MIN = 28.55
```

PROCESSING SELECTED:

```
        Trace Stacking: 2
        Points Stacking: 1
        Trace Differencing: N
        Correction: DEWOW
        Gain Type: NONE
        Selection: Time = 0 to 350ns
                   Position = all
        Picture Id: 08/23/02-00:05:26
```

PLOT LAYOUT PARAMETERS:

```
        Traces per inch: 10.000
        Width/Spacing Ratio: 2.0000
        Trace Position: 1.000" to 6.000"
```

Left/Right Margin: 0.000” / 0.000”
Border Size: 0.000”
Page Length/Width: 11.000” / 8.500”
Printer Name: HP LaserJet II 150dpi

GPR Survey 2 – PWMA Transect 1 (B-B’) Setup parameters

PulseEKKO Data Sheet

DATA FILE #1 PARAMETERS:
Data file = C:\EKKO42\PWMA1COR.hd

23/08/102
NUMBER OF TRACES = 173
NUMBER OF PTS/TRC = 640
TIMEZERO AT POINT = 40
TOTAL TIME WINDOW = 512
STARTING POSITION = 0.0000
FINAL POSITION = 86.0000
STEP SIZE USED = 0.5000
POSITION UNITS = meters
NOMINAL FREQUENCY = 100.00
ANTENNA SEPARATION = 1.0000
PULSER VOLTAGE (V) = 400
NUMBER OF STACKS = 4
SURVEY MODE = Reflection
COLLECTED BY PE100 – CON: 971111 RX: 971023
TX: 980603 ANT: ??
SOURCE DATA FILE = C:\EKKO42\PWMA1
ELEVATION DATA ENTERED: MAX = 30.48 MIN = 24.80

PROCESSING SELECTED:
Trace Stacking: 2
Points Stacking: 1
Trace Differencing: N
Correction: DEWOW
Gain Type: NONE
Selection: Time = 0 to 350ns
Position = all
Picture Id: 08/23/02-00:05:26

PLOT LAYOUT PARAMETERS:
Traces per inch: 10.000
Width/Spacing Ratio: 2.0000
Trace Position: 1.000” to 6.000”
Left/Right Margin: 0.000” / 0.000”

Border Size: 0.000”
Page Length/Width: 11.000” / 8.500”
Printer Name: HP LaserJet II 150dpi

GPR Survey 3 – PWMA Transect 2 (C-C’) Setup parameters

PulseEKKO Data Sheet

DATA FILE #1 PARAMETERS:
Data file = C:\EKKO42\PWMAT2T.hd

23/08/102
NUMBER OF TRACES = 198
NUMBER OF PTS/TRC = 640
TIMEZERO AT POINT = 48
TOTAL TIME WINDOW = 512
STARTING POSITION = 0.0000
FINAL POSITION = 98.5000
STEP SIZE USED = 0.5000
POSITION UNITS = meters
NOMINAL FREQUENCY = 100.00
ANTENNA SEPARATION = 1.0000
PULSER VOLTAGE (V) = 400
NUMBER OF STACKS = 4
SURVEY MODE = Reflection
COLLECTED BY PE100 – CON: 971111 RX: 971023
TX: 980603 ANT: ??
SOURCE DATA FILE = C:\EKKO42\PWMA2
ELEVATION DATA ENTERED: MAX = 30.48 MIN = 26.83

PROCESSING SELECTED:
Trace Stacking: 2
Points Stacking: 1
Trace Differencing: N
Correction: DEWOW
Gain Type: NONE
Selection: Time = 0 to 350ns
Position = all
Picture Id: 08/23/02-00:05:26

PLOT LAYOUT PARAMETERS:
Traces per inch: 10.000
Width/Spacing Ratio: 2.0000
Trace Position: 1.000” to 6.000”
Left/Right Margin: 0.000” / 0.000”
Border Size: 0.000”

Page Length/Width: 11.000” / 8.500”
Printer Name: HP LaserJet II 150dpi

Topographic Surveys for GPR Data Topographic Correction

Pocahontas State Forest (PSP) Topographic Survey Data for GPR

Location/Well ID	Surface Elevation* (m)	Position on Profile (m)
Survey 1 Start (A)	31.09	0.00
Hillslope (HS)	30.48	11.00
Toe-slope (TS)	29.20	20.00
Mid-floodplain (MF)	29.18	37.00
Dry Edge (DE)	29.42	50.00
Top of Streambank 1	29.42	51.00
Base of Streambank 1	28.55	51.10
Base of Streambank 2	28.55	52.10
Top of Streambank 2 (A’)	29.42	53.10 – 59.00

*Surface elevations are relative based on an arbitrary datum.

Powhatan WMA (PWMA) Topographic Survey Data for GPR

Location/Well ID	Surface Elevation* (m)	Position on Profile (m)
Survey 2 Start (B)	30.48	0.00
Hillslope (HS)	28.25	10.00
Toe-slope (TS)	26.54	17.00
Mid-floodplain (MF)	26.90	35.00
Dry Edge (DE)	26.90	60.00
Top of Streambank 1	26.90	70.00
Base of Streambank 1	24.94	71.00
Middle of Streambed	24.80	74.00
Base of Streambank 2	24.98	75.50
Top of Streambank 2 (B’)	26.98	77.00 – 86.00
Survey 3 Start (C)	30.48	0.00
Hillslope (HS)	28.71	4.50
Toe-slope (TS)	27.06	32.00
Mid-floodplain (MF)	26.90	68.00
Dry Edge (DE, C’)	26.83	98.50

*Surface elevations are relative based on an arbitrary datum.

APPENDIX C

WATER LEVEL DATA SUMMARIES

Pocahontas State Park Transect A-A' Water Level Data

PSP transect A-A' continuous water level data summary				
	Hillslope		Toe-slope	
	Head elev. (m)	Water level relative to surface (m)	Head elev. (m)	Water level relative to surface (m)
Avg.	29.22	-1.26	29.00	-0.2
Max	30.04	-0.44	29.25	0.05
Min.	28.28	-2.2	28.12	-1.08
Range	1.76	1.76	1.13	1.13

Data in the table above pertains to the hydrographs shown in Figure 21.

PSP transect A-A' monthly well dip summary (May 2011-August 2012): relative head elevation (m)																	
		5/15/11	6/2/11	7/2/11	8/2/11	9/2/11	10/2/11	11/1/11	12/2/11	1/2/12	2/2/12	3/4/12	4/5/12	5/1/12	6/1/12	7/2/12	8/1/12
Hillslope	MW	29.40	29.08	28.71	28.86	29.03	29.29	29.23	29.54	29.52	29.51	29.62	29.47	29.42	29.19	28.63	28.73
	SP	29.32	29.05	28.69	28.81	28.99	29.36	29.33	29.20	29.51	29.47	29.58	29.44	29.38	-	28.61	28.69
	DP	29.38	29.18	28.79	28.90	29.00	29.39	29.36	29.55	29.54	29.53	29.61	29.52	29.43	-	28.64	28.73
Toe-slope	MW	29.18	28.89	28.61	28.75	28.92	29.14	29.16	29.20	29.18	29.20	29.22	29.18	29.19	29.00	28.53	28.65
	SP	29.20	28.91	28.64	28.71	28.93	29.18	29.20	29.22	29.22	29.22	29.23	29.22	29.22	-	28.54	28.64
	DP	29.22	28.92	28.65	28.77	28.94	29.21	29.22	29.27	29.26	29.26	29.29	29.22	29.22	-	28.55	28.68
Mid-floodplain	MW	29.16	28.60	28.51	28.55	28.79	29.09	29.14	29.15	29.16	29.16	28.99	29.13	29.16	-	28.46	28.56
	SP	29.06	28.68	dry	28.51	28.84	29.12	29.10	29.16	29.17	29.17	29.19	29.18	29.14	-	dry	28.55
	DP	28.99	28.77	28.57	28.65	28.81	28.75	29.06	29.12	29.11	29.11	28.86	29.07	29.04	-	28.44	28.56
Dry Edge	MW	29.08	28.72	28.56	28.64	28.79	28.99	29.05	29.10	29.08	29.11	29.16	29.02	29.02	-	28.45	28.58
	SP	29.07	28.74	28.58	28.63	28.79	29.00	28.74	29.09	29.08	29.09	29.15	29.02	29.01	-	28.48	28.60
	DP	28.98	28.76	28.58	28.60	28.80	29.03	29.05	29.11	29.10	29.19	29.16	29.04	29.02	-	28.49	28.60

PSP transect A-A' monthly well dip summary (May 2011-August 2012): water level relative to surface (m)																	
		5/15/11	6/2/11	7/2/11	8/2/11	9/2/11	10/2/11	11/1/11	12/2/11	1/2/12	2/2/12	3/4/12	4/5/12	5/1/12	6/1/12	7/2/12	8/1/12
Hillslope	MW	-1.08	-1.40	-1.77	-1.62	-1.45	-1.19	-1.25	-0.94	-0.96	-0.97	-0.86	-1.01	-1.06	-1.29	-1.85	-1.75
	SP	-1.16	-1.43	-1.79	-1.67	-1.49	-1.12	-1.15	-1.28	-0.97	-1.01	-0.90	-1.04	-1.10	-	-1.87	-1.79
	DP	-1.10	-1.30	-1.69	-1.58	-1.48	-1.09	-1.12	-0.93	-0.94	-0.95	-0.87	-0.96	-1.05	-	-1.84	-1.75
Toe-slope	MW	-0.02	-0.31	-0.59	-0.45	-0.28	-0.06	-0.04	0.00	-0.02	0.00	0.02	-0.02	-0.01	-0.20	-0.67	-0.55
	SP	0.00	-0.29	-0.56	-0.49	-0.27	-0.02	0.00	0.02	0.02	0.02	0.03	0.02	0.02	-	-0.66	-0.56
	DP	0.02	-0.28	-0.55	-0.43	-0.26	0.01	0.02	0.07	0.06	0.06	0.09	0.02	0.02	-	-0.65	-0.52
Mid-floodplain	MW	-0.02	-0.58	-0.67	-0.63	-0.39	-0.09	-0.04	-0.03	-0.02	-0.02	-0.19	-0.05	-0.02	-	-0.72	-0.62
	SP	-0.12	-0.50	dry	-0.67	-0.34	-0.06	-0.08	-0.02	-0.01	-0.01	0.01	0.00	-0.04	-	dry	-0.63
	DP	-0.19	-0.41	-0.61	-0.53	-0.37	-0.43	-0.12	-0.06	-0.07	-0.07	-0.32	-0.11	-0.14	-	-0.74	-0.62
Dry Edge	MW	-0.34	-0.70	-0.86	-0.78	-0.63	-0.43	-0.37	-0.32	-0.34	-0.31	-0.26	-0.40	-0.40	-	-0.97	-0.84
	SP	-0.35	-0.68	-0.84	-0.79	-0.63	-0.42	-0.68	-0.33	-0.34	-0.33	-0.27	-0.40	-0.41	-	-0.94	-0.82
	DP	-0.44	-0.66	-0.84	-0.82	-0.62	-0.39	-0.37	-0.31	-0.32	-0.23	-0.26	-0.38	-0.40	-	-0.93	-0.82

MW = monitoring well, SP = shallow piezometer, DP = deep piezometer

Powhatan WMA Transect B-B’ Water Level Data

PWMA transect B-B’ continuous water level data summary						
	Hillslope		Toe-slope		Mid-floodplain	
	Head elev. (m)	Water level relative to surface (m)	Head elev. (m)	Water level relative to surface (m)	Head elev. (m)	Water level relative to surface (m)
Avg.	26.71	-1.54	26.37	-0.17	26.21	-0.69
Max	27.22	-1.02	26.95	0.41	27.01	0.1
Min.	26.13	-2.12	25.71	-0.83	25.39	-1.51
Range	1.10	1.1	1.24	1.24	1.62	1.62

Data in the table above pertains to the hydrographs shown in Figure 23.

PWMAtransect B-B’ monthly well dip summary (August 2011-August 2012): relative head elevation (m)														
		8/2/11	9/2/11	10/2/11	11/2/11	12/2/11	1/3/12	2/2/12	3/6/12	4/5/12	5/1/12	6/1/12	7/2/12	8/1/12
Hillslope	MW	26.31	26.29	26.67	26.81	26.90	26.90	26.92	26.99	26.96	26.94	-	26.45	26.24
	SP	-	26.30	26.68	26.83	26.96	26.97	26.92	27.02	26.96	26.95	-	26.46	26.23
	DP	-	26.26	26.65	26.80	26.87	26.88	26.91	26.97	26.95	26.94	-	26.44	26.22
Toe-slope	MW	25.85	25.91	26.44	26.62	26.67	26.69	26.63	26.71	26.60	26.71	26.52	25.95	25.83
	SP	25.90	25.93	26.49	26.41	26.71	26.65	26.67	26.71	26.65	26.65	26.46	25.99	25.84
	DP	26.03	26.05	26.48	26.23	26.69	26.66	26.69	26.71	26.69	26.69	26.53	26.13	25.97
Mid-floodplain	MW	25.72	25.72	26.29	26.50	26.57	26.45	26.54	26.57	26.37	26.37	-	25.80	25.63
	SP	25.41	25.41	26.27	26.50	26.57	26.46	26.53	26.57	26.36	26.36	-	25.52	25.30
	DP	25.83	25.83	26.40	26.56	26.62	26.58	26.56	26.66	26.56	26.54	-	25.96	25.78
Dry edge	MW	-	-	-	-	-	-	26.11	26.15	26.08	26.06	-	25.70	25.60

PWMAtransect B-B’ monthly well dip summary (August 2011-August 2012): water level relative to surface (m)														
		8/2/11	9/2/11	10/2/11	11/2/11	12/2/11	1/3/12	2/2/12	3/6/12	4/5/12	5/1/12	6/1/12	7/2/12	8/1/12
Hillslope	MW	-1.94	-1.96	-1.58	-1.44	-1.35	-1.35	-1.33	-1.26	-1.29	-1.31	-	-1.80	-2.01
	SP	-	-1.95	-1.57	-1.42	-1.29	-1.28	-1.33	-1.23	-1.29	-1.30	-	-1.79	-2.02
	DP	-	-1.99	-1.60	-1.45	-1.38	-1.37	-1.34	-1.28	-1.30	-1.31	-	-1.81	-2.03
Toe-slope	MW	-0.69	-0.63	-0.10	0.08	0.13	0.15	0.09	0.17	0.06	0.17	-0.02	-0.59	-0.71
	SP	-0.64	-0.61	-0.05	-0.13	0.17	0.11	0.13	0.17	0.11	0.11	-0.08	-0.55	-0.70
	DP	-0.51	-0.49	-0.06	-0.31	0.15	0.12	0.15	0.17	0.15	0.15	-0.01	-0.41	-0.57
Mid-floodplain	MW	-1.18	-1.18	-0.61	-0.40	-0.33	-0.45	-0.36	-0.33	-0.53	-0.53	-	-1.10	-1.27
	SP	-1.49	-1.49	-0.63	-0.40	-0.33	-0.44	-0.37	-0.33	-0.54	-0.54	-	-1.38	-1.60
	DP	-1.07	-1.07	-0.50	-0.34	-0.28	-0.32	-0.34	-0.24	-0.34	-0.36	-	-0.94	-1.12
Dry edge	MW	-	-	-	-	-	-	-0.79	-0.75	-0.82	-0.84	-	-1.20	-1.30

MW = monitoring well, SP = shallow piezometer, DP = deep piezometer

Powhatan WMA Transect C-C' Water Level Data

PWMA transect C-C' continuous water level data summary						
	Hillslope swale		Toe-slope		Mid-floodplain	
	Head elev. (m)	Water level relative to surface (m)	Head elev. (m)	Water level relative to surface (m)	Head elev. (m)	Water level relative to surface (m)
Avg.	27.40	-1.31	26.86	-0.2	26.66	-0.24
Max	28.61	-0.1	27.17	0.11	27.06	0.16
Min.	26.64	-2.07	26.33	-0.73	26.10	-0.8
Range	1.97	1.97	0.85	0.85	0.96	0.96

Data in the table above pertains to the hydrographs shown in Figure 25.

PWMAtransect C-C' monthly well dip summary (August 2011-August 2012): relative head elevation (m)														
		8/2/11	9/2/11	10/2/11	11/2/11	12/2/11	1/3/12	2/2/12	3/6/12	4/5/12	5/1/12	6/1/12	7/2/12	8/1/12
Hillslope	MW	26.77	26.72	27.04	27.26	27.59	27.49	28.01	28.14	27.59	27.50	-	26.98	26.77
	SP	26.75	26.69	27.03	27.21	27.37	27.37	27.44	27.64	27.45	27.42	-	26.95	26.74
	DP	25.43	26.76	27.08	27.27	27.52	27.48	27.66	28.03	27.55	27.49	-	26.98	26.77
Toe-slope	MW	26.40	26.44	26.80	26.93	27.03	27.01	27.04	27.06	27.06	27.06	26.85	26.58	26.44
	SP	24.95	26.21	26.33	26.91	27.03	27.04	27.01	27.06	27.02	27.04	26.81	26.52	26.42
	DP	24.33	26.44	26.84	26.98	27.06	27.06	27.05	27.16	27.09	27.09	-	26.60	26.45
Mid-floodplain	MW	-	26.19	26.68	26.84	26.87	26.85	26.90	26.90	26.78	26.83	-	26.26	26.14
	SP	-	26.04	26.70	26.88	26.89	26.86	26.85	26.90	26.79	26.83	-	26.08	25.96
	DP	-	26.18	26.66	26.76	26.84	26.83	26.81	26.90	26.85	26.79	-	26.34	26.16
Dry edge	MW	-	-	-	-	-	-	26.33	26.43	26.23	26.24	-	25.68	25.50

PWMAtransect C-C' monthly well dip summary (August 2011-August 2012): water level relative to surface (m)														
		8/2/11	9/2/11	10/2/11	11/2/11	12/2/11	1/3/12	2/2/12	3/6/12	4/5/12	5/1/12	6/1/12	7/2/12	8/1/12
Hillslope	MW	-1.94	-1.99	-1.67	-1.45	-1.12	-1.22	-0.70	-0.57	-1.12	-1.21	-	-1.73	-1.94
	SP	-1.96	-2.02	-1.68	-1.50	-1.34	-1.34	-1.27	-1.07	-1.26	-1.29	-	-1.76	-1.97
	DP	-3.28	-1.95	-1.63	-1.44	-1.19	-1.23	-1.05	-0.68	-1.16	-1.22	-	-1.73	-1.94
Toe-slope	MW	-0.66	-0.63	-0.26	-0.13	-0.03	-0.05	-0.02	0.00	0.00	0.00	-0.21	-0.48	-0.62
	SP	-2.11	-0.85	-0.73	-0.15	-0.03	-0.02	-0.05	0.00	-0.04	-0.02	-0.25	-0.54	-0.64
	DP	-2.73	-0.62	-0.22	-0.08	0.00	0.00	-0.01	0.10	0.03	0.03	-	-0.46	-0.61
Mid-floodplain	MW	-	-0.71	-0.22	-0.06	-0.03	-0.05	0.00	0.00	-0.12	-0.07	-	-0.64	-0.76
	SP	-	0.86	-0.20	-0.02	-0.01	-0.04	-0.05	0.00	-0.11	-0.07	-	-0.82	-0.94
	DP	-	-0.72	-0.24	-0.14	-0.06	-0.07	-0.09	0.00	-0.05	-0.11	-	-0.56	-0.74
Dry edge	MW	-	-	-	-	-	-	-0.50	-0.40	-0.60	-0.59	-	-1.15	-1.33

MW = monitoring well, SP = shallow piezometer, DP = deep piezometer

APPENDIX D

SLUG TEST DATA

PSP Hillslope Deep Piezometer Slug Test Data

Material tested: granitic saprolite

Date: 4/5/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**
0	0.52	1.00	0.51	1.00	0.51	1.00
60	0.49	0.94	0.47	0.92	0.47	0.92
120	0.49	0.94	0.47	0.92	0.45	0.89
180	0.49	0.94	0.46	0.90	0.44	0.87
240	0.49	0.94	0.46	0.89	0.43	0.85
300	0.49	0.94	0.45	0.88	0.42	0.83
360	0.48	0.93	0.44	0.86	0.41	0.81
420	0.48	0.92	0.44	0.85	0.40	0.79
480	0.48	0.93	0.42	0.83	0.39	0.78
540	0.48	0.92	0.42	0.82	0.38	0.76
600	0.47	0.91	0.42	0.81	0.37	0.74
660	0.48	0.91	0.41	0.80	0.36	0.72
720	0.47	0.90	0.40	0.79	0.35	0.69
780	0.46	0.89	0.40	0.78	0.34	0.68
840	0.47	0.89	0.39	0.77	0.34	0.66
900	0.46	0.88	0.38	0.75	0.33	0.64
960	0.46	0.89	0.38	0.73	0.32	0.63
1020	0.46	0.88	0.37	0.73	0.31	0.61
1080	0.46	0.88	0.37	0.72	0.30	0.60
1140	0.45	0.87	0.36	0.71	0.29	0.58
1200	0.45	0.86	0.36	0.70	0.28	0.56

PSP Toe-slope Shallow Piezometer Slug Test Data

Material tested: coarse sand and gravel above saprolite

Date: 4/5/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H$_0$**	**H (m)**	**H/H$_0$**	**H (m)**	**H/H$_0$**
0	1.00	1.00	0.61	1.00	0.32	1.00
60	0.94	0.93	0.53	0.88	0.25	0.79
120	0.88	0.87	0.47	0.78	0.18	0.58
180	0.82	0.82	0.41	0.68	0.12	0.38
240	0.77	0.77	0.36	0.59	0.06	0.19
300	0.72	0.72	0.30	0.50	0.01	0.02
360	0.67	0.67				
420	0.63	0.63				
480	0.59	0.59				
540	0.55	0.55				
600	0.52	0.52				
660	0.48	0.48				

PWMA Hillslope B-B' Deep Piezometer Slug Test Data

Material tested: biotite gneiss saprolite

Date: 5/1/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H$_0$**	**H (m)**	**H/H$_0$**	**H (m)**	**H/H$_0$**
0	0.51	1.00	0.52	1.00	0.52	1.00
60	0.41	0.80	0.41	0.78	0.41	0.79
120	0.34	0.66	0.33	0.64	0.33	0.64
180	0.28	0.54	0.27	0.52	0.27	0.52
240	0.23	0.45	0.23	0.43	0.22	0.43
300	0.19	0.37	0.19	0.36	0.18	0.35
360	0.16	0.31	0.16	0.30	0.15	0.30
420	0.14	0.27	0.13	0.25	0.13	0.25
480	0.11	0.22	0.11	0.21	0.11	0.21
540	0.10	0.19	0.09	0.18	0.09	0.17
600	0.08	0.16	0.08	0.15	0.08	0.15
660	0.07	0.14	0.07	0.13	0.06	0.12
720	0.06	0.12	0.06	0.11	0.06	0.11
780	0.05	0.11			0.05	0.09
840	0.05	0.10				
900	0.04	0.08				
960	0.04	0.07				
1020	0.03	0.07				
1080	0.03	0.06				
1140	0.03	0.05				
1200	0.03	0.05				
1260	0.02	0.04				
1320	0.02	0.04				

PWMA Toe-slope B-B' Deep Piezometer Slug Test Data

Material tested: coarse sand and gravel						
Date: 5/1/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**
0	0.59	1.00	0.58	1.00	0.58	1.00
60	0.48	0.82	0.48	0.82	0.45	0.78
120	0.41	0.70	0.41	0.70	0.38	0.66
180	0.36	0.60	0.35	0.60	0.32	0.56
240	0.31	0.53	0.31	0.53	0.28	0.49
300	0.27	0.46	0.27	0.46	0.25	0.43
360	0.24	0.41	0.24	0.41	0.21	0.37
420	0.22	0.37	0.21	0.36	0.19	0.33
480	0.19	0.33	0.19	0.32	0.17	0.29
540	0.18	0.30	0.17	0.29	0.15	0.26
600	0.16	0.27	0.15	0.26	0.13	0.23
660	0.14	0.24	0.14	0.23	0.11	0.20
720	0.13	0.22	0.12	0.21	0.10	0.18
780	0.12	0.20	0.11	0.19	0.09	0.16
840	0.11	0.19	0.10	0.17	0.08	0.14
900	0.10	0.17	0.09	0.16	0.07	0.12
960	0.09	0.16	0.08	0.14	0.06	0.11
1020	0.09	0.15	0.08	0.13	0.06	0.10
1080	0.08	0.13	0.07	0.12	0.05	0.09
1140	0.07	0.13	0.06	0.11		
1200	0.07	0.12	0.06	0.10		
1260	0.06	0.11	0.05	0.09		
1320	0.06	0.10	0.05	0.08		

PWMA Mid-floodplain B-B' Deep Piezometer Slug Test Data

Material tested: clayey fine sand with coarse sand lenses						
Date: 5/1/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**
0	0.50	1.00	0.51	1.00		
60	0.49	0.97	0.50	0.98		
120	0.48	0.96	0.50	0.97		
180	0.48	0.96	0.49	0.97		
240	0.48	0.95	0.49	0.96		
300	0.48	0.96	0.49	0.97		
360	0.48	0.96	0.49	0.96		
420	0.48	0.96	0.49	0.96		
480	0.48	0.96	0.48	0.95		
540	0.48	0.96	0.48	0.95		
600	0.48	0.95	0.48	0.94		
660	0.48	0.95	0.48	0.94		
720	0.48	0.95	0.48	0.94		
780	0.48	0.95	0.47	0.93		
840	0.48	0.95	0.47	0.93		
900	0.47	0.95	0.47	0.93		
960	0.47	0.95	0.47	0.93		
1020	0.47	0.95	0.47	0.92		
1080	0.47	0.94	0.46	0.91		
1140	0.47	0.94	0.47	0.92		
1200	0.47	0.93	0.46	0.91		
1260	0.47	0.94	0.46	0.91		
1320	0.47	0.93	0.46	0.90		

PWMA Hillslope C-C' Deep Piezometer Slug Test Data

Material tested: clayey colluvium-saprolite mix						
Date: 5/1/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**
0	0.50	1.00				
3540	0.49	0.98				
7140	0.48	0.97				
10740	0.48	0.96				
14340	0.46	0.93				

PWMA Toe-slope C-C' Deep Piezometer Slug Test Data

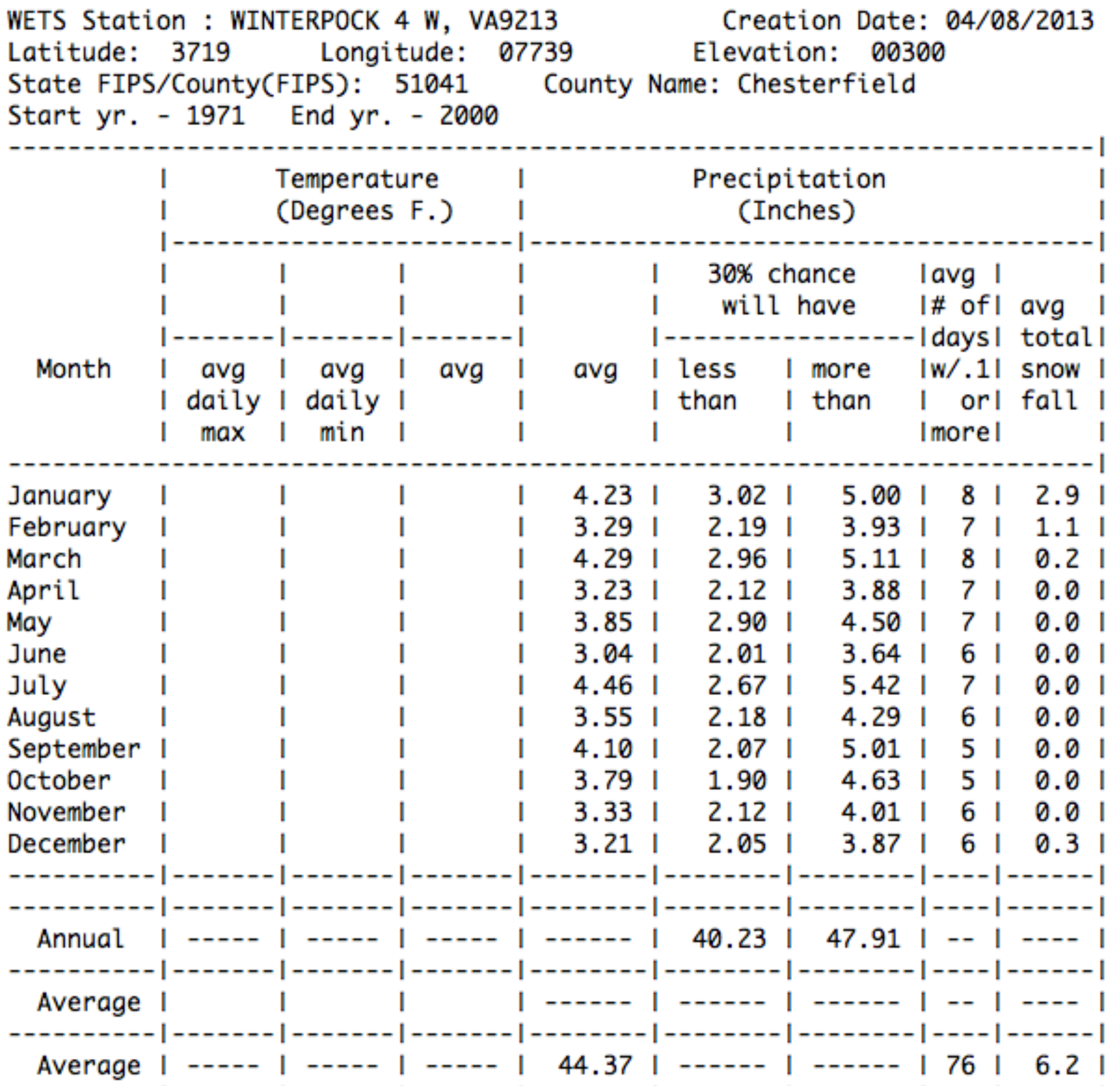
Material tested: clayey very coarse sand and gravel

Date: 5/1/12	Trial 1		Trial 2		Trial 3	
T (secs)	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**	**H (m)**	**H/H_0**
0	0.53	1.00	0.51	1.00	0.52	1.00
60	0.52	0.97	0.50	0.98	0.50	0.96
120	0.52	0.97	0.50	0.97	0.50	0.96
180	0.52	0.97	0.50	0.97	0.50	0.96
240	0.52	0.96	0.50	0.97	0.50	0.95
300	0.51	0.96	0.50	0.97	0.49	0.95
360	0.51	0.96	0.50	0.96	0.49	0.95
420	0.51	0.96	0.49	0.96	0.49	0.94
480	0.51	0.96	0.49	0.96	0.49	0.94
540	0.51	0.96	0.49	0.96	0.49	0.94
600	0.51	0.96	0.49	0.95	0.49	0.94
660	0.51	0.95	0.49	0.95	0.48	0.93
720	0.51	0.95	0.49	0.95	0.48	0.93
780	0.51	0.95	0.48	0.94	0.48	0.92
840	0.51	0.95	0.48	0.94	0.48	0.92
900	0.51	0.95	0.48	0.94	0.48	0.92
960	0.51	0.95	0.48	0.94	0.47	0.91
1020	0.51	0.95	0.48	0.93	0.47	0.91
1080	0.51	0.95	0.48	0.93	0.47	0.91
1140	0.51	0.95	0.48	0.93	0.47	0.90
1200	0.50	0.94	0.48	0.93	0.47	0.90
1260	0.50	0.94	0.48	0.93	0.46	0.89
1320	0.50	0.94	0.47	0.92	0.46	0.89

APPENDIX E

WETS TABLES AND TOTAL ANNUAL PRECIPITATION

WETS table for Pocahontas State Park Study Site

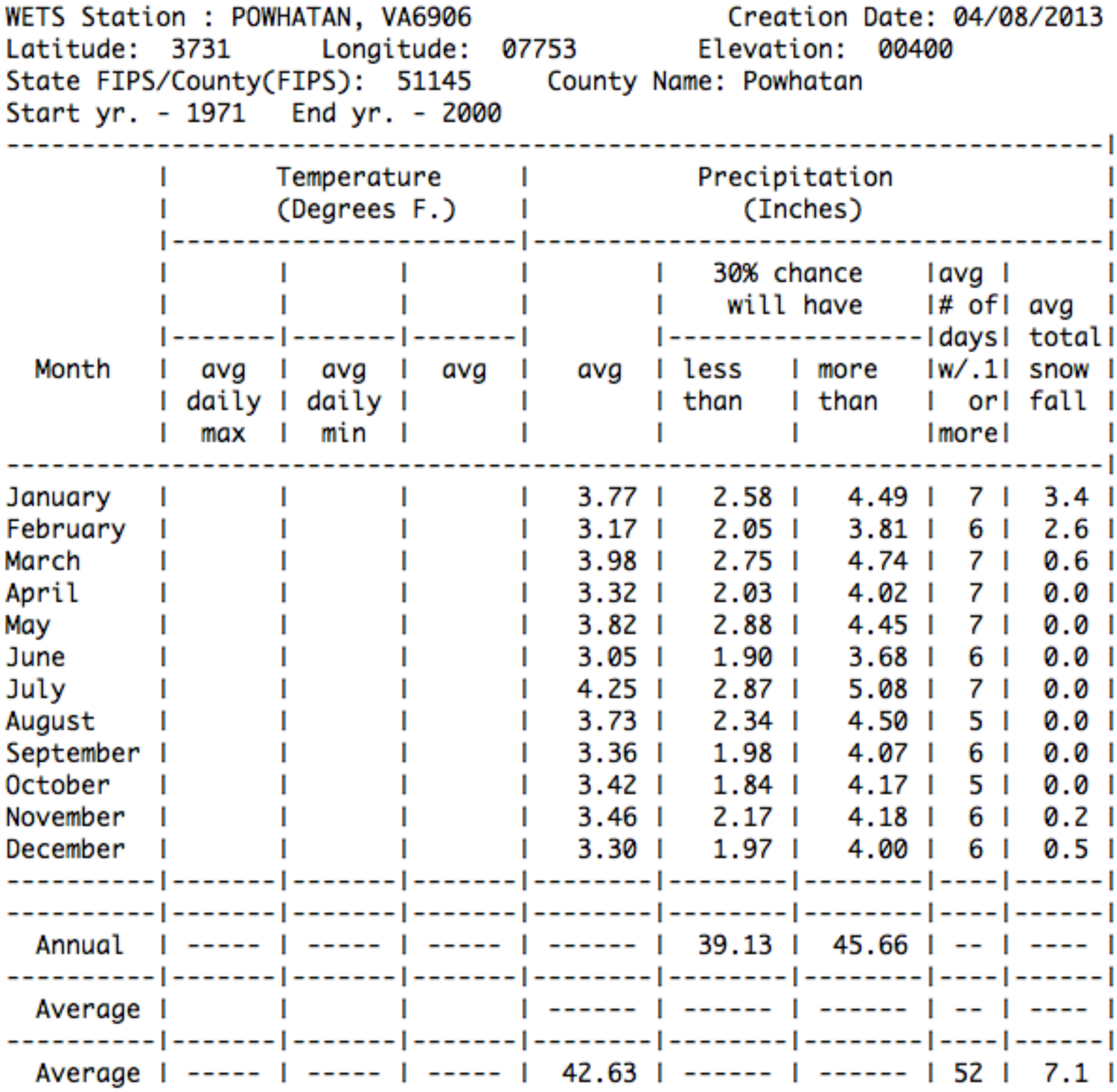


```
WETS Station : WINTERPOCK 4 W, VA9213          Creation Date: 04/08/2013
Latitude:  3719      Longitude:  07739       Elevation:  00300
State FIPS/County(FIPS):  51041     County Name: Chesterfield
Start yr. - 1971   End yr. - 2000
-----------------------------------------------------------------------|
          |       Temperature      |             Precipitation            |
          |       (Degrees F.)     |                (Inches)              |
          |------------------------|--------------------------------------|
          |       |       |        |        |   30% chance    |avg |      |
          |       |       |        |        |    will have    |# of| avg  |
          |-------|-------|--------|        |-----------------|days| total|
  Month   |  avg  |  avg  |  avg   |  avg   | less    | more   |w/.1| snow |
          | daily | daily |        |        | than    | than   |  or| fall |
          |  max  |  min  |        |        |         |        |more|      |
-----------------------------------------------------------------------|
January   |       |       |        |  4.23  |   3.02  |   5.00 |  8 |  2.9 |
February  |       |       |        |  3.29  |   2.19  |   3.93 |  7 |  1.1 |
March     |       |       |        |  4.29  |   2.96  |   5.11 |  8 |  0.2 |
April     |       |       |        |  3.23  |   2.12  |   3.88 |  7 |  0.0 |
May       |       |       |        |  3.85  |   2.90  |   4.50 |  7 |  0.0 |
June      |       |       |        |  3.04  |   2.01  |   3.64 |  6 |  0.0 |
July      |       |       |        |  4.46  |   2.67  |   5.42 |  7 |  0.0 |
August    |       |       |        |  3.55  |   2.18  |   4.29 |  6 |  0.0 |
September |       |       |        |  4.10  |   2.07  |   5.01 |  5 |  0.0 |
October   |       |       |        |  3.79  |   1.90  |   4.63 |  5 |  0.0 |
November  |       |       |        |  3.33  |   2.12  |   4.01 |  6 |  0.0 |
December  |       |       |        |  3.21  |   2.05  |   3.87 |  6 |  0.3 |
----------|-------|-------|--------|--------|---------|--------|----|------|
----------|-------|-------|--------|--------|---------|--------|----|------|
  Annual  | ----- | ----- | -----  | ------ |  40.23  |  47.91 | -- | ---- |
----------|-------|-------|--------|--------|---------|--------|----|------|
  Average |       |       |        | ------ | ------  | ------ | -- | ---- |
----------|-------|-------|--------|--------|---------|--------|----|------|
  Average | ----- | ----- | -----  | 44.37  | ------  | ------ | 76 |  6.2 |
```

Total Annual Precipitation for Winterpock, VA shown in wet, normal, and dry year splits

Year	Total ppt (cm)	
2012	30.31	Dry
2001	32.84	
1986	35.39	
1981	35.48	
1997	35.9	
1991	36.42	
1990	37.57	
1992	38.24	
2005	38.25	
2002	38.71	
1980	39.03	
1988	39.41	
1987	40.67	Normal
2007	41.28	
2010	41.4	
2000	41.45	
1994	43.96	
1995	44.01	
2011	44.41	
1985	44.72	
1993	45.82	
1989	46.47	
1999	46.61	
1998	47.59	
2008	47.84	
1983	49.03	Wet
1984	49.11	
1982	51.37	
2009	52.59	
2006	52.74	
1996	61.4	
2004	62.65	
2003	68.26	

WETS table for Powhatan WMA Study Site



```
WETS Station : POWHATAN, VA6906             Creation Date: 04/08/2013
Latitude:  3731      Longitude:  07753       Elevation:  00400
State FIPS/County(FIPS):  51145     County Name: Powhatan
Start yr. - 1971   End yr. - 2000
-------------------------------------------------------------------------|
          |       Temperature     |           Precipitation              |
          |       (Degrees F.)    |              (Inches)                |
          |-----------------------|--------------------------------------|
          |       |       |       |        |   30% chance    |avg |      |
          |       |       |       |        |    will have    |# of| avg  |
          |-------|-------|-------|        |-----------------|days| total|
  Month   |  avg  | avg   |  avg  |   avg  | less    | more  |w/.1| snow |
          | daily | daily |       |        | than    | than  |  or| fall |
          |  max  |  min  |       |        |         |       |more|      |
-------------------------------------------------------------------------|
January   |       |       |       |   3.77 |   2.58 |   4.49 |  7 |  3.4 |
February  |       |       |       |   3.17 |   2.05 |   3.81 |  6 |  2.6 |
March     |       |       |       |   3.98 |   2.75 |   4.74 |  7 |  0.6 |
April     |       |       |       |   3.32 |   2.03 |   4.02 |  7 |  0.0 |
May       |       |       |       |   3.82 |   2.88 |   4.45 |  7 |  0.0 |
June      |       |       |       |   3.05 |   1.90 |   3.68 |  6 |  0.0 |
July      |       |       |       |   4.25 |   2.87 |   5.08 |  7 |  0.0 |
August    |       |       |       |   3.73 |   2.34 |   4.50 |  5 |  0.0 |
September |       |       |       |   3.36 |   1.98 |   4.07 |  6 |  0.0 |
October   |       |       |       |   3.42 |   1.84 |   4.17 |  5 |  0.0 |
November  |       |       |       |   3.46 |   2.17 |   4.18 |  6 |  0.2 |
December  |       |       |       |   3.30 |   1.97 |   4.00 |  6 |  0.5 |
----------|-------|-------|-------|--------|--------|--------|----|------|
----------|-------|-------|-------|--------|--------|--------|----|------|
  Annual  | ----- | ----- | ----- |  ------|  39.13 |  45.66 | -- | ---- |
----------|-------|-------|-------|--------|--------|--------|----|------|
  Average |       |       |       |  ------| ------ | ------ | -- | ---- |
----------|-------|-------|-------|--------|--------|--------|----|------|
  Average | ----- | ----- | ----- |  42.63 | ------ | ------ | 52 |  7.1 |
```

Total Annual Precipitation for Powhatan, VA shown in wet, normal, and dry year splits

Year	Total ppt (cm)	
1980	27.33	Dry
2001	32.38	
1988	32.74	
1997	33.95	
2012	35.55	
2007	35.84	
1986	36.34	
2005	36.65	
1991	38.84	
1992	39.09	
2010	39.68	Normal
1990	41.08	
2002	42.03	
2011	42.6	
1999	42.72	
1983	42.74	
1998	42.92	
1984	43.21	
1994	43.56	
1982	43.8	
1985	43.91	
2008	44.57	
2000	44.99	
1987	46.35	Wet
1989	48.66	
1993	49.17	
1995	49.42	
2004	49.77	
2009	50.32	
2006	50.38	
1996	51.65	
2003	68.28	

APPENDIX F

EFFECTIVE MONTHLY RECHARGE (W_{em}) MODEL RESULTS

Pocahontas State Park Calibration Period Transect A-A’ W_{em} Results

Hillslope A-A'

Mo./Yr.	Wem15 (cm)	Pred. head (m)	Obs. head (m)	AE (cm)
May-11	-19.68	29.26	29.40	-0.15
Jun-11	-24.09	29.11	29.07	0.04
Jul-11	-32.10	28.84	28.72	0.12
Aug-11	-30.22	28.91	28.87	0.04
Sep-11	-29.44	28.93	29.01	-0.08
Oct-11	-19.00	29.28	29.36	-0.08
Nov-11	-17.26	29.34	29.36	-0.02
Dec-11	-11.65	29.53	29.51	0.02
Jan-12	-9.57	29.60	29.52	0.08
Feb-12	-10.87	29.55	29.49	0.06
Mar-12	-10.22	29.58	29.56	0.02
Apr-12	-12.92	29.48	29.44	0.04
May-12	-19.37	29.27	29.38	-0.11
Jun-12	-23.47	29.13	29.20	-0.07
Jul-12	-33.54	28.79	28.65	0.14
Aug-12	-37.39	28.67	28.74	-0.07

Toe-slope A-A'

Mo./Yr.	Wem9 (cm)	Pred. head (m)	Obs. head (m)	AE (cm)
May-11	-11.49	29.09	29.18	-0.09
Jun-11	-15.83	28.97	28.90	0.07
Jul-11	-23.46	28.77	28.61	0.16
Aug-11	-22.45	28.79	28.75	0.05
Sep-11	-21.87	28.81	28.92	-0.11
Oct-11	-12.60	29.06	29.16	-0.10
Nov-11	-12.26	29.07	29.16	-0.09
Dec-11	-6.47	29.23	29.20	0.04
Jan-12	-5.35	29.26	29.18	0.08
Feb-12	-6.13	29.24	29.17	0.07
Mar-12	-5.19	29.27	29.22	0.05
Apr-12	-6.71	29.23	29.18	0.04
May-12	-13.25	29.05	29.19	-0.14
Jun-12	-17.44	28.93	29.03	-0.10

Jul-12	-28.14	28.64	28.53	0.10
Aug-12	-31.73	28.54	28.57	-0.03

WemX = effective monthly recharge.
Pred head = predicted head elevation.
Obs. head = observed head elevation.
AE = absolute error between predicted and observed head elevation.

Pocahontas State Park Transect A-A’ W_{em} Results

Effective Monthly Recharge (W_{em}) (cm)

	Dry Year		**Normal Year**		**Wet Year**	
	1991	**2012**	**1999**	**2000**	**1983**	**1984**
			Hillslope			
Jan	-25.61	-9.69	-13.95	-7.30	-4.35	-6.94
Feb	-15.23	-10.92	-5.53	-0.19	-3.00	0.23
Mar	-15.59	-10.23	-7.49	-1.77	6.50	6.54
Apr	-8.63	-12.92	-7.36	-4.82	12.99	17.92
May	-16.25	-19.37	-13.54	-5.20	9.79	14.51
Jun	-26.52	-23.47	-20.45	-12.51	-0.72	7.91
Jul	-33.37	-33.54	-25.45	-17.42	-6.22	-3.09
Aug	-34.60	-37.39	-31.29	-17.35	-22.24	0.28
Sep	-39.38	-33.83	-36.28	-18.77	-29.06	-1.14
Oct	-37.75	-30.19	-9.61	-16.52	-30.49	-5.90
Nov	-32.60	-25.50	-8.40	-21.00	-24.27	-5.98
Dec	-30.68	-26.10	-9.73	-19.08	-16.37	-3.07
			Toe-slope			
Jan	-19.11	-5.35	-14.88	-5.03	-3.31	-5.94
Feb	-8.09	-6.13	-5.57	2.25	-1.10	1.45
Mar	-8.98	-5.19	-6.33	1.02	9.11	8.66
Apr	-0.15	-6.71	-4.41	-0.78	15.42	20.43
May	-7.32	-13.25	-7.64	0.12	12.36	18.04
Jun	-18.54	-17.44	-12.69	-6.86	1.31	12.24
Jul	-24.69	-28.14	-16.58	-15.06	-3.93	1.47
Aug	-25.86	-31.73	-22.17	-14.92	-20.84	3.86
Sep	-30.27	-28.41	-27.31	-16.19	-27.74	0.39
Oct	-30.21	-25.15	-2.57	-14.20	-28.68	-5.99
Nov	-26.55	-19.92	-4.42	-19.91	-21.83	-8.12
Dec	-23.97	-20.57	-6.78	-17.77	-14.28	-6.31

Hillslope W_{em}: n =15, d = 0.85, y = 0.0335x + 29.9179
Toe-slope W_{em}: n = 9, d = 0.80, y = 0.0275x + 29.4102

Predicted heads were generated by using W_{em} value as ‘x’ in calibration equation for each respective well. See appendix X3 for predicted heads.

Powhatan WMA Calibration Period Transect B-B’ W_{em} Results

Hillslope B-B'

Mo./Yr.	Wem12 (cm)	Pred. head (m)	Obs. head (m)	AE (cm)
Aug-11	-20.03	26.24	26.25	-0.01
Sep-11	-18.31	26.32	26.26	0.06
Oct-11	-12.14	26.61	26.62	-0.01
Nov-11	-11.05	26.66	26.80	-0.14
Dec-11	-7.15	26.85	26.94	-0.09
Jan-12	-2.83	27.05	26.90	0.16
Feb-12	-4.90	26.95	26.93	0.02
Mar-12	-5.33	26.93	27.00	-0.07
Apr-12	-3.19	27.03	26.96	0.07
May-12	-7.97	26.81	26.95	-0.14
Jun-12	-6.85	26.86	26.80	0.06
Jul-12	-16.54	26.40	26.40	0.00
Aug-12	-19.28	26.27	26.19	0.08

Toe-slope B-B'

Mo./Yr.	Wem14 (cm)	Pred. head (m)	Obs. head (m)	AE (cm)
Aug-11	-19.01	25.83	25.79	0.04
Sep-11	-15.98	25.98	25.86	0.12
Oct-11	-9.45	26.30	26.39	-0.09
Nov-11	-7.93	26.38	26.59	-0.21
Dec-11	-4.12	26.57	26.62	-0.05
Jan-12	0.16	26.78	26.57	0.21
Feb-12	-2.33	26.66	26.62	0.04
Mar-12	-3.87	26.58	26.65	-0.07
Apr-12	-1.78	26.68	26.55	0.13
May-12	-7.68	26.39	26.58	-0.19
Jun-12	-7.18	26.42	26.42	0.00
Jul-12	-17.46	25.90	25.89	0.01
Aug-12	-18.67	25.85	25.77	0.08

WemX = effective monthly recharge.
Pred head = predicted head elevation.
Obs. head = observed head elevation.
AE = absolute error between predicted and observed head elevation.

Powhatan WMA Transect B-B' W_{em} Results

Effective Monthly Recharge (cm)						
	Dry Year		**Normal Year**		**Wet Year**	
	1980	**2007**	**1983**	**2002**	**1993**	**2003**
			Hillslope			
Jan	8.51	4.27	-0.59	-22.90	-5.07	-3.16
Feb	11.39	8.69	-1.37	-17.03	1.82	-2.74
Mar	4.40	5.88	2.81	-19.68	3.32	6.40
Apr	-1.23	1.40	4.83	-15.66	13.24	10.15
May	-7.31	-1.91	7.27	-18.06	16.11	12.18
Jun	-10.07	-6.39	2.65	-19.20	6.40	17.96
Jul	-22.98	-13.44	-5.34	-28.11	-5.54	13.34
Aug	-26.85	-20.31	-20.45	-34.85	-16.68	18.91
Sep	-36.78	-20.17	-29.36	-36.56	-23.51	15.04
Oct	-37.39	-28.49	-32.64	-34.94	-25.99	29.07
Nov	-32.96	-23.34	-24.25	-20.55	-22.43	21.57
Dec	-31.45	-26.19	-14.58	-9.81	-12.04	20.91
			Toe-slope			
Jan	7.94	6.81	1.52	-18.41	-1.83	1.02
Feb	11.90	10.52	1.27	-11.93	4.84	1.37
Mar	5.56	6.40	5.64	-14.83	5.56	9.04
Apr	-1.31	0.04	6.65	-10.26	14.82	12.06
May	-8.01	-4.27	7.19	-13.97	15.75	12.62
Jun	-10.62	-8.95	0.88	-15.96	5.31	16.97
Jul	-23.98	-15.39	-6.89	-25.15	-7.44	10.10
Aug	-26.79	-21.94	-21.65	-32.03	-19.13	14.13
Sep	-35.58	-19.38	-29.59	-32.67	-24.65	9.78
Oct	-33.17	-25.51	-31.50	-30.73	-25.77	23.94
Nov	-26.58	-19.00	-21.55	-16.43	-21.21	17.48
Dec	-24.61	-20.57	-10.61	-5.84	-9.52	17.77

Hillslope W_{em}: $n = 12$, $d = 0.85$, $y = 0.0472x + 27.1848$

Toe-slope W_{em}: $n = 14$, $d = 0.80$, $y = 0.0496x + 26.771$

Predicted heads were generated by using W_{em} value as 'x' in calibration equation for each respective well. See appendix X3 for predicted heads.

Powhatan WMA Calibration Period Transect C-C' W_{em} Results

Hillslope C-C'

Mo./Yr.	Wem7 (cm)	Pred. head (m)	Obs. head (m)	AE (cm)
Aug-11	-22.46	26.79	26.78	0.01
Sep-11	-21.43	26.83	26.72	0.11
Oct-11	-14.19	27.15	27.04	0.11
Nov-11	-13.03	27.20	27.33	-0.13
Dec-11	-5.62	27.52	27.64	-0.12
Jan-12	1.76	27.84	27.52	0.32
Feb-12	3.69	27.92	28.06	-0.14
Mar-12	0.67	27.79	28.19	-0.40
Apr-12	2.58	27.87	27.62	0.25
May-12	-5.42	27.53	27.55	-0.02
Jun-12	-5.73	27.51	27.40	0.11
Jul-12	-18.21	26.97	27.01	-0.04
Aug-12	-23.09	26.76	26.81	-0.05

Toe-slope C-C'

Mo./Yr.	Wem12 (cm)	Pred. head (m)	Obs. head (m)	AE (cm)
Aug-11	-20.03	26.43	26.42	0.01
Sep-11	-18.31	26.50	26.42	0.08
Oct-11	-12.14	26.76	26.78	-0.02
Nov-11	-11.05	26.80	26.94	-0.14
Dec-11	-7.15	26.97	27.02	-0.05
Jan-12	-2.83	27.15	26.99	0.16
Feb-12	-4.90	27.06	27.07	-0.01
Mar-12	-5.33	27.04	27.11	-0.07
Apr-12	-3.19	27.13	27.05	0.08
May-12	-7.97	26.93	27.06	-0.13
Jun-12	-6.85	26.98	26.95	0.03
Jul-12	-16.54	26.57	26.56	0.01
Aug-12	-19.28	26.46	26.42	0.04

WemX = effective monthly recharge.
Pred head = predicted head elevation.
Obs. head = observed head elevation.
AE = absolute error between predicted and observed head elevation.

Powhatan WMA Transect C-C' W_{em} Results

Effective Monthly Recharge (cm)

	Dry Year		Normal Year		Wet Year	
	1980	2007	1983	2002	1993	2003
	Hillslope					
Jan	6.19	13.05	1.24	-25.22	-6.63	-4.21
Feb	15.07	18.80	2.03	-16.86	3.54	2.62
Mar	11.25	18.97	8.79	-16.37	9.20	16.16
Apr	6.65	8.98	11.60	-11.72	19.72	23.00
May	-4.81	0.38	13.71	-12.63	23.13	25.81
Jun	-11.89	-8.37	7.33	-12.19	14.69	26.34
Jul	-27.89	-20.48	-2.97	-21.36	0.26	16.64
Aug	-32.64	-27.51	-21.84	-31.91	-15.75	18.27
Sep	-46.59	-29.17	-31.94	-37.38	-26.77	14.20
Oct	-44.98	-35.78	-39.06	-36.13	-31.45	24.54
Nov	-38.16	-28.08	-32.76	-25.30	-33.96	17.72
Dec	-34.19	-28.25	-23.97	-13.05	-25.14	18.21
	Toe-slope					
Jan	8.51	4.27	-0.59	-22.90	-5.07	-3.16
Feb	11.39	8.69	-1.37	-17.03	1.82	-2.74
Mar	4.40	5.88	2.81	-19.68	3.32	6.40
Apr	-1.23	1.40	4.83	-15.66	13.24	10.15
May	-7.31	-1.91	7.27	-18.06	16.11	12.18
Jun	-10.07	-6.39	2.65	-19.20	6.40	17.96
Jul	-22.98	-13.44	-5.34	-28.11	-5.54	13.34
Aug	-26.85	-20.31	-20.45	-34.85	-16.68	18.91
Sep	-36.78	-20.17	-29.36	-36.56	-23.51	15.04
Oct	-37.39	-28.49	-32.64	-34.94	-25.99	29.07
Nov	-32.96	-23.34	-24.25	-20.55	-22.43	21.57
Dec	-31.45	-26.19	-14.58	-9.81	-12.04	20.91

Hillslope W_{em}: $n = 7$, $d = 0.90$, $y = 0.0433x + 27.76$

Toe-slope W_{em}: $n = 12$, $d = 0.85$, $y = 0.0418x + 27.266$

Predicted heads were generated by using W_{em} value as 'x' in calibration equation for each respective well. See appendix X3 for predicted heads.

APPENDIX G

GROUNDWATER INPUT AND OUTPUT CALCULATIONS

Pocahontas State Park Transect A-A’: Groundwater Input

Darcy's Law Parameters for PSP Transect A-A'

K (m/sec)	2.30E-06
Cross-sectional area (m^2)	150
Width (m)	50
Depth (m)	3.0
Wetland surface area (m^2)	1550
Width (m)	50
Length (m)	31
Hydraulic gradient (Δh/Δl)	
Δh (m)	HS head - TS head
Δl (m)	9

HS = hillslope. TS = toe-slope.

Observed Monthly Groundwater Input Calculations for Pocahontas Study Site Transect A-A'

	Average Head Elevation			Groundwater discharge (Q)		Groundwater Input
Mo./Yr.	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Aug-11	28.72	28.65	0.01	2.53E-06	6.79E+00	0.44
Sep-11	29.28	29.09	0.02	7.42E-06	1.92E+01	1.24
Oct-11	29.30	29.12	0.02	6.89E-06	1.84E+01	1.19
Nov-11	29.45	29.19	0.03	9.95E-06	2.58E+01	1.66
Dec-11	29.53	29.18	0.04	1.33E-05	3.55E+01	2.29
Jan-12	29.50	29.17	0.04	1.26E-05	3.36E+01	2.17
Feb-12	29.51	29.18	0.04	1.26E-05	3.15E+01	2.03
Mar-12	29.51	29.19	0.04	1.22E-05	3.26E+01	2.10
Apr-12	29.40	29.18	0.02	8.33E-06	2.16E+01	1.39
May-12	29.29	29.12	0.02	6.64E-06	1.78E+01	1.15
Jun-12	28.91	28.77	0.02	5.39E-06	1.40E+01	0.90
Jul-12	28.61	28.52	0.01	3.50E-06	9.37E+00	0.60
Aug-12	28.25	28.05	0.02	7.64E-06	2.05E+01	1.32

Pocahontas State Park Transect A-A’: Groundwater Input for Dry Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1991 (Dry)	Hillslope (m)	Toe-slope (m)	Δh/Δl	(m^3/sec)	(m^3/mo.)	(cm)
Jan	29.06	28.88	0.02	6.71E-06	1.80E+01	1.16
Feb	29.41	29.19	0.02	8.43E-06	2.26E+01	1.46
Mar	29.40	29.16	0.03	8.91E-06	2.39E+01	1.54
Apr	29.63	29.41	0.02	8.54E-06	2.29E+01	1.48
May	29.37	29.21	0.02	6.32E-06	1.64E+01	1.06
Jun	29.03	28.90	0.01	4.96E-06	1.33E+01	0.86
Jul	28.80	28.73	0.01	2.63E-06	6.82E+00	0.44
Aug	28.76	28.70	0.01	2.29E-06	6.14E+00	0.40
Sep	28.60	28.58	0.00	8.09E-07	2.17E+00	0.14
Oct	28.65	28.58	0.01	2.83E-06	6.84E+00	0.44
Nov	28.83	28.68	0.02	5.59E-06	1.50E+01	0.97
Dec	28.89	28.75	0.02	5.33E-06	1.38E+01	0.89

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2012 (Dry)	Hillslope (m)	Toe-slope (m)	Δh/Δl	(m^3/sec)	(m^3/mo.)	(cm)
Jan	29.59	29.26	0.04	1.27E-05	3.39E+01	2.19
Feb	29.55	29.24	0.03	1.19E-05	3.19E+01	2.06
Mar	29.58	29.27	0.03	1.18E-05	3.16E+01	2.04
Apr	29.48	29.23	0.03	9.93E-06	2.66E+01	1.72
May	29.27	29.05	0.02	8.55E-06	2.22E+01	1.43
Jun	29.13	28.93	0.02	7.71E-06	2.06E+01	1.33
Jul	28.79	28.64	0.02	6.05E-06	1.57E+01	1.01
Aug	28.67	28.54	0.01	4.90E-06	1.31E+01	0.85
Sep	28.78	28.63	0.02	5.98E-06	1.60E+01	1.03
Oct	28.91	28.72	0.02	7.21E-06	1.74E+01	1.13
Nov	29.06	28.86	0.02	7.71E-06	2.07E+01	1.33
Dec	29.04	28.84	0.02	7.63E-06	1.98E+01	1.28

Pocahontas State Park Transect A-A’: Groundwater Input for Normal Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1999 (Normal)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	29.45	29.00	0.05	1.72E-05	4.62E+01	2.98
Feb	29.73	29.26	0.05	1.82E-05	4.88E+01	3.15
Mar	29.67	29.24	0.05	1.65E-05	4.42E+01	2.85
Apr	29.67	29.29	0.04	1.47E-05	3.93E+01	2.53
May	29.46	29.20	0.03	1.01E-05	2.63E+01	1.69
Jun	29.23	29.06	0.02	6.58E-06	1.76E+01	1.14
Jul	29.07	28.95	0.01	4.26E-06	1.10E+01	0.71
Aug	28.87	28.80	0.01	2.65E-06	7.11E+00	0.46
Sep	28.70	28.66	0.00	1.67E-06	4.46E+00	0.29
Oct	29.60	29.34	0.03	9.83E-06	2.38E+01	1.53
Nov	29.64	29.29	0.04	1.33E-05	3.57E+01	2.30
Dec	29.59	29.22	0.04	1.41E-05	3.66E+01	2.36

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2000 (Normal)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	29.67	29.27	0.04	1.54E-05	4.12E+01	2.66
Feb	29.91	29.47	0.05	1.68E-05	4.51E+01	2.91
Mar	29.86	29.44	0.05	1.61E-05	4.31E+01	2.78
Apr	29.76	29.39	0.04	1.41E-05	3.77E+01	2.44
May	29.74	29.41	0.04	1.27E-05	3.28E+01	2.12
Jun	29.50	29.22	0.03	1.06E-05	2.84E+01	1.84
Jul	29.33	29.00	0.04	1.30E-05	3.36E+01	2.17
Aug	29.34	29.00	0.04	1.29E-05	3.46E+01	2.23
Sep	29.29	28.97	0.04	1.24E-05	3.33E+01	2.15
Oct	29.36	29.02	0.04	1.32E-05	3.20E+01	2.06
Nov	29.21	28.86	0.04	1.35E-05	3.61E+01	2.33
Dec	29.28	28.92	0.04	1.37E-05	3.55E+01	2.29

Pocahontas State Park Transect A-A’: Groundwater Input for Wet Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1983 (Wet)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	29.77	29.32	0.05	1.74E-05	4.65E+01	3.00
Feb	29.82	29.38	0.05	1.68E-05	4.49E+01	2.90
Mar	30.14	29.66	0.05	1.82E-05	4.88E+01	3.15
Apr	30.35	29.83	0.06	1.99E-05	5.33E+01	3.44
May	30.25	29.75	0.06	1.90E-05	4.92E+01	3.18
Jun	29.89	29.45	0.05	1.72E-05	4.59E+01	2.96
Jul	29.71	29.30	0.05	1.56E-05	4.05E+01	2.61
Aug	29.17	28.84	0.04	1.29E-05	3.44E+01	2.22
Sep	28.94	28.65	0.03	1.14E-05	3.05E+01	1.97
Oct	28.90	28.62	0.03	1.05E-05	2.55E+01	1.64
Nov	29.10	28.81	0.03	1.13E-05	3.03E+01	1.95
Dec	29.37	29.02	0.04	1.35E-05	3.50E+01	2.26

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1984 (Wet)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	29.69	29.25	0.05	1.68E-05	4.50E+01	2.91
Feb	29.93	29.45	0.05	1.82E-05	4.88E+01	3.15
Mar	30.14	29.65	0.05	1.87E-05	5.02E+01	3.24
Apr	30.52	29.97	0.06	2.09E-05	5.61E+01	3.62
May	30.40	29.91	0.06	1.91E-05	4.95E+01	3.19
Jun	30.18	29.75	0.05	1.67E-05	4.48E+01	2.89
Jul	29.81	29.45	0.04	1.39E-05	3.62E+01	2.33
Aug	29.93	29.52	0.05	1.58E-05	4.22E+01	2.72
Sep	29.88	29.42	0.05	1.76E-05	4.71E+01	3.04
Oct	29.72	29.25	0.05	1.82E-05	4.40E+01	2.84
Nov	29.72	29.19	0.06	2.03E-05	5.45E+01	3.52
Dec	29.81	29.24	0.06	2.22E-05	5.75E+01	3.71

Pocahontas State Park Transect A-A’: Groundwater Output

Darcy's Law Parameters for PSP Transect A-A'

K (m/sec)	2.50E-07
Cross-sectional area (m^2)	150
Width (m)	50
Depth (m)	3.0
Wetland surface area (m^2)	1550
Width (m)	50
Length (m)	31
Hydraulic gradient (Δh/Δl)	
Δh (m)	DE head - stream head
Δl (m)	1.5

DE = dry edge

Observed Monthly Groundwater Output Calculations for Pocahontas Study Site Transect A-A'

	Head Elevation			Groundwater discharge (Q)		Groundwater output
Mo./Yr.	**Dry edge (m)**	**Stream* (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Aug-11	28.64	28.55	0.06	2.25E-06	6.03E+00	0.39
Sep-11	28.79	28.70	0.06	2.25E-06	5.83E+00	0.38
Oct-11	28.99	28.94	0.03	1.25E-06	3.35E+00	0.22
Nov-11	29.05	29.00	0.03	1.25E-06	3.24E+00	0.21
Dec-11	29.10	29.05	0.03	1.25E-06	3.35E+00	0.22
Jan-12	29.08	29.03	0.03	1.25E-06	3.35E+00	0.22
Feb-12	29.11	29.06	0.03	1.25E-06	3.13E+00	0.20
Mar-12	29.16	29.11	0.03	1.25E-06	3.24E+00	0.22
Apr-12	29.02	28.97	0.03	1.25E-06	3.24E+00	0.21
May-12	29.02	28.95	0.05	1.75E-06	4.69E+00	0.30
Jun-12	-	-	-	-	-	-
Jul-12	28.45	28.40	0.03	1.25E-06	3.35E+00	0.22
Aug-12	28.58	28.55	0.02	7.50E-07	2.01E+00	0.25

* Stream head was estimated based on observations during monthly visits to the site.

Powhatan WMA Transect B-B’: Groundwater Input

Darcy's Law Parameters for PWMA Transect B-B'

K (m/sec)	8.37E-06
Cross-sectional area (m^2)	400
Width (m)	100
Depth (m)	4.0
Wetland surface area (m^2)	8100
Width (m)	100
Length (m)	60
Hydraulic gradient (Δh/Δl)	
Δh (m)	HS head - TS head
Δl (m)	7.0

HS = hillslope, TS = toe-slope

Observed Monthly Groundwater Input Calculations for Powhatan WMA Study Site Transect B-B'

	Average Monthly Head Elev.			Groundwater discharge (Q)		Groundwater Input
Mo./Yr.	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Aug-11	26.20	25.78	0.06	1.99E-04	5.34E+02	6.60
Sep-11	26.46	26.20	0.04	1.25E-04	3.25E+02	4.01
Oct-11	26.69	26.44	0.04	1.18E-04	3.16E+02	3.90
Nov-11	26.88	26.60	0.04	1.34E-04	3.46E+02	4.28
Dec-11	26.94	26.62	0.05	1.51E-04	4.05E+02	5.00
Jan-12	26.94	26.61	0.05	1.58E-04	4.22E+02	5.21
Feb-12	26.96	26.61	0.05	1.65E-04	4.12E+02	5.09
Mar-12	27.03	26.64	0.06	1.87E-04	5.01E+02	6.19
Apr-12	26.93	26.51	0.06	1.98E-04	5.14E+02	6.35
May-12	26.85	26.43	0.06	2.00E-04	5.35E+02	6.60
Jun-12	26.62	26.15	0.07	2.25E-04	5.82E+02	7.18
Jul-12	26.28	25.81	0.07	2.24E-04	6.00E+02	7.41
Aug-12	26.10	25.70	0.06	1.90E-04	5.10E+02	6.30

Powhatan WMA Transect B-B’: Groundwater Input for Dry Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1980 (Dry)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	27.58	27.16	0.06	2.01E-04	5.38E+02	6.65
Feb	27.72	27.36	0.05	1.72E-04	4.60E+02	5.68
Mar	27.39	27.05	0.05	1.65E-04	4.41E+02	5.45
Apr	27.13	26.71	0.06	2.01E-04	5.38E+02	6.64
May	26.84	26.37	0.07	2.23E-04	5.78E+02	7.13
Jun	26.71	26.24	0.07	2.22E-04	5.96E+02	7.36
Jul	26.10	25.58	0.07	2.49E-04	6.45E+02	7.96
Aug	25.92	25.44	0.07	2.28E-04	6.11E+02	7.55
Sep	25.45	25.01	0.06	2.13E-04	5.71E+02	7.04
Oct	25.42	25.13	0.04	1.42E-04	3.44E+02	4.25
Nov	25.63	25.45	0.03	8.57E-05	2.30E+02	2.83
Dec	25.70	25.55	0.02	7.29E-05	1.89E+02	2.33

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2007 (Dry)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	27.39	27.11	0.04	1.32E-04	3.54E+02	4.37
Feb	27.59	27.29	0.04	1.44E-04	3.85E+02	4.75
Mar	27.46	27.09	0.05	1.78E-04	4.77E+02	5.89
Apr	27.25	26.77	0.07	2.28E-04	6.11E+02	7.54
May	27.09	26.56	0.08	2.56E-04	6.63E+02	8.19
Jun	26.88	26.33	0.08	2.66E-04	7.12E+02	8.79
Jul	26.55	26.01	0.08	2.60E-04	6.73E+02	8.31
Aug	26.23	25.68	0.08	2.60E-04	6.97E+02	8.61
Sep	26.23	25.81	0.06	2.03E-04	5.43E+02	6.71
Oct	25.84	25.51	0.05	1.61E-04	3.89E+02	4.81
Nov	26.08	25.83	0.04	1.22E-04	3.28E+02	4.05
Dec	25.95	25.75	0.03	9.55E-05	2.48E+02	3.06

Powhatan WMA Transect B-B': Groundwater Input for Normal Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1983 (Normal)	Hillslope (m)	Toe-slope (m)	Δh/Δl	(m^3/sec)	(m^3/mo.)	(cm)
Jan	27.16	26.85	0.04	1.48E-04	3.97E+02	4.90
Feb	27.12	26.83	0.04	1.37E-04	3.66E+02	4.52
Mar	27.32	27.05	0.04	1.27E-04	3.40E+02	4.20
Apr	27.41	27.10	0.04	1.49E-04	3.98E+02	4.91
May	27.53	27.13	0.06	1.91E-04	4.95E+02	6.11
Jun	27.31	26.81	0.07	2.36E-04	6.33E+02	7.82
Jul	26.93	26.43	0.07	2.41E-04	6.24E+02	7.70
Aug	26.22	25.70	0.07	2.50E-04	6.71E+02	8.28
Sep	25.80	25.30	0.07	2.38E-04	6.38E+02	7.87
Oct	25.65	25.21	0.06	2.10E-04	5.07E+02	6.26
Nov	26.04	25.70	0.05	1.63E-04	4.35E+02	5.37
Dec	26.50	26.24	0.04	1.21E-04	3.13E+02	3.87

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2002 (Normal)	Hillslope (m)	Toe-slope (m)	Δh/Δl	(m^3/sec)	(m^3/mo.)	(cm)
Jan	26.11	25.86	0.04	1.18E-04	3.17E+02	3.92
Feb	26.38	26.18	0.03	9.68E-05	2.59E+02	3.20
Mar	26.26	26.04	0.03	1.06E-04	2.84E+02	3.50
Apr	26.45	26.26	0.03	8.80E-05	2.36E+02	2.91
May	26.33	26.08	0.04	1.22E-04	3.17E+02	3.91
Jun	26.28	25.98	0.04	1.44E-04	3.85E+02	4.75
Jul	25.86	25.52	0.05	1.61E-04	4.17E+02	5.15
Aug	25.54	25.18	0.05	1.72E-04	4.62E+02	5.70
Sep	25.46	25.15	0.04	1.49E-04	3.99E+02	4.93
Oct	25.54	25.25	0.04	1.39E-04	3.37E+02	4.16
Nov	26.22	25.96	0.04	1.24E-04	3.33E+02	4.11
Dec	26.72	26.48	0.03	1.15E-04	2.98E+02	3.68

Powhatan WMA Transect B-B': Groundwater Input for Wet Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1993 (Wet)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	26.95	26.68	0.04	1.27E-04	3.40E+02	4.19
Feb	27.27	27.01	0.04	1.24E-04	3.32E+02	4.09
Mar	27.34	27.05	0.04	1.40E-04	3.76E+02	4.64
Apr	27.81	27.51	0.04	1.44E-04	3.86E+02	4.77
May	27.94	27.55	0.06	1.87E-04	4.84E+02	5.98
Jun	27.49	27.03	0.06	2.16E-04	5.77E+02	7.13
Jul	26.92	26.40	0.07	2.49E-04	6.46E+02	7.97
Aug	26.40	25.82	0.08	2.76E-04	7.38E+02	9.12
Sep	26.08	25.55	0.08	2.53E-04	6.77E+02	8.35
Oct	25.96	25.49	0.07	2.24E-04	5.41E+02	6.68
Nov	26.13	25.72	0.06	1.95E-04	5.23E+02	6.46
Dec	26.62	26.30	0.05	1.52E-04	3.94E+02	4.87

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2003 (Wet)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	27.03	26.82	0.03	1.02E-04	2.74E+02	3.38
Feb	27.05	26.84	0.03	1.03E-04	2.77E+02	3.42
Mar	27.49	27.22	0.04	1.27E-04	3.41E+02	4.21
Apr	27.66	27.37	0.04	1.40E-04	3.75E+02	4.63
May	27.76	27.40	0.05	1.73E-04	4.48E+02	5.53
Jun	28.03	27.61	0.06	2.00E-04	5.34E+02	6.60
Jul	27.81	27.27	0.08	2.59E-04	6.70E+02	8.27
Aug	28.07	27.47	0.09	2.88E-04	7.73E+02	9.54
Sep	27.89	27.26	0.09	3.04E-04	8.15E+02	10.06
Oct	28.55	27.96	0.08	2.84E-04	6.88E+02	8.50
Nov	28.20	27.64	0.08	2.69E-04	7.20E+02	8.89
Dec	28.17	27.65	0.07	2.47E-04	6.41E+02	7.91

Powhatan WMA Transect C-C': Groundwater Input

Darcy's Law Parameters for PWMA Transect C-C'

K (m/sec)	8.37E-06
Cross-sectional area (m^2)	400
Width (m)	100
Depth (m)	4.0
Wetland surface area (m^2)	8100
Width (m)	100
Length (m)	60
Hydraulic gradient (Δh/Δl)	
Δh (m)	HS head - TS head
Δl (m)	27.5

HS = hillslope, TS = toe-slope

Observed Monthly Groundwater Input Calculations for Powhatan WMA Study Site Transect C-C'

	Average Monthly Head Elev.			Groundwater discharge (Q)		Groundwater Input
Mo./Yr.	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Aug-11	26.70	26.39	0.01	3.84E-05	1.03E+02	1.27
Sep-11	26.91	26.63	0.01	3.33E-05	8.64E+01	1.07
Oct-11	27.14	26.84	0.01	3.63E-05	9.73E+01	1.20
Nov-11	27.49	26.98	0.02	6.20E-05	1.61E+02	1.98
Dec-11	27.70	27.02	0.02	8.31E-05	2.23E+02	2.75
Jan-12	27.72	27.04	0.02	8.21E-05	2.20E+02	2.71
Feb-12	27.85	27.06	0.03	9.60E-05	2.40E+02	2.97
Mar-12	28.14	27.12	0.04	1.25E-04	3.35E+02	4.13
Apr-12	27.58	27.03	0.02	6.71E-05	1.74E+02	2.15
May-12	27.46	26.96	0.02	6.10E-05	1.64E+02	2.02
Jun-12	27.22	26.77	0.02	5.49E-05	1.42E+02	1.76
Jul-12	26.90	26.48	0.02	5.06E-05	1.35E+02	1.67
Aug-12	26.71	26.35	0.01	4.33E-05	1.16E+02	1.43

Powhatan WMA Transect C-C’: Groundwater Input for Dry Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1980 (Dry)	Hillslope (m)	Toe-slope (m)	Δh/Δl	(m^3/sec)	(m^3/mo.)	(cm)
Jan	28.03	27.62	0.01	4.94E-05	1.32E+02	1.63
Feb	28.41	27.74	0.02	8.15E-05	2.18E+02	2.69
Mar	28.25	27.45	0.03	9.69E-05	2.60E+02	3.21
Apr	28.05	27.21	0.03	1.01E-04	2.72E+02	3.35
May	27.55	26.96	0.02	7.21E-05	1.87E+02	2.31
Jun	27.25	26.84	0.01	4.89E-05	1.31E+02	1.62
Jul	26.56	26.31	0.01	3.04E-05	7.87E+01	0.97
Aug	26.35	26.14	0.01	2.51E-05	6.73E+01	0.83
Sep	25.75	25.73	0.00	2.31E-06	6.18E+00	0.08
Oct	25.82	25.70	0.00	1.39E-05	3.35E+01	0.41
Nov	26.11	25.89	0.01	2.72E-05	7.28E+01	0.90
Dec	26.28	25.95	0.01	4.04E-05	1.05E+02	1.29

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2007 (Dry)	Hillslope (m)	Toe-slope (m)	Δh/Δl	(m^3/sec)	(m^3/mo.)	(cm)
Jan	28.32	27.44	0.03	1.07E-04	2.87E+02	3.54
Feb	28.57	27.63	0.03	1.15E-04	3.07E+02	3.80
Mar	28.58	27.51	0.04	1.30E-04	3.48E+02	4.30
Apr	28.15	27.32	0.03	1.00E-04	2.68E+02	3.31
May	27.78	27.19	0.02	7.19E-05	1.86E+02	2.30
Jun	27.40	27.00	0.01	4.86E-05	1.30E+02	1.61
Jul	26.88	26.70	0.01	2.08E-05	5.39E+01	0.67
Aug	26.57	26.42	0.01	1.88E-05	5.05E+01	0.62
Sep	26.50	26.42	0.00	9.41E-06	2.52E+01	0.31
Oct	26.21	26.08	0.01	1.69E-05	4.09E+01	0.51
Nov	26.55	26.29	0.01	3.12E-05	8.37E+01	1.03
Dec	26.54	26.17	0.01	4.49E-05	1.16E+02	1.44

Powhatan WMA Transect C-C': Groundwater Input for Normal Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1983 (Normal)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	27.81	27.24	0.02	6.97E-05	1.87E+02	2.30
Feb	27.85	27.21	0.02	7.78E-05	2.08E+02	2.57
Mar	28.14	27.38	0.03	9.21E-05	2.47E+02	3.04
Apr	28.26	27.47	0.03	9.65E-05	2.59E+02	3.19
May	28.35	27.57	0.03	9.53E-05	2.47E+02	3.05
Jun	28.08	27.38	0.03	8.52E-05	2.28E+02	2.82
Jul	27.63	27.04	0.02	7.17E-05	1.86E+02	2.29
Aug	26.82	26.41	0.01	4.94E-05	1.32E+02	1.63
Sep	26.38	26.04	0.01	4.15E-05	1.11E+02	1.37
Oct	26.07	25.90	0.01	2.08E-05	5.03E+01	0.62
Nov	26.34	26.25	0.00	1.13E-05	3.02E+01	0.37
Dec	26.72	26.66	0.00	8.28E-06	2.15E+01	0.27

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2002 (Normal)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	26.67	26.31	0.01	4.40E-05	1.18E+02	1.46
Feb	27.03	26.55	0.02	5.81E-05	1.56E+02	1.92
Mar	27.05	26.44	0.02	7.42E-05	1.99E+02	2.45
Apr	27.25	26.61	0.02	7.82E-05	2.10E+02	2.59
May	27.21	26.51	0.03	8.56E-05	2.22E+02	2.74
Jun	27.23	26.46	0.03	9.37E-05	2.51E+02	3.10
Jul	26.84	26.09	0.03	9.08E-05	2.35E+02	2.91
Aug	26.38	25.81	0.02	6.96E-05	1.86E+02	2.30
Sep	26.15	25.74	0.01	4.96E-05	1.33E+02	1.64
Oct	26.20	25.81	0.01	4.79E-05	1.16E+02	1.43
Nov	26.67	26.41	0.01	3.17E-05	8.48E+01	1.05
Dec	27.20	26.86	0.01	4.14E-05	1.07E+02	1.33

Powhatan WMA Transect C-C’: Groundwater Input for Wet Years

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
1993 (Wet)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	27.47	27.05	0.02	5.11E-05	1.37E+02	1.69
Feb	27.91	27.34	0.02	6.95E-05	1.86E+02	2.30
Mar	28.16	27.40	0.03	9.17E-05	2.46E+02	3.03
Apr	28.61	27.82	0.03	9.65E-05	2.58E+02	3.19
May	28.76	27.94	0.03	9.98E-05	2.59E+02	3.19
Jun	28.39	27.53	0.03	1.05E-04	2.81E+02	3.47
Jul	27.77	27.03	0.03	8.97E-05	2.33E+02	2.87
Aug	27.08	26.57	0.02	6.22E-05	1.67E+02	2.06
Sep	26.60	26.28	0.01	3.90E-05	1.04E+02	1.29
Oct	26.40	26.18	0.01	2.69E-05	6.52E+01	0.80
Nov	26.29	26.33	0.00	-4.33E-06	-1.16E+01	-0.14
Dec	26.67	26.76	0.00	-1.08E-05	-2.80E+01	-0.35

	Predicted Head Elevation			Groundwater discharge (Q)		Groundwater Input
2003 (Wet)	**Hillslope (m)**	**Toe-slope (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Jan	27.58	27.13	0.02	5.41E-05	1.45E+02	1.79
Feb	27.87	27.15	0.03	8.79E-05	2.35E+02	2.91
Mar	28.46	27.53	0.03	1.13E-04	3.02E+02	3.72
Apr	28.75	27.69	0.04	1.29E-04	3.47E+02	4.28
May	28.88	27.78	0.04	1.34E-04	3.47E+02	4.28
Jun	28.90	28.02	0.03	1.07E-04	2.87E+02	3.55
Jul	28.48	27.82	0.02	7.98E-05	2.07E+02	2.55
Aug	28.55	28.06	0.02	6.00E-05	1.61E+02	1.98
Sep	28.37	27.89	0.02	5.83E-05	1.56E+02	1.93
Oct	28.82	28.48	0.01	4.13E-05	9.98E+01	1.23
Nov	28.53	28.17	0.01	4.36E-05	1.17E+02	1.44
Dec	28.55	28.14	0.01	4.95E-05	1.28E+02	1.58

Powhatan WMA: Groundwater Output

Darcy's Law Parameters for PWMA	
K (m/sec)	1.50E-06
Cross-sectional area (m^2)	400
Width (m)	100
Depth (m)	4.0
Wetland surface area (m^2)	8100
Width (m)	100
Length (m)	60
Hydraulic gradient (Δh/Δl)	
Δh (m)	DE head - stream head
Δl (m)	5.0

DE = dry edge

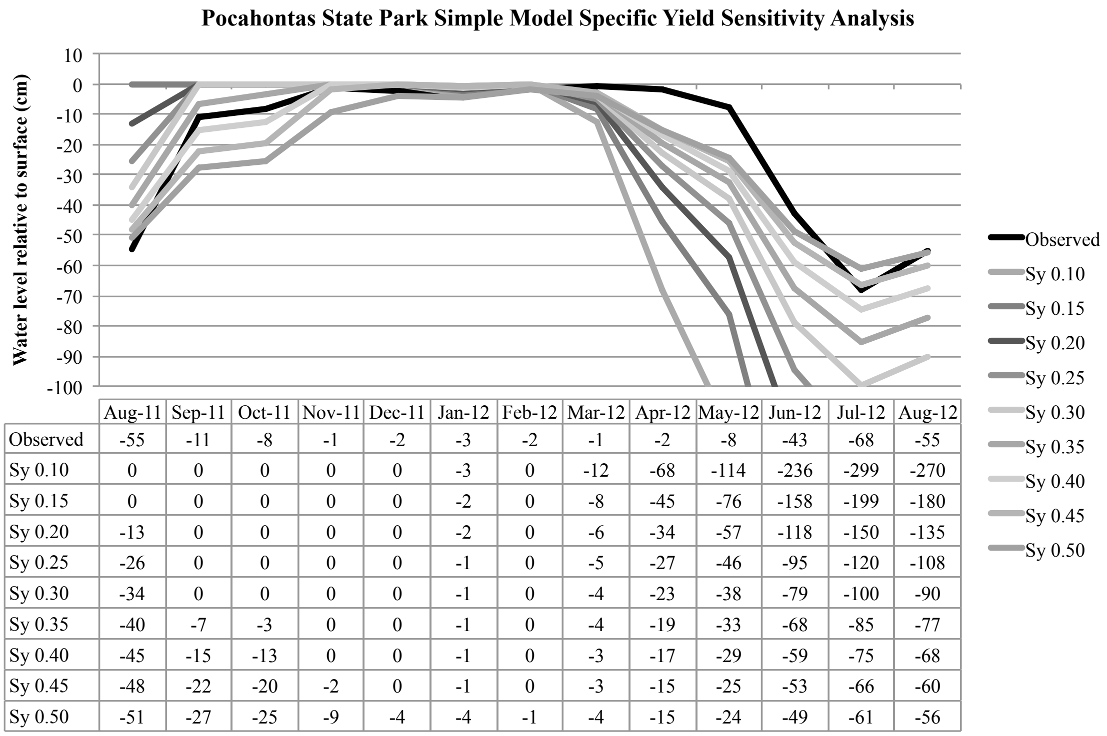
Observed Monthly Groundwater Output Calculations for Powhatan WMA Study Site

	Head Elevation			Groundwater discharge (Q)		Groundwater output
Mo./Yr.	**Dry edge (m)**	**Stream* (m)**	**Δh/Δl**	**(m^3/sec)**	**(m^3/mo.)**	**(cm)**
Feb-12	26.11	25.14	0.19	1.17E-04	2.83E+02	3.49
Mar-12	26.15	25.14	0.20	1.22E-04	3.26E+02	4.02
Apr-12	26.08	25.14	0.19	1.12E-04	2.91E+02	3.60
May-12	26.06	25.14	0.18	1.10E-04	2.95E+02	3.65
Jun-12	-	-	-	-	-	-
Jul-12	25.70	25.14	0.11	6.71E-05	1.80E+02	2.22
Aug-12	25.61	25.14	0.09	5.58E-05	1.49E+02	1.85

* Stream head was estimated based on observations during monthly visits to the site.

APPENDIX H

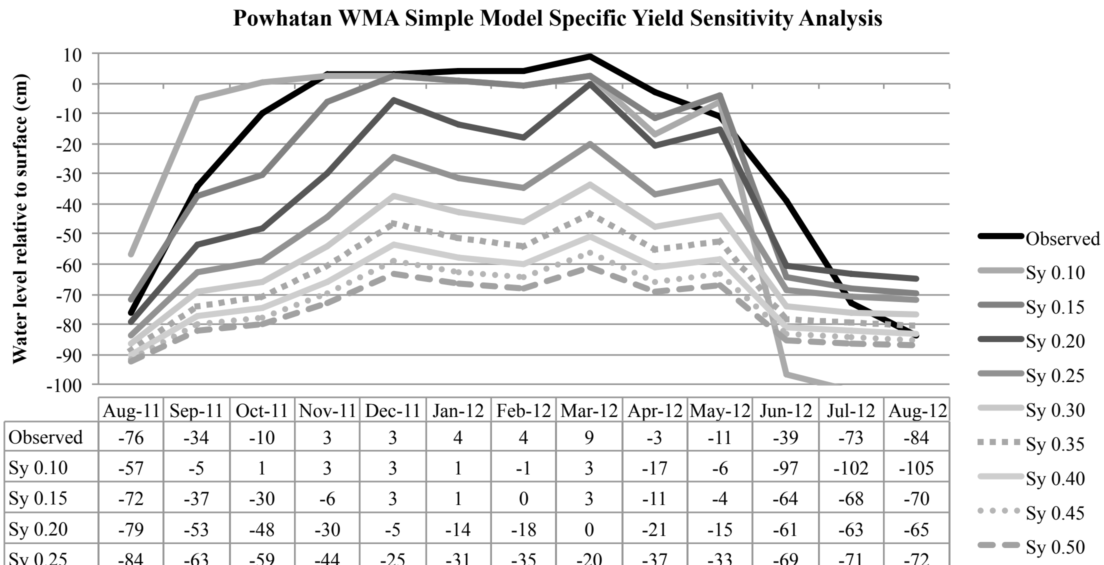
SENSITIVITY ANALYSIS


Pocahontas State Park Simple Model Specific Yield Sensitivity Analysis

	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12
Observed	-55	-11	-8	-1	-2	-3	-2	-1	-2	-8	-43	-68	-55
Sy 0.10	0	0	0	0	0	-3	0	-12	-68	-114	-236	-299	-270
Sy 0.15	0	0	0	0	0	-2	0	-8	-45	-76	-158	-199	-180
Sy 0.20	-13	0	0	0	0	-2	0	-6	-34	-57	-118	-150	-135
Sy 0.25	-26	0	0	0	0	-1	0	-5	-27	-46	-95	-120	-108
Sy 0.30	-34	0	0	0	0	-1	0	-4	-23	-38	-79	-100	-90
Sy 0.35	-40	-7	-3	0	0	-1	0	-4	-19	-33	-68	-85	-77
Sy 0.40	-45	-15	-13	0	0	-1	0	-3	-17	-29	-59	-75	-68
Sy 0.45	-48	-22	-20	-2	0	-1	0	-3	-15	-25	-53	-66	-60
Sy 0.50	-51	-27	-25	-9	-4	-4	-1	-4	-15	-24	-49	-61	-56

Pocahontas State Park Nash-Sutcliffe Efficiency Test Results

Specific Yield (Sy)	NSE
0.10	-19.4019
0.15	-6.3024
0.20	-2.1641
0.25	-0.4854
0.30	0.2752
0.35	0.6595
0.40	0.8300
0.45	0.8798
0.50	0.8492



	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12
Observed	-76	-34	-10	3	3	4	4	9	-3	-11	-39	-73	-84
Sy 0.10	-57	-5	1	3	3	1	-1	3	-17	-6	-97	-102	-105
Sy 0.15	-72	-37	-30	-6	3	1	0	3	-11	-4	-64	-68	-70
Sy 0.20	-79	-53	-48	-30	-5	-14	-18	0	-21	-15	-61	-63	-65
Sy 0.25	-84	-63	-59	-44	-25	-31	-35	-20	-37	-33	-69	-71	-72
Sy 0.30	-87	-69	-66	-54	-37	-43	-46	-34	-48	-44	-74	-76	-77
Sy 0.35	-89	-74	-71	-61	-47	-51	-54	-43	-55	-52	-78	-80	-81
Sy 0.40	-90	-77	-75	-66	-53	-58	-60	-51	-61	-58	-81	-82	-83
Sy 0.45	-92	-80	-78	-70	-59	-63	-64	-56	-66	-63	-83	-85	-85
Sy 0.50	-93	-82	-80	-73	-63	-66	-68	-61	-69	-67	-85	-86	-87

Powhatan WMA Nash-Sutcliffe Efficiency Test Results

Specific Yield (Sy)	NSE
0.10	0.5512
0.15	0.8906
0.20	0.6314
0.25	0.0986
0.30	-0.4543
0.35	-0.9459
0.40	-1.3748
0.45	-1.7429
0.50	-2.0393

APPENDIX I

WATER BUDGET RESULTS

Key for water budget results table headings:

PET = Potential evapotranspiration (cm)
S = Storage (cm)
WL = Water level relative to surface (cm)
Gwin = Groundwater input (cm)
O = Surface outflow (cm)
P = Precipitation (cm)
R = Runoff inflow (cm)
Total = Total water (cm)
Gwout = Groundwater output (cm)
M = Mass balance (cm)

Pocahontas State Park Water Budget Results

Pocahontas State Park Calibration Period Water Budget Model Results (cm)

Mo./Yr.	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Aug-11	13.65	-34.29	-48.15	0.43	0.00	13.34	12.76	-21.67	0.25	12.62
Sep-11	8.01	-21.67	-21.99	1.24	0.00	18.80	0.00	-9.90	0.25	11.77
Oct-11	7.55	-9.90	-19.63	1.19	0.00	7.65	0.00	-8.83	0.23	1.06
Nov-11	5.53	-8.83	-1.86	1.68	0.00	11.76	0.29	-0.84	0.20	8.00
Dec-11	4.44	-0.84	0.00	2.29	1.96	5.18	0.00	0.00	0.23	0.84
Jan-12	6.08	0.00	-0.71	2.16	0.00	3.84	0.00	-0.32	0.23	-0.32
Feb-12	6.06	-0.32	0.00	2.03	1.12	5.66	0.00	0.00	0.20	0.32
Mar-12	9.56	0.00	-2.74	2.11	0.00	6.45	0.00	-1.23	0.23	-1.23
Apr-12	12.20	-1.23	-15.11	1.40	0.00	5.44	0.00	-6.80	0.20	-5.57
May-12	11.87	-6.80	-25.40	1.14	0.00	6.35	0.00	-11.43	0.25	-4.63
Jun-12	14.97	-11.43	-52.51	0.91	0.00	2.11	0.00	-23.63	0.25	-12.20
Jul-12	15.38	-23.63	-66.48	0.61	0.00	8.38	0.34	-29.92	0.23	-6.28
Aug-12	11.54	-29.92	-60.04	1.32	0.00	12.67	0.70	-27.02	0.25	2.90
Total	**126.86**	**-**	**-**	**18.52**	**3.08**	**107.62**	**14.09**	**-**	**3.02**	**7.27**

Pocahontas State Park Dry Year 1991 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	3.77	0.00	0.00	1.37	9.42	12.07	0.01	0.00	0.25	0.00
Feb	5.68	0.00	-1.27	1.88	0.00	3.48	0.00	-0.57	0.25	-0.57
Mar	8.14	-0.57	0.00	1.83	10.97	15.16	2.94	0.00	0.25	0.57
Apr	11.32	0.00	-13.47	1.83	0.00	3.68	0.00	-6.06	0.25	-6.06
May	15.43	-6.06	-37.66	1.14	0.00	3.66	0.00	-16.95	0.25	-10.89
Jun	15.68	-16.95	-57.16	0.69	0.00	6.48	0.00	-25.72	0.25	-8.77
Jul	14.97	-25.72	-62.61	0.20	0.00	11.84	0.73	-28.18	0.25	-2.46
Aug	13.77	-28.18	-81.65	0.23	0.00	5.23	0.00	-36.74	0.25	-8.57
Sep	11.70	-36.74	-89.32	0.03	0.00	8.48	0.00	-40.19	0.25	-3.45
Oct	7.45	-40.19	-86.80	0.36	0.00	8.48	0.00	-39.06	0.25	1.13
Nov	5.56	-39.06	-89.68	0.99	0.00	3.53	0.00	-40.35	0.25	-1.30
Dec	4.65	-40.35	-74.70	1.04	0.00	10.41	0.19	-33.62	0.25	6.74
Total	**118.14**	**-**	**-**	**11.58**	**20.39**	**92.51**	**3.87**	**-**	**3.05**	**-33.62**

Pocahontas State Park Dry Year 2012 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	6.08	0.00	-0.76	2.16	0.00	3.84	0.00	-0.34	0.25	-0.34
Feb	6.06	-0.34	0.00	1.92	0.93	5.66	0.00	0.00	0.25	0.34
Mar	9.56	0.00	-3.39	1.84	0.00	6.45	0.00	-1.53	0.25	-1.53
Apr	12.20	-1.53	-15.74	1.46	0.00	5.44	0.00	-7.08	0.25	-5.56
May	11.87	-7.08	-26.19	1.07	0.00	6.35	0.00	-11.79	0.25	-4.70
Jun	14.97	-11.79	-53.34	0.90	0.00	2.11	0.00	-24.00	0.25	-12.22
Jul	15.38	-24.00	-67.52	0.54	0.00	8.38	0.34	-30.38	0.25	-6.38
Aug	11.54	-30.38	-63.08	0.42	0.00	12.67	0.70	-28.39	0.25	2.00
Sep	9.04	-28.39	-60.05	0.82	0.00	9.45	0.39	-27.02	0.25	1.36
Oct	6.10	-27.02	-53.13	1.02	0.00	8.46	0.00	-23.91	0.25	3.12
Nov	5.15	-23.91	-60.95	1.38	0.00	0.51	0.00	-27.43	0.25	-3.52
Dec	4.10	-27.43	-50.70	1.30	0.00	7.67	0.00	-22.82	0.25	4.61
Total	**112.07**	**-**	**-**	**14.82**	**0.93**	**76.99**	**1.43**	**-**	**3.05**	**-22.82**

Pocahontas State Park Normal Year 1999 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	4.77	0.00	0.00	2.62	10.56	12.88	0.09	0.00	0.25	0.00
Feb	5.01	0.00	0.00	2.97	0.88	3.17	0.00	0.00	0.25	0.00
Mar	9.17	0.00	0.00	2.64	3.25	10.03	0.00	0.00	0.25	0.00
Apr	11.37	0.00	-3.99	2.31	0.00	7.52	0.00	-1.79	0.25	-1.80
May	13.13	-1.79	-14.32	1.50	0.00	7.24	0.00	-6.45	0.25	-4.65
Jun	12.78	-6.45	-24.32	0.91	0.00	7.62	0.00	-10.94	0.25	-4.50
Jul	15.13	-10.94	-40.21	0.56	0.00	7.67	0.00	-18.09	0.25	-7.15
Aug	14.52	-18.09	-58.02	0.25	0.00	6.50	0.00	-26.11	0.25	-8.02
Sep	8.38	-26.11	0.00	0.10	71.44	41.10	64.98	0.00	0.25	26.11
Oct	6.23	0.00	0.00	1.88	2.10	6.71	0.00	0.00	0.25	0.00
Nov	5.44	0.00	-1.42	2.36	0.00	2.69	0.00	-0.64	0.25	-0.64
Dec	4.16	-0.64	0.00	2.18	2.39	5.26	0.00	0.00	0.25	0.64
Total	**110.08**	**-**	**-**	**20.29**	**90.63**	**118.39**	**65.08**	**-**	**3.05**	**0.00**

Pocahontas State Park Normal Year 2000 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	4.95	0.00	0.00	2.39	9.42	12.24	0.00	0.00	0.25	0.00
Feb	5.25	0.00	0.00	2.64	1.13	3.99	0.00	0.00	0.25	0.00
Mar	9.38	0.00	0.00	2.36	0.70	7.98	0.00	0.00	0.25	0.00
Apr	9.88	0.00	0.00	2.01	7.86	13.31	2.67	0.00	0.25	0.00
May	14.73	0.00	-8.97	1.75	0.00	9.19	0.00	-4.04	0.25	-4.04
Jun	14.54	-4.04	-14.63	1.24	0.00	11.00	0.00	-6.59	0.25	-2.55
Jul	12.94	-6.59	-9.10	1.57	0.00	14.10	0.02	-4.09	0.25	2.49
Aug	12.27	-4.09	-7.86	1.65	0.00	10.77	0.66	-3.54	0.25	0.56
Sep	8.66	-3.54	-0.58	1.55	0.00	10.64	0.00	-0.26	0.25	3.28
Oct	7.85	-0.26	-14.97	1.57	0.00	0.05	0.00	-6.74	0.25	-6.48
Nov	5.03	-6.74	-13.67	1.68	0.00	4.19	0.00	-6.15	0.25	0.59
Dec	3.51	-6.15	0.00	1.73	0.64	7.82	1.00	0.00	0.25	6.15
Total	**109.00**	**-**	**-**	**22.15**	**19.75**	**105.28**	**4.36**	**-**	**3.05**	**0.00**

Pocahontas State Park Wet Year 1983 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	3.37	0.00	0.00	2.69	3.46	4.39	0.00	0.00	0.25	0.00
Feb	4.25	0.00	0.00	2.51	13.99	15.14	0.84	0.00	0.25	0.00
Mar	8.05	0.00	0.00	2.84	20.43	18.87	7.02	0.00	0.25	0.00
Apr	10.41	0.00	0.00	3.17	7.40	13.84	1.05	0.00	0.25	0.00
May	13.92	0.00	-8.07	2.74	0.00	7.80	0.00	-3.63	0.25	-3.63
Jun	14.83	-3.63	0.00	2.26	14.13	13.16	17.43	0.00	0.25	3.63
Jul	18.29	0.00	-35.34	1.83	0.00	0.81	0.00	-15.90	0.25	-15.90
Aug	14.92	-15.90	-54.44	1.04	0.00	5.54	0.00	-24.50	0.25	-8.59
Sep	11.15	-24.50	-61.32	0.79	0.00	7.52	0.00	-27.59	0.25	-3.10
Oct	6.66	-27.59	-49.99	0.84	0.00	11.18	0.00	-22.49	0.25	5.10
Nov	5.42	-22.49	-25.59	1.40	0.00	13.94	1.32	-11.51	0.25	10.98
Dec	3.94	-11.51	-2.96	2.03	0.00	12.34	0.00	-1.33	0.25	10.18
Total	**115.22**	**-**	**-**	**24.16**	**59.41**	**124.54**	**27.66**	**-**	**3.05**	**-1.33**

Pocahontas State Park Wet Year 1984 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	3.00	0.00	0.00	2.82	11.17	10.72	0.88	0.00	0.25	0.00
Feb	4.95	0.00	0.00	3.12	11.23	13.31	0.00	0.00	0.25	0.00
Mar	6.77	0.00	0.00	3.17	23.40	22.96	4.29	0.00	0.25	0.00
Apr	8.60	0.00	0.00	3.63	7.64	11.30	1.56	0.00	0.25	0.00
May	11.14	0.00	0.00	2.87	4.75	10.67	2.61	0.00	0.25	0.00
Jun	12.47	0.00	-12.41	2.34	0.00	4.80	0.00	-5.59	0.25	-5.59
Jul	10.53	-5.59	0.00	1.57	4.36	19.10	0.05	0.00	0.25	5.59
Aug	8.07	0.00	0.00	2.03	2.22	8.51	0.00	0.00	0.25	0.00
Sep	6.94	0.00	-6.27	2.21	0.00	2.16	0.00	-2.82	0.25	-2.82
Oct	7.04	-2.82	-3.74	1.96	0.00	6.48	0.00	-1.68	0.25	1.14
Nov	5.82	-1.68	0.00	2.41	4.46	9.80	0.00	0.00	0.25	1.68
Dec	4.59	0.00	0.00	2.67	2.75	4.93	0.00	0.00	0.25	0.00
Total	**89.92**	**-**	**-**	**30.81**	**71.98**	**124.74**	**9.40**	**-**	**3.05**	**0.00**

Powhatan WMA Water Budget Results

Powhatan WMA Calibration Period Water Budget Model Results (cm)

Mo./Yr.	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Aug-11	13.66	-15.24	-71.79	3.94	0.00	14.76	1.29	-10.77	1.85	4.47
Sep-11	8.01	-10.77	-37.15	2.54	0.00	12.83	0.38	-5.57	2.54	5.20
Oct-11	7.55	-5.57	-30.08	2.54	0.00	8.61	0.00	-4.51	2.54	1.06
Nov-11	5.53	-4.51	-6.04	3.12	0.00	9.04	0.32	-0.91	3.35	3.61
Dec-11	4.44	-0.91	2.54	3.89	1.52	8.89	0.06	2.49	3.48	3.40
Jan-12	6.09	2.49	0.84	3.96	0.00	3.94	0.00	0.82	3.48	-1.67
Feb-12	6.06	0.82	-0.38	4.04	0.00	4.62	0.00	-0.06	3.48	-0.88
Mar-12	9.56	-0.06	2.54	5.16	1.10	12.07	0.00	2.49	4.01	2.55
Apr-12	12.20	2.49	-11.33	4.24	0.00	6.88	0.49	-1.70	3.61	-4.19
May-12	11.86	-1.70	-3.93	4.32	0.00	13.03	0.45	-0.59	4.83	1.11
Jun-12	14.97	-0.59	-64.45	4.47	0.00	3.45	0.00	-9.67	2.03	-9.08
Jul-12	15.39	-9.67	-67.90	4.55	0.00	12.52	0.01	-10.18	2.21	-0.52
Aug-12	11.54	-10.18	-69.86	3.86	0.00	9.40	1.29	-10.48	3.30	-0.29
Total	**126.87**	**-**	**-**	**50.62**	**2.62**	**120.04**	**4.30**	**-**	**40.72**	**4.76**

Powhatan WMA Dry Year 1980 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	3.50	2.49	2.54	3.92	7.48	10.19	0.00	2.49	3.12	0.00
Feb	4.55	2.49	-0.65	4.20	0.00	0.89	0.00	-0.10	3.12	-2.59
Mar	8.49	-0.10	-24.27	4.92	0.00	3.15	0.00	-3.64	3.12	-3.54
Apr	12.35	-3.64	-45.12	5.29	0.00	7.06	0.00	-6.77	3.12	-3.13
May	13.67	-6.77	-40.23	4.83	0.00	11.28	1.42	-6.04	3.12	0.73
Jun	16.48	-6.04	-132.47	4.65	0.00	1.12	0.00	-19.87	3.12	-13.83
Jul	17.21	-19.87	-159.29	4.91	0.00	11.40	0.00	-23.89	3.12	-4.02
Aug	16.00	-23.89	-242.31	4.87	0.00	1.80	0.00	-36.35	3.12	-12.45
Sep	12.22	-36.35	-245.50	4.87	0.00	8.89	1.10	-36.83	3.12	-0.48
Oct	7.57	-36.83	-230.68	4.05	0.00	8.86	0.00	-34.60	3.12	2.22
Nov	5.94	-34.60	-240.71	3.95	0.00	3.61	0.00	-36.11	3.12	-1.50
Dec	4.90	-36.11	-264.22	3.74	0.00	0.76	0.00	-39.63	3.12	-3.53
Total	**122.88**	**-**	**-**	**54.20**	**7.48**	**69.01**	**2.52**	**-**	**37.49**	**-42.12**

Powhatan WMA Dry Year 2007 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	5.79	2.49	2.54	3.84	8.11	11.99	1.19	2.49	3.12	0.00
Feb	5.55	2.49	2.12	3.99	0.00	4.27	0.00	2.07	3.12	-0.41
Mar	11.07	2.07	-5.55	4.66	0.00	6.63	0.00	-0.83	3.12	-2.91
Apr	11.85	-0.83	-13.23	4.78	0.00	9.02	0.03	-1.98	3.12	-1.15
May	13.88	-1.98	-33.27	4.50	0.00	9.50	0.00	-4.99	3.12	-3.01
Jun	15.60	-4.99	-71.01	4.66	0.00	8.41	0.00	-10.65	3.12	-5.66
Jul	15.93	-10.65	-120.87	4.44	0.00	7.14	0.00	-18.13	3.12	-7.48
Aug	14.29	-18.13	-26.96	4.90	0.00	14.78	11.82	-4.04	3.12	14.09
Sep	11.95	-4.04	-85.92	4.30	0.00	1.93	0.00	-12.89	3.12	-8.84
Oct	8.14	-12.89	-19.23	4.27	0.00	11.84	5.16	-2.89	3.12	10.00
Nov	6.08	-2.89	-45.63	4.03	0.00	1.22	0.00	-6.84	3.12	-3.96
Dec	3.97	-6.84	-37.35	4.02	0.00	4.32	0.00	-5.60	3.12	1.24
Total	**124.12**	**-**	**-**	**52.39**	**8.11**	**91.03**	**18.20**	**-**	**37.49**	**-8.09**

Powhatan WMA Normal Year 1983 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	3.37	2.49	2.54	3.43	0.49	3.56	0.00	2.49	3.12	0.00
Feb	4.25	2.49	2.54	3.84	6.57	10.03	0.07	2.49	3.12	0.00
Mar	8.05	2.49	2.54	3.86	4.25	11.56	0.01	2.49	3.12	0.00
Apr	10.41	2.49	2.54	3.97	7.45	15.09	1.93	2.49	3.12	0.00
May	13.92	2.49	1.89	3.83	0.00	10.87	1.70	1.85	3.12	-0.64
Jun	14.83	1.85	-20.43	4.35	0.00	8.33	0.36	-3.06	3.12	-4.92
Jul	18.29	-3.06	-118.49	4.62	0.00	2.08	0.00	-17.77	3.12	-14.71
Aug	14.92	-17.77	-181.88	5.46	0.00	3.07	0.00	-27.28	3.12	-9.51
Sep	11.15	-27.28	-215.10	5.53	0.00	3.76	0.00	-32.27	3.12	-4.98
Oct	6.66	-32.27	-168.54	4.50	0.00	12.27	0.00	-25.28	3.12	6.98
Nov	5.43	-25.28	-101.12	3.77	0.00	14.40	0.49	-15.17	3.12	10.11
Dec	3.94	-15.17	-34.57	3.51	0.00	13.54	0.00	-5.19	3.12	9.98
Total	**115.21**	**-**	**-**	**50.67**	**18.76**	**108.56**	**4.56**	**-**	**37.49**	**-7.67**

Powhatan WMA Normal Year 2002 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	4.43	2.49	2.54	3.75	4.19	8.00	0.00	2.49	3.12	0.00
Feb	7.03	2.49	-14.13	3.46	0.00	2.08	0.00	-2.12	3.12	-4.61
Mar	7.64	-2.12	1.59	3.88	0.00	10.39	0.17	1.56	3.12	3.68
Apr	11.42	1.56	-16.99	3.61	0.00	6.83	0.00	-2.55	3.12	-4.11
May	14.24	-2.55	-29.24	3.89	0.00	11.63	0.00	-4.39	3.12	-1.84
Jun	16.70	-4.39	-101.33	4.19	0.00	4.83	0.00	-15.20	3.12	-10.81
Jul	16.92	-15.20	-165.18	4.70	0.00	5.77	0.00	-24.78	3.12	-9.58
Aug	16.06	-24.78	-180.44	4.86	0.00	10.52	1.52	-27.07	3.12	-2.29
Sep	10.18	-27.07	-197.79	4.40	0.00	6.30	0.00	-29.67	3.12	-2.60
Oct	5.78	-29.67	-121.39	3.73	0.00	16.64	0.00	-18.21	3.12	11.46
Nov	4.12	-18.21	-62.68	2.69	0.00	13.36	0.00	-9.40	3.12	8.81
Dec	4.03	-9.40	-21.15	2.97	0.00	10.41	0.00	-3.17	3.12	6.23
Total	**118.56**	**-**	**-**	**46.13**	**4.19**	**106.76**	**1.70**	**-**	**37.49**	**-5.66**

Powhatan WMA Wet Year 1993 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	4.19	2.49	2.54	3.18	7.37	11.51	0.00	2.49	3.12	0.00
Feb	5.21	2.49	2.54	3.22	2.83	7.95	0.00	2.49	3.12	0.00
Mar	6.33	2.49	2.54	3.66	14.02	18.57	1.24	2.49	3.12	0.00
Apr	11.61	2.49	2.54	3.37	11.58	18.75	4.20	2.49	3.12	0.00
May	14.00	2.49	-20.35	3.50	0.00	8.08	0.00	-3.05	3.12	-5.54
Jun	16.44	-3.05	-83.94	4.64	0.00	5.38	0.00	-12.59	3.12	-9.54
Jul	17.86	-12.59	-151.50	5.21	0.00	5.64	0.00	-22.73	3.12	-10.14
Aug	14.88	-22.73	-179.80	5.53	0.00	6.30	1.93	-26.97	3.12	-4.24
Sep	10.96	-26.97	-201.90	5.31	0.00	5.46	0.00	-30.28	3.12	-3.32
Oct	6.93	-30.28	-188.83	4.50	0.00	7.52	0.00	-28.32	3.12	1.96
Nov	5.48	-28.32	-4.49	3.84	0.00	15.42	16.99	-0.67	3.12	27.65
Dec	3.50	-0.67	2.54	3.48	8.02	14.33	0.00	2.49	3.12	3.16
Total	**117.38**	**-**	**-**	**49.44**	**43.83**	**124.89**	**24.37**	**-**	**37.49**	**0.00**

Powhatan WMA Wet Year 2003 Water Budget Results (cm)

Month	PET	S	WL	Gwin	O	P	R	T	Gwout	M
Jan	3.93	2.49	2.54	2.43	0.12	4.75	0.00	2.49	3.12	0.00
Feb	3.64	2.49	2.54	3.34	9.50	12.93	0.00	2.49	3.12	0.00
Mar	6.96	2.49	2.54	3.49	6.75	13.23	0.11	2.49	3.12	0.00
Apr	9.74	2.49	2.54	3.85	6.02	15.04	0.00	2.49	3.12	0.00
May	9.28	2.49	2.54	4.12	11.54	19.56	0.27	2.49	3.12	0.00
Jun	12.84	2.49	1.21	3.68	0.00	10.97	0.00	1.18	3.12	-1.31
Jul	13.82	1.18	2.54	3.91	9.40	23.70	0.04	2.49	3.12	1.31
Aug	11.65	2.49	2.54	3.64	1.06	11.53	0.67	2.49	3.12	0.00
Sep	8.66	2.49	2.54	4.29	50.75	29.21	29.03	2.49	3.12	0.00
Oct	6.49	2.49	1.34	3.03	0.00	5.41	0.00	1.31	3.12	-1.18
Nov	5.01	1.31	2.54	4.21	7.61	10.34	2.37	2.49	3.12	1.18
Dec	3.83	2.49	2.54	4.84	16.30	16.76	1.65	2.49	3.12	0.00
Total	**95.85**	**-**	**-**	**44.83**	**119.07**	**173.43**	**34.14**	**-**	**37.49**	**0.00**

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