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Hydrologic Response Caused by Wetland Expansion at Huntley Meadows Park in Hybla Valley, Virginia

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HYDROLOGIC RESPONSE CAUSED BY WETLAND EXPANSION AT HUNTLEY MEADOWS PARK IN HYBLA VALLEY, VIRGINIA

by

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ABSTRACT

HYDROLOGIC RESPONSE CAUSED BY WETLAND EXPANSION AT HUNTLEY MEADOWS PARK IN HYBLA VALLEY, VIRGINIA

Stephen Fraser Stone
Old Dominion University, 2017
Director: Dr. G. Richard Whittecar

The goal of this study was to understand the effects of wetland expansion across a watershed. The 2013 restoration and expansion of the wetlands at Huntley Meadows Park (Fairfax County, VA) performed by Wetland Studies and Solutions, Inc. provided the opportunity to study this process. The 630 ha park contains more than 364 ha of freshwater emergent and freshwater forested wetlands. The restoration and expansion project used a subsurface vinyl-piling dam that impedes groundwater flow leaving the wetland, thus expanding the existing pond and the surrounding wetland.

This study used a network of more than twenty monitoring instruments making observations of hydrologic and weather data, along with soils maps and soil borings, and observations of vegetation provided by scientists from Virginia Tech. Data from these sources were used to characterize the hydrologic drivers and responses throughout the area before and after wetland expansion for the purpose of developing wetland water budgets within Wetbud to model the effects of wetland expansion. Observations of water table elevations made throughout the park indicated the water levels in the pond at Huntley Meadows Park are not strongly influenced by regional groundwater flow. However, observations of diurnal fluctuations of the water table at monitoring wells located in emergent and forested/shrub wetlands revealed that spatial variations in actual evapotranspiration (AET) rates strongly influence the distribution of

water throughout the park. The effects of AET are strong enough to induce a seasonal reversal in hydraulic gradients where water table elevations surrounding the pond are greater than the pond during the winter months and lower than the pond during the growing season.

Wetland expansion during the study initiated changes in vegetation and hydrology. To model the potential effects of AET that may change due to expansion, monthly crop coefficients (Kc) were developed with reference ET coming from the Reagan National Airport NOAA weather station and AET coming from diurnal fluctuations of the water table analyzed with a MATLAB-adapted version of White's Method. Monthly predictions of head within the wetland and outflow through the weir, modeled using Wetbud's Basic Scenario tools, were improved when area-weighted Kc values were applied to the model. Additionally, daily predictions of head, made using Wetbud's Advanced Scenarios tools (a graphical user interface for USGS MODFLOW), were improved when spatially appropriate Kc values were applied to the model. However, when modeling differences in the distribution of plant communities from two consecutive years during the transitional period, there was little difference in predicted head values. Based on the differences in observed AET rates between emergent and forested/shrub wetlands, we suspect models of expanded wetlands that have had sufficient time to fully transition from the pre-construction distribution of plant communities to the design-intended distribution will require different distributions of crop coefficients and corresponding evapotranspiration rates in those models in order to accurately predict water levels for the design-intended distribution of plant communities.

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CHAPTER 1

INTRODUCTION

Overview

The goal of this study is to understand the hydrologic effects of wetland expansion across the watershed contributing to the wetlands at Huntley Meadows Park located in Alexandria, Virginia. Huntley Meadows Park, situated within the Hybla Valley of the northern Virginia Coastal Plain, is bound by the steep margins of an apparent meander scar of the Potomac River. The 630 ha park contains more than 364 ha of freshwater emergent and freshwater forested wetlands. Deterioration of the wetlands led to the restoration and expansion project completed by the Fairfax County Park Authority and Wetland Studies and Solutions Inc. during 2014. The restoration and expansion project used a subsurface vinyl-piling dam that impedes groundwater flow leaving the wetland, thus expanding the existing pond and the surrounding wetland. This design provides the opportunity to study the hydrologic response of an expanded wetland. An understanding of the hydrologic response is necessary to ensure the success of future expansion projects and to encourage wetland designers to develop more dynamic wetlands that better resemble the environments being replaced or improved upon by mitigation and restoration efforts.

Location and Geologic Setting

Huntley Meadows Park is situated within Hybla Valley and located in the northernmost reaches of the Virginia Coastal Plain physiographic province, approximately 15 km southwest of Washington, D.C on the western flank of the Potomac River (Fig. 1). Virginia’s Coastal Plain physiographic province is composed of unconsolidated to partly consolidated sediments of

Cretaceous, Tertiary, and Quaternary age that dip gently towards the east and are incised by numerous rivers that drain either to the Chesapeake Bay or directly to the Atlantic Ocean (McFarland and Bruce, 2006; Whittecar et al., 2016). One of the major rivers incising these sediments is the Potomac River.

The Potomac River has been transporting water and sediment at varying rates, and with varying volumes, for roughly 30 million years (Stanton, 1993). During that time there have also been significant fluctuations in relative sea level in the region (Scott et al., 2010; Litwin et al., 2010; Litwin et al., 2013). It has been postulated that the combination of these factors, along with a possible normal fault on the northwestern edge of Hybla Valley, created a deep valley and a prominent meander scar (Huffman et al., 1975; Fleming, 2016). This valley provided the accommodation space and depositional environments necessary to accumulate the large bodies of fine-grained sediment seen in the Hybla cores taken by the United States Geological Survey (USGS) (Mixon and Newell, 1977; Seiders and Mixon, 1981; Mixon et al., 2005; Litwin et al., 2013). Core Hybla 7 (Fig. 2) recovered 35 m of sand, silt, and mud and was refused in a pebble conglomerate. The adjacent Hybla 8 core recovered 20 m and was composited with Hybla 7 to obtain near-complete recovery. These cores, taken roughly midway along the north-south access road at the heart of Huntley Meadows Park, reveal the lithology from 34 m to 10 m depth is dominated by mud and silt with the top ten meters containing a greater fraction of sand-sized particles in places. In addition to answering questions about composition, Litwin et al. (2010) used four optically stimulated luminescence (OSL) samples from the Hybla cores to establish that Quaternary deposition has taken place for at least 145,000 years in the region, and by examining pollen assemblages from the cores they determined that wet conditions have been persistent in the area for a large part of that time.

While the minutiae of Hybla Valley deposition are interesting, it is important to consider them in the broad context of the geologic setting. Drake et al. (1979) mapped the geology of the area and determined that the units present within Huntley Meadows Park include the Cretaceous Potomac and Quaternary Shirley formations (Fig. 2). The Potomac formation underlies the hills surrounding Huntley Meadows Park and is the unit in which Hybla Valley was carved. Fleming (2008) described the Potomac formation as heterogeneous river deposits composed of unconsolidated to poorly consolidated sands, silts, and clays with small amounts of gravel. The floor of Hybla Valley itself is largely carpeted with the Quaternary Shirley formation. The Shirley formation unconformably overlies the Potomac formation and at its type section is a fining-upward sequence made up of a gravelly sand at its base that grades upward to a coarse to fine sand that is capped by clayey silt or clayey, silty fine-sand (Johnson and Berquist, 1989). Eolian silts also carpet the valley bottom deposits (Litwin et al., 2013).

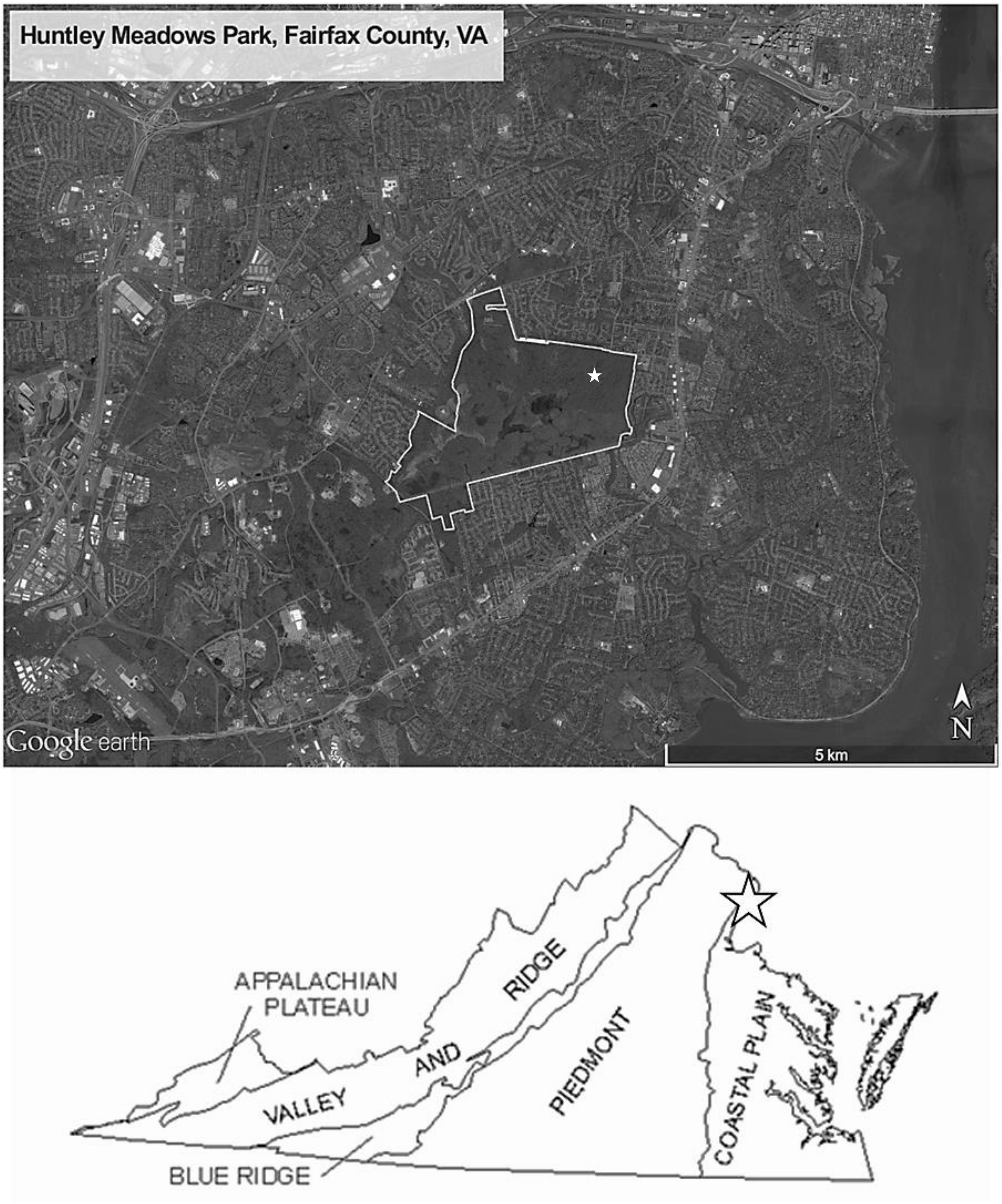


Fig. 1. Aerial image of Huntley Meadows Park from Google Earth. White border shows Huntley Meadows Park boundary, white star indicates location of visitor's center. The visitor's center is located at (decimal degrees) lat. 38.757692, lon. -77.098116. The Potomac River is shown along the eastern edge of the image. The lower schematic map shows the Physiographic Provinces of Virginia with the location of Huntley Meadows Park indicated by a star. Virginia map source: http://va.water.usgs.gov/GLOBAL/AWWALAST_files/image004.gif

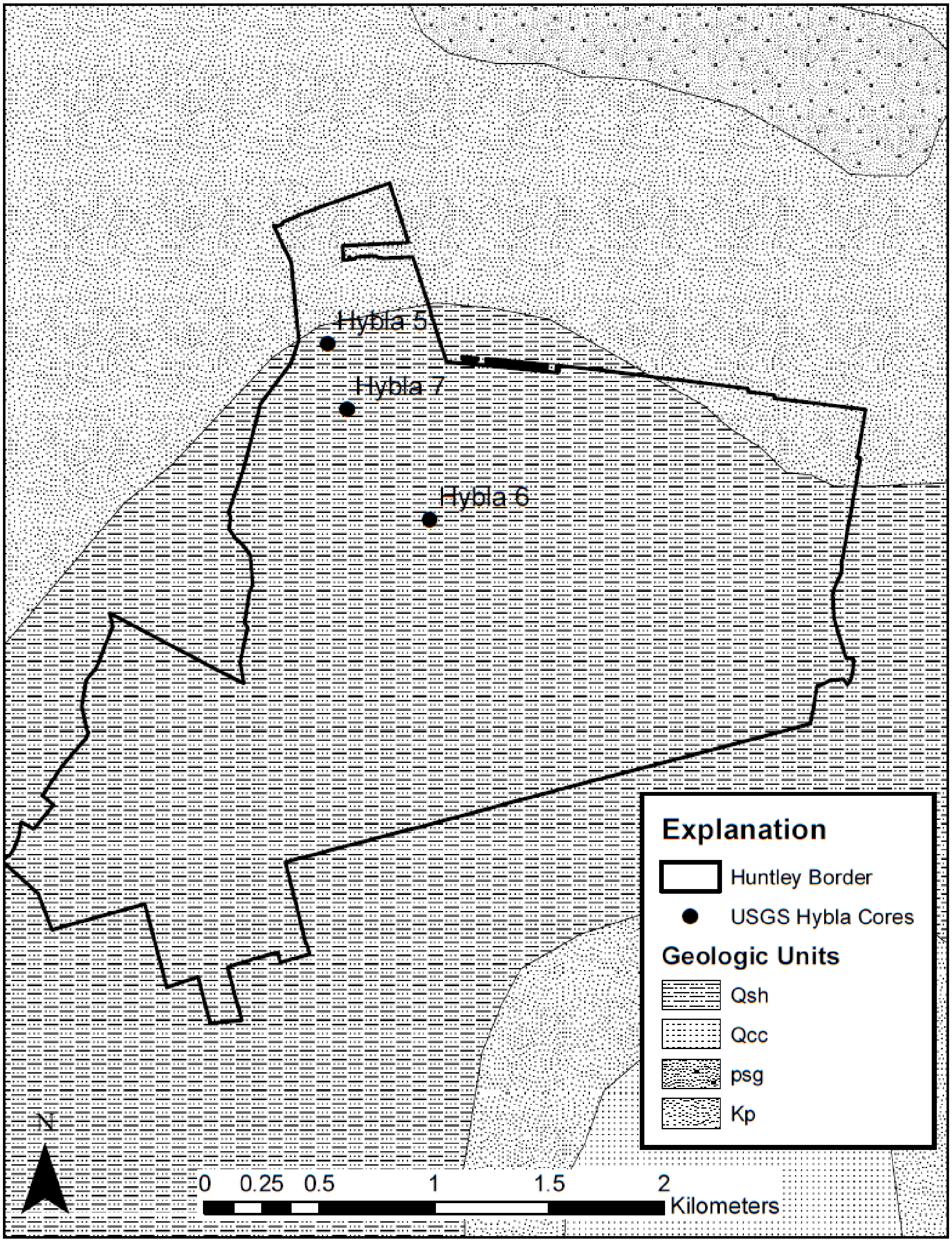


Fig. 2. Geologic map of Huntley Meadows Park with locations of USGS Hybla cores. Geologic units include Kp- Cretaceous Potomac Formation, psg- Pliocene sand and gravel, Qcc- Quaternary Charles City Formation, Qsh- Quaternary Shirley Formation.

Background

The foundation of a successful created wetland is the construction of a water budget with accurate inputs for the sources and losses of water as it moves through the wetland. Mitsch and Gosselink (1993) presented the following equation as a general water budget for wetlands:

$$\Delta V/\Delta t = P_n + S_i + G_i - ET - S_o - G_o \pm T \tag{1}$$

where: $\Delta V/\Delta T$ = change in wetland water storage volume per unit time, t
P_n = net precipitation
S_i = surface water in, including flooding streams
G_i = groundwater inflows
ET = evapotranspiration
S_o = surface water outflows
G_o = groundwater outflows
T = tidal inflow/outflow

Most wetland water budgets take the form of a mass balance equation using some combination of the components listed above depending on which terms apply to the wetland.

To determine which components of the wetland water budget apply to a given wetland, it is important to consider the hydrogeomorphic (HGM) classification of the wetland. Brinson's (1993) HGM classification scheme is based upon three central properties of wetlands, the geomorphic setting, how water is sourced and transported, and hydrodynamics. Depending on the combination of these properties, wetlands typically fall into one of seven HGM settings: depressional wetlands, slope wetlands, mineral soil flats, organic soil flats, riverine wetlands, lacustrine fringe wetlands, or estuarine fringe wetlands. Understanding the HGM processes active at a given site, by examination of surface and subsurface processes, provides insight into the natural formation of wetlands in that area, which leads to higher success rates of created wetlands (Whittecar and Daniels, 1999). The HGM classification can then be used as a guide for which components of the wetland water budget to include when constructing a budget, and which components dominate the system and therefore require more accurate representation within the water budget.

There are few published site-specific water budgets for wetlands in eastern Virginia; however, there are some notable studies that have been carried out both in Virginia and the surrounding southeastern United States that contribute to understanding the water budget at Huntley Meadows Park. Some of these studies look at how components of the water budget can be accurately determined and used to construct a budget, while others construct a budget and use it to deduce sources or losses of water that can be difficult to measure directly such as evapotranspiration (ET). Sanford and Selnick (2013) used a water balance approach combined with a climate and land-cover regression equation to estimate actual ET for 838 watersheds across the conterminous United States. Their study concluded that ET rates could be reasonably predicted at watershed or county scales using climate variables alone. To predict watershed scale potential evapotranspiration (PET) rates, most planners use one of two equations: the FAO-56 Penman-Monteith equation (Jensen et al., 1990) or the Thornthwaite (1948) equation. The Penman-Monteith equation, though developed for a grass reference crop, has proven to be a viable estimate for many types of vegetation due to the number of high resolution input parameters such as solar radiation, relative humidity, and wind speed (Chaubey and Ward, 2006). The Thornthwaite (1948) method is more commonly used because it determines monthly values for PET based on monthly air temperatures which are more readily available than the high resolution data sets required for the Penman-Monteith equation. With the proper equipment and sufficient time, data can be collected from shallow monitoring wells to determine actual rates of ET using the White (1932) method. This method assumes groundwater-in is constant unless there is a precipitation event, and that ET by vegetation affects water levels in the riparian zone except from midnight to 4 AM when there is no solar energy to drive the process and the water table recovers. Under these conditions, the sum of the daily recovery rate (12 AM – 4 AM) and the 24-hour change in head (typically 12 AM to 12 AM), adjusted for specific yield, is the ET rate. While ET tends to be the most significant form of water loss in wetlands, groundwater seepage and surface flow out play a role too. Despite these losses most Coastal Plain wetlands are maintained by precipitation, overland runoff, stream overflow, and groundwater discharge into the wetland (Hayes, 1996).

Chaubey and Ward (2006) constructed a site-specific water budget for a wetland in Hale County, west central Alabama and compared the results to outputs of regional predictions for components of the water budget. Using data collected from 1994 and 1995, Chaubey and Ward (2006) determined that most of the prediction methods produced values that were comparable to those determined using data collected within the wetland. However, the observed gains and losses varied spatially and temporally depending on vegetation and site specific weather patterns.

A similar approach was used by Dobbs (2013) for two wetlands in the Piedmont physiographic province outside of Richmond, VA. Field data were collected for just over one year at each site and used to create site-specific water budgets. This study used the wetland water budget modeling software Wetbud, described next. Each of the components of the water budget were parameterized and used to create a model that could reconstruct historic hydrographs for typical wet, normal, and dry years. These specific years were determined by using data from WETS tables developed by the National Resources Conservation Service (NCRS) in conjunction with the conditions suggested by McLeod (2013), which consider the hydrologic conditions of the growing season specifically rather than for the entire year (Wetbud User Manual, 2014).

Wetbud is a water budget model software package that is being developed by Wetland Studies and Solutions Inc, Virginia Polytechnic Institute, and Old Dominion University. Wetbud uses characteristics intrinsic to the wetland, such as catchment area and soil permeability, combined with thirty-year daily weather records from weather stations located in Virginia, to predict water levels within the wetland. Wetbud uses the weather station records to calculate PET rates by either the FAO-56 Penman-Monteith equation (Jensen et al., 1990) or the Thornthwaite (1948) equation. Additionally, the weather data are used to generate rates of groundwater input using the effective monthly recharge (W_{em}) method via synthetic hydrographs. Using observed head elevations from the study site, the W_{em} model determines the relationship between precipitation, ET, and observed head values that can then be used to produce historic groundwater inputs from precipitation records (Whittecar and others, 2016). Wetbud allows users to parameterize all of the components of the wetland water budget to generate Basic Models or Advanced Models. Basic Models produce monthly water levels for the wet, normal, and dry years calculated for the selected weather station. Conversely, Wetbud’s Advanced Model suite serves as a graphical user interface for the USGS ground water modeling package MODFLOW. The Advanced Model enables users to produce three dimensional models of their study sites, with user-defined time steps, that account for spatial variability as well as temporal variability. Wetbud’s Basic Model package has been used to develop water budgets at a few locations in Virginia (Dobbs, 2013; McLeod, 2013) and Neuhaus (2013) tested the

Advanced Model as a design tool, though no calibrated models have been developed using the Advanced Model package as of yet.

Statement of the Problem

Many constructed wetlands fail due to poor estimates of components of the wetland water budget. The two components that have the largest associated error, groundwater flux and ET, also tend to be significant moderators on water levels within wetlands. However, the dynamics of an expanded wetland change over time and these changes should be better understood so that more wetlands can be constructed in a manner that involves conversion with minimal mechanical reworking and incorporation of groundwater. Constructing a wetland water budget with accurate inputs for each of the components, and using those parameters to calibrate a three-dimensional finite difference model, will allow predictions of future dynamics within the wetland that could then be used to ensure the success of the desired plant communities.

Hypotheses

1. Stratigraphy affects the distribution of water throughout the site and influences the locations of wetlands.
2. Wetland expansion causes no changes in ET intensity or duration that significantly affect water levels across the wetland and recharge zones and discharge zones are constant throughout the year.
3. Calibrated computer models of the area can be used to predict changes in the water budget associated with raising the water table and facilitating the redistribution of plant communities.

CHAPTER 2

METHODS

In order to address the three proposed hypotheses several methods were needed. While some methods were appropriate for multiple hypotheses, each method pairs best with one specific hypothesis. This chapter explains the methods used to test each hypothesis.

Effects of Stratigraphy

To test the first hypothesis, that stratigraphy affects the distribution of water throughout the site and influences the locations of wetlands, the following methods were used:

- Review soil maps and use hand auger to verify soils
- Review geotechnical report from United Research Services (URS) that included borings taken prior to expansion project
- Use National Wetland Inventory maps to get a sense of the types and extents of existing wetlands
- Install a monitoring array
- Perform slug tests to determine hydraulic conductivity of hydrologic units

Soils Maps

A simplified history of Hybla Valley, an abandoned meander scar of the Potomac River later carpeted with the Shirley Formation, would suggest a suite of soils that lacks complexity. However, the subtly undulating landscape of the park indicated there was more to be told, and, in order to better understand the dynamics of the wetland hydrology at Huntley Meadows Park within Hybla Valley it was necessary to investigate the characteristics and extents of the soils. Soil types were identified using Web Soil Survey (WSS), a web application provided by the United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS). An area of interest (AOI) was defined in WSS using a Huntley Meadows Park shapefile acquired from Fairfax County’s Open Data GIS webpage (http://www.fairfaxcounty.gov/maps/data.htm). The soils map and explanation produced using the WSS data displayed in ArcGIS can be seen in Appendix A. Soil types and extents were confirmed using an open-bucket hand auger and extensions that facilitated borings to a maximum depth of 8.2 m (27 feet). As the interest was in discerning hydrostratigraphy rather than specifics of soil taxonomy, soil boring logs were brief and primarily included notes on texture, redoximorphic features, and colors as identified using a Munsell soil color book. Several soil borings were performed to confirm the extents of the soils reported on the soils map though few detailed descriptions were made. The locations of the soils borings that have descriptions, and their descriptions, can also be seen in Appendix A. To complement the data derived from the soils maps and confirmed by the soil borings, work done by Litwin et al. (2010) and Pavich et al. (2008), describing the Hybla cores and general stratigraphy of the region, was employed to characterize the material at depth in the Hybla Valley region. USGS Hybla core locations in Huntley Meadows Park can be seen in Fig. 2 (Chapter 1, Introduction).

URS Site Investigation

Prior to the initiation of the restoration project at Huntley Meadows a geotechnical consulting agency, United Research Services (URS), was contracted by WSSI to assess the soil conditions near the proposed dam location. This assessment took place during the summer of 2012. While on site, URS performed 8 soil borings to a maximum depth of 10.67 m. Findings from the URS report were used to complement the WSS soils map and soil borings performed at the site as mentioned in the previous section.

Wetlands Present at Huntley Meadows Park

As stated before, Huntley Meadows Park is a 630 ha park with more than 365 ha of wetlands (fairfaxcounty.gov/parks). Huntley Meadows Park contains an impressive abundance and wide assortment of wetlands enhanced by restoration efforts. In order to characterize the wetlands present within the park and determine their extents prior to restoration, the National Wetland Inventory (NWI), a United States Fish and Wildlife Service organization, was consulted. The NWI webpage provides publicly available GIS data that can be downloaded on a state-by-state basis. Within each state's database, NWI maps show habitats based on the classification designed by Cowardin and others (1979). For this project the October 1st, 2015 NWI dataset was used.

Monitoring Array

To determine whether or not stratigraphy affects the distribution of water and wetlands throughout the site it was necessary to understand the distribution of soils and wetlands, and to install a network of monitoring wells throughout the park in key locations. All of the monitoring wells were installed according to the standard procedures from Lapham et. al (1997); Fig. 3 shows a typical well design. In total, twenty monitoring wells and three stream gages were installed by workers from Virginia Tech (VT) and Old Dominion University (ODU).

The team from VT installed three shallow wells (A, B, and C) along four transects, with data collection starting October 2012. The transect wells were installed to monitor hydrologic changes caused by wetland expansion after water levels were raised within the park. The A well in each transect was installed at the edge of the seasonally ponded area adjacent to the forest edge or the woody shrub/scrub. The B wells were installed in the surrounding forested area at elevations deemed to be barely above seasonal flooding based on soil indicators and local vegetation. The C wells in each transect were placed further uphill above the potential 100-year flood level in what were presumed to be upland environments. In addition to the twelve transect wells, two wells were placed in the ponded portion of the existing wetland for a total of fourteen monitoring points. Each of the shallow VT wells were installed using a 3.5” (0.09 m) soil auger. The wells have 12” (0.305 m) of 2” (0.051 m) slotted well screen at the bottom; the remainder of each well was constructed with 2” (0.051 m) PVC with sufficient length to have a riser that was roughly 0.3 m above the ground surface. The VT wells were installed to depths ranging from 0.6 m to 1.5 m. The annulus of each well was filled with sand filter pack and the riser was sealed with bentonite to prevent surface water from influencing the well. Each of the VT wells were capped with a fitting made to accommodate Odyssey™ capacitance water loggers (product code ODYWL), which recorded water depth every hour with 0.8 mm accuracy. No well construction logs exist for the VT transect wells.

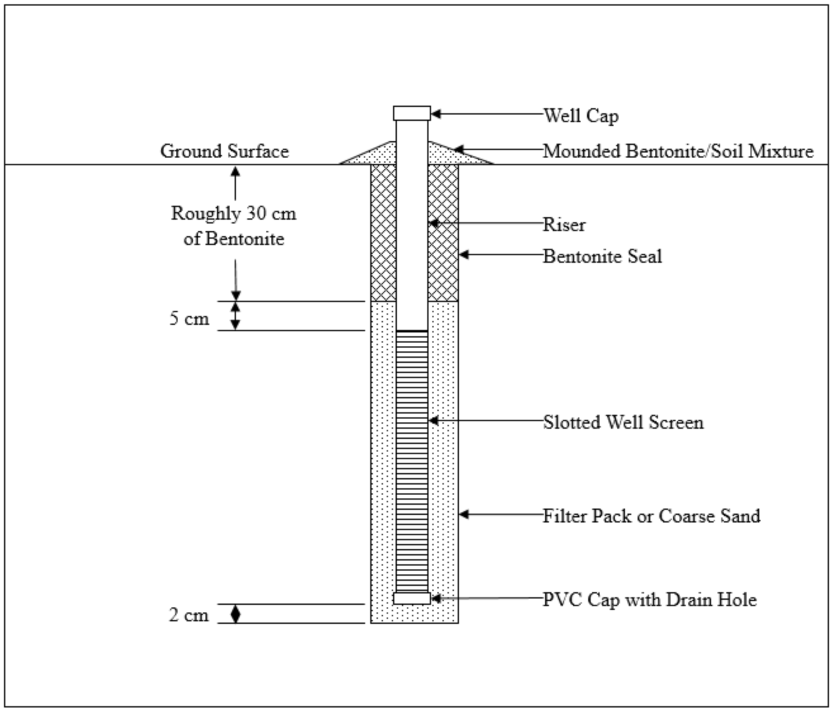
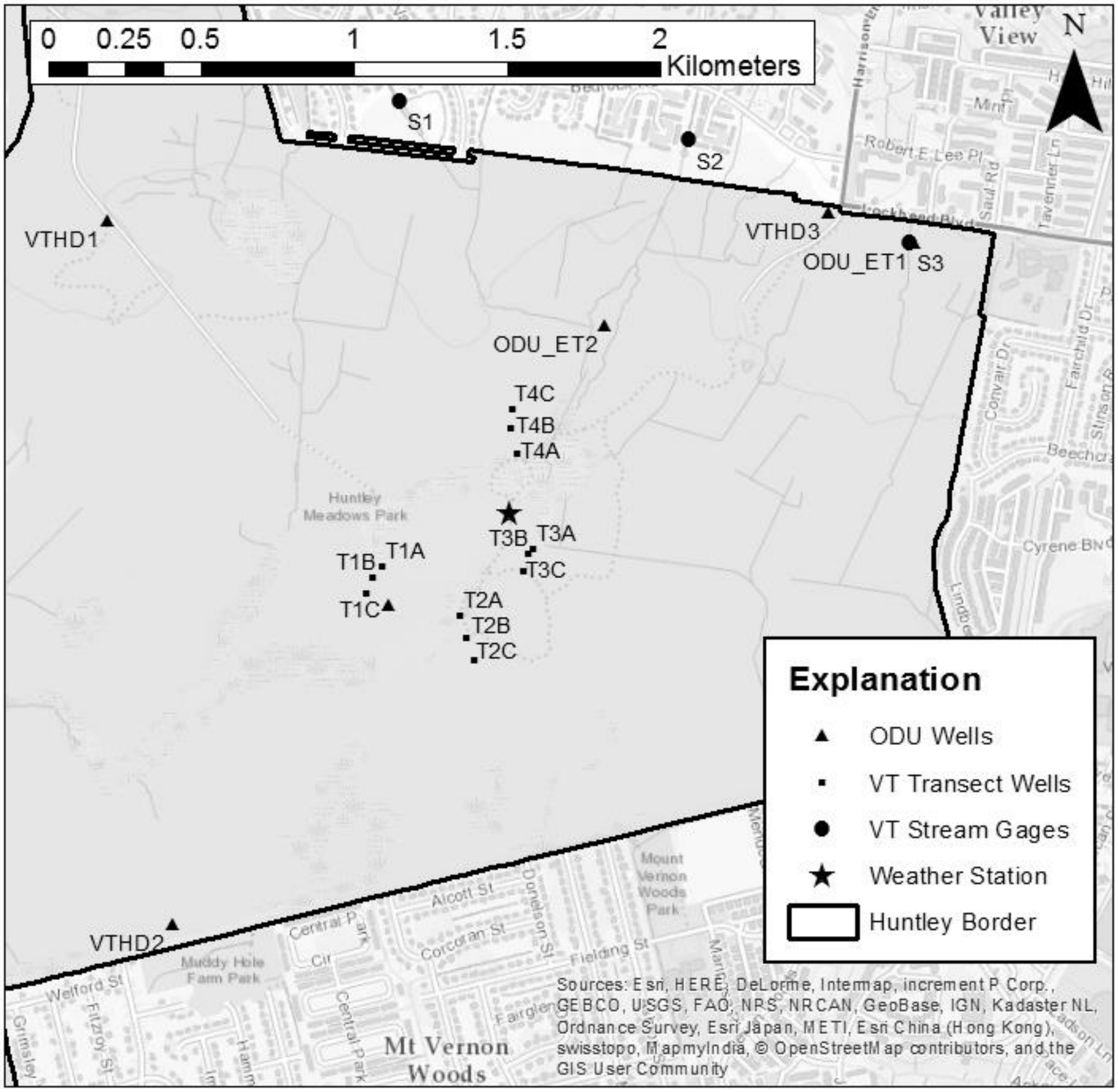


Fig. 3. Typical monitoring well installation (modified from Lapham et. al, 1997).

ODU installed and maintained six wells: VTHD1, VTHD2, VTHD3, ODU_HM1, ODU_ET1, and ODU_ET2. The VTHD wells and ODU_HM1 were installed at depths ranging from 12.95 m to 3.80 m to determine regional groundwater influences on the site. ODU_ET1 and ODU_ET2 were installed to a depth of 3 m and screened for nearly all of that depth to monitor diurnal water table fluctuations; these wells were used to estimate actual ET rates in two locations outside of the areas monitored by the transect wells. ODU_ET1 was installed in a forested portion of the watershed not mapped as a wetland by NWI. ODU_ET2 was installed in a part of the watershed mapped as freshwater forested/shrub wetland by NWI. VTHD1, VTHD2, and ODU_HM1 were installed using a six-inch hollow-stem auger. VTHD3, ODU_ET1, and ODU_ET2 were installed using a four-inch open-bucket hand auger. The tops of the casings for all of the wells (VT and ODU) were surveyed by WSSI to determine elevation with 0.01 foot (3 mm) accuracy. Refer to Appendix B for ODU well construction logs.

Except for ODU_HM1, all of the wells installed by ODU were fitted with Solinst Model 3001 Leveloggers™ suspended by Kevlar cable and set to record water temperature and water column height each hour by measuring absolute pressure with accuracies of either 2.5 mm or 5 mm depending on the vintage of the transducer. A Solinst Barologger™ Edge transducer was suspended in VTHD2 at a level below the ground surface but well above the expected range of the water table to record fluctuations in barometric pressure each hour. Data were downloaded several times throughout the year using Solinst Levelogger™ software, versions 3.1.1 and 4.1.0 depending on the vintage of the data logger. The Solinst software was then used to correct for barometric pressure by subtracting the barometric pressure from the absolute pressure resulting in true water column height. To determine head values, water column height was added to the elevation of the Levelogger™ using Microsoft Excel. During each site visit actual head values were determined by measuring depth to water using a Slope Indicator Co. water level meter (±0.01 ft, 3 mm), and battery level and free memory, or number of remaining readings, were recorded. See Fig. 4 for a map of monitoring point locations within Huntley Meadows.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Fig. 4. Map showing monitoring equipment relative to Huntley Meadows Park boundary.

Determining Hydraulic Conductivity

Slug tests were performed on the deeper wells (VTHD1, VTHD2, VTHD3, ODU_ET1, ODU_ET2, and ODU_HM1) to determine hydraulic conductivity (K) rates at multiple points throughout the park. Two types of slug tests were used. The selection of the method used was dependent on the position of the water table relative to the screened interval on the day of the test. If on the day the slug test was performed the water table was above the screened interval, the Hvorslev (1951) Slug-Test was used (Eq. (2)). If the water table was within the screened interval on the day the test was performed, the Bouwer and Rice (1976) Slug-Test was used (Eq. (3)). For a synopsis of slug test methods, assumptions, and limitations see Fetter (2001). Regardless of the method used, the test consisted of rapidly removing a single bailer's worth of water from the well and collecting head data at 5-second intervals using a Solinst Model 3001 Levelogger™ to record the water table response.

The equation for the Hvorslev (1951) method is as follows:

$$K = \frac{r^2 \ln(\frac{L_e}{R})}{2L_e t_{37}} \qquad (2)$$

where: K = hydraulic conductivity (m s^{-1})

r = radius of the well annulus (m)

R = radius of the well screen (m)

L_e = length of the well screen or gravel pack in low permeability settings (m)

t_{37} = the time it takes for water level to rise or fall to 37% of the initial change (s)

The equations for the Bouwer and Rice (1976) method are as follows:

$$K = \frac{r_c^2 \ln(\frac{R_e}{R})}{2L_e} \frac{1}{t} \ln(\frac{H_o}{H_t}) \qquad (3)$$

where: K = hydraulic conductivity (m s^{-1})

r_c = radius of the well casing (m)

R = radius of the well annulus (m)

R_e = effective radial distance over which head is dissipated (m)

L_e = length of the screen or open section of the well (m)

H_o = drawdown at time $t = 0$ (m)

H_t = drawdown at time $t = t$ (m)

t = time since $H = H_o$ (s)

Bouwer and Rice (1989) proposed two methods for estimating the dimensionless ratio *ln(R_e/R)*. If L_w, the water column height in the well or bore hole, is less than h, the saturated thickness of the aquifer, then:

$$\ln\left(\frac{R_e}{R}\right) = [\frac{1.1}{\ln\left(\frac{L_w}{R}\right)} + \frac{A+B\ln\left[\frac{(h-L_w)}{R}\right]}{\frac{L_e}{R}}]^{-1} \qquad (4)$$

If L_w is equal to h, then:

$$\ln\left(\frac{R_e}{R}\right) = [\frac{1.1}{\ln\left(\frac{L_w}{R}\right)} + \frac{C}{(\frac{L_e}{R})}]^{-1} \qquad (5)$$

where: R_e = effective radial distance over which head is dissipated (m)

R = radius of the well annulus (m)

L_w = water column height in the well or bore hole (m)

h = saturated thickness of the aquifer (m)

Dimensionless numbers A, B, and C can be found by referring to the plot of A, B, and C as a function of L_e/R seen in Bouwer and Rice (1989).

Variations in Evapotranspiration Rates

To test the second hypothesis, wetland expansion changes ET intensity and/or duration, which significantly affects water levels across the wetland and recharge zones and discharge zones are constant throughout the year, the following methods were employed:

- Use the monitoring array to observe how expansion affects hydrology
- Use White's method to determine actual ET rates for different plant communities
- Compare ET rates as obtained using White's method to those derived from Penman-Monteith method and the Thornthwaite equation to determine which is most appropriate for parameterizing ET throughout the watershed

Monitoring Wetland Expansion

In addition to contributing to the understanding of the distribution of water throughout the park, the monitoring array was used to observe the response to wetland expansion by evaluating hydrographs containing data collected over a period of almost three years. These data were used to measure the change in water levels through time. Specifically, the transect well hydrographs were analyzed to determine differences in average water levels between wells, seasonal variation in water levels between wells, water level response rate due to precipitation events between wells, and differences in diurnal fluctuations between wells screened in the riparian zone.

Determining Actual Evapotranspiration Rates

In order to determine actual ET rates from a variety of plant communities and soil types, diurnal fluctuations of the water table were evaluated using a modified version of White's (1932) method and hydrologic data collected between August 8th, 2014 and March 31st, 2016 from fourteen wells within Huntley Meadows Park. The underlying premise of White's Method is that drawdown of the water table occurs each day as a result of water lost due to ET and groundwater seeping out of the system. Each night, when the sun is no longer driving photosynthesis or providing heat that would cause groundwater to evaporate, the water table rebounds due to seepage from adjacent up-gradient areas. Therefore, loss due to ET or groundwater can be estimated as the net sum of the rebound rate and the decline rate over the period that ET is being estimated, assuming the diurnal fluctuations have not been affected by antecedent precipitation. This value is then multiplied by a coefficient that corrects for the soil conditions surrounding the well screen. White (1932) suggested that coefficient should be specific yield (Sy), which describes the volume of water lost per unit decline in head within an unconfined aquifer (Heath, 1983). Fig. 5 shows an example of a signal that would be ideal for analysis with White's method. The version of White's method used for this work is the same as that shown in Davis and DeWiest (1966):

$$q = Sy\left(\frac{\Delta s_1}{\Delta t_1} \pm \frac{\Delta s_2}{\Delta t_2}\right) \qquad (6)$$

where: q = evapotranspiration (L T^{-1})

Sy = specific yield (unitless)

$(\Delta s_1/\Delta t_1)$ = average daily response rate (L T^{-1})

$(\Delta s_2/\Delta t_2)$ = long term decline rate (L T^{-1})

The coefficient used to normalize ET rates in various soil settings, Sy, was estimated for each well used to determine actual ET rates. Specific yield can be approximated using multiple techniques. Field samples of the material present throughout the screened interval of the well can be collected and analyzed in the laboratory using a pressure plate extractor apparatus to equilibrate samples to various set pressure potentials based on the methods described in Richards (1931). Conversely, the texture of the field samples can be analyzed in the laboratory using a hydrometer analysis, or by evaluating texture in the field using the ribbon test. Once the texture is known, specific yield values can be determined by referencing tables such as

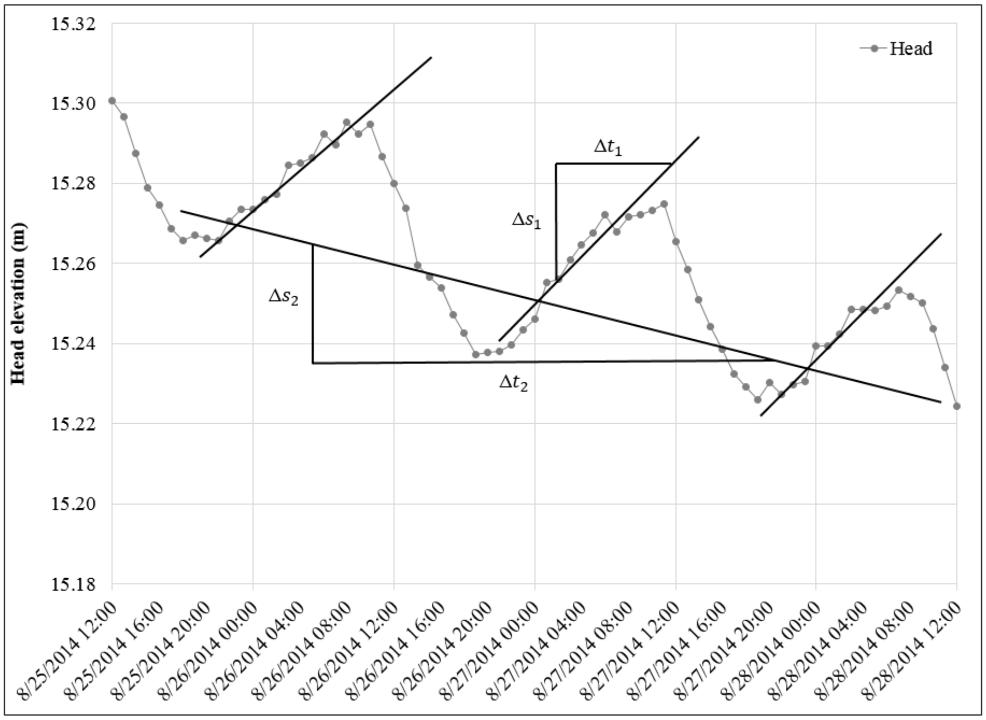


Fig. 5. Traditional White's Method approximation of actual ET from hourly head data. Hourly data from ODU_ET1. Overlain lines represent slopes used to estimate actual ET. $\Delta s_1/\Delta t_1$ is hand drawn best fit line from 00:00-06:00, $\Delta s_2/\Delta t_2$ is hand drawn best fit line through 00:00 of each day in the subset of data. Approximate actual ET rate for August 27th, 2014 = 8 mm/day.

those presented in Johnson (1967) or Loheide et al. (2005). In situations where detailed data related to soil texture were not collected during well installation, the water table response to precipitation events can be analyzed to estimate drainable porosity. Drainable porosity is a property similar to specific yield (Harder et al., 2007), and can be obtained using the equation developed by Williams (1978) shown below.

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

where: n_d = drainable porosity (percent)

P_e = precipitation event total (L)

ΔWT = rise in water table (L)

Field data regarding soil texture were not collected for the majority of the wells used to estimate ET rates through the watershed; therefore, Sy was approximated using the water table response to precipitation events method for all of the wells that needed Sy estimates. Williams (1978) suggested that the water table response should be less than one day and the water table rise should occur within the top 1.0 m of the soil to reduce errors that would arise due to deviations from atmospheric pressure, which can affect capillary action within the soils. For this study, multiple isolated precipitation events were evaluated at each well location.

To complement the water table response to precipitation-derived specific yield estimates, samples were collected and processed by the team from VT at six key well locations (ODU_ET1, ODU_ET2, T1A, T3A, T4A, and T4B) for determination of Sy using a pressure plate extractor apparatus. When a Sy estimate was available from the pressure plate method, it was used rather than the water table response derived Sy estimate. The pressure plate method is an analytically-derived estimate of Sy and is a more accurate approximation of Sy than water table response to precipitation. The pressure plate method is far more resource-intensive than the hydrograph method, so it was not practical to use for estimating Sy for each of the well locations. The pressure plate method involves collecting intact samples using a bulk density core sampler at two depths (approximately 20 cm and 60 cm) from three locations within one meter of each well of interest. The samples were then taken to the lab where they were saturated with water and placed in the pressure plate extractor apparatus. Pneumatic pressure was applied at 0.3, 1.0, and 15.0 bars. As pressure is applied water drains out of the apparatus and the moisture content in the soil samples is in equilibrium with the various applied pressures. After achieving equilibrium, the wet samples were removed and weighed, before being dried in an oven. The difference in water weight from samples held at different pressure potentials is proportional to the water holding capacity of the soil and can be interpreted as specific yield. For details about the procedure performed by VT see Johnson and Daniels (2015).

Once Sy values were approximated for each of the wells, actual ET (AET) rates could be calculated using a version of White's method. Traditionally, White's (1932) method is time consuming because it is based on best fit lines from multiple slopes on a single hydrograph. Additionally, the points on the hydrograph along which the best fit lines are to be fit have been the subject of debate. Many authors have invested time in refining the selection of points for analysis to estimate AET using White's method (Loheide et al., 2005, Loheide et al., 2008, Soylu et al., 2012, and Zhang et al., 2016). Using data from a site in the Tarim Basin in northwestern China, Zhang and others (2016) compared the output of previously suggested combinations of methods for attaining these points, and slopes, to estimates of AET derived using the Eddy Covariance method. This method uses measures of latent heat fluxes in eddies generated by convective heat flow between the Earth's surface and the atmosphere. Zhang and others' (2016) work concluded that observations of water table elevation made from 12 AM to 6 AM provided the best approximation of the daily rebound rate and that averaging this rate over multiple days improved its estimate. However, there was no significant difference observed when this rate was averaged over seven days compared to just two days. They also concluded that the best way to represent the overall decline for a daily estimate of AET was to use a twenty-four hour period; they suggested midnight to midnight. Zhang and others' (2016) calibration of the points for the best fit lines for White's type AET estimates relative to observations of AET made using the eddy covariance method resulted in a technique that costs far less to execute than the eddy covariance method while producing comparable AET rates.

While Zhang and others' (2016) work contributed to greater accuracy of estimates of AET, it did not reduce the time needed to process AET rates. For this project, a Matlab script based on the point selection criteria of Zhang and others (2016) was developed which allows one to estimate many daily AET rates across a study site in a more time-efficient fashion. As the script was developed it was verified against manual calculations of the same time frame. A copy of the script, as well as a description of the process used to develop it, can be found in Appendix E. In this study, potential AET evaluation dates were selected solely on based on whether the sum of the precipitation three days prior to the day of interest was zero, to reduce influence from precipitation. An exception was made during the month of June 2015 due to the frequency of small rain events. For June 2015 the sum of the three-day precipitation prior to the day of interest needed to be 5 mm or less in order to consider that day usable for estimating AET.

Comparing ET Rates

In order to determine the best way to represent ET within the watershed, multiple methods for estimation were compared. PET estimates were generated using both the FAO-56 Penman-Montieth equation (Jensen et al., 1990) and the Thornthwaite equation (1948) within the wetland water budget modeling software, Wetbud. Both methods of estimating PET require regional weather data. The FAO Penman-Montieth equation uses many variables, while the Thornthwaite equation requires only average daily temperature. For this study, daily weather data came from the Global Historical Climatology Network (GHCN) Reagan National Airport Weather Station (RNAWS, GHCND:USW00013743) and a temporary weather station located in the ponded area at Huntley Meadows Park (HWS). Data from these stations were supplemented by weather data from nearby stations to account for any gaps in data collection. Thornthwaite PET estimates for the Basic Models were calculated in Wetbud. While Penman-Monteith PET estimates from RNAWS were calculated in Wetbud, PET estimates from HWS were calculated in Microsoft Excel via an adaptation of the technique in Zotarelli and others (2010) (Eq. (8)).

The Penman-Monteith PET equation (FAO-56 method) is as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (8)$$

where: ET_o = potential evapotranspiration (mm d^{-1})

Δ = slope of the saturated vapor pressure curve (kPa ^{o}C^{-1})

R_n = net radiation flux (MJ m^{-2}d^{-1})

G = sensible heat flux into the soil (MJ m^{-2}d^{-1})

γ = psychrometric constant (kPa ^{o}C^{-1})

T = mean air temperature (^{o}C)

u_2 = wind speed 2 m above ground surface (m s^{-1})

e_s = mean saturated vapor pressure, computed as (daily minimum + daily maximum)/2 (kPa)

e_a = mean daily ambient vapor pressure (kPa)

AET estimates derived from the monitoring wells on site using the Matlab script variation of White’s (1932) method were compared to Penman-Monteith PET rates derived from both the Reagan and Huntley weather stations, to develop crop coefficient (K_c, Eq. (9)) values for the different plant communities within the park.

$$K_c = \frac{AET}{PET} \qquad (9)$$

where: K_c = crop coefficient

AET = actual evapotranspiration

PET = potential evapotranspiration

Crop coefficients are widely used for irrigation planning in agricultural applications; however, few K_c estimates exist for wetland settings and wetland water budget applications (Howes et al., 2015). In this study, monthly K_c values were estimated by comparing PET from the RNAWS and the HWS to AET estimated from water table fluctuation observations made at Huntley Meadows Park from multiple wells in various plant communities. While the monitoring array at Huntley Meadows Park was not installed with the intention of using it to estimate AET, it did result in a network of wells screened in the rooting zone of multiple plant communities that could be used to estimate AET. The intended purpose of the monitoring array was to observe changes in the water table surrounding the ponded area after installing the subterraneous dam (VT transect wells) and to determine the magnitude of regional influences on water levels at Huntley Meadows (VTHD wells). In addition to monitoring changes in groundwater levels, changes in vegetation were monitored at each of the transect-well locations by Sara Klopf (VT Research Associate), resulting in a data set that could also be used to determine AET rates unique to various plant communities.

For this study, K_c estimates were derived for three plant communities: forested non-wetland areas, forested/shrub wetlands (forested wetlands lumped with scrub shrub wetlands), and emergent wetlands (open water areas were lumped with emergent wetlands). The forested and forested/shrub wetlands consisted primarily of sweet gum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), black gum (*Nyssa sylvatica*), and pin oak (*Quercus palustris*) trees. The groundcover and shrubbery consisted of a mixture of Japanese stiltgrass (*Microstegium vimineum*), creeping charlie (*Glechoma hederacea*), poison ivy (*Toxicodendron radicans*), jewelweed (*Impatiens capensis*), and river oats (*Chasmanthium latifolium*). The emergent wetland areas were dominated by Japanese stiltgrass (*Microstegium vimineum*), cattails (*Typha latifolia L*), and floating pennywort (*Hydrocotyle ranunculoides*). Plant identification was performed by VT (species list from personal communication with Sara Klopf).

Wetland Water Budget Models

Testing the third hypothesis, that calibrated computer models of the area can be used to predict changes in the water budget associated with raising the water table and facilitating the redistribution of plant communities, required the following methods:

- Create a Basic Scenario model in Wetbud to produce monthly head hydrographs to compare observed values to predicted values using multiple ET estimators
- Build a calibrated three-dimensional, finite-difference model using Wetbud's Advanced Models package capable of evaluating the effects of varying ET throughout the park and changing them through time

Two approaches were used to model wetland water budgets within Huntley Meadows Park using Wetbud. The first approach was an analytical model produced as a 'Basic Scenario' that summed inputs and outputs for the wetland area and produced hydrographs of monthly water levels within the wetland. The second approach was to produce a three-dimensional, finite-difference numerical model using Wetbud's 'Advanced Scenario' tool.

Basic Scenarios

Basic Scenarios within Wetbud predict the elevation of water levels within the wetland by treating the wetland as a level pool confined by a material with a given hydraulic conductivity (K) and specific yield (Sy). By assigning K and Sy values to the soils within the modeled area, the model output is more accurate for wetland settings that have groundwater fluxes or that have water levels that drop below grade. All Basic Scenarios in Wetbud use Sy. However, only Scenarios using the Effective Monthly Recharge model (W_{em}) to estimate groundwater inputs use K. Due to the low relief in the park and the low hydraulic conductivity of the soils, W_{em} was not used. The average specific yield value (Sy = 0.11) estimated from wells throughout the park based on water table response to precipitation events was used as the Sy value for the Basic Scenario. The area considered in the Basic Scenario for this study was 26.14 ha (64.6 acres), which is equal to the area of land inundated when the pool is at the designed maximum elevation (35 feet, 10.67 m).

Surface water input (S_i) to the site was accounted for within Wetbud by calculating the runoff generated from precipitation events occurring over the 317.27 ha watershed less the inundated area (26.14 ha), resulting in 291.13 ha contributing runoff. The initial curve number (CN) used to calculate runoff was 79.8. Both the watershed area and the CN values were those reported in WSSI's design plans for the wetland restoration at Huntley Meadows. The watershed area was determined using the Army Corp of Engineers' Hydrologic Modeling System (HEC-HMS) software and field checked by WSSI to account for irregularities in the watershed due to manmade diversions such as roads and culverts. WSSI's plans indicated that the CN was calculated as the weighted CN depending on land cover type and area. While the CN method worked well to represent runoff events, it did not account for the baseflow in the streams coming from sub basins 1 and 2 (Fig. 6). Based on stage observations made in these streams channels by VT, a baseflow discharge estimate of 0.04 m^3/s was added to the model each month. In Wetbud the baseflow input was modeled with a User Time Series and adjusted for wetland area, resulting in a monthly input of 0.40 m.

Contributions to the wetland from precipitation, and losses attributed to ET, were estimated using weather information from the Ronald Reagan Washington National Airport Global Summary of the Day (GSOD 724050, RNAWS) weather station that was packaged with Wetbud, unless precipitation data were available from the Huntley Weather Station (HWS).

Wetbud is distributed with fourteen preloaded weather stations with a minimum of thirty years of continuous data for each station (Wetbud User Manual). For each of these preloaded stations, the bulk of the weather data is from the weather station for which the preloaded station is named. Any gaps in data collection due to downed equipment or routine maintenance have been populated by the Wetbud development team from nearby weather stations. As the preloaded stations were compiled in 2014, it was necessary to import weather data in addition to the years included in the preloaded RNAWS in order to compare water levels predicted by Wetbud to those observed during the calibration period.

ET within the Basic Scenario was represented three ways, the first of which was the monthly sum of daily PET as calculated by the Penman-Montieth FAO-56 equation. The second method used to calculate ET was the monthly average PET as calculated by the Thornthwaite equation. The third method used to represent ET in the Basic Scenario was PET adjusted by a crop coefficient determined by comparing AET estimates derived from the monitoring wells throughout the site to PET estimates for the same days using the Penman-Montieth approach.

In addition to water lost due to ET, lateral and vertical head differences in key piezometers and monitoring wells led to the conclusion that groundwater was leaving the system via slow seepage through the clayey soils lining the wetland bottom, through the sandier soils under the new access road (and shallow topographic divide) between transects one and two, and through the sandier soils on either side of the subterraneous dam. To account for the groundwater lost each month, a constant groundwater out rate of 0.16 m/month (roughly 6 inches/month) was applied to the model.

Surface water leaving the system (S_o) within the Basic Scenario was controlled by parameterizing the variable height outlet that was installed by WSSI in the southwest corner of the wetland. It should be noted that Wetbud does not produce head values that are actual elevations; rather, it produces water levels relative to the wetland bottom elevation (9.66 m) yielding positive values for water levels above ground, negative values for water levels below ground, and a value of zero for a water level equal to the wetland bottom elevation. Table 1 shows the outlet elevations for the calibration period along with their corresponding relative stage elevations (relative to wetland bottom elevation).

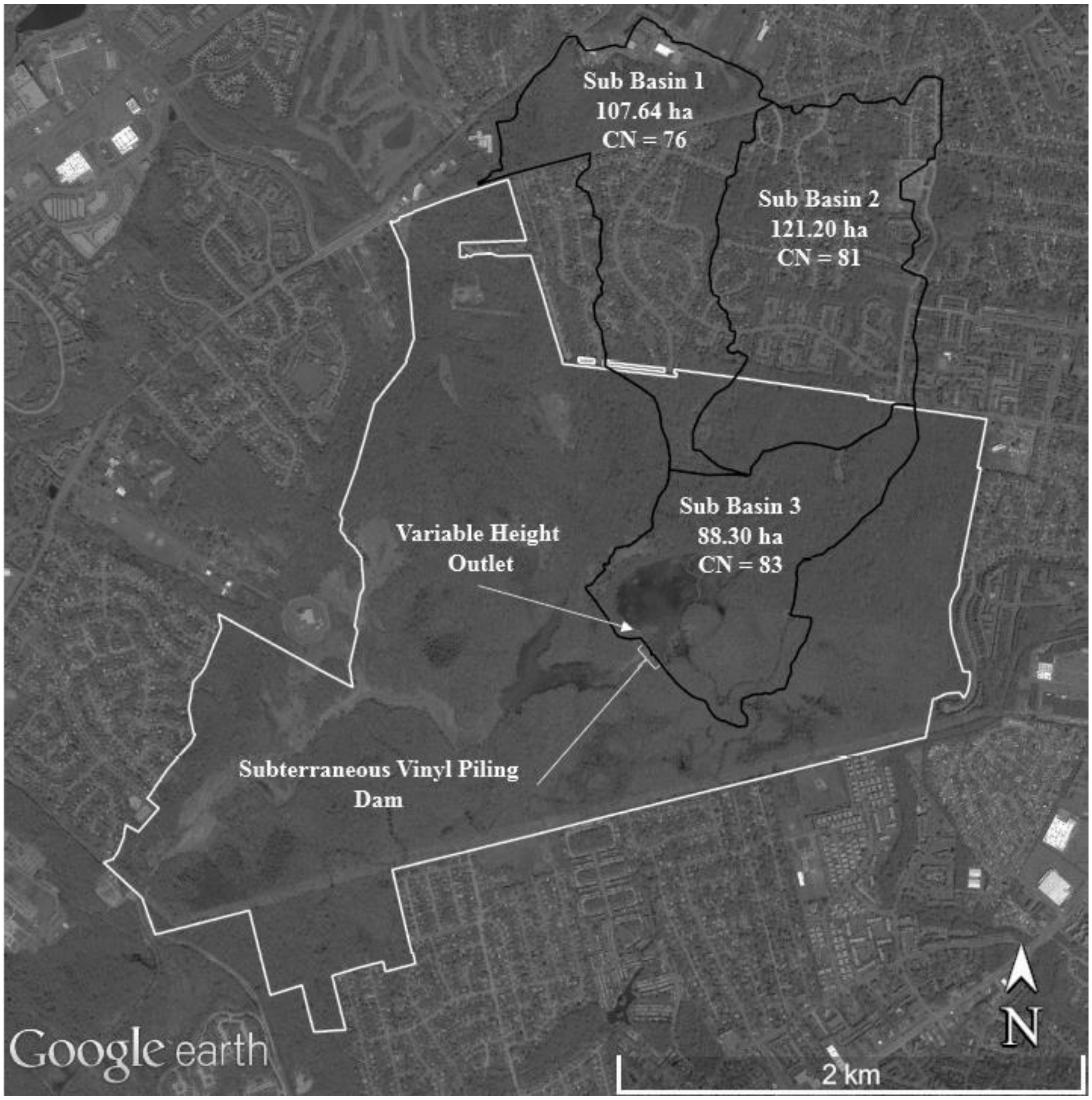


Fig. 6. Watershed area map. Huntley Meadows Park boundary shown in white, and watershed boundaries indicated with solid black lines. Watershed boundary data from WSSI.

Table 1
Depth to weir values used for Basic Model water budgets. Values used are the weighted average of the observed depth to weir for each month.

Year	Month	Depth to Weir (cm)
2014	1	37
2014	2	61
2014	3	70
2014	4	61
2014	5	63
2014	6	60
2014	7	54
2014	8	50
2014	9	53
2014	10	63
2014	11	67
2014	12	67
2015	1	66
2015	2	66
2015	3	65
2015	4	53
2015	5	49
2015	6	48
2015	7	38
2015	8	33
2015	9	31
2015	10	28
2015	11	55
2015	12	65
2016	1	71
2016	2	73
2016	3	70

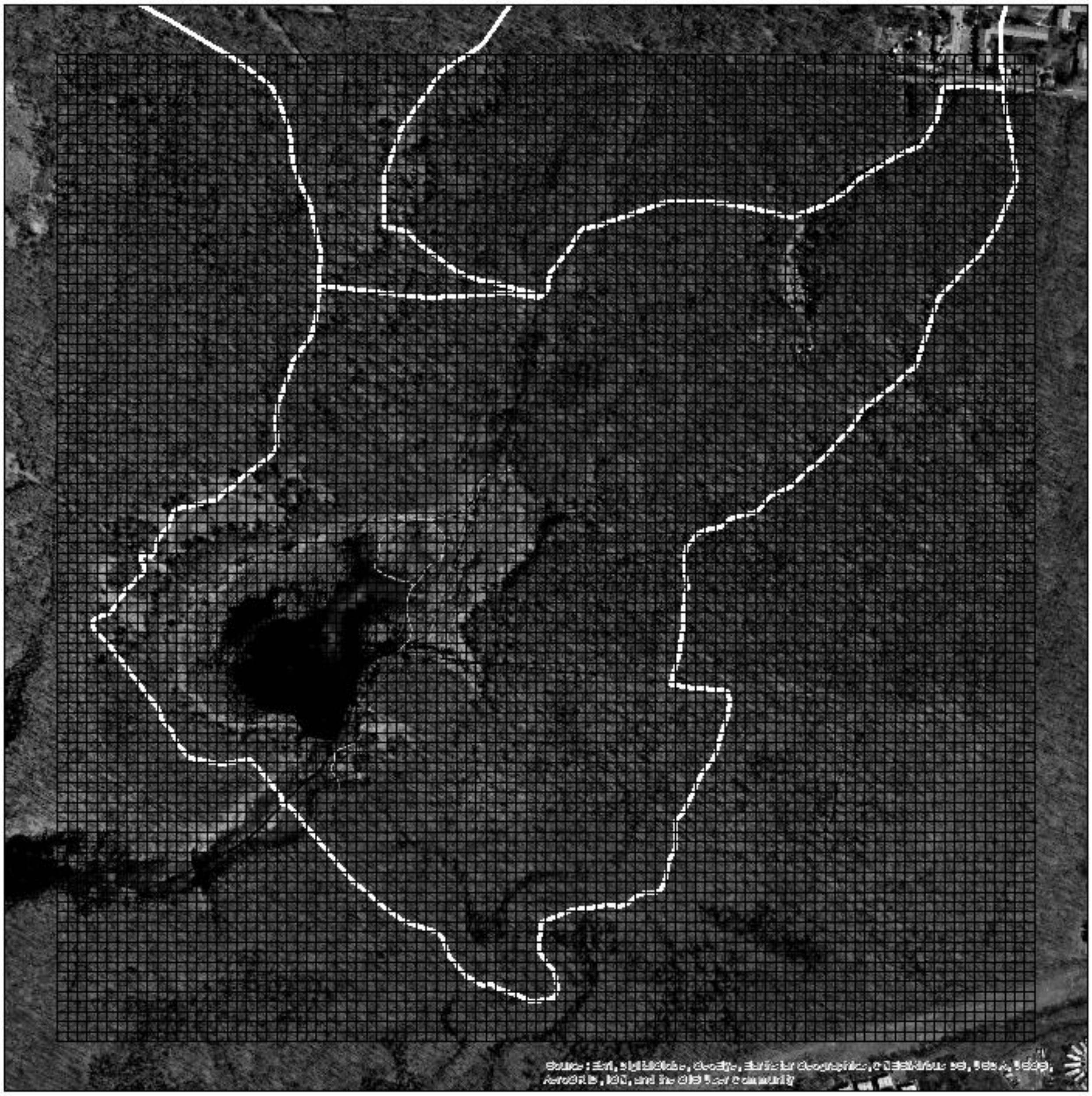
Advanced Scenarios

The Advanced Scenario tool in Wetbud is a graphical user interface (GUI) for the USGS groundwater flow modeling software MODFLOW. There are two primary advantages to using Wetbud to develop a numerical model for a wetland site over existing GUIs: the first is the incorporation of a surficial vegetation layer, and the second is that Wetbud creates time steps for models directly from weather stations used to develop Basic Scenarios for the same sites. While Wetbud has been used previously to test its functionality as a design tool (Nehaus, 2013), this study is the first to use Wetbud to develop a calibrated groundwater flow model. Developing a calibrated model also allowed for further testing of Wetbud, which required extensive interaction with the project's programmer to improve Wetbud's functionality and user interface and to validate Wetbud's calculations. The design presented in this study represents the capabilities and limitations of Wetbud at the time of model development.

Perhaps the most important part of a three-dimensional groundwater flow model is the part developed outside of the software, the conceptual model. The conceptual model is designed based on two primary factors, field observations and the objectives of the project. For this project the objective of the study was to determine if conversion of forested land, in close proximity to the existing wetland, to emergent wetland by raising water levels within the park has an effect on the water budget due to observed differences in ET rates between these two plant communities. A model capable of meeting that objective required reasonably accurate water level predictions (±0.10 m) in the areas immediately surrounding the wetland and lesser accuracy at locations distal to the wetland; it also needed relatively small cell sizes in order to account for the subtle changes in topography, plant communities, and soil types throughout the 88.30 ha portion of the watershed that was modeled.

WSSI identified three sub-basins that contribute to the ponded area at the center of Huntley Meadows Park (Fig. 6, as seen earlier) separated by shallow topographic divides. Sub-basin one (107.64 ha, CN = 75.7) and sub-basin two (121.20 ha, CN = 81.1) are north of sub-basin three and contribute a considerable volume of runoff to sub-basin three (88.30 ha, CN = 82.8) which contains the wetland this study was focused on. Conceptually, water levels in the wetland are driven by precipitation, either direct to the wetland or from runoff discharged from sub-basins one and two into sub-basin three, with water accumulating over the clay-rich soils deposited throughout much of Huntley Meadows Park. Water then leaves the wetland by ET or by slowly draining into the relatively coarse materials surrounding the subterraneous dam. When precipitation and runoff are in excess of ET and groundwater seepage, water levels are controlled by a variable height outlet weir maintained by the park staff, which was represented in the model as a drain with conductance estimated from outlet specifications in WSSI's restoration plans. Though in reality the conductance of the outlet would change as the water level in the wetland changes, the conductance value used in the model was held constant at the maximum value estimated based on the outlet width and the highest anticipated water level in WSSI's design plans. The modeled constant conductance was 2.97 m^2/s and outlet height varied based on documented changes in outlet height.

To laterally confine the area to be modeled, the shallow topographic divide surrounding sub-basin three was used. The majority of that boundary was represented with no-flow conditions based on the assumption that the topographic divides were also water-table divides, with the exception of the area surrounding the subterraneous dam that was installed at the southwest edge of the wetland. The dam was represented as a drain with an elevation equal to the ground surface across the top of the dam (10.516 m, 34.5 ft) and conductance sufficient to support open channel flow across the top of the dam (46 m^2/s). Based on these assumptions, little water is contributed to the wetland by way of groundwater discharge, and the distribution of water throughout the park, as well as water levels in the ponded portion of the park, are significantly influenced by topography. The relief across the 88.30 ha area in sub-basin three is only 9 m, with elevations ranging roughly from 9.6 m to 18.6 m. Though cells may be any dimension, Wetbud does not allow for variable mesh refinement. Therefore, the subtle variations in topography and hydrologic conditions throughout sub-basin three were represented by 15.24 m x 15.24 m (50 ft x 50 ft) square cells. To encompass all of sub-basin three (roughly 1.5 km in each direction), a grid with 98 cells in the east-west direction by 99 cells in the north-south direction was used. Fig. 7 shows the domain of the model relative to sub-basin three.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 7. Advanced Model domain relative to sub-basin 3. Sub-basin 3 shown as thick white line, model grid is roughly 1.5 km wide in the east-west direction and 1.5 km tall in the north-south direction. Aerial image from ArcGIS.

Elevation values for each of the cells were derived from a digital elevation model (DEM) provided by WSSI (from Fairfax County GIS, www.fairfaxcounty.gov/maps/data.htm). A multi-step process was used to determine the elevation assigned to each cell in the model. The first step was creating a grid in ArcGIS using the CreateFishnet tool with dimensions equal to the extent of the Wetbud model. The DEM was then clipped using the extent of the grid produced by the CreateFishnet tool. The clipped DEM, with 5 ft (1.52 m) pixel resolution, was then aggregated to create a raster image with pixels equal to 50 ft (15.24 m) with elevation values equal to the average of the aggregated pixels. The aggregated raster image was then exported from ArcGIS as an ASCII text file and imported into Wetbud to generate a reasonable approximation of variation in topography throughout the model. After importing the elevations for each of the cells, the values were checked against surveyed locations within random cells to ensure the averaged elevations were truly a reasonable approximation of topography throughout sub-basin three. Adjustments were made to the elevations within the ponded portion of the park to compensate for the flat surface derived from the DEM, which was originally the surface of the pond. Elevations were lowered from 32.9 ft (10.02 m) to 31.7 ft (9.66 m), which is the average elevation of the ground surface within the ponded portion of the park reported in WSSI's restoration plans.

Hydrologic conditions were represented in the model using two layers. The top layer was a vegetative layer with varying hydraulic conductivities used to represent different vegetative cover ranging from open water to forested land, and the bottom layer had different hydraulic conductivity zones used to represent the distribution of soils throughout sub-basin three. The elevations from the aggregated DEM were imported as the bottom elevation of the vegetative layer and the top elevations were determined by creating a flat surface with an elevation of 35 ft

(10.66 m), the designed maximum pool elevation, and then adding one meter to all of the elevations from the actual ground surface and the flat pond elevations. Creating a flat surface at the designed maximum pool elevation with surface-layer hydrologic conditions, and adding one meter to that elevation, resulted in space within the first layer of the model with gradually sloping sides that could accumulate surface water quickly. A flat bottom was applied to the bottom (sub-surface) layer of the entire model at an elevation of 1.00 m above sea level. Additional information about how the Advanced Models were constructed can be found in Appendix F.

In total, eight hydraulic conductivity and storage zones were used to represent hydrologic conditions throughout the park. Based on the soils maps and observations made during well installation and from soils borings, five zones were developed to represent the soils within the park. Three additional Ksat zones were used to represent the surface conditions present within the model area. Surface conditions were simplified to three categories: forested (including forested wetlands), emergent wetlands (the most dense vegetation, cattails etc.), and open water. Storage zone assignments, representing specific storage and specific yield, corresponded to Ksat zone assignments. Previous work done by Eric Nehaus (2013) indicated a range of hydraulic conductivities from 1.3 m/s to 4.25 m/s for different plant communities depending on vegetative cover and density, while work done by Candice Piercy (2010) resulted in Ksat values as high as 100 m/s for vegetation zones. Based on their work and personnel communication with their thesis advisor, Dr. Tess Thompson, three zones were used to represent vegetation within the model. The zone with the fastest hydraulic conductivity was that meant to represent the open water, the zone with the slowest hydraulic conductivity was the scrub-shrub emergent wetlands with the highest density of vegetation close to the ground, and the forested areas fell roughly between the other two zones. Hydraulic conductivities and storage values for the remaining zones, meant to represent the soils within the model, were determined by model calibration with starting values from slug tests and texture based estimates. Final Ksat and Storage values for each of the zones used in the model are shown in Chapter 3, Results.

Model Calibration

The Basic Model was calibrated using observations of water levels at the upstream and downstream locations of the variable height outlet. The upstream data represented water level in the wetland, and correspond directly to the target water level estimated by Wetbud. The downstream data were used to quantify outflow and ensure the flux of water leaving the model was close to that observed on the downstream side of the outlet weir. The model was calibrated using data from RNAWS and HWS collected between April 1st, 2015 and February 29th, 2016, and validated using data collected during April 1st, 2014 to April 30th, 2015. The calibration period corresponds to the time when entire months of quality precipitation data from the HWS were available. The Basic Model calibration and validation periods were evaluated using the Nash-Sutcliffe Efficiency (NSE) parameter Eq. (10), and by calculating the Root Mean Square Error (RMSE, Eq. (11)). The RMSE represents the average error of any point predicted by the model. Conversely, the Nash-Sutcliffe Efficiency parameter calculates model efficiency. NSE values range from $-\infty$ to 1, with a value of 1 indicating a perfect match between modeled and observed data. A value of 0 would indicate the model output is as accurate as the mean of the observed data, and values less than 1 reveal the mean of the observed values is a better predictor than the model (Nash and Sutcliffe, 1970).

The Nash-Sutcliffe Efficiency parameter for quantifying model performance (Nash and Sutcliffe, 1970) follows:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \tag{10}$$

where: NSE = Nash-Sutcliffe Efficiency value (dimensionless)

Q_o = observed discharge (rate), at a given time, t

Q_m = modeled discharge (rate), at a given time, t

The Root Mean Square Error formula, used to determine the magnitude of the average error for any value predicted by the model (after Barnston, 1992) is:

$$RMSE = \left[\sum_{i=1}^{N}(Q_{mi} - Q_{oi})^2/N\right]^{1/2} \tag{11}$$

where: $RMSE$ = Root Mean Square Error (L)

Q_m = modeled head (L)

Q_o = observed head (L)

N = number of calculated residuals

The Advanced Model was calibrated using data collected between March 15th, 2015 and March 15th, 2016, which was the period with the most usable AET estimates derived from monitoring wells at Huntley Meadows. The validation period was March 12th, 2014 to December 31st, 2014, the remainder of the period with the most usable weather data, though far fewer usable AET estimates. Fifteen monitoring points in and around the wetland were used to calibrate the Advanced Model. Calibration criteria were different for different groups of monitoring points depending on their locations and ranges of observed water levels. In addition to NSE and RMSE, calibration criteria were extended to modeled and predicted range of water levels, and correlation of major trends in observed and predicted data. The correlation of major trends relates to having the model predict major fluctuations when water levels drop below the level of the pressure transducer in the well or when there are changes in flow gradients. Transect well data at Huntley indicated that during the winter months, the hydraulic gradient was towards the wetland, and in the summer months the gradient reversed and the pond became a source of water. For locations close to the ponded area (mostly A locations in the transects) the goal was a RMSE of 0.1 m and NSE of 0.5 or greater. As well distance from the pond increased, RMSE error mattered less and the goal was to have positive NSE values and similar ranges and gradients.

CHAPTER 3

RESULTS

This chapter reports the results of the tests for each of the three proposed hypotheses. The results are presented in the same manner as they were in the methods section, which groups them by the hypothesis to which they relate. The results from the methods used for the first two hypotheses influenced model design for testing the third hypothesis.

Effects of Stratigraphy

The following paragraphs describe the results of the tests of the first hypothesis, that stratigraphy affects the distribution of water throughout the site and influences the locations of wetlands.

Soils Maps

The WSS soils map identified seventeen map units, with four of those units accounting for more than 90% of the soils in the park. Descriptions of the four prominent soil units follow in order of landscape position within the park, from the ponded areas to the areas of highest elevation. The soils descriptions below are compilations of descriptions from the United States Department of Agriculture's web site (soilseriesdesc.sc.egov.usda.gov/) and soil borings taken within Huntley Meadows Park.

The Hatboro (unit 49A, 10.1% of the park, 63.50 ha) soil series makes up most of the ponded areas as well as the river beds downstream of the ponded area. The Hatboro silt loam is described as a loamy alluvium eroded from schist, granite, and gneiss parent material and it is commonly found in the floodplains of the region. Within Huntley Meadows Park, the Hatboro is often surrounded by the Elkton silt loam (unit 36A, 12.0% of the park, 76.00 ha) or the Gunston silt loam (unit 48A, 53.2% of the park, 335.36 ha). The Elkton series is described as a poorly-drained eolian silt loam overlying loamy alluvium or marine sediments. The Gunston series is described as a somewhat poorly drained silt loam derived from marine sediments. In the field, the Gunston series proved to be very similar to the Elkton, with borings in both series yielding shallow redoximorphic features, such as mottles and rhizospheres, that transitioned to thick pedons with reduced colors. Soil borings indicated that areas mapped as the Elkton series were slightly coarser, containing lenses of silt and sometimes very fine sand bounded by clay or transitioning to include a greater fraction of clay within the matrix of the soil. The highest portions of the park, 12-15 m elevation versus 9-10 m, were often composed of the Mattapex loam (unit 77A, 17.8% of the park, 112.46 ha). The Mattapex series is described as a moderately well drained eolian silt loam underlain by fluviomarine sediments.

The nature of the soil types, as wells as their extents, were confirmed with five described soil borings, as well as several borings that were not described. The locations of the described borings and boring logs can be found in Appendix A. The borings performed for this study agree with what was found in URS' geotechnical report, which indicated that the soils in the immediate area upstream of the vinyl piling dam and in what is now the ponded area are largely composed of thick gray clay loams with a greater sand fraction at depth and sandier deposits at either side of the dam.

Wetlands Present at Huntley Meadows Park

The NWI database indicated there are two wetland types present in Huntley Meadows Park: Freshwater Forested/Shrub Wetlands and Freshwater Emergent Wetlands. A map showing the locations of these wetland types as mapped by NWI within the model area (sub-basin 3) at Huntley Meadows Park can be seen in Fig. 8. The Classification of Wetlands and Deepwater

Habitats of the United States (Federal Geographic Data Committee, 2013) defines the units as follows:

> Freshwater Forested/Shrub Wetland: the dominant life form is woody plants less than 6 m tall that account for at least 30% of the areal coverage. The term 'shrub' includes young trees that have not yet reached 6 m height and woody plants that are stunted due to environmental conditions.
>
> Freshwater Emergent Wetland: emergent plants (erect, rooted, herbaceous hydrophytes) are the tallest plants and provide at least 30% areal coverage.

Comparison of the NWI map to the soils map shows that the majority of the wetlands in Huntley Meadows Park, freshwater forested/shrub wetlands (213.96 ha), exist in the areas dominated by the Gunston and Elkton soils (clays and silty loams underlain by clays respectively). The freshwater emergent wetlands (31.65 ha) exist primarily in the ponded portions of the park. The remainder of the area (~385 ha) is composed primarily of deciduous forest with a few grassy meadows, which are maintained with controlled burns, and a small fraction of land occupied by parking lots, a visitor's center, and maintenance buildings.

While the NWI maps were a useful starting point for approximating the extent of each type of wetland that would be used for Kc estimates and representation in the models, the NWI extents and vegetation assignments were refined based on systematic observations of vegetation (VT, Sara Klopf, personal communication). The data in Table 2 summarize the vegetation observations at each of the wells used to estimate AET. Table 3 indicates how each of the wells were used to estimate Kc values during 2014 and 2015, and how they were represented in the Advanced Model. Observed plant communities were simplified to correspond with NWI map units for AET estimation and modeling purposes.

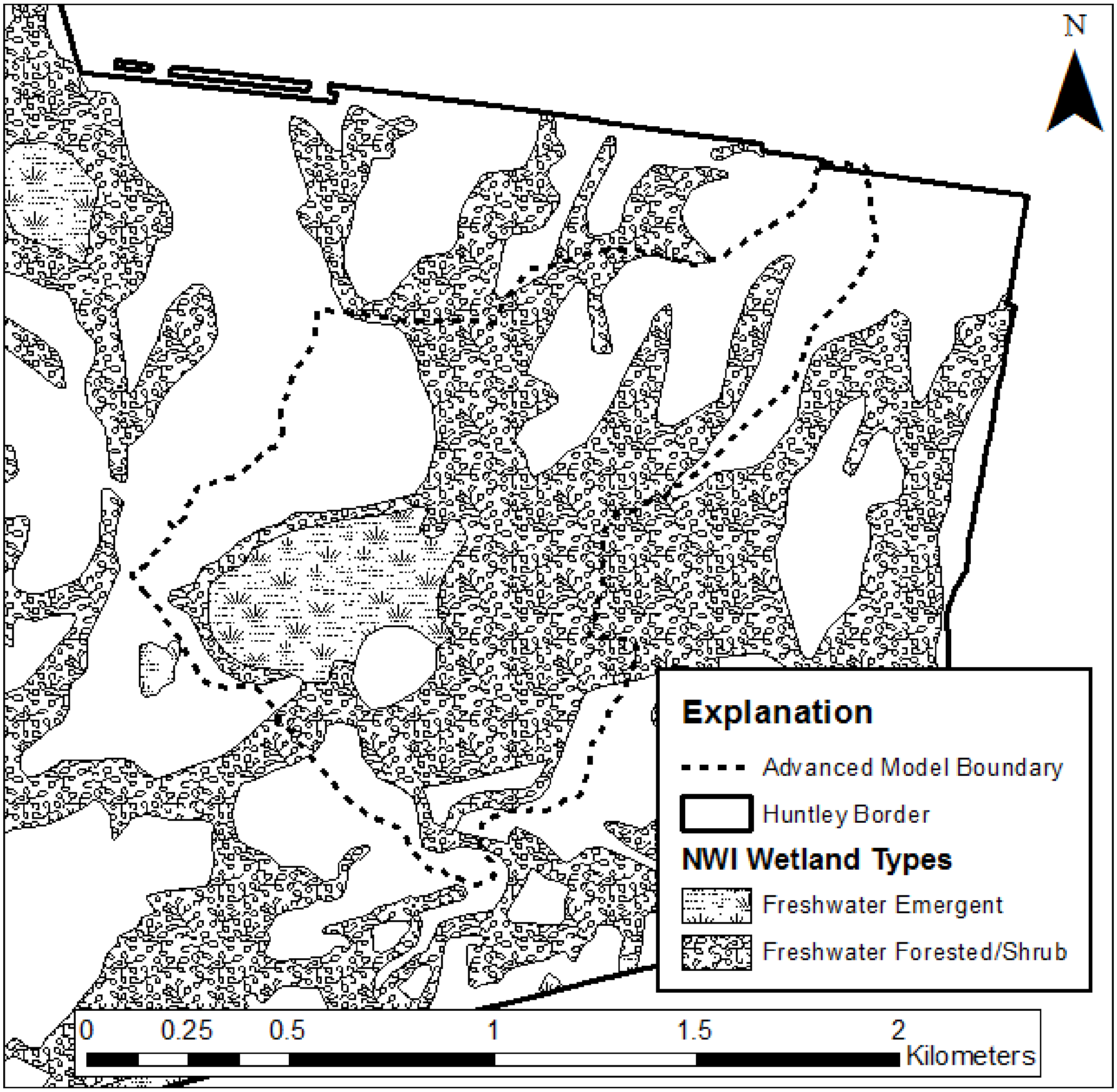


Fig. 8. Map of NWI identified wetlands within Advanced Model area. Areas not mapped as wetlands by NWI were interpreted as forested non-wetland areas.

Table 2

Observations of vegetation at wells used to estimate AET. Data from personal communication with Sara Klopf (VT). No observations of vegetation were made at ODU_ET1 and ODU_ET2 until 2016.

Well	2013 Obs. Veg.	2014 Obs. Veg.	2015 Obs. Veg.	2016 Obs. Veg.
T1A	Emergent WL	Emergent WL/Aq. bed	Emergent WL	Emergent WL/Aq. bed
T1B	Forested (non-WL)	Forested (non-WL)	Forested WL	Forested WL
T1C	Forested (non-WL)	Forested (non-WL)	Forest/shrub WL	Forest/shrub WL
T2A	Forested WL	Forested WL	Aquatic bed	Aquatic bed
T2B	Forested (non-WL)	Forested WL	Forest/shrub WL	Forest/shrub WL
T2C	Forested WL	Forested WL	Forested WL	Forested WL
T3A	Forest/shrub WL	Scrub/shrub WL	Emergent WL	Emergent WL
T3B	Forested WL	Forested WL	Forested WL	Forested WL
T3C	Forested (non-WL)	Forested (non-WL)	Forested (non-WL)	Forested (non-WL)
T4A	Scrub/shrub WL	Scrub/shrub WL	Emergent WL	Emergent WL
T4B	Forested WL	Forested WL	Forested WL	Forested WL
T4C	Forested WL	Forested WL	Forested WL	Forested WL
ODU_ET1				Forest/shrub WL
ODU_ET2				Forest/shrub WL

Note: Obs. = observed, Veg. = vegetation, WL = wetland, Aq. Beg = aquatic bed.

Table 3

Well plant community assignments for AET, Kc, and modeling purposes.

Well	Assignment for ET Rates and Modeling
T1A	Emergent WL
T1B	Forested (non-WL) 2014, Forest/Shrub WL 2015
T1C	Forested (non-WL) 2014, Forest/Shrub WL 2015
T2A	Forest/Shrub WL 2014, Emergent WL 2015
T2B	Forested (non-WL) 2014, Forest/Shrub WL 2015
T2C	Forest/Shrub WL
T3A	Forest/Shrub WL 2014, Emergent 2015
T3B	Forest/Shrub WL
T3C	Forested (non-WL)
T4A	Forested/Shrub WL 2014, Emergent 2015
T4B	Forest/Shrub WL
T4C	Forest/Shrub WL
ODU_ET1	Forest/Shrub WL
ODU_ET2	Forest/Shrub WL

Monitoring Array

The three monitoring wells installed by ODU to constrain regional groundwater influence (VTHD1, VTHD2, and VTHD3) exhibited similar patterns in their hydrographs with a few key differences between them. Fig. 9 and 10 show the hydrographs from wells VTHD1 and VTHD3 screened from elevations of 11.64 – 8.60 m and 15.02 – 13.27 m, respectively. Both wells showed seasonal fluctuations with high water levels occurring between late November and early May then dropping by approximately two meters in both wells over the course of the 2014 growing season, when ET rates were highest. The range of water levels observed from winter 2014 into spring and summer of 2015 was similar to that observed from 2013 into 2014 for both wells. The key difference between the two wells was the rate of change observed over short periods of time at each well. The response to rain events, as well as the decline following them, was more rapid in VTHD3 than that observed in VTHD1 though the patterns match closely. Fluctuations occurred more slowly in VTHD1 compared to VTHD3. The similarities of the patterns suggest the wells are screened in the same unconfined aquifer. The differences suggest the soils present around the screened interval of VTHD3 are likely more coarse, which would increase hydraulic conductivity. It is also possible that soils around VTHD3 have less connected pore space, which would decrease specific yield allowing greater fluctuations in water levels observed below ground due to smaller changes in volumes of water passing through the soils.

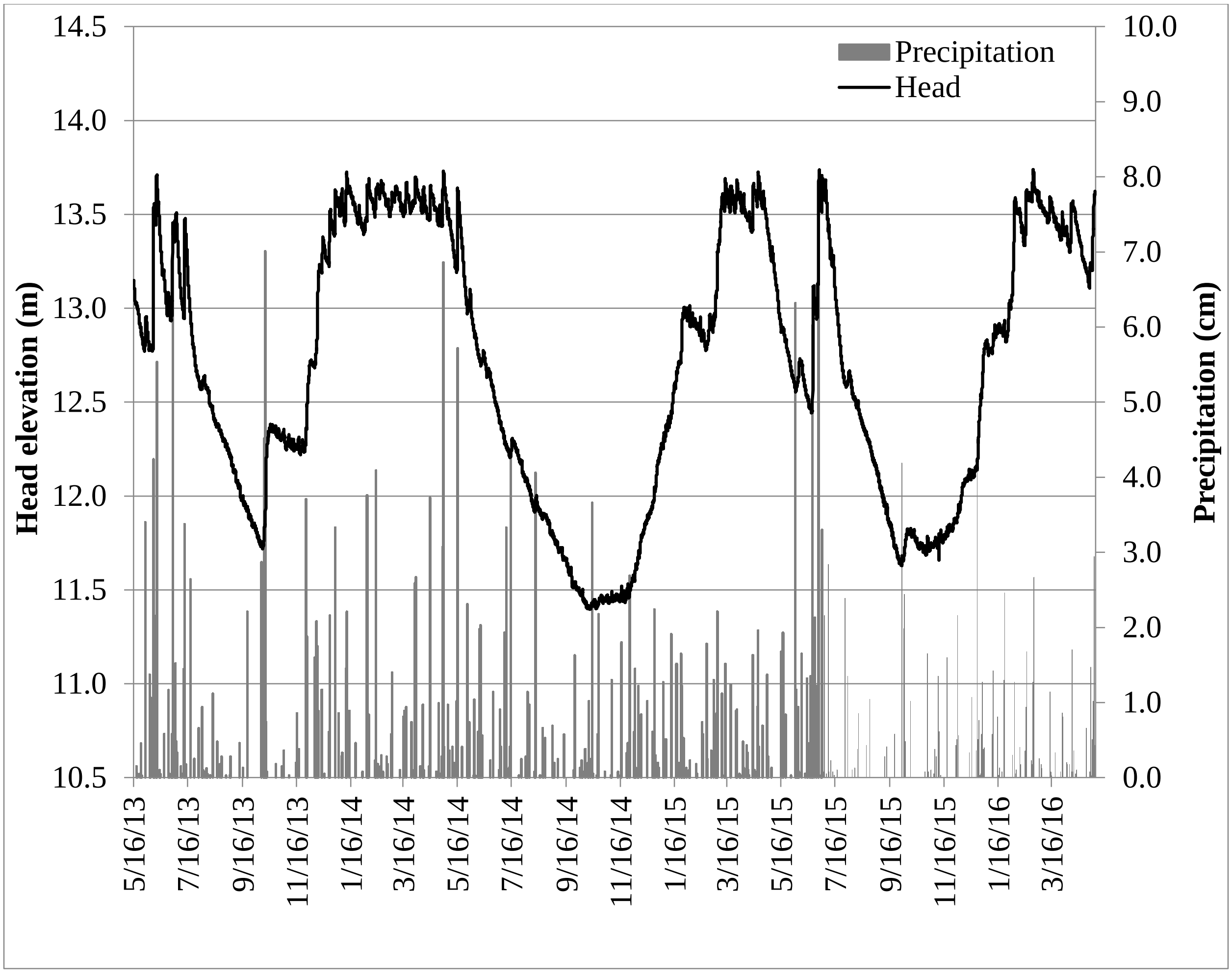


Fig. 9. VTHD1 hydrograph from hourly head data. Vertical bars represent total daily precipitation.

Note: unless otherwise stated, all hydrographs and elevation references in this document are relative to sea level.

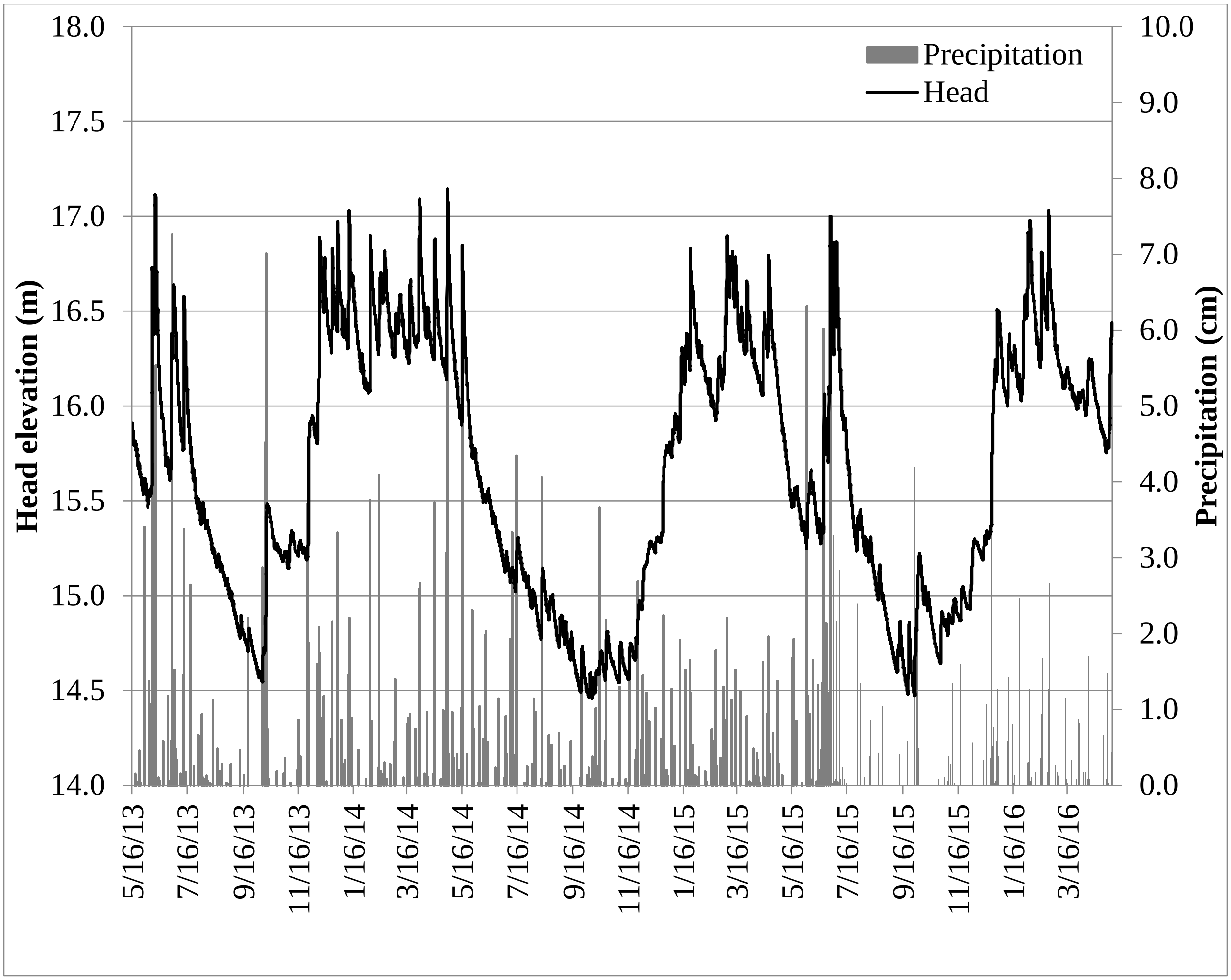


Fig. 10. VTHD3 hydrograph from hourly head data. Vertical bars represent total daily precipitation.

The hydrograph from VTHD2 (Fig. 11) shows a similar pattern to the hydrographs from VTHD1 and VTHD3, although the signal appears muted relative to the patterns seen in those wells. VTHD2 was screened from 2.08 m below sea level to 0.97 m above sea level in material that is considerably coarser than the soils VTHD1 and VTHD3 were screened in. The screened interval at VTHD2 terminated in sandy material with gravels common, compared to clay or sandy clay at VTHD1 and VTHD3. The range of water table fluctuations observed in VTHD2 spanned roughly one meter, compared to the two meter range seen in VTHD1 and VTHD3. The rate of change seen in VTHD2 was slower than that seen in VTHD1 and VTHD3. This difference in the way the water table responds to precipitation, coupled with the coarse material seen at depth in VTHD3, suggests there is an aquitard under much of the study area that impedes regional groundwater flow passing below the park from strongly influencing water levels in the ponded area of Huntley Meadows Park.

The muted signal in VTHD2 relative to VTHD1 and VTHD3 and the hypothesis that an aquitard exists between these wells suggested the installation of a deep monitoring well, ODU_HM1, in close proximity (55 m) to the variable height outlet weir to determine if the vertical gradient was ever great enough to source groundwater from depth to the ponded area. Depth to water measurements were taken at ODU_HM1 whenever data were downloaded from the pressure transducers throughout the rest of the park. Water levels from ODU_HM1 were compared to water levels observed at the outlet structure. Table 4 shows the water table elevations of ODU_HM1, corresponding pond surface elevations recorded at the outlet structure, and gradients calculated from those differences in elevation. Observed water levels in ODU_HM1 do not exceed pond levels. These findings suggest there is no significant regional groundwater input to these wetlands; rather, water usually seeps downward out of the system.

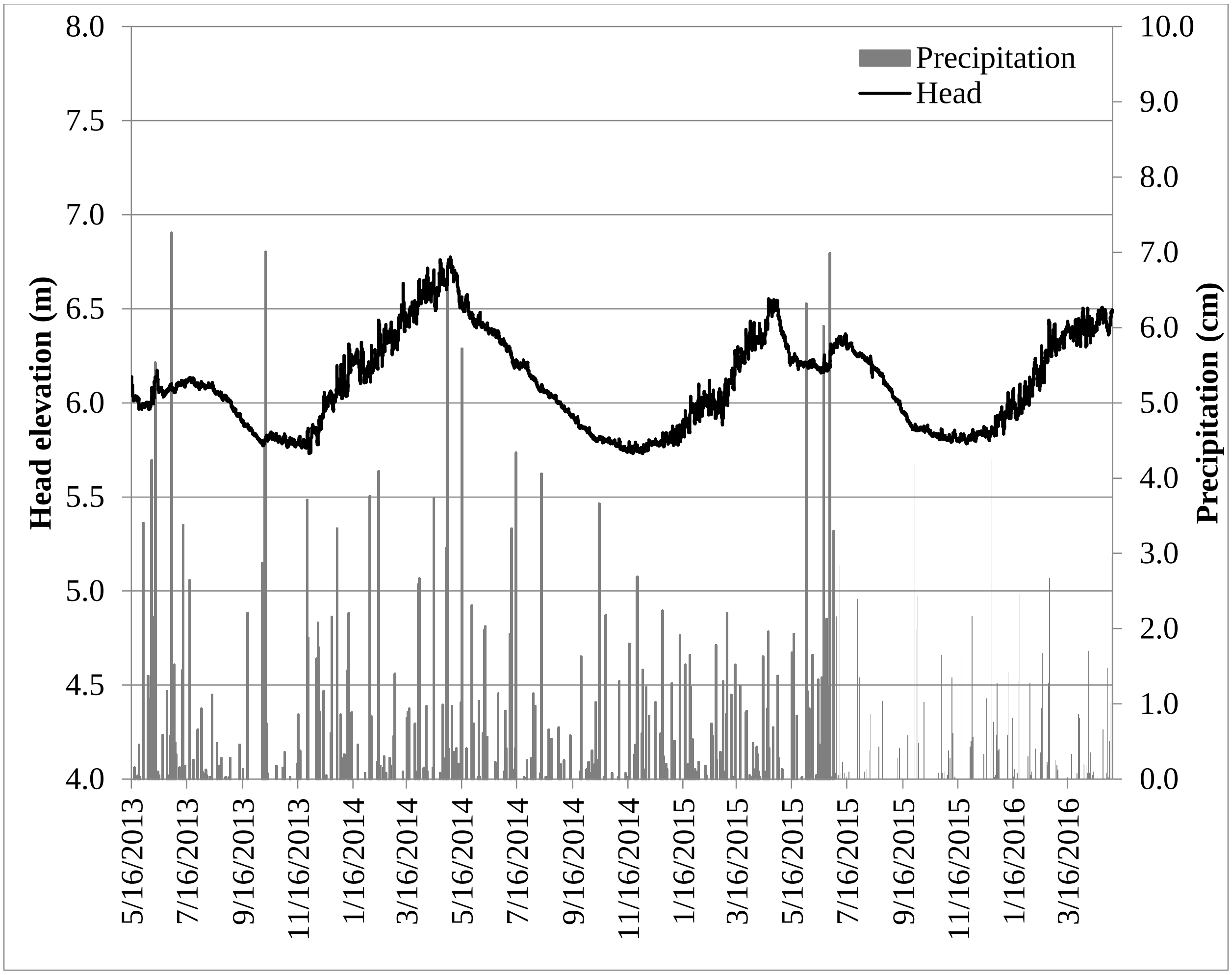


Fig. 11. VTHD2 hydrograph from hourly head data. Vertical bars represent total daily precipitation.

Table 4
Gradients from outlet to observed head at ODU_HM1. Horizontal distance between wells = 55 m.

Date	Time	ODU_HM1 Head (m)	Outlet Head (m)	Gradient (m/m)
2/15/2015	15:00	5.97	10.35	-0.08
3/14/2015	16:00	6.39	10.43	-0.07
5/18/2015	16:00	6.26	10.13	-0.07
7/9/2015	17:00	6.38	10.03	-0.07
8/4/2015	08:20	6.24	10.02	-0.07
10/5/2015	14:55	5.86	9.88	-0.07
11/10/2015	11:20	5.87	10.02	-0.08
12/15/2015	13:10	5.86	10.28	-0.08
1/5/2016	12:25	5.86	10.31	-0.08
2/4/2016	09:40	6.17	10.48	-0.08

Wells ODU_ET1 and ODU_ET2 also have hydrographs (Fig. 12 and Fig. 13, respectively) which resemble patterns seen in VTHD1 and VTHD3. ODU_ET1 and ODU_ET2 were both screened continuously, roughly three meters below the surface. ODU_ET1 was screened from 14.44 m to 16.88 m of elevation and ODU_ET2 was screened from 8.45 m to 11.34 m of elevation. The response to precipitation in ODU_ET1 was almost immediate and less dramatic compared to the response seen in ODU_ET2. For example, a 41.9 mm rain event on September 29, 2015 (RNAWS) caused roughly a 0.5 m rise in just one hour on September 29th at ODU_ET1, followed by a rapid decline in the water table a few hours later, though there was no immediate response seen in ODU_ET2 during the same precipitation event. Between September 29th and October 2nd, 2015 there was a total of 86.1 mm of rain. The two rain events that followed the September 29th event caused water table fluctuations of less than half a meter at ODU_ET1. The total 86.1 mm of rain caused approximately two meters of rise at ODU_ET2 that occurred over eighteen hours, from 21:00 October 1st, 2015 to 13:00 October 2nd, 2015.

These types of responses, flashy with a small range in ODU_ET1 and delayed with a large range of water table fluctuation and slow decline afterwards in ODU_ET2, were observed throughout the entirety of each of their hydrographs.

These differences in response to precipitation events were likely due to differences in the soils surrounding the wells. ODU_ET1 was installed in an area mapped as the Mattapex series. This series is typically seen at relatively high elevations within the park and has been described as a moderately well-drained eolian silt loam underlain by fluviomarine sediments. During installation of ODU_ET1, we encountered a pale-yellow clayey sand with oxidized mottles with increasing sand at depth that transitioned quickly to a dense clay at depth. The bottom of the screened interval at ODU_ET1 terminated at the transition to the dense clay bed. Conversely, ODU_ET2 was installed in an area mapped as the Elkton series. Often seen in relatively low portions of the park, the Elkton soil is also described as a poorly drained eolian silt loam overlying alluvium or marine sediments. During installation of ODU_ET2, we encountered a poorly drained silty loam that transitioned to dense light gray clay. The coarser soils around ODU_ET1 likely have faster conductivity rates and higher specific yield values than the soils around ODU_ET2.

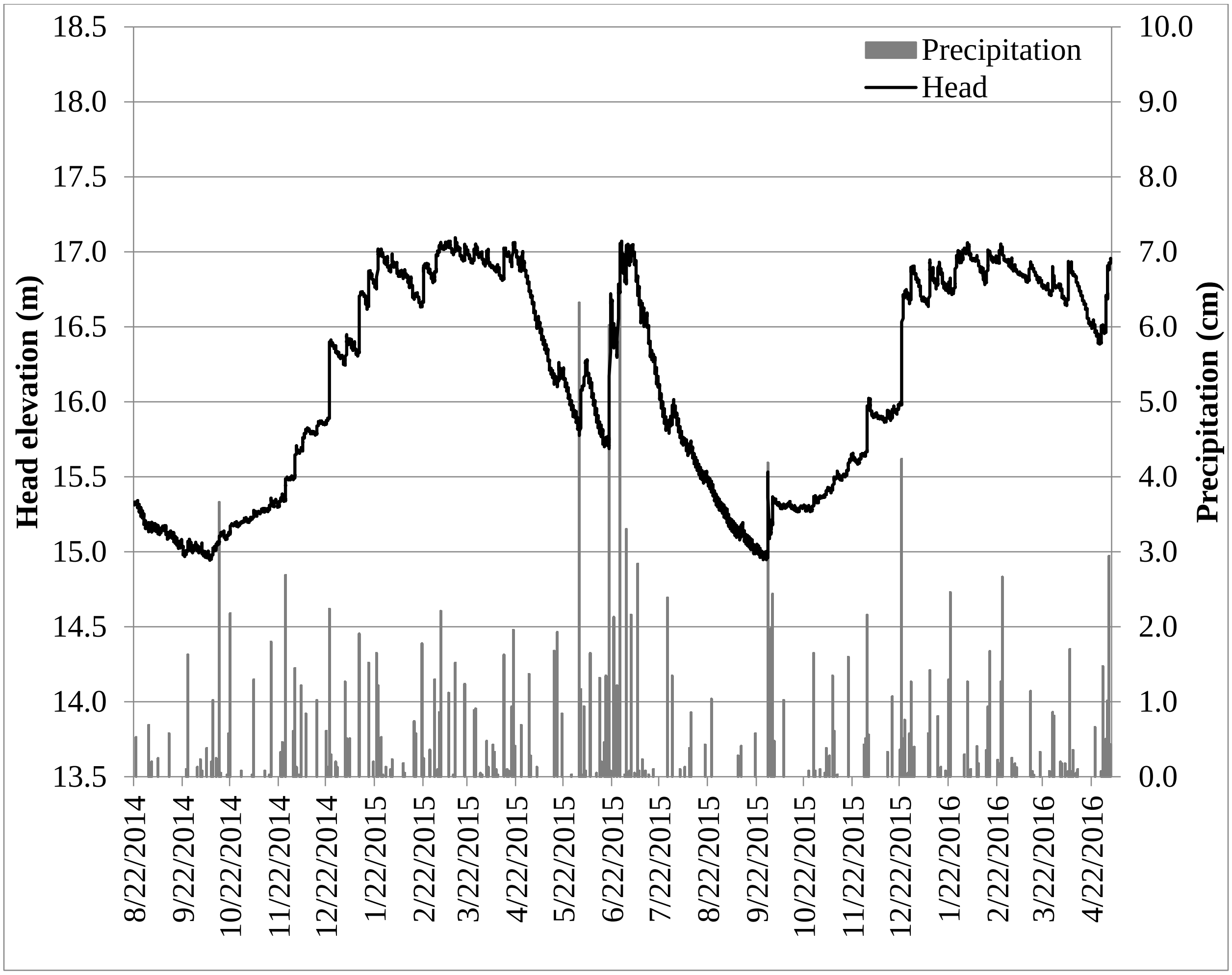


Fig. 12. ODU_ET1 hydrograph from hourly head data. Vertical bars represent total daily precipitation.

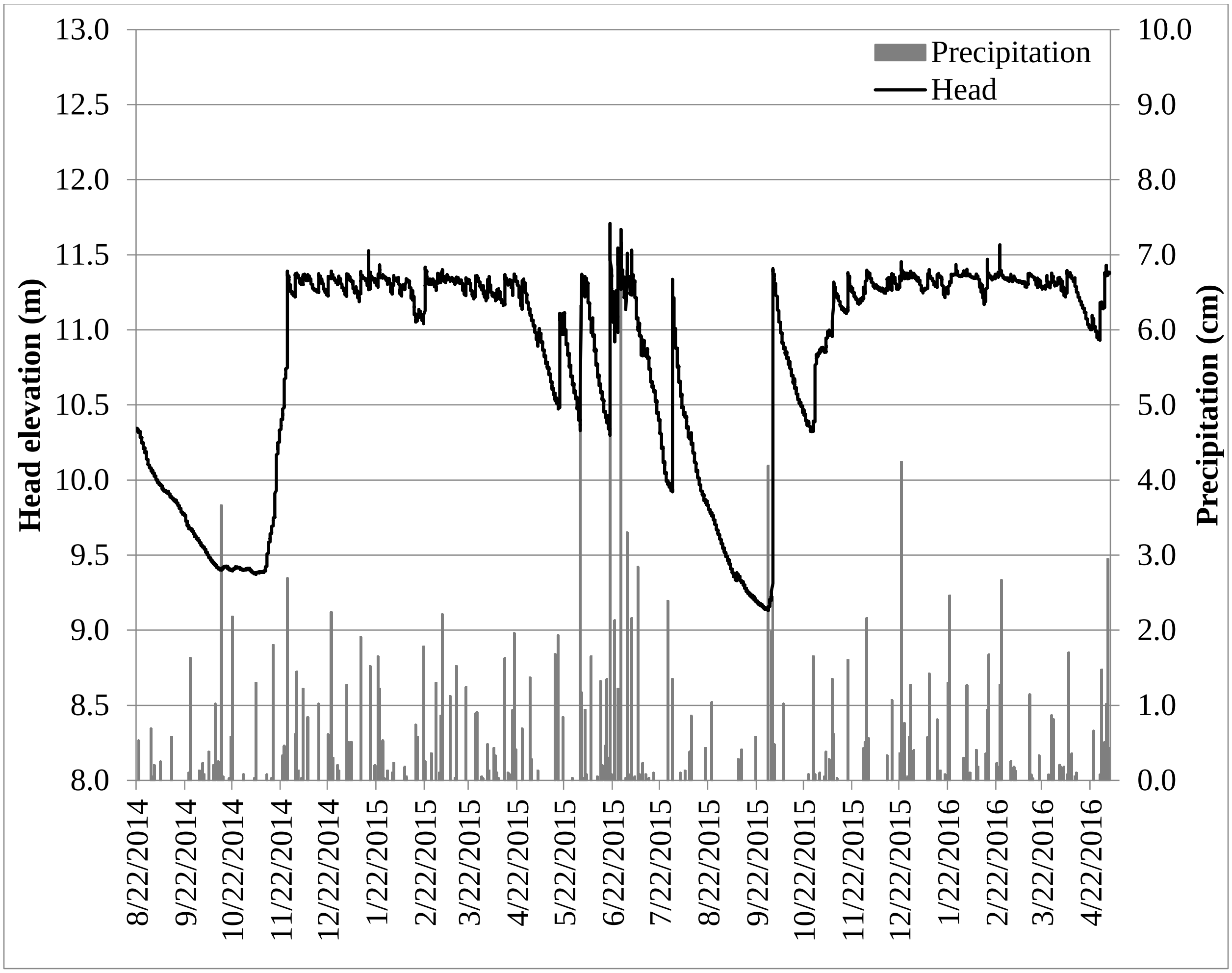


Fig. 13. ODU_ET2 hydrograph from hourly head data. Vertical bars represent total daily precipitation.

In conjunction with the wells maintained by ODU, which were installed to better constrain the influence of regional groundwater flow to the ponded area at Huntley Meadows Park, fourteen wells were installed along four transects in and around the ponded area to monitor the extent of the ponded area and changes in groundwater surrounding the ponded area post-construction. Rather than evaluating the data from each well individually, data from each of the transects are described in the following paragraphs. Each of the four transects contain an A, B, and C location well, with transects one and three having an additional well in the ponded area of the transect that is indicated by the marker ‘P.’ In the transect hydrographs it is reasonable for the A location well to be interpreted as the pond elevation along that transect unless there is a P location well. Periods during which there were no data collected are indicated by gaps in the hydrographs. Periods when the monitoring equipment was functional but the water table was below the range of the monitoring equipment are indicated by flat sections at depth. General information, including data collection start date, ground elevation, transducer elevation, maximum water table elevation, and median depth to water for each year data were collected, can be found in Table 5. The median depth to water values represent the depth to water from the surface at each well location, during each year of observation. Negative depth to water values indicate periods of inundation and the magnitude of the negative value indicates the depth of the standing water above the ground surface. Only 2013, 2014, and 2015 should be evaluated with the median depth to water parameter, as these are the only years with complete data sets.

Additionally, it should be noted that the construction associated with the restoration project was carried out during the growing season of 2013 and the water levels were lowered in the ponded area to facilitate construction. Post construction, the median depth to water decreased each year. The decrease in median depth to water from 2013 to 2015 indicates the subterraneous vinyl piling dam and variable height outlet weir have raised water levels not only in the pond, but in the surrounding areas. Increasing the water levels in the surrounding areas will help to establish a larger extent of transitional plant communities surrounding the pond.

When evaluating the hydrographs from the four transects (Fig. 14 - 17) the most prominent consistency was the drop in water table elevation during the growing season. Each year in late April or early May, the water table dropped in each of the well locations. Most years the water table at the wetter well locations (A and P) remained within the observational ranges of the wells, except along transect four, where the water table dropped below the range of observation each year at all of the well locations. At B and C well locations, along each transect, the water table dropped below the range of observation each year during the growing season. While one would expect water table fluctuations to correspond changes in the seasons, it is less common for flow gradients to reverse with the changing of the seasons. Along each of the transects surrounding the pond, the flow gradient is towards the pond (C to A) during the winter months, with the topographic highs being the sources of groundwater. Then, almost as soon as the growing period begins, the water table drops more at B and C location wells and the pond becomes the local high point in the water table acting as a reservoir sourcing groundwater rather than a catchment receiving surface and groundwater.

The range of fluctuations at the B and C locations in each of the transects, and the nature of the response to precipitation and ET, suggests the B and C wells are all screened in the same unconfined aquifer, with possible subtle differences in hydraulic conductivity and storage properties in different parts of the system. However, the persistent water table elevations of the P and A locations wells indicates the soils lining the pond have slower conductivity rates than the B and C location wells, which facilitates the accumulation of water in the winter and slow drainage away from the pond during the growing season.

Table 5
VT transect well summary data.

Well	Collection Start Date	Ground Elev. (m)	Trans. Elev. (m)	Max WT Elev. (m)	Median Depth to Water (m)				
					2012	2013	2014	2015	2016
T1P	11/19/2012	9.89	9.37	10.57	0.03	-0.11	-0.36	-0.26	-0.26
T1A	10/8/2012	10.21	9.74	10.53	0.45	0.27	0.00	0.12	0.10
T1B	10/8/2012	10.77	9.50	10.54	1.30	1.20	1.29	1.28	1.29
T1C	10/8/2012	11.07	9.63	11.01	1.46	0.52	0.79	0.72	0.51
T2A	10/8/2012	9.79	9.30	10.53	0.16	0.04	-0.43	-0.35	-0.34
T2B	10/8/2012	10.33	9.22	10.45	1.17	0.71	0.23	0.37	0.27
T2C	1/31/2013	11.05	9.40	10.93		0.78	1.44	1.32	0.60
T3P	11/19/2012	9.89	9.60	10.64	0.04	-0.07	-0.30	-0.26	-0.47
T3A	10/8/2012	10.20	9.80	10.55	0.38	0.22	-0.03	0.09	0.07
T3B	10/8/2012	10.83	9.75	10.83	1.11	0.96	1.07	1.06	0.66
T3C	1/31/2013	11.16	9.44	11.22		0.54	1.73	1.59	1.04
T4A	11/19/2012	10.32	9.73	10.63	0.16	0.17	0.01	0.19	0.07
T4B	11/19/2012	10.92	9.79	11.02	1.15	1.07	1.13	1.14	0.33
T4C	11/19/2012	11.35	9.54	11.30	1.44	0.81	1.67	1.36	0.51

Note: Elev. = elevation, Trans. = transducer, WT = water table, negative depth to water values indicate water table height above ground.

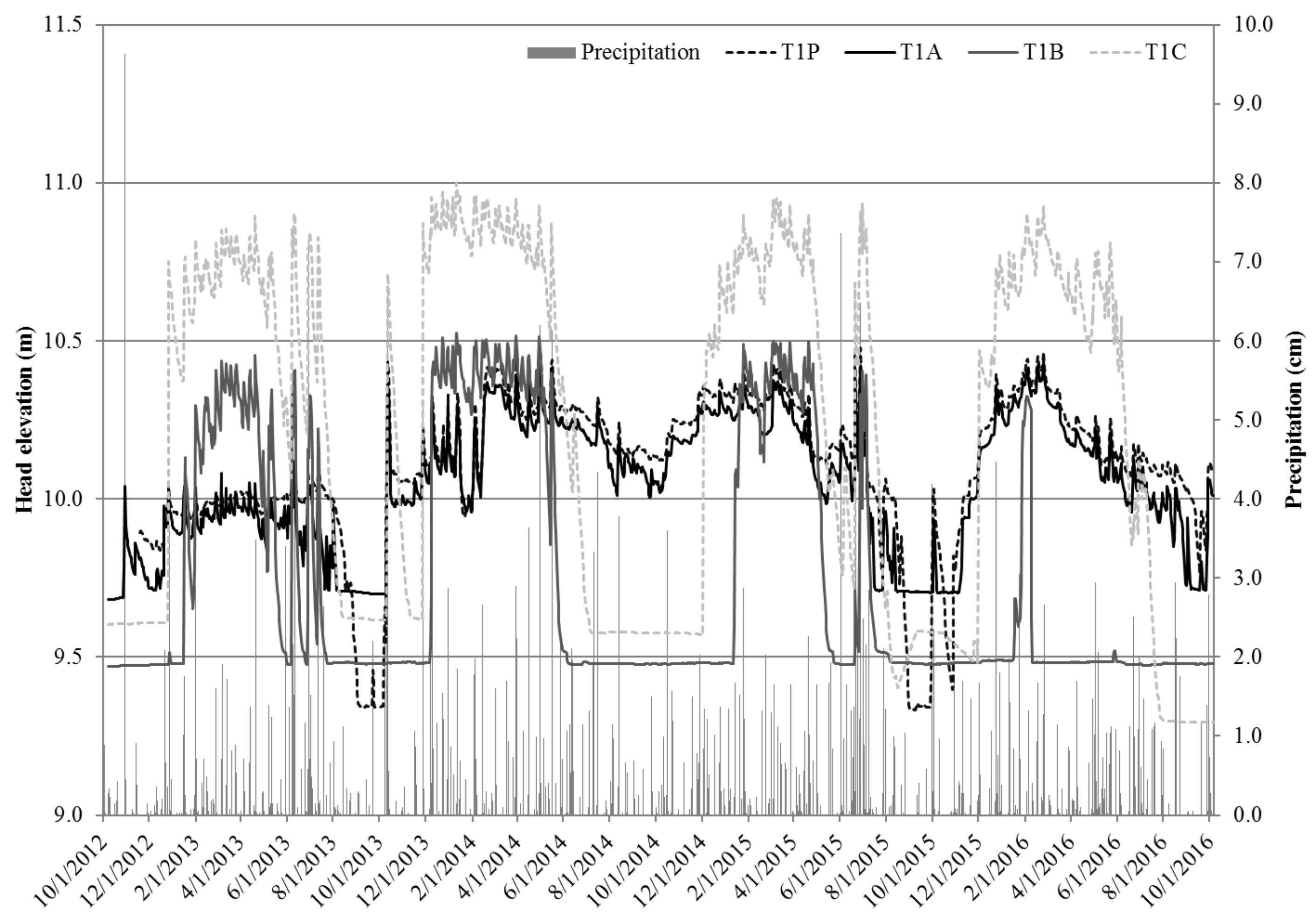


Fig. 14. Transect 1 hydrograph. The large range of head values in T1C during each year compared to the pond (T1P) generates a seasonal reversal of flow direction along the transect. Heads are higher in the woods during the winter and lower during the summer.

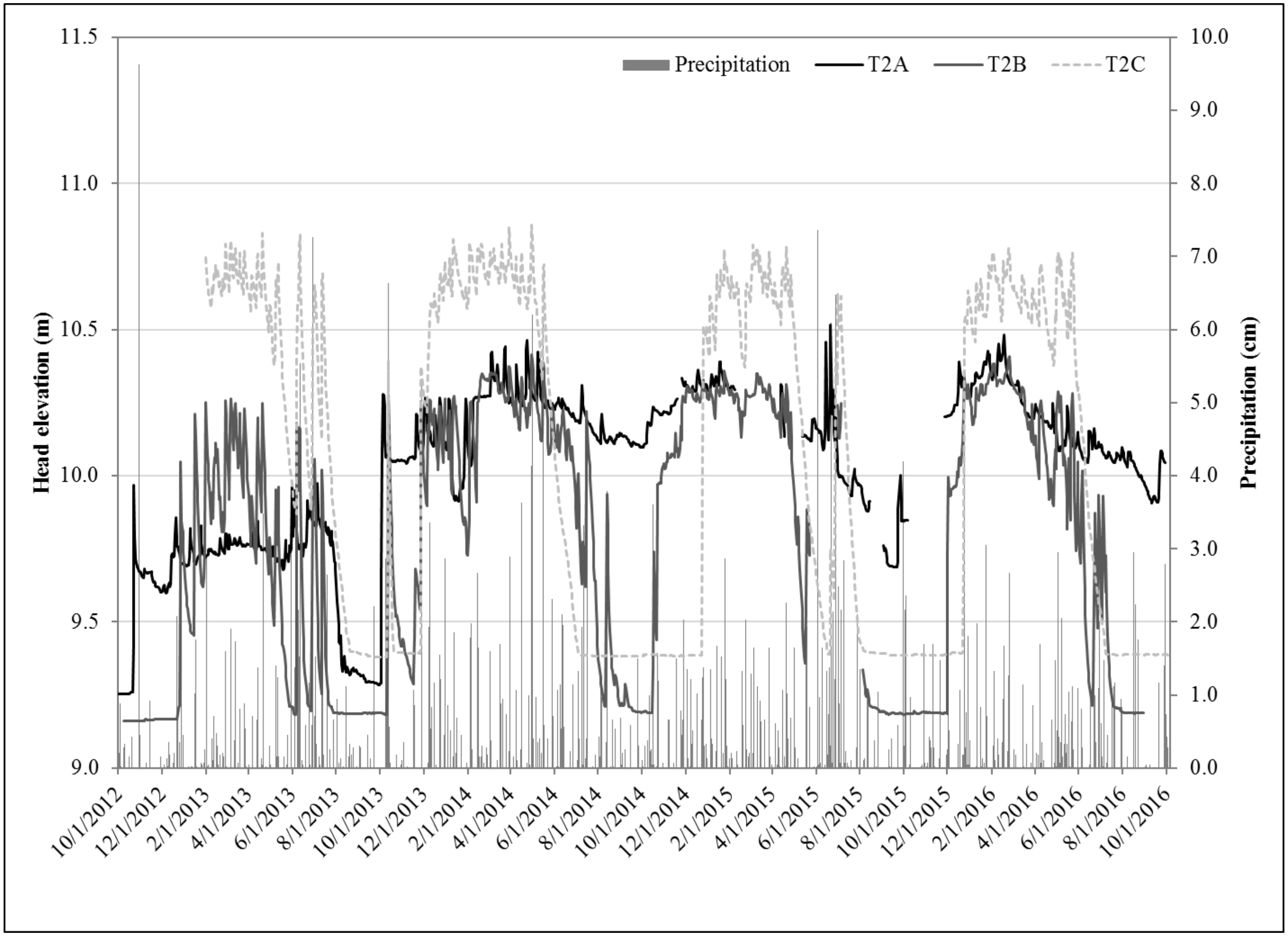


Fig. 15. Transect 2 hydrograph. The large range of head values in T2C during each year compared to the emergent vegetation (T2A) generates a seasonal reversal of flow direction along the transect. Heads are higher in the woods during the winter and lower during the summer.

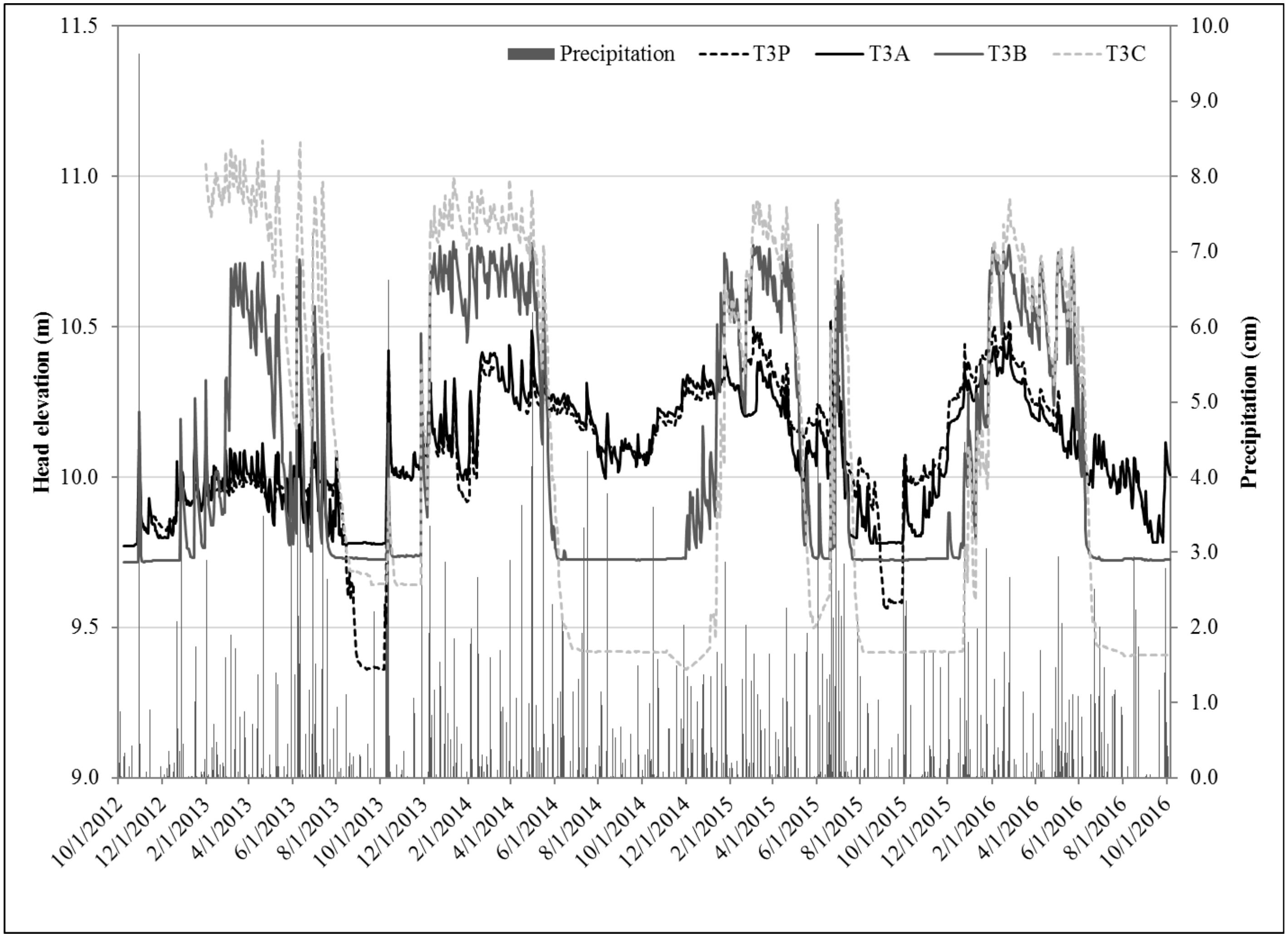


Fig. 16. Transect 3 hydrograph. The large range of head values in T3C during each year compared to the pond (T3P) generates a seasonal reversal of flow direction along the transect. Heads are higher in the woods during the winter and lower during the summer.

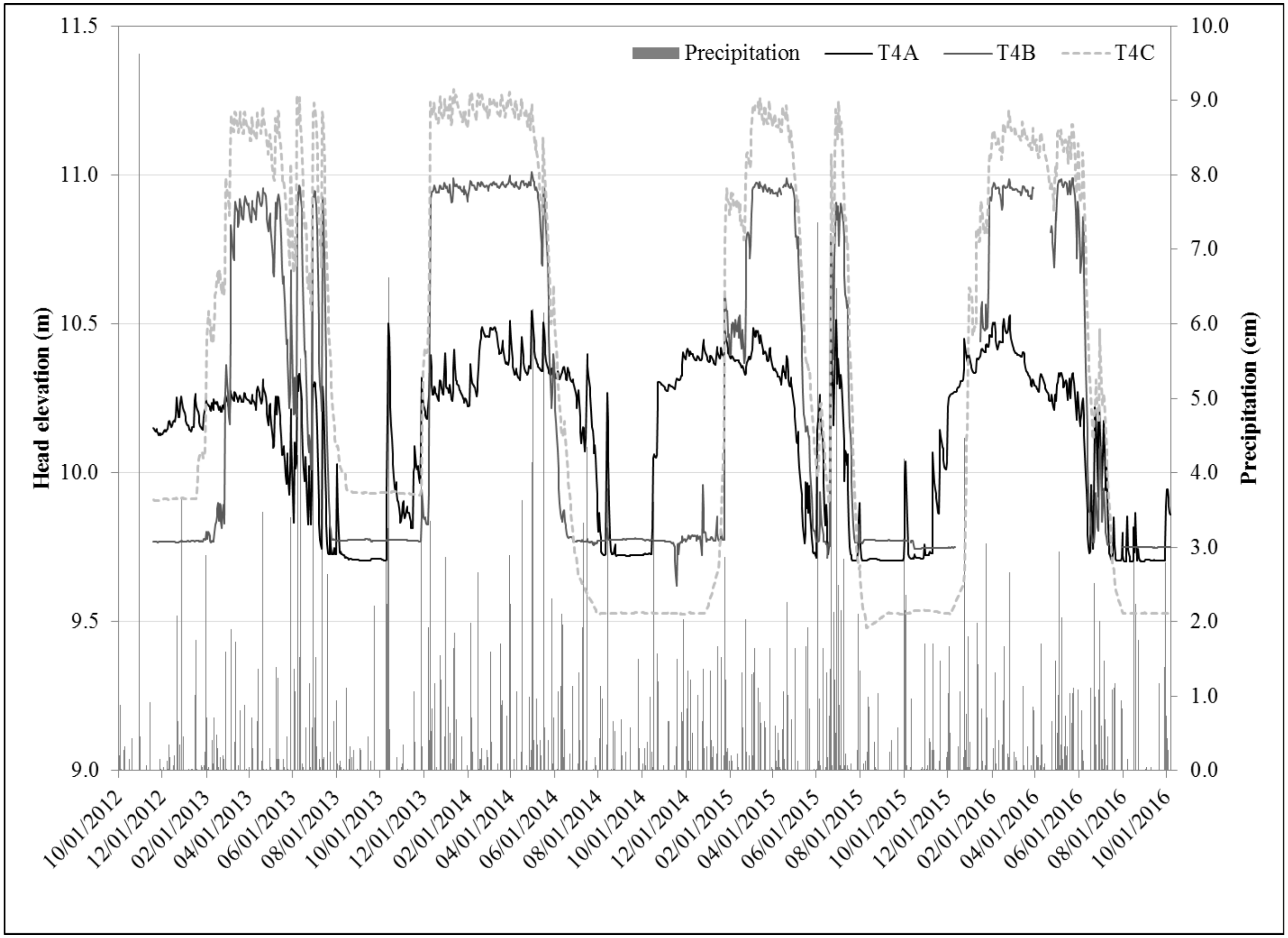


Fig. 17. Transect 4 hydrograph. The large range of head values in T4C during each year compared to the emergent vegetation (T4A) generates a seasonal reversal of flow direction along the transect. Heads are higher in the woods during the winter and lower during the summer.

Hydraulic Conductivity

Slug tests were performed at VTHD1, VTHD2, VTHD3, ODU_ET1, ODU_ET2, and ODU_HM1 to parameterize hydraulic conductivity rates across the park. Three trials were performed at each well with the exception of ODU_ET2, where only two trials were performed, on two separate days, due to the slow rebound rates. See Table 6 for a summary of the slug test results. Hydraulic conductivity rates throughout the park varied by four orders of magnitude. The fastest rates, an average of 1.21×10^{-4} m/s, were observed at VTHD2 and the slowest rates, an average of 6.74×10^{-7} m/s, were observed at ODU_ET2. While the rate observed at VTHD2 was two orders of magnitude faster than Web Soil Survey (WSS) reports for the soils at the surface at the location of VTHD2, it should be noted that the top of the roughly one meter screened interval is almost nine meters below ground and terminates in gravelly sand. The slow hydraulic conductivity rates observed at ODU_ET2 are consistent with the ranges reported by WSS for the Elkton silt loam. Hydraulic conductivity rates varied within the same order of magnitude for each of the trials at a given well except for ODU_ET2. The second trial at ODU_ET2 produced a rate almost a full order of magnitude greater than the first trial, 1.65×10^{-7} m/s versus 1.18×10^{-6} m/s for the second trial. It is possible that the difference in static head at the start of each of these trials influenced the rates that were determined. At the start of trial one, the head was 10.33 m. At the start of trial two, the head was 11.27 m. Both of these head values occurred within the screened interval at ODU_ET2. The faster rate derived from trial two could be attributed to the coarser soils present near the surface, which transitioned to clay at depth, representing a coarsening upward sequence. Raw data from each of the slug test trials that were performed can be found in Appendix C.

Table 6
Slug test results for wells maintained by ODU.

Well	Method	Trial 1 (m/s)	Trial 2 (m/s)	Trial 3 (m/s)	Avg. K (m/s)
VTHD 1	Hvorslev	5.53E-06	7.10E-06	5.93E-06	6.19E-06
VTHD 3	Bouwer/Rice	1.26E-05	1.26E-05	1.27E-05	1.26E-05
VTHD 2	Hvorslev	1.23E-04	1.11E-04	1.30E-04	1.21E-04
ODU_ET1	Bouwer/Rice	6.01E-07	5.96E-07	2.02E-07	4.67E-07
ODU_ET2	Bouwer/Rice	1.65E-07	1.18E-06		6.74E-07
ODU_HM1	Hvorslev	3.18E-05	5.72E-05	3.44E-05	4.11E-05

Variations in Evapotranspiration Rates

Once an understanding of the distribution of soils, wetlands, and water distribution throughout the park was developed, the ET rates associated with each of the plant communities were assessed. To characterize these effects, it was necessary to assign wetland types to wells used to estimate AET, estimate the specific yield of the soils surrounding the wells used to determine AET, calculate actual ET rates associated with each wetland type, and then compare the ET rates derived from monitoring wells in those wetland types.

Actual Evapotranspiration Rates

Fourteen wells were used to determine AET rates in a variety of settings within Huntley Meadows Park. Each setting was comprised of a plant community and a soil storage value associated with each well. Three categories were used to differentiate vegetation surrounding the wells used to estimate AET, Forested Non-Wetlands, Forested/ Scrub-Shrub Wetlands, and Emergent Wetlands, as described in Chapter 2. Refer to Table 3, shown earlier, to see how wells were assigned plant communities. Results of the two methods used to approximate Sy and the Sy value used at each well are shown in Table 7. Appendix D contains the data for each of the water table response Sy estimates. The resulting range of Sy values used for AET estimation

(0.05 to 0.29) was consistent with the range of Sy values seen in Johnson (1967) and Loheide et al. (2005) for soil textures similar to the map units these wells exist in. After establishing plant communities and soil storage values for each of the wells, subsets of hourly head data were processed using the MATLAB version of White's Method for determining AET.

Table 7
Specific yield determination results.

Well	n WT Response Events	Avg. WT Response Sy	WT Response Std. Dv.	Avg. Upper Depth PP Sy	Avg. Lower Depth PP Sy	Sy Used for AET Estimates
T1A	7	0.09	0.02	0.20	0.09	0.09
T1B	5	0.08	0.03			0.08
T1C	5	0.09	0.02			0.09
T2A	2	0.29	0.01			0.29
T2B	5	0.05	0.02			0.05
T2C	5	0.08	0.02			0.08
T3A	7	0.09	0.03	0.14	0.13	0.13
T3B	5	0.06	0.03			0.06
T3C	4	0.08	0.03			0.08
T4A	5	0.26	0.05	0.20	0.21	0.21
T4B	3	0.04	0.04	0.22	0.10	0.10
T4C	4	0.1	0.04			0.10
ODU_ET1	4	0.09	0.05	0.23	0.19	0.19
ODU_ET2	4	0.11	0.02	0.22	0.13	0.13
	Avg.	0.11	0.03	0.20	0.14	0.12

Note: WT Response = water table response method, Sy = specific yield, Std. Dv. = standard deviation, PP = pressure plate method. The pressure plate technique was only used at six locations.

Subsets of hourly head data were selected based on the criterion that the sum of the Reagan National Airport Weather Station (RNAWS) precipitation three days prior to the day of interest was zero. This criterion resulted in 209 days, between August 8th, 2014 and March 31st, 2016, where data from the fourteen wells used for estimating AET could be evaluated. Of the

2,926 potential AET rates (209 days * 14 wells), only 191 rates were considered usable. Seven of the wells did not produce usable AET rates. For a rate to be considered usable the hydrograph derived from the subset of data used to determine the AET rate needed to meet three criteria: (1) it had to exhibit an obvious diurnal signal, (2) the sign of the three recovery slopes needed to be the same, and (3) the data from the last day included in the subset could not exhibit influences from precipitation. Subsets of data that were recorded when the water level was above ground surface were not used to determine AET rates. Additionally, there were many times during the growing season when the water table would drop below the monitoring equipment; during these periods ET was active, even if no AET estimate could be derived. Table 8 shows the total number of usable rates from each well, as well as the maximum, minimum, and median derived AET rates.

Table 8
Usable AET rates summary. Maximum, minimum, and median usable AET rates shown.

Well	n Usable Rates	Max. (mm/d)	Min. (mm/d)	Med. (mm/d)
T1A	33	7.5	1.0	3.9
T1B	0			
T1C	0			
T2A	0			
T2B	0			
T2C	0			
T3A	32	11.3	0.7	3.9
T3B	0			
T3C	0			
T4A	16	34.3	0.1	21.5
T4B	6	15.1	5.7	9.6
T4C	3	7.8	4.5	5.1
ODU_ET1	81	30.3	4.4	19.4
ODU_ET2	20	16.1	2.2	7.9
Sum	191			

Crop Coefficient Values

Crop coefficients (Kc) were calculated for each of the 191 usable rates using both the Reagan National Airport Weather Station (RNAWS) and the Huntley Weather Station (HWS) derived Penman-Monteith PET rates for the corresponding days. The HWS was not functional until March of 2015 and therefore yielded fewer PET rates and corresponding Kc values. Kc values derived from the HWS (located in the emergent wetlands at Huntley Meadows Park) also had a greater range than the RNAWS Kc values. We attribute the greater range of Kc values derived from the HWS to the typically lower estimate of PET derived from the data collected at Huntley Meadows Park (Fig. 18). The lower estimates of PET are due to the typically lower observed temperature and higher relative humidity reported at the HWS relative to the RNAWS. Fig. 19 shows a graph of observed daily mean temperature reported at both weather stations. Fig. 20 shows the average daily relative humidity reported by each of the weather stations. We believe the higher relative humidity and the lower average daily temperatures are artifacts of the placement of the Huntley Weather Station. As stated earlier, the HWS is situated in an emergent wetland. While the HWS might be a good representation of emergent wetlands at Huntley Meadows Park, PET rates derived from that setting likely underrepresent conditions throughout the remainder of the watershed.

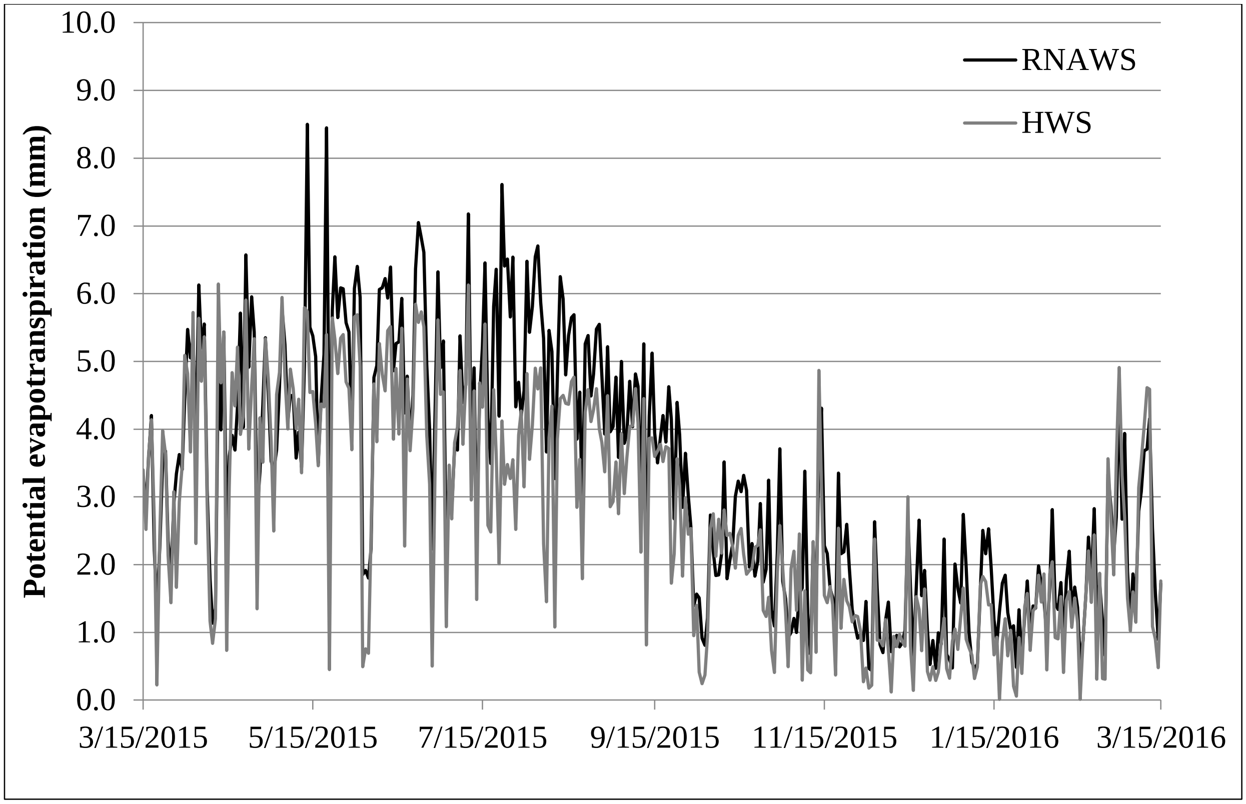


Fig. 18. Daily PET from RNAWS and HWS.

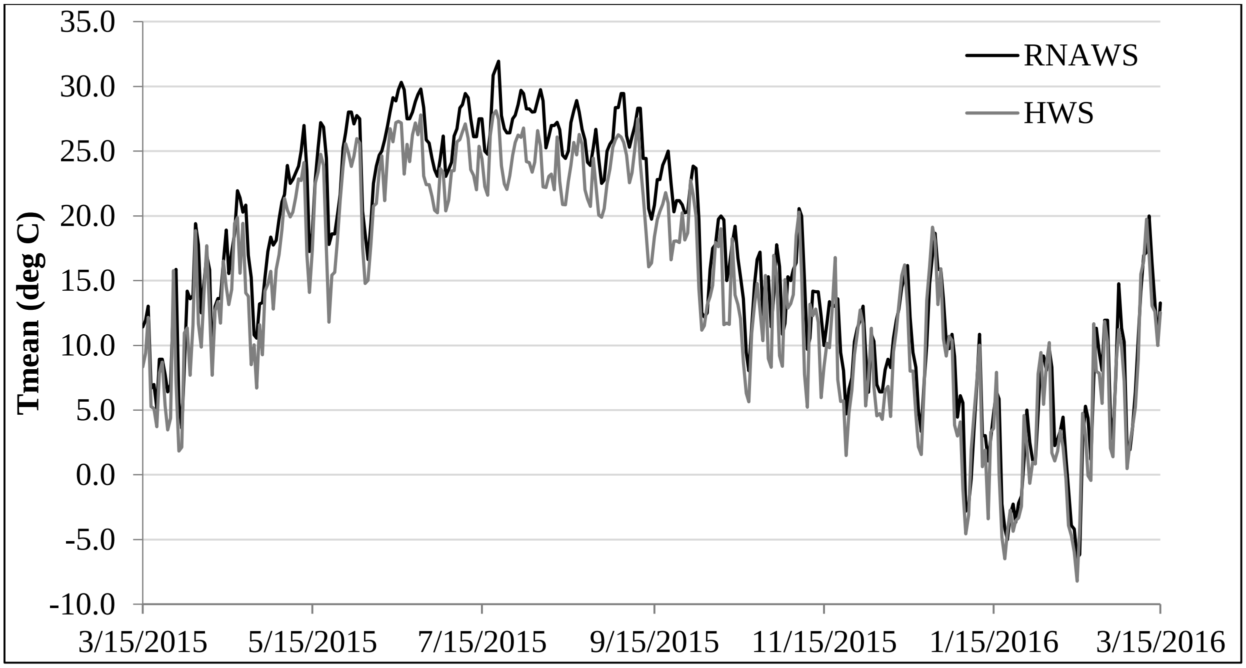


Fig. 19. Daily mean temperature at RNAWS and HWS. For the purposes of calculating PET, Tmean is calculated as the average of the maximum and minimum temperatures reported each day.

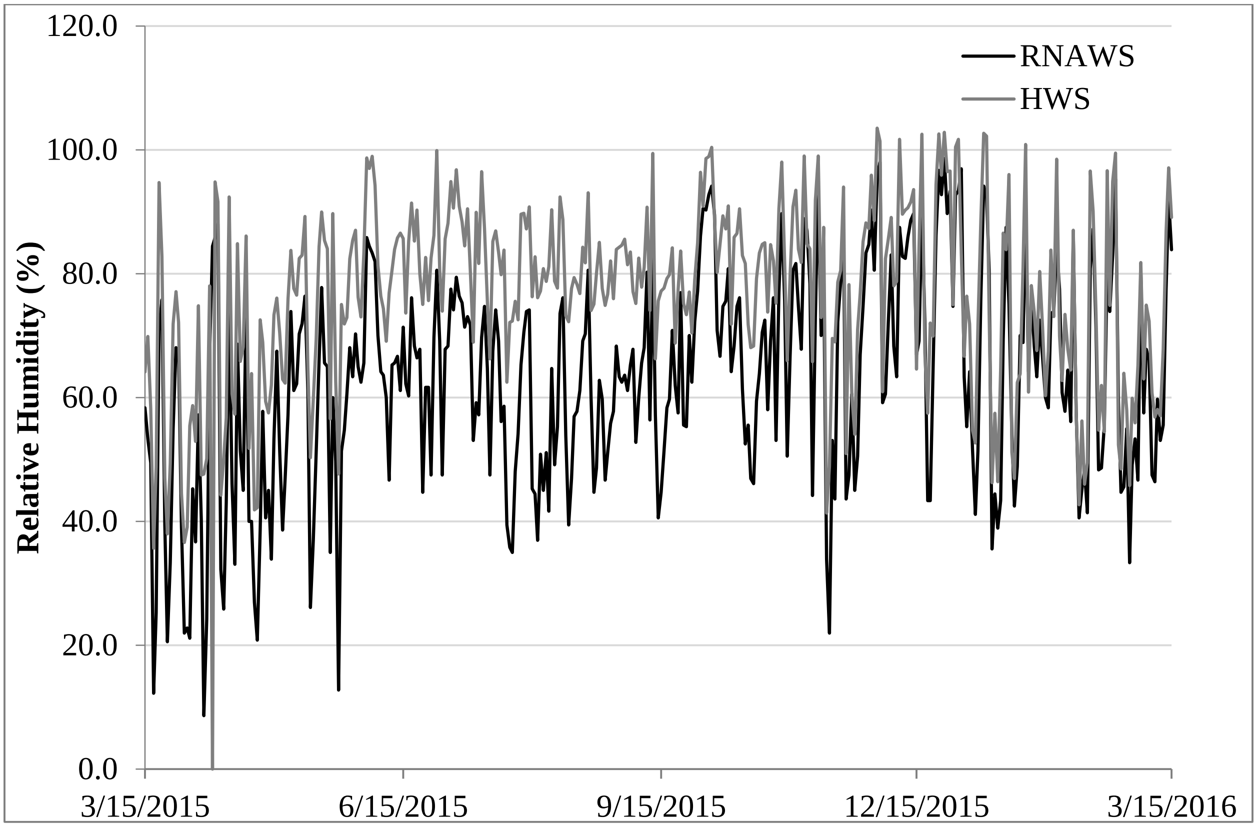


Fig. 20. Daily mean relative humidity RNAWS and HWS. Note: when HWS-reported relative humidity values were greater than 100% (likely instrument error), they were limited to 100% for the purposes of calculating PET.

Kc values were grouped by referring to the plant communities observed by VT at the time the subset of data used to estimate the AET value was collected. The most usable rates came from wells located in the ‘Forested/ Shrub Wetland’ plant community. This community accounted for 129 of the usable AET rates and corresponding Kc estimates. Kc values for Forested/ Shrub Wetland community ranged from 0.35 to 7.30 during the growing season using the RNAWS PET values, with those minimum and maximum Kc values both occurring during September. The Emergent plant community also produced several usable AET rates and corresponding Kc values. The Emergent plant community yielded 46 usable AET rates and corresponding Kc values. Kc values ranged from 0.29 (August) to 2.66 (June) during the growing season at wells in the Emergent plant community group using the RNAWS PET values. The remaining 16 usable AET rates came from well T4A. Wells situated in Forested Non-Wetland plant communities did not yield any usable AET rates.

AET estimates and corresponding Kc values from well T4A were typically much greater than corresponding estimates and rates from other wells that had vegetation classified as Emergent. Kc values derived using the RNAWS PET data and the T4A AET estimates ranged from 0.08 (December) to 7.05 (May). Other authors have reported AET rates that are high relative to the other locations in their sites and have attributed the high rates to the ‘clothesline effect’ (Runyan and Welty, 2010; Hill and Neary, 2007). The ‘clothesline effect’ has been observed at locations with abrupt transitions in vegetative cover and considerable areas where the fetch is oriented such that as the wind blows across an area with a relatively low-lying cover crop into an area with a relatively tall crop resulting in lateral advection. The localized increase in advection creates an isolated area with relatively high AET rates (Allen, 1998). Well T4A is situated at the edge of the emergent wetland and the forested wetland along the northern perimeter of the pond. It is northeast of the variable height outlet, and located directly at the transitional zone occurring at the end of an area with considerable fetch oriented in the direction the wind most commonly blows through the park, from the southwest to the northeast. Due to well T4A’s unique placement and conditions, its AET rates and corresponding Kc values were considered separately from the other AET rates and Kc values. Tables 9 and 10 show the total number of Kc values determined for forested/shrub wetlands and emergent wetlands, respectively, as well as the mean, maximum, minimum, and median Kc values, and the standard deviation of the Kc values for each month as determined by using the RNAWS PET estimates.

For comparison, Table 11 shows the Kc values derived from T4A AET estimates. Again, Kc values derived from well T4A (from 2015, vegetation identified as emergent) were not included in the determination of emergent Kc values which were used to represent all emergent locations within the wetland water budget models. To represent ET in the area immediately surrounding T4A in the Advanced Model, missing monthly Kc values for the area immediately surrounding T4A were adjusted proportionally to the difference in the Kc estimates from T4A and wells occurring in emergent wetlands at Huntley Meadows. T4A yielded one AET estimate during 2014, when the vegetation was considered forested/scrub-shrub, which was 0.72 during the month of October. Tables 12 and 13 show the total number of Kc values determined for forested/scrub shrub wetlands and emergent wetlands, respectively, as well as the mean, maximum, minimum, and median Kc values, and the standard deviation of the Kc values for each month as determined by using the HWS PET estimates.

Table 9
Kc values from forested/shrub wells using RNAWS PET.

	n	Mean	Max.	Min.	Med.	Std. Dev.
Jan	0					
Feb	0					
Mar	0					
Apr	0					
May	20	2.61	4.78	0.84	2.50	1.04
Jun	8	3.11	5.02	1.17	3.23	1.28
Jul	11	3.49	5.64	1.37	3.76	1.41
Aug	29	3.18	5.87	0.51	3.79	1.76
Sep	48	4.00	7.30	0.35	4.66	2.13
Oct	13	3.01	4.71	1.41	2.89	1.08
Nov	0					
Dec	0					
Sum	129					

Table 10
Kc values from emergent wells using RNAWS PET.

	n	Mean	Max.	Min.	Med.	Std. Dev.
Jan	0					
Feb	0					
Mar	0					
Apr	0					
May	22	1.21	2.66	0.32	1.05	0.65
Jun	5	0.50	0.56	0.43	1.11	0.05
Jul	0					
Aug	10	0.99	1.69	0.29	1.02	0.45
Sep	8	0.71	1.37	0.30	0.63	0.33
Oct	1	0.60	0.60	0.60	0.60	
Nov	0					
Dec	0					
Sum	46					

Table 11
Kc values from T4A using RNAWS PET.

	n	Mean	Max.	Min.	Med.	Std. Dev.
Jan	0					
Feb	0					
Mar	0					
Apr	0					
May	11	4.58	7.05	2.42	4.56	1.43
Jun	3	5.36	5.78	4.92	5.37	0.35
Jul	0					
Aug	0					
Sep	0					
Oct	0					
Nov	0					
Dec	1	0.08	0.08	0.08	0.08	
Sum	15					

Table 12
Kc values from forested/shrub wells using HWS PET.

	n	Mean	Max.	Min.	Med.	Std. Dev.
Jan	0					
Feb	0					
Mar	0					
Apr	0					
May	20	2.62	4.90	0.96	2.39	1.01
Jun	8	3.69	6.34	1.27	3.65	1.63
Jul	11	5.87	9.52	1.61	6.95	2.69
Aug	14	5.80	7.93	4.17	5.62	1.17
Sep	20	6.72	8.62	5.62	6.41	0.91
Oct	12	3.35	5.59	2.12	3.40	0.95
Nov	0					
Dec	0					
Sum	85					

Table 13
Kc values from emergent wells using HWS PET.

	n	Mean	Max.	Min.	Med.	Std. Dev.
Jan	0					
Feb	0					
Mar	0					
Apr	0					
May	22	1.25	2.73	0.37	1.20	0.63
Jun	5	0.59	0.70	0.50	1.18	0.09
Jul	0					
Aug	2	1.30	1.52	1.07	1.30	0.31
Sep	0					
Oct	1	0.79	0.79	0.79	0.79	
Nov	0					
Dec	0					
Sum	30					

For months that produced no usable AET values and corresponding Kc estimates, Kc values were populated using values reported for similar plant communities and conditions as close to those at Huntley Meadows as possible. Supplemental Kc values for deciduous forests came from work done by Rao et al. (2011) on modeling PET in forested watersheds in the Southern Appalachians of North Carolina. Their study involved evaluating several different methods for calculating PET by comparing the PET estimator to AET estimates, derived at monthly and annual scales, determined as the difference between measured precipitation and measured streamflow. The Kc values reported in Rao et al. (2011) for FAO-56 Penman-Monteith derived PET estimates for forested non-wetland areas are shown in Table 14, along with supplemental Kc values for the two wetland communities that came from work done by Howes et al. (2015).

Table 14
Kc values from literature. Forested Non-Wetland values are from Rao et al. (2011). Forested/Scrub-Shrub and Emergent Wetland Kc values are from Howes et al. (2015).

	Forested Non-WL	Forested/Shrub	Emergent
Jan	1.10	0.82	0.73
Feb	1.10	0.70	0.66
Mar	1.20	0.65	0.79
Apr	1.20	0.75	0.84
May	1.30	0.81	0.78
Jun	1.30	0.93	1.10
Jul	1.30	1.03	1.16
Aug	1.30	1.06	1.20
Sep	1.30	1.17	0.87
Oct	1.20	1.11	1.13
Nov	1.10	0.94	0.99
Dec	1.10	0.87	0.82

Note: Emergent Kc values reported here are the non-Florida averages from Howes et al. (2015) except for May, June, July, August, and September, when data were available to calculate Kc as the average from settings with long-term freeze cycles, similar to Huntley.

Howes et al. (2015) compiled Kc estimates for numerous vegetation types by examining reported AET estimates for those plant communities from areas throughout the United States. Their work resulted in a repository of Kc estimates that they used to construct historical water budgets for a site in the Central Valley of California to better understand hydrodynamics prior to the arrival of European settlers. Though the Kc estimates reported in the literature are lower during the growing season than those derived from data collected at Huntley Meadows, the Kc values that were missing typically occurred during the winter months, when ET is not as active. Therefore, the non-growing season Kc values in the literature were considered reasonable for use in creating continuous adjusted PET data sets for use in the wetland water budget models. Continuous Kc adjusted PET data sets were developed using median monthly Kc values derived from Huntley AET estimates and RNAWS PET whenever possible. Months that lacked data were supplemented using Kc estimates from the sources described above. Fig. 21 graphs the median monthly Kc values, for each plant community, that were used to generate adjusted PET time series for the wetland water budget models. Error bars on Fig. 21 represent one standard deviation from the mean Kc value determined for a given month.

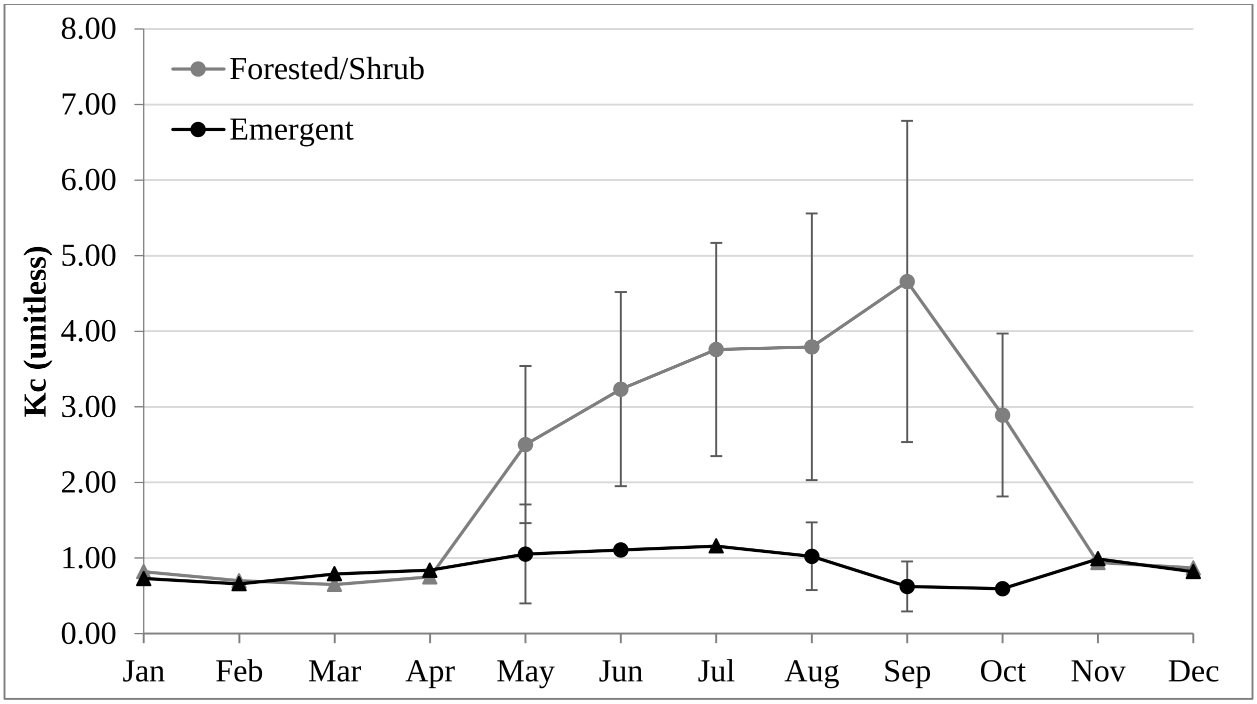


Fig. 21. Graph of median monthly Kc values resulting from AET estimates and RNAWS PET. No wells occurring in forested non-wetland areas yielded usable AET rates or Kc values. Error bars represent one standard deviation from the mean. Triangular points represent values from literature used to construct continuous Kc data sets.

Wetland Water Budget Models

The results from each of the previous sections led to the design of wetland water budget models capable of testing the third hypothesis, which states calibrated computer models of the area can be used to predict changes in the water budget associated with raising the water table and facilitating the redistribution of plant communities. Two types of models were developed in Wetbud to test this hypothesis, Basic (analytical) Models, and Advanced (numerical) Models.

Basic Scenarios

In Wetbud, Basic Models produce monthly hydrographs, as well as monthly totals for each of the inputs and outputs that contributed to the resulting hydrograph (Wetbud User Manual, 2014). To understand the effects of changing the distribution of plant communities through time, predicted monthly head values were compared to the head values observed on the last hour of each month. The model was calibrated using Penman-Monteith PET values derived from the RNAWS weather station packaged with Wetbud and precipitation data from the HWS (when available).

Calibration involved parameterizing each of the inputs and outputs and adjusting surface water-in and groundwater-out values to achieve the highest NSE value derived from comparing observed head to predicted head. The calibrated model surface-in consisted of a combination of the CN method and a constant User Time Series input of 0.4 m/month to account for baseflow in the streams contributing to the northern part of the ponded area. The groundwater-out was set to 0.16 m/month (roughly six inches) to account for groundwater seepage. The calibrated model, which ran from April of 2015 through February of 2016, resulted in a predicted head vs observed head NSE value of 0.89 and a RMSE of 0.06 m.

After calibrating the model, a Validation model was run using the same conditions but with different weather data for a period not in the calibration time window but a time when head data exist. The Validation model ran from April 2014 through April 2015, using unadjusted RNAWS PET, had a resulting NSE value of 0.67 and a RMSE of 0.06 m. While it seems this model configuration was producing good estimates of predicted head, the predicted outflow was greater than that observed on the downstream side of the variable height outlet. When comparing the predicted outflow to the observed outflow for the calibration period, the NSE was 0.02 and the RMSE was 0.23 m. For the validation period, the predicted outflow resulted in a NSE of 0.23 and a RMSE 0.30 m. While the NSE values for both the Calibration and Validation periods indicate the model using unadjusted RNAWS PET performed better than an approximation made by taking the mean of the observed value to make predictions, the relatively low Outflow NSE indicated there was room for improvement and the model was under predicting some form of loss in the system.

To better constrain the amount of water leaving the system, four additional weather data sets were constructed. Each of these data sets used the same precipitation as the Calibration configuration. However, the RNAWS PET values were adjusted using the median monthly Kc values derived from the White's type AET estimates made from the wells located at Huntley Meadows Park. The four additional weather stations tested the effects of uniformly applying the Emergent Kc, the Forested/Shrub Wetland Kc, and the Forested Non-Wetland Kc to the RNAWS Penman-Monteith PET rates, as well as applying an area-weighted Kc value to the RNAWS PET rates. Table 15 shows the median Kc value applied each month for each of the four additional weather station configurations. Table 16 shows the area of each plant community used to calculate the weighted Kc values.

Table 15
Monthly Kc values applied to wetland water budgets. The weighted Kc was only used in the Basic Model.

	Emergent	Forested/Scrub-Shrub	Forested non-WL	Weighted
Jan	0.73	0.82	1.10	0.80
Feb	0.66	0.70	1.10	0.71
Mar	0.79	0.65	1.20	0.75
Apr	0.84	0.75	1.20	0.82
May	1.05	2.50	1.30	1.82
Jun	1.11	3.23	1.30	2.22
Jul	1.16	3.76	1.30	2.51
Aug	1.02	3.79	1.30	2.47
Sep	0.63	4.66	1.30	2.76
Oct	0.60	2.89	1.20	1.82
Nov	0.99	0.94	1.10	0.97
Dec	0.82	0.87	1.10	0.87

Table 16
Basic Model plant community areas for determining weighted Kc values.

Plant Community	Area (ha)	Proportion of model
Emergent	10.76	0.41
Forested/Shrub	13.49	0.52
Forested non-WL	1.89	0.07
Sum	26.14	

To determine which Kc resulted in the best representation of the site, the predicted outflow values, in addition to the predicted head values, were evaluated using the NSE and RMSE parameters. The model was also run using PET estimated using RNAWS data in the Thornthwaite equation, calculated using Wetbud. Table 17 shows the resulting NSE and RMSE values for each of the weather station configurations during the Calibration time period. Table 18 shows the resulting NSE and RMSE values for each of the weather station configurations during the Validation time period.

Table 17
Calibration period NSE and RMSE values resulting from different Basic Model configurations. NSE and RMSE shown for both predicted and observed head values and predicted and observed outflow values.

	Head		Outflow	
Model	NSE	RMSE (m)	NSE	RMSE (m)
Reagan PET	0.89	0.06	0.02	0.23
Thornthwaite PET	0.89	0.07	0.00	0.23
Emergent Kc	0.89	0.06	0.02	0.23
Forested/Shrub WL Kc	-15.81	0.79	0.38	0.18
Forested Non-WL Kc	0.90	0.06	0.15	0.21
Weighted Kc	0.95	0.04	0.40	0.18

Table 18
Validation period NSE and RMSE values resulting from different Basic Model configurations. NSE and RMSE shown for both predicted and observed head values and predicted and observed outflow values.

	Head		Outflow	
Model	NSE	RMSE (m)	NSE	RMSE (m)
Reagan PET	0.67	0.06	0.23	0.29
Thornthwaite PET	0.67	0.06	0.32	0.27
Emergent Kc	0.67	0.06	0.26	0.29
Forested/Shrub WL Kc	-21.88	0.46	0.22	0.30
Forested Non-WL Kc	0.67	0.06	0.25	0.29
Weighted Kc	0.64	0.06	0.42	0.25

Of the six weather station configurations, the weighted Kc data set yielded the highest NSE (0.95) and lowest RMSE (0.04 m) for predicted head values during the Calibration period. The weighted Kc data set also produced the highest NSE (0.40) and lowest RMSE (0.18 m) for the predicted outflow during the Calibration period. When applied uniformly, the forested/shrub wetland Kc data set yielded the lowest NSE (-15.81) and the largest RMSE (0.79 m) for predicted head values. However, the NSE and RMSE values for the forested/shrub wetland Kc predicted outflow (0.38 and 0.18 m, respectively) were actually the second best of the six weather station configurations for the Calibration period. The Thornthwaite unadjusted PET values yielded the lowest NSE (0.00) and a RMSE of 0.23 m for predicted outflow fluxes during the Calibration period.

During the Validation period, the RNAWS unadjusted PET, the Thornthwaite unadjusted, the emergent Kc, and the forested non-wetland Kc weather stations yielded identical NSE (0.67) and RMSE (0.06 m) values for the predicted heads. The weighted Kc predicted heads were only slightly different from the RNAWS unadjusted, emergent Kc, and forested non-wetland Kc weather data sets, resulting in an NSE of 0.64 and RMSE of 0.06 m. The forested/shrub wetland Kc data set predicted head values that were significantly lower during the growing season than the other data sets, resulting in a NSE of -21.88 and a RMSE of 0.46 m. Despite producing identical NSE and RMSE values for predicted heads, the RNAWS unadjusted, Thornthwaite unadjusted, emergent Kc, and forested non-wetland Kc weather data sets yielded different NSE and RMSE for their respective predicted outflow fluxes. Of the six possible weather data set configurations, the weighted Kc data set had the best NSE (0.42) and RMSE (0.25 m) for its predicted outflow fluxes. The weather data set that produced the lowest NSE and largest RMSE was the forested/shrub wetland Kc data set, which yielded a NSE of 0.22 and a RMSE of 0.30 m.

Fig. 22 and 23 show the graphs of the predicted and observed head, and the predicted and observed outflow, respectively, for the calibration period using the weighted Kc approach. Fig. 24 and 25 show the graphs of the predicted and observed head, and the predicted and observed outflow, respectively, for the validation period using the weighted Kc approach. Note that in Wetbud Outflow refers to the head lost to Outflow. To determine the volume of water leaving the model, one would need to multiply the head lost to Outflow by the model area.

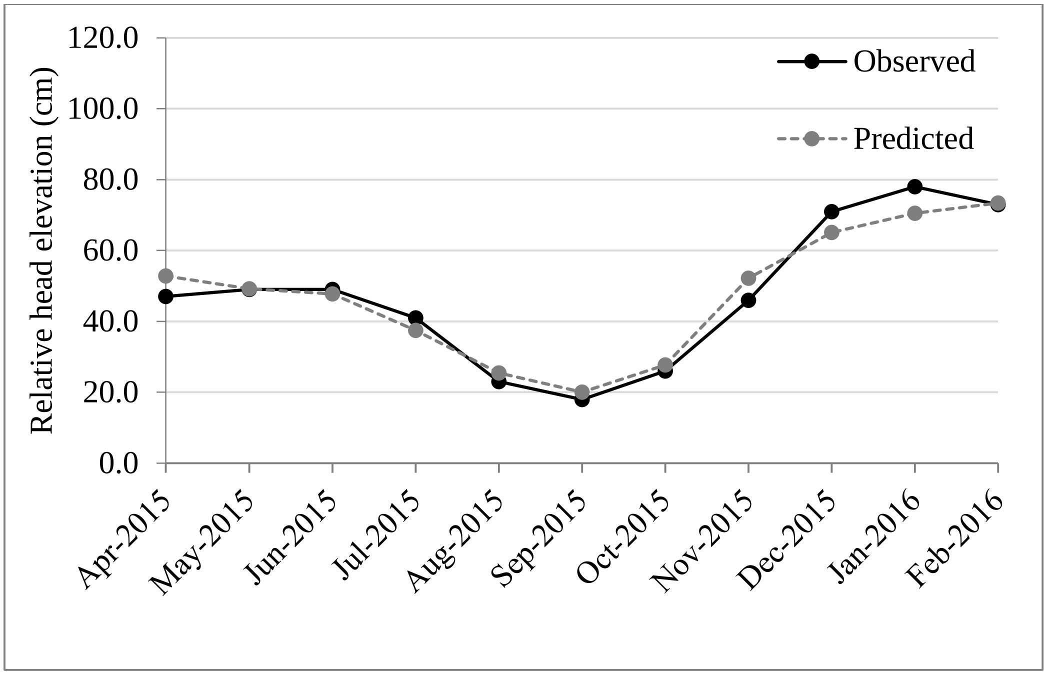


Fig. 22. Basic Model relative head predictions using weighted Kc adjusted PET during Calibration period. Head is relative to wetland bottom elevation (9.66 m). NSE = 0.95, RMSE = 0.04 m.

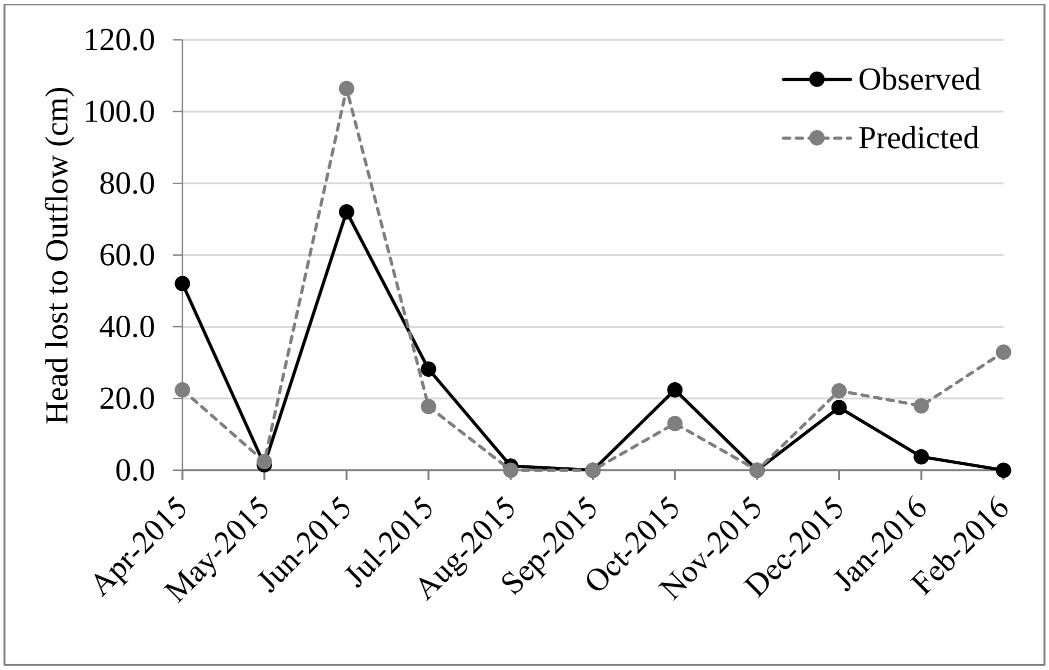


Fig. 23. Basic Model Outflow predictions using weighted Kc adjusted PET during Calibration period. NSE = 0.40, RMSE = 0.18 m.

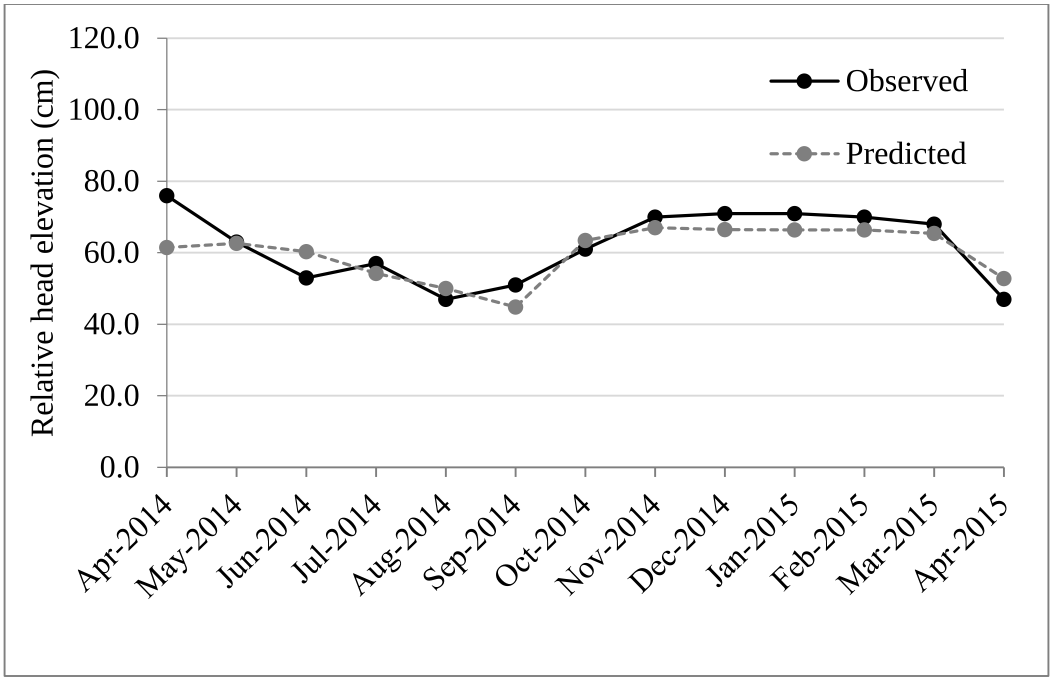


Fig. 24. Basic Model relative head predictions using weighted Kc adjusted PET during Validation period. Head is relative to wetland bottom elevation (9.66 m). NSE = 0.64, RMSE = 0.06 m.

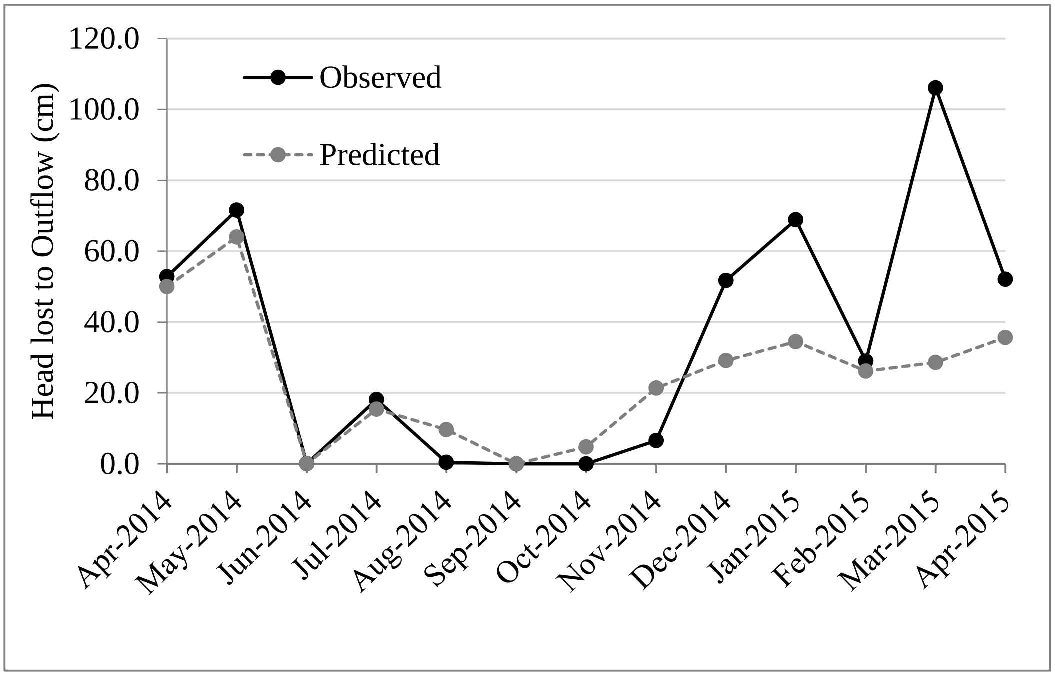


Fig. 25. Basic Model Outflow predictions using weighted Kc adjusted PET during Validation period. NSE = 0.42, RMSE = 0.25 m.

While the NSE value for the weighted Kc data set derived outflow values was nearly twice that of the worst performing weather data set, the RMSE was only a few centimeters better than the worst performing weather data set. These NSE and RMSE values indicated that while a weighted Kc value did a better job at predicting the outflow flux than any other ET estimator, there was still about 25 cm of possible error each month in that prediction during the Validation period. The relatively large error that occurs during the Validation period was a result of the model underpredicting the outflow during December of 2014, and January and March of 2015 (as seen in Figure 24). It is possible that there were isolated rain events that occurred at Huntley Meadows during these times that did not occur at the RNAWS, or, there was snowfall and snowmelt, not modeled by Wetbud, that resulted in an actual surface-water-in value that was larger than that predicted by that model. Nonetheless, the improvement seen in the model resulting from utilizing a weighted Kc value suggests that at this scale the nature and distribution of plant communities within the model strongly affects the model output. To further test this notion, multiple distributions of plant communities were applied to three-dimensional, finite difference models, each a different Advanced Scenario in Wetbud, and varied through time.

Advanced Scenarios

Four scenarios were used to understand the effects of employing variations in crop coefficients to model the redistribution of plant communities in wetland groundwater flow models: (1) the Calibration Model with Kc dependent on observed plant communities, (2) a Validation Model with Kc dependent on observed plant communities for a different time period, (3) a Test Configuration which used the weather time series from the Validation model and the plant community distribution from the Calibration Model, and (4) a Control Model that was calibrated with a uniform ET zone not adjusted using any Kc values. This combination of model configurations, coupled with the level of complexity employed in each of them, also provided an opportunity to test Wetbud's capabilities and to work with the development team to improve the user interface and functionality of Wetbud.

Calibrating scenario 1, the Calibration Model, involved adjusting the initial head value for each layer, the ET extinction depth, the magnitude of the constant conductance value used at the variable height outlet weir, and the hydraulic conductivity, specific storage, and specific yield values for each of the eight soil or vegetation zones used in the model. After trying eighty-seven different configurations, it was determined that the eighty-fourth configuration would be the best for representing the site. The final values for each of the calibrated variables used in the model are reported in Table 19. The Ksat and Sy values determined through model calibration did result in values within the same orders of magnitude as the slug tests for the Ksat values, and within the same range of Sy values determined by the water table response to precipitation and pressure plate techniques. Note that the calibrated initial head value for both layers was 10.4 m, the ET extinction depth that was uniformly applied was 3 m, and the variable height outlet drain conductance was held constant at 1.93 m^2 s^{-1}.

Table 19
Calibrated values for zones used in Advanced Scenarios with multiple ET Zones.

Zone	Material	Ksat (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.15
2	Loam 2	1.00E-05	1.00E-03	0.10
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.30
4	Sandy Loam	1.00E-05	1.00E-03	0.20
5	Vegetation - Forested	4.50E+01	9.80E-01	0.98
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.90
7	Open Water	6.40E+01	9.90E-01	0.99
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.35

Configuration eighty-four resulted in NSE values ranging from -0.23 through 0.86 for predicted head values at the fifteen calibration points, with a median NSE value of 0.54. In addition to the NSE and RMSE values, the predicted and observed water table elevation ranges were calculated. Those values for each of the wells in the Calibration Model, along with the number of days when the observed water table elevation was within the range of the monitoring equipment, are shown in Table 20. It is important to note that, while predicted heads for times when there was no observed head data were plotted in the hydrograph figures, they were not used for calculating NSE and RMSE model evaluation statistics. Oftentimes, the water table would drop below the transect well transducers, so the Observed Range would be less than the actual water table range.

Table 20
Advanced Scenarios Calibration Model evaluation statistics.

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.54	0.45	1.96	2.39
ODU_ET2	367	0.22	0.57	0.50	2.26
Outlet	367	0.86	0.08	0.61	0.86
T1A	273	0.54	0.11	0.94	0.73
T1B	367	0.74	0.19	1.67	1.02
T2A	228	0.82	0.08	0.57	0.83
T2B	190	0.41	0.22	1.25	1.23
T2C	226	0.77	0.21	2.13	1.40
T3P	340	-0.23	0.20	1.34	0.98
T3A	319	0.27	0.16	1.44	0.69
T3B	200	0.49	0.25	1.75	1.05
T3C	225	0.69	0.28	1.81	1.51
T4A	263	0.22	0.20	1.80	0.83
T4B	176	0.01	0.37	2.33	1.28
T4C	242	0.55	0.37	2.41	1.77
	Median	0.54	0.21		

The only negative NSE value (-0.23) resulting from configuration eighty-four was at well T3P (Fig. 26), which is located in the ponded area of the park, a few meters north of an old channel which is approximately 1.5 m wide and 0.60 m deep. When the model predicts water levels above the ground surface at this location it does so with great accuracy. However, when the water levels drop below the ground surface the model underpredicts water levels by approximately 0.20 m. There was a period during the growing season when the water table dropped below the level of the transducer, though the lowest predicted head value was below the lowest observed head value for the corresponding time steps and the predicted rebound in the water table closely corresponds to the observed rebound at T3P. It is possible that the 15.24 x 15.24 m cell size is too large to accurately represent the influence of the channel between wells T3P and T3A, as T3A is a few meters south of the old channel located in the adjacent cell in the model.

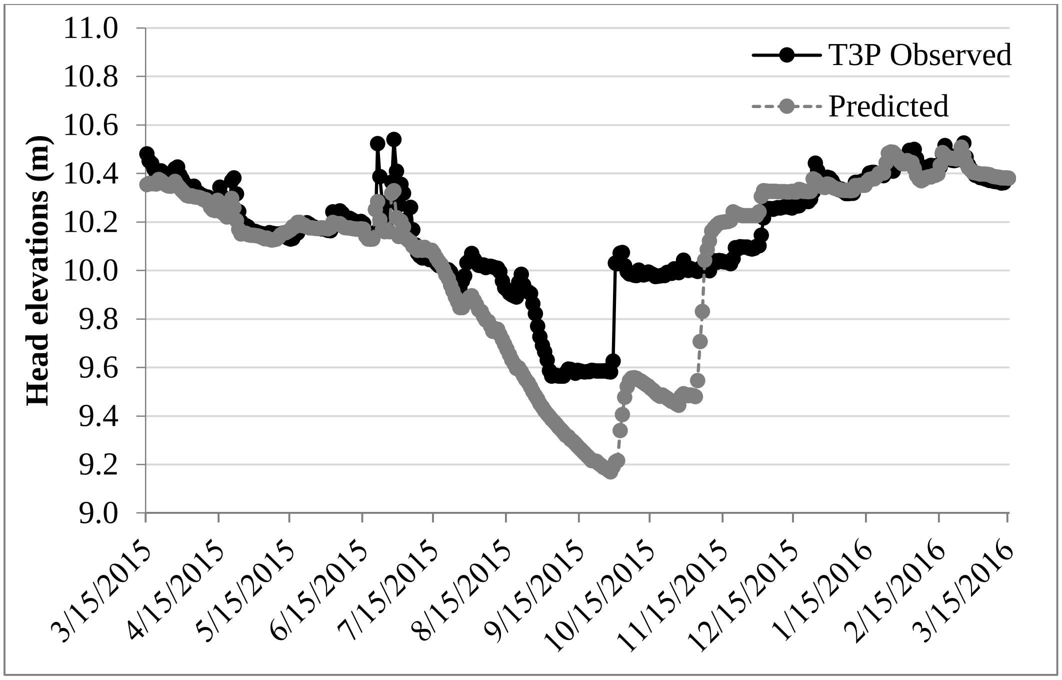


Fig. 26. Advanced Scenarios Calibration Model predicted head values at T3P. NSE = -0.23, RMSE = 0.20 m. The model predicted head values at this location with relatively small RMSE despite having a negative NSE value.

The largest RMSE value resulting from configuration eighty-four was 0.57 m, reported at ODU_ET2 (Fig. 27), while the smallest was 0.08 m, reported at both the Outlet (Fig. 28) and well T2A (Fig. 29). We suspect that ODU_ET2's close proximity to the model boundary (2 cells from boundary) and close proximity to the cell used to add water from the two adjoining sub basins (2 cells from that location as well) affected the ability of the cell located at ODU_ET2 to predict realistic head levels. While the RMSE was larger at ODU_ET2 (0.57 m) than it was a T3P (0.20 m), the NSE at ODU_ET2 (0.22) was better than that reported at T3P (-0.23). These differences indicate that while one evaluation value or the other might be useful for assessing the model's ability to predict head levels at a given well, multiple evaluation values should be considered when assessing the model as a whole. Given the median RMSE (0.21 m, 0.69 ft) and median NSE (0.54) values, the relatively small RMSE at the A location wells, and that the model was predicting seasonal changes in horizontal flow gradients, the model was considered calibrated.

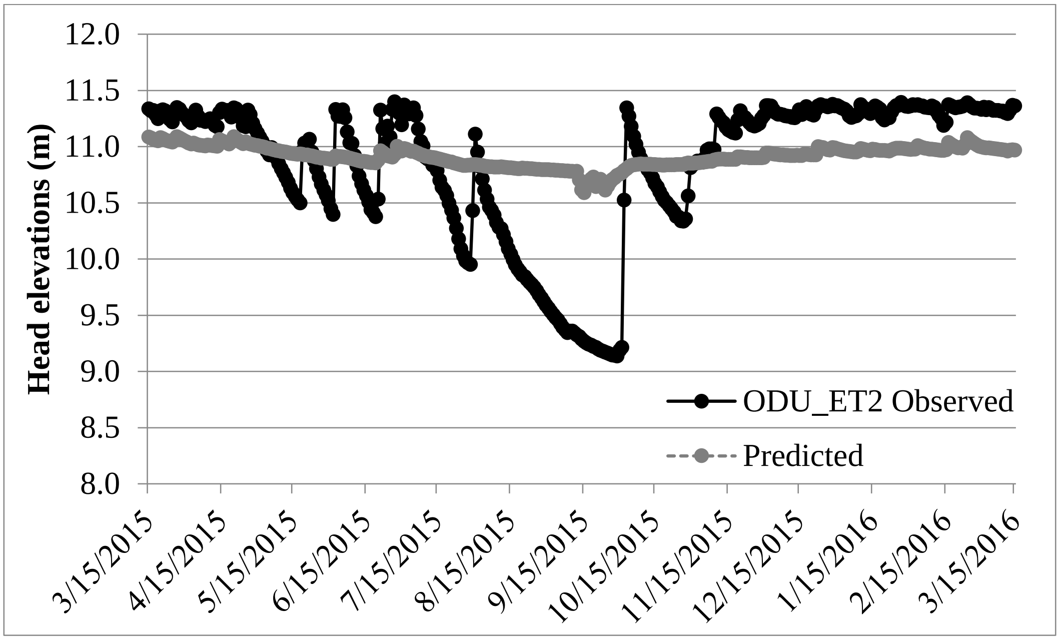


Fig. 27. Advanced Scenarios Calibration Model predicted head values at ODU_ET2. NSE = 0.22, RMSE = 0.57 m. At this site the model performed least effectively.

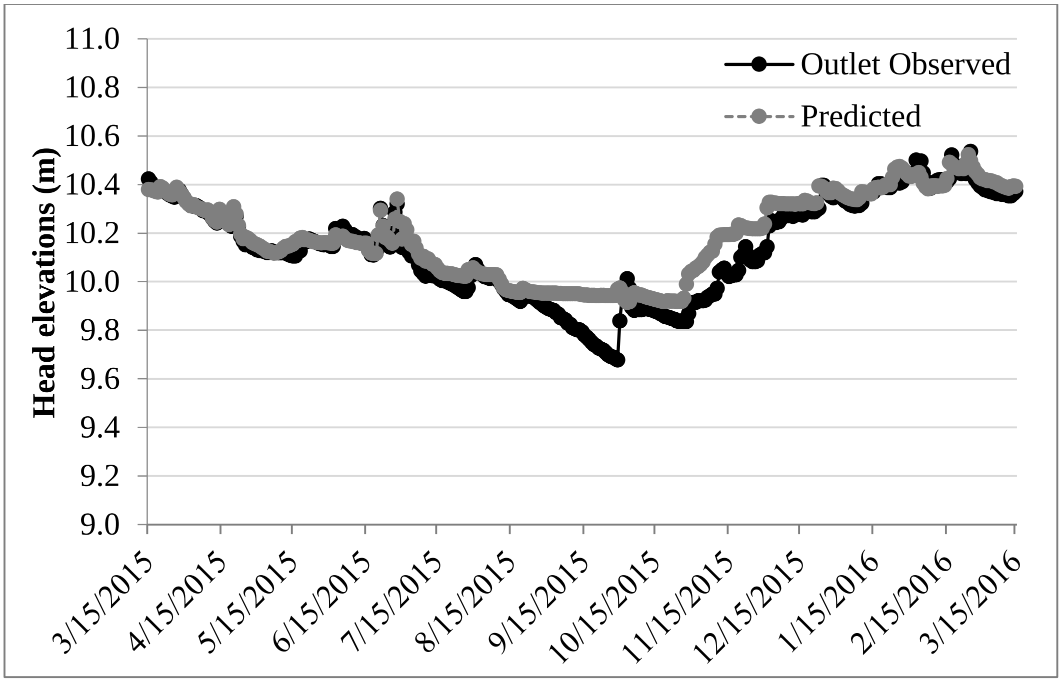


Fig. 28. Advanced Scenarios Calibration Model predicted head values at the Outlet. NSE = 0.86, RMSE = 0.08 m. This is one of two sites where the model was the most effective.

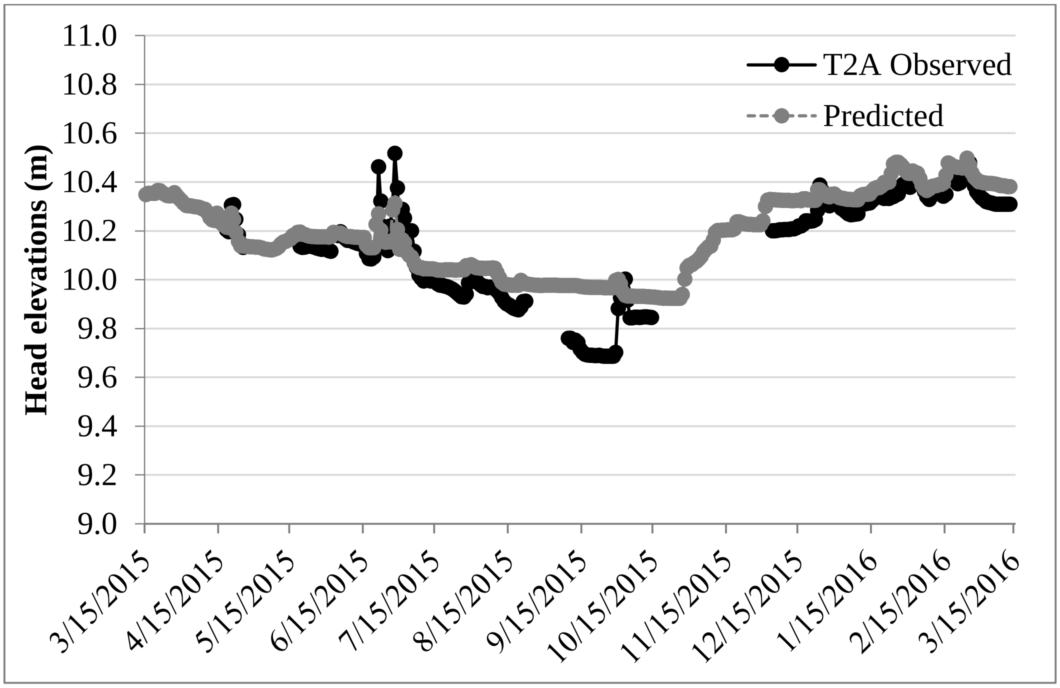


Fig. 29. Advanced Scenarios Calibration Model predicted head values at T2A. NSE = 0.82, RMSE = 0.08 m. This is one of two sites where the model was the most effective.

Zone characteristics were only adjusted in the Calibration Model. Once the calibration configuration had been established, a second model, the Validation Model, was run to ensure the configuration was capable of accurately predicting head levels during a time period other than the one used to calibrate each of the parameters in the model. The Validation Model used all of the same parameter values from configuration eighty-four. However, the weather data came from observed values from 3/12/2014 – 12/31/2014 and the extents of the each of the ET zones used to represent the plant communities were adjusted, based on observations made by Sara Klopf (VT), to reflect the distribution appropriate to the time series used in the Validation Model. To adjust the extents of the ET zones, each well was assigned a community; community boundaries were drawn along corresponding 6 inch (0.15 m) contour lines on a map provided by WSSI. For comparison, Fig. 30 shows the distribution of ET zones used in the Calibration Model in Wetbud, while Fig. 31 shows the distribution of ET zones used in the Validation Model in Wetbud. Note that both figures focus on the area around the pond. Table 21 lists the ET Zone assignments that correspond to the vegetation distributions shown in Fig. 30 and Fig. 31. These assignments represent how RNAWS PET was adjusted using Kc values to compensate for the observed spatial differences in ET.

Table 21
ET Zone plant communities for Advanced Scenarios.

Zone	ET Community
21	Emergent Wetlands
22	Forest/Shrub Wetlands
23	Forested Non-Wetlands
24	Clothesline Effect Area

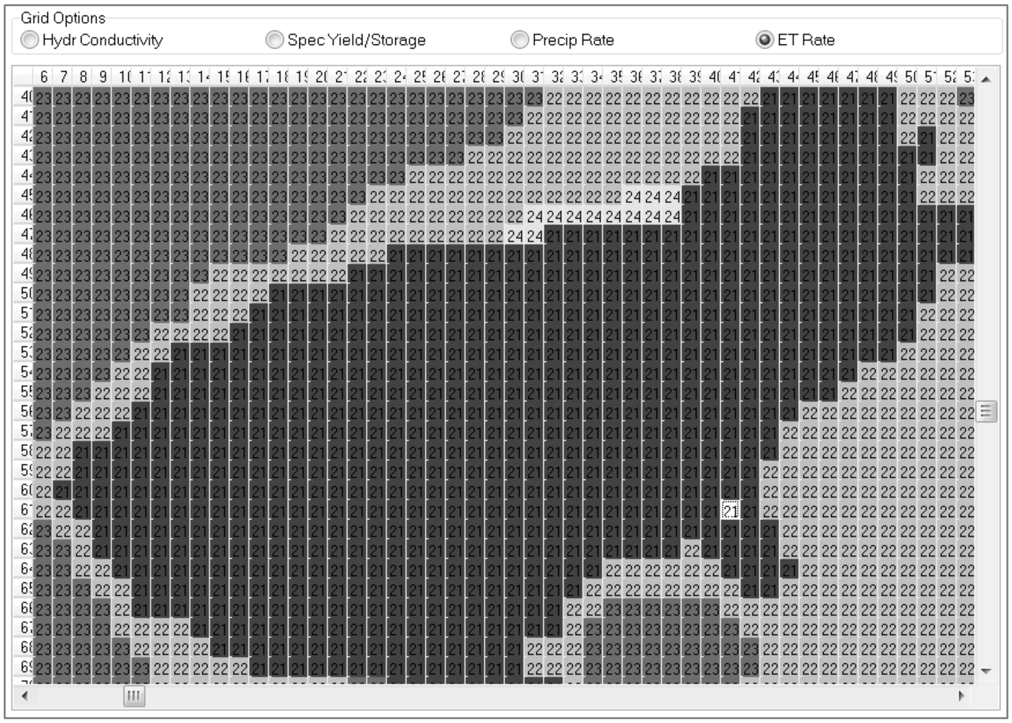


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Fig. 30. Advanced Scenarios Calibration times series ET Zone distribution. Screenshot from Wetbud grid interface, and the location of well T3P is highlighted white for reference. Each cell in the model is equal to 15.24 m by 15.24 m. Zone 21 is shown in darkest gray.

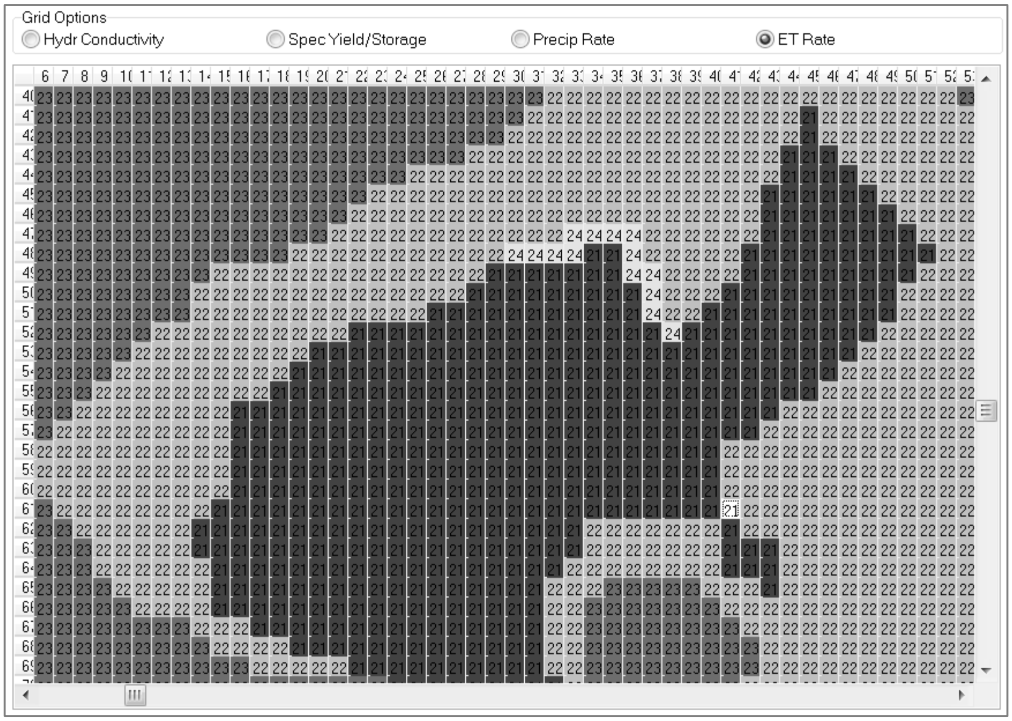

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Fig. 31. Advanced Scenarios Validation time series ET Zone distribution. Screenshot from Wetbud grid interface, and the location of well T3P is highlighted white for reference. Each cell in the model is equal to 15.24 m by 15.24 m.

The Validation Model resulted in NSE values ranging from -0.96 (at well T3P, RMSE = 0.11 m) through 0.94 (at well T4C, RMSE = 0.16 m) for predicted head values at the fifteen calibration points, with a median NSE value of 0.33. While the NSE values had a greater range and the median NSE value was lower for the Validation Model, the median RMSE was smaller at 0.17 m (0.56 ft) compared to 0.21 m for the Calibration Model. The range of RMSE values for the Validation Model was from 0.89 m, at ODU_ET2, down to 0.06 m, at the Outlet. For a full summary of the evaluation statistics resulting from the Validation Model see Table 22.

Table 22
Advanced Scenarios Validation Model evaluation statistics.

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	295	0.33	0.56	2.05	2.54
ODU_ET2	132	-0.37	0.89	1.00	2.00
Outlet	295	0.60	0.06	0.40	0.54
T1A	295	0.01	0.09	0.49	0.43
T1B	295	-0.12	0.33	1.29	1.04
T2A	289	0.12	0.07	0.37	0.37
T2B	252	-0.30	0.37	0.44	1.22
T2C	252	0.83	0.17	1.90	1.47
T3P	240	-0.96	0.11	0.44	0.37
T3A	295	0.41	0.08	0.48	0.49
T3B	116	0.26	0.33	1.23	1.05
T3C	104	0.54	0.35	1.73	1.63
T4A	234	0.77	0.07	0.69	0.82
T4B	105	0.71	0.24	1.89	1.39
T4C	140	0.94	0.16	2.32	1.75
	Median	0.33	0.17		

Even in the Validation Model, T3P yielded the lowest NSE (-0.96). However, the RMSE was more than acceptable at only 0.11 m. Examination of T3P's hydrograph from the Validation Model (Fig. 32) indicates that the model typically overpredicts water levels at this location by approximately 0.15 m. It is possible that the channel between T3P and T3A, which was too small to show up in the model grid representation, affected water level predictions at T3P and T3A in the Validation Model as well. If the channel were not present, the volume of water that existed in it would have been displaced evenly throughout the cell, effectively raising the water levels within the cell a few centimeters as is seen in the predicted head elevations.

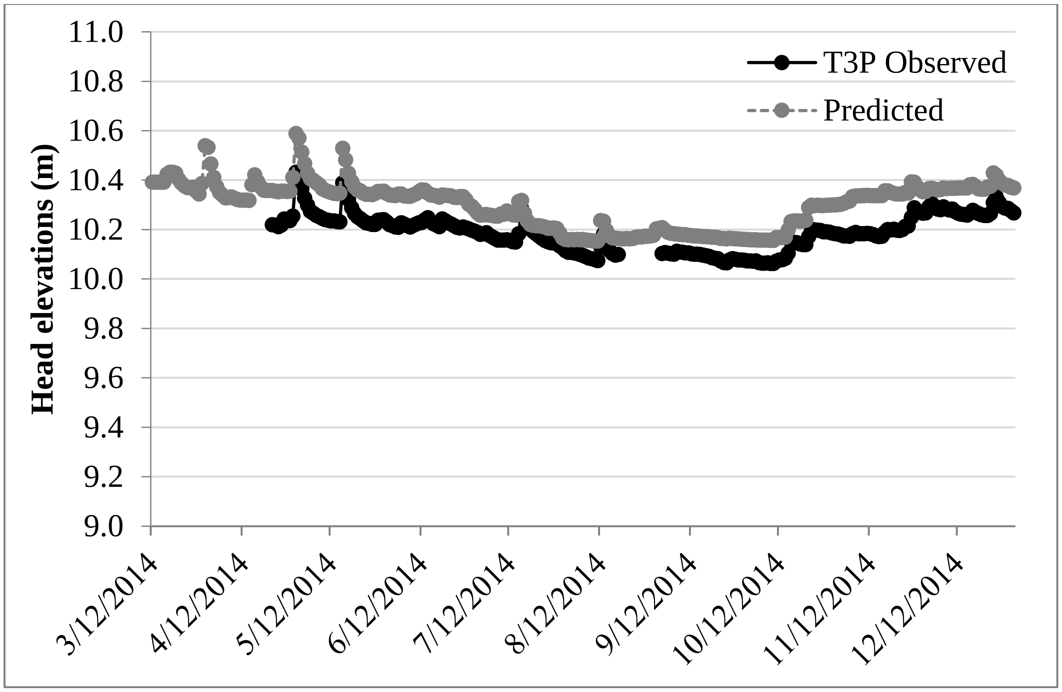

Fig. 32. Advanced Scenarios Validation Model predicted head values at T3P. NSE = -0.96, RMSE = 0.11 m.

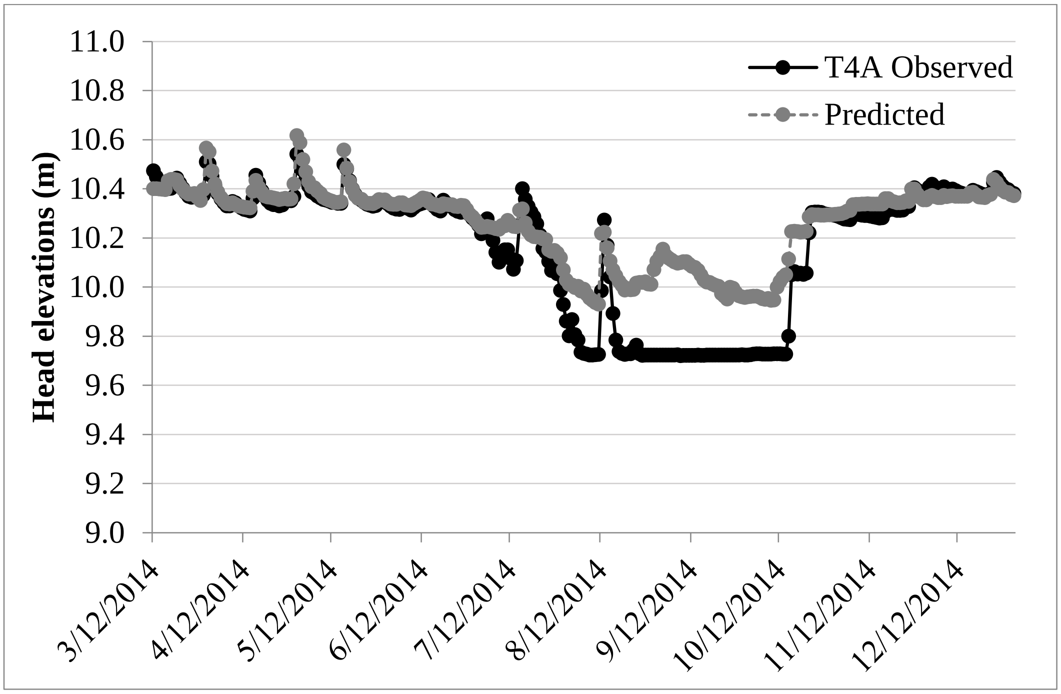

Fig. 33. Advanced Scenarios Validation Model predicted head values at T4A. NSE = 0.77, RMSE = 0.07 m.

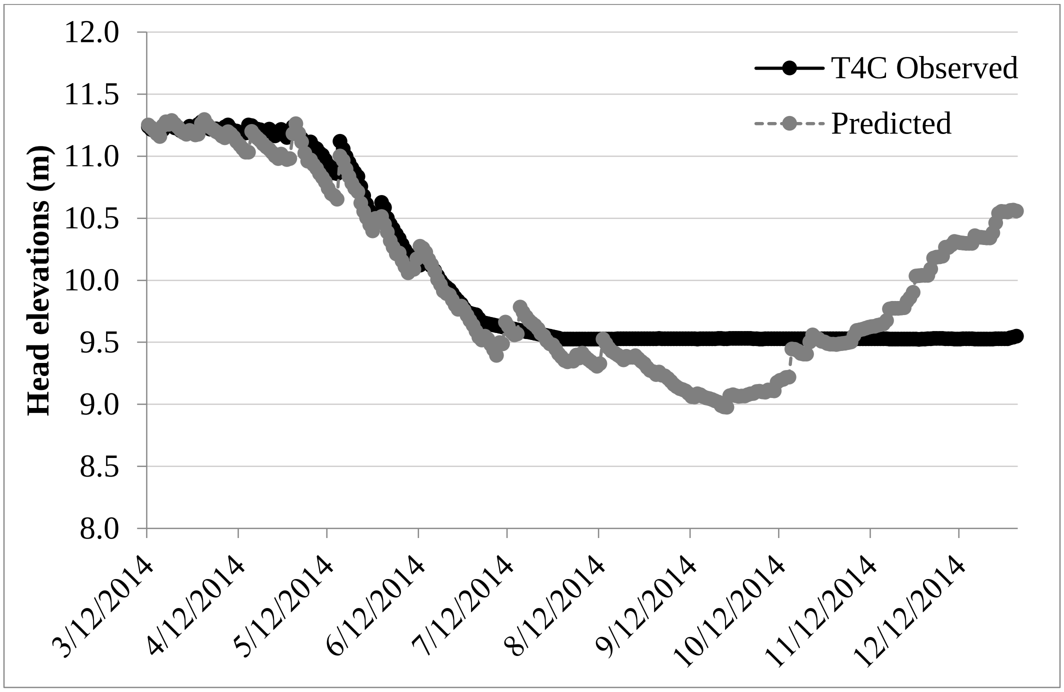

Fig. 34. Advanced Scenarios Validation Model predicted head values at T4C. NSE = 0.94, RMSE = 0.16 m.

Overall, even though the Validation Model did not perform as well as the Calibration Model, it still produced acceptable predicted water table elevations. Additionally, the RMSE values at the A location wells remained small, and the model did predict a change in gradient that corresponded to the observed change in gradient and groundwater flow direction. The change in gradient was most evident when examining the hydrographs from wells T4A and T4C (Fig. 33 and Fig. 34, respectively). At the start of the model period, mid-March, the water levels were higher at T4C than they were at T4A. As spring set in and ET increased, the water levels at T4C dropped below those at T4A. The water levels dropped at T4A as well, although they were better maintained by the ponded area immediately adjacent to T4A. Additionally, the predicted water levels rebounded in the fall while the observed water levels did not. It could be that while the modeled ET was capable of reversing the flow gradients, the model was not drawing water levels down far enough; therefore, the model recovered more quickly than the observed water levels. Regardless, the Validation Model NSE and RMSE values, coupled with the model's confirmed ability to predict reversals in flow gradients, indicated the Calibration configuration was acceptable and the model could be used to evaluate the effects of redistributing plant communities.

After validating the model configuration, a Test Configuration model was developed to determine the effects of facilitating the redistribution of plant communities by changing the hydrology of the area. This process was modeled by varying the extents of the ET zones, to represent a distribution of plant communities that differed from the observed distribution of plant communities for the time period used in the model. This model used the Validation Model weather data, for 3/12/2014 – 12/31/2014, with the ET zone distribution from the Calibration Model, which corresponds to vegetation observed at each of the wells during 3/15/2015 –

3/15/2016. The Test Configuration yielded NSE values ranging from -1.25 (T3P, RMSE = 0.11 m) to 0.94 (T4C, RMSE = 0.16 m), with a median NSE value of 0.25. The median RMSE was the same as the Validation Model, at 0.17 m. RMSE values for the Test Configuration ranged from 0.89 m at ODU_ET2 to 0.06 m at the Outlet, just as they did in the Validation Model. Overall, the Test Configuration output was not significantly different from the Validation Model output as is evident in the hydrograph for T3P resulting from the Test Configuration (Fig. 35). Again, however, despite having the lowest NSE value, the RMSE for T3P was exceptional (0.11 m). The Test Configuration evaluation statistics, Table 23, varied little from the Validation Model evaluation statistics. The lack of difference between the Validation Model output and the Test Configuration output suggests large changes in the extent of each plant community do not strongly correlate to changes in model output

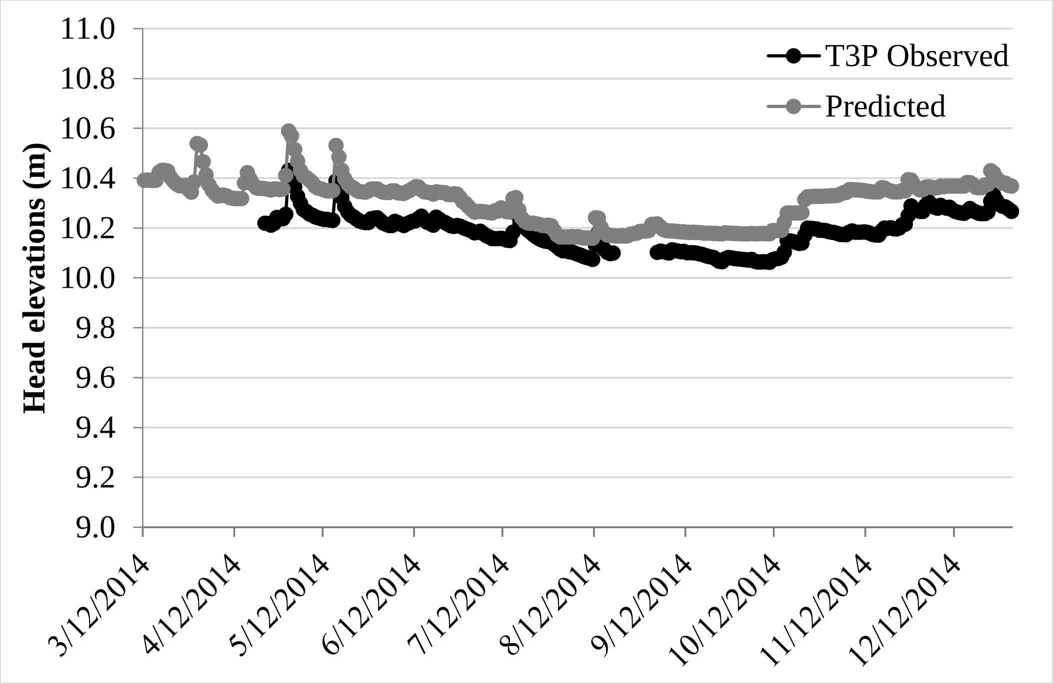

Fig. 35. Advanced Scenarios Test Configuration predicted head values at T3P. NSE = -1.25, RMSE = 0.11 m.

Table 23
Advanced Scenarios Test Configuration evaluation statistics.

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	295	0.33	0.56	2.05	2.54
ODU_ET2	132	-0.38	0.89	1.00	2.00
Outlet	295	0.58	0.06	0.41	0.54
T1A	295	-0.16	0.09	0.45	0.43
T1B	295	0.09	0.30	1.37	1.04
T2A	289	-0.03	0.08	0.37	0.37
T2B	252	-0.28	0.37	0.46	1.22
T2C	252	0.84	0.17	1.93	1.47
T3P	240	-1.25	0.11	0.43	0.37
T3A	295	0.25	0.09	0.46	0.49
T3B	116	0.22	0.33	1.11	1.05
T3C	104	0.62	0.31	1.75	1.63
T4A	234	0.71	0.08	0.69	0.82
T4B	105	0.70	0.24	1.87	1.39
T4C	140	0.94	0.16	2.32	1.75
	Median	0.25	0.17		

To better constrain the effects of using a model that employs multiple Kc adjusted ET zones compared to a traditional model that uses a uniform ET zone with unadjusted Penman-Monteith derived PET estimates, a Control Model was built and calibrated using PET estimates from the RNAWS. The Control Model ran from 3/15/2015 – 3/15/2016. Sixty-one different configurations were attempted before settling on the Control Model calibrated configuration, configuration sixty-two. The final initial head used in both layers was 10.4 m, the ET extinction depth that was uniformly applied was 4 m, and the variable height outlet weir drain conductance was held constant at 2.97 $m^2 s^{-1}$. Calibrated hydraulic conductivity, specific storage, and specific yield values for the Control Model are reported in Table 24. The Control Model produced NSE values ranging from -0.44 (T4B) to 0.83 (at the Outlet), with a median NSE value of 0.33. The median RMSE was greater than any other configuration, at 0.31 m. RMSE values for the

Control Model ranged from 0.62 m at ODU_ET2 to 0.09 m at the Outlet. For a full summary of the evaluation statistics resulting from the Control Model see Table 25.

Table 24
Calibrated values for zones used in Control Model.

Zone	Material	Ksat (m/s)	Ss	Sy
1	Loam	8.00E-06	1.00E-03	0.15
2	Loam 2	5.00E-06	1.00E-03	0.1
3	Interbedded Clay, Silt, and Sand	3.00E-06	1.00E-03	0.1
4	Sandy Loam	1.00E-03	1.00E-03	0.1
5	Vegetation - Forested	6.00E+00	9.80E-01	0.98
6	Vegetation - Scrub Shrub	4.60E+00	6.00E-01	0.6
7	Open Water	8.00E+00	9.80E-01	0.98

Table 25
Advanced Scenarios Control Model evaluation statistics.

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.46	0.49	1.87	2.39
ODU_ET2	367	0.07	0.62	0.35	2.26
Outlet	367	0.83	0.09	0.58	0.86
T1A	273	0.43	0.12	1.04	0.73
T1B	367	0.22	0.34	1.64	1.02
T2A	228	0.80	0.08	0.57	0.83
T2B	190	0.20	0.26	0.90	1.23
T2C	226	0.33	0.36	1.62	1.40
T3P	340	0.74	0.09	1.20	0.98
T3A	319	0.38	0.15	1.19	0.69
T3B	200	0.20	0.31	1.41	1.05
T3C	225	0.33	0.41	1.76	1.51
T4A	263	0.69	0.13	1.42	0.83
T4B	176	-0.44	0.44	1.63	1.28
T4C	242	0.15	0.51	1.61	1.77
	Median	0.33	0.31		

The Control Model calibration configuration resulted in slower hydraulic conductivity rates and lower specific yield values than those used in Calibration Model that referenced multiple ET zones. These results indicate that one could arrive at what some might consider to be an acceptable solution without employing multiple ET zones; however, the magnitudes of the calibrated parameters would be different in order to compensate for fluctuations attributed to variation in ET. In addition, it is likely that the median RMSE would be greater, and the median NSE would be lower, than a solution derived from a configuration that employs multiple ET zones.

To summarize, the Calibration Model was the best performing of the four Advanced Scenarios developed for this study. The Validation Model, which used the same hydraulic conductivity, specific storage, and specific yield values as the Calibration Model, but a different weather data set and vegetation distribution appropriate to the time period, yielded acceptable results. The results of the Validation Model indicated the calibration process was successful and the model could be used to evaluate the effects of redistribution plant communities. The Test Configuration, which used the Validation Model weather data and the Calibration Model ET Zone distribution, was meant to represent a change to the anticipated distribution of plant communities associated with a change in hydrology. This model was considered a reasonable representation as the extent of the emergent wetland ET Zone was much greater in the Calibration Model than the Validation Model, as would be expected when increasing the water table elevation and pond elevation. Much to our surprise, the Test Configuration model evaluation statistics were not significantly different from the Validation Model evaluation statistics, suggesting ET Zones had less impact than we might have thought. To verify that there would be a difference in model output resulting from the incorporation of multiple ET Zones, a

Control Model was built without multiple ET Zones. The Control Model was built, as most models are, with a uniform ET rate derived from unadjusted Penman-Monteith based PET estimates. The Control Model calibration process resulted in NSE and RMSE values that many might consider acceptable for modeling a large wetland. However, the calibrated ET extinction depth, hydraulic conductivity rates, and specific yield values had to be adjusted to make up for the water table fluctuations resulting from a model that includes multiple ET zones. For reference, the median NSE and RMSE values for each of the Advanced Scenario configurations can be seen in Table 26.

Table 26
Advanced Scenarios median NSE and RMSE.

Configuration	Median NSE	Median RMSE (m)
Calibration Model	0.54	0.21
Validation Model	0.33	0.17
Test Configuration	0.25	0.17
Control Model	0.33	0.31

CHAPTER 4

DISCUSSION AND CONCLUSIONS

The results reveal several insights into the dynamics of wetlands within the park and contribute to the understanding of the dynamics of expanded wetlands as well.

Effects of Stratigraphy

The first hypothesis tested was that stratigraphy affects the distribution of water throughout the site and influences the location of wetlands. Drake and others' (1979) geologic map of the region indicated that Hybla Valley, in which Huntley Meadows Parks is located, appears as a U-shaped deposit of the Shirley Formation bound by the Potomac Formation. The Potomac (poorly consolidated sands, silts, and clays) is unconformably overlain by the Shirley, which is a fining upward sequence that grades from gravelly sand at its base to fine sand that is capped by clayey silt, or clayey, silty fine-sand (Johnson and Berquist, 1989). In northern Virginia the Shirley usually was deposited at a lower elevation than the top of the surrounding Potomac formation. Fleming (2008) suggested the Shirley deposits accumulated in an abandoned meander of the Potomac River.

The distribution of soils within the park is consistent with the hypothesis of an abandoned meander. The majority of the park is carpeted by the Elkton silt loam, an eolian silt loam overlying loamy alluvium or marine sediments, or the Gunston silt loam, which is a silt loam derived from marine sediments. These silt loams are interfingered with the Mattapex loam, which has been described as a moderately well drained eolian silt loam underlain by fluviomarine sediments (WSS). The lowest portions of the park consist of the Hatboro silt loam, a loamy alluvium eroded from schist, granite, and gneiss parent material. The fluctuations in sea level and climate, as postulated by Litwin et al. (2010) after examining pollen assemblages from the Hybla Cores, would have provided the oscillations in climatic conditions and accommodation space necessary to facilitate the distribution of soils seen in Huntley Meadows Park. It is possible that as sea levels dropped during cold climates, the meander bottom was either a fluvial wetland or relatively dry environment and subsequently filled when sea levels rose, to create an estuary or other low energy environment that could accumulate fine grained material. When sea levels dropped during subsequent cold periods these estuarine deposits in Hybla Valley could have been incised by small tributaries to the Potomac River. As cycles of oscillating sea levels repeated, sediments eroded from the sandy Potomac Formation high along the sides of the meander valley walls washed down into the floor of Hybla Valley during cold periods with low water levels. These coarse lenses would later be covered by fine-grained fluviomarine sediments during high stands, resulting in interfingered beds dominated by loamy alluvium or fluviomarine parent materials for the soils within Huntley Meadows Park. In this scenario, the last vestiges of the Potomac River would have deposited sediments derived from schist, granite, and gneiss parent material which later formed the relatively clay rich Hatboro silt loam in the lowlands of Huntley Meadows Park.

The distribution of clay soils, sandy aquifers, and hydraulic gradients within them produce clear relationships with the valley bottom wetlands. Comparisons of soil maps, NWI maps and vegetation reveal that clay-rich soils underlie the wetlands in the lower portions of the park. The slug tests revealed those soils had lower hydraulic conductivity rates than loamy soils around the wetland margins. The sandy sediments below the wetlands at depth (VTHD2) were considerably more permeable than the overlying materials containing the wetlands. Although it would not be unreasonable to find that groundwater moved up from the underlying regional aquifer to feed the wetlands from below, well data did not support that possibility; the observed water levels in the deeper wells (VTHD2 and ODU_HM1) were never great enough to create a vertical gradient that would contribute water to the wetlands within Huntley Meadows Park. Instead, analyses of the transect well hydrographs indicated that local groundwater flow from the loamy low terraces surrounding the wetlands during the winter months allowed water to accumulate seasonally in the ponded area. This flow pattern is similar to the pattern of surface water flow in the park. However, the gradients would reverse during the growing season as the forest draws down the water table and the ponded area becomes the relative high in the water table making the pond the source of water rather than the accumulation point.

Variations in Evapotranspiration Rates

The second hypothesis tested was that wetland expansion causes no changes in ET intensity or duration that significantly affect water levels across the wetland. The first part of testing this hypothesis involved determining actual evapotranspiration (AET) rates from multiple settings within Huntley Meadows Park and comparing them both to Penman-Montieth-derived potential evapotranspiration (PET) rates and to AET rates from different plant communities within Huntley Meadows Park. The second part, determining the effects of ET on water levels within the wetland, was addressed further with the third hypothesis.

The first step towards determining AET rates was to acquire reasonable estimates of the specific yield of the soils around the wells that were being used to estimate AET. Of the two methods used to estimate Sy, the water table response to precipitation method and the pressure plate extraction method, the water table response method was certainly the less resource-intensive approach. For wells that either produced a considerable number of usable AET rates, such as ODU_ET1 (81 usable rates), or relatively high Sy values, such as T4A (Sy = 0.26 from water table response method), the pressure plate extractor method was used to determine a more accurate estimate of Sy. Both methods yielded Sy values that were within the ranges presented in the literature for soils with similar textures. For the purposes of estimating AET from water table fluctuations, Sy estimates derived from the water-table-response-to-precipitation method would likely be sufficient for future studies.

The MATLAB script used in this study to estimate AET rates from water table fluctuations proved to be a more efficient means of estimating AET than the traditional hand-derived method using White's Method (1932). However, the method was still somewhat time consuming as users must ensure their data are continuous, format their data for the script, prepare individual subsets of hourly data for each AET estimate, and evaluate each AET estimate to determine whether or not it is acceptable. Once the data were prepared, a subset could be extracted, the script could be edited and run, and the output could be inspected and recorded at a rate of roughly one minute per AET estimate. While this time requirement was manageable for the 2,926 rates processed for this study, future investigators may want to improve the script so that it could select subsets of data based on observed precipitation, process and evaluate AET rates, and compile the resulting AET rates in a single output file. Revising the script would enable future investigators to derive more AET rates and corresponding Kc values in a more efficient manner.

Of the 2,926 potential AET rates, only 191 proved to be usable. While the number of usable rates was reduced by the occurrence of precipitation events, there were many potentially usable rates that could not be estimated as the water table frequently dropped below the transducer in the transect wells during the growing season. Bearing in mind that the transect wells were not installed specifically for deriving AET, future investigators should consider installing their wells deeper than typical monitoring wells installed to establish wetland hydrology. The wells that produced the most usable rates in this study were screened continuously nearly three meters below the ground surface. In both of those locations, the water table rarely dropped more than two meters below the ground surface.

While wells that could be used to estimate AET were installed in each of the three plant communities considered in this study, forested non-wetlands, forested/shrub wetlands, and emergent wetlands, only wells existing in forested/shrub and emergent wetlands yielded usable AET rates. Unfortunately, neither of the three-meter-deep wells were in areas identified as forested non-wetlands by the team from VT that was monitoring vegetation. Nonetheless, the 191 usable rates provided a great deal of insight into the magnitudes and variations in ET throughout Huntley Meadows Park.

AET estimates from forested/shrub wetlands were typically higher than AET estimates from emergent wetlands on corresponding days. Kc values derived for forested/shrub wetlands (Kc max = 7.30) at Huntley Meadows Park, and the area surrounding well T4A (Kc max = 7.05), were higher than any accepted Kc values defined for agricultural purposes. These high values are not out of the realm of possibility, though, because the literature is sparse with respect to Kc estimates based on water-table-fluctuation-derived Kc values for wetland communities. While the rates at T4A were high relative to the other wells existing in areas that were identified as emergent wetlands within Huntley Meadows Park, other authors have reported water-table-fluctuation-derived AET estimates, or Kc values of similar magnitudes, from similar settings at transitional boundaries between low-lying crops and taller crops and attribute those high AET estimates to locations susceptible to the ‘clothesline effect’ (Runyan and Welty, 2010; Hill and Neary, 2007). Well T4A is situated in a way that it is certainly susceptible to increased advection as it is located at the terminus of a long fetch where the vegetation transitions from relatively short and dense (emergent wetland) to taller vegetation that is less dense (forested wetland).

Investigators looking to utilize Kc estimates for these wetland communities at their own sites should exercise caution. The range of species possible in these two plant communities is expansive and additional work should be done to validate these Kc estimates by deriving additional Kc estimates for similar environments throughout the mid-Atlantic states. Regardless of the source used to estimate Kc, this study shows that wetland planners who are developing water budgets for sites that are intended to be forested wetlands should plan for their sites to have greater water needs as the vegetation matures. Additionally, wetland planners that are looking to alter the extent of existing forested wetlands, by perhaps increasing the area of emergent wetlands, will likely have sites that are wetter than intended as the once-forested wetland areas would not be using as much water.

Wetland Water Budget Models

The third hypothesis tested was that calibrated computer models of the area can be used to predict changes in the water budget associated with raising the water table and facilitating the redistribution of plant communities. Two types of models tested this hypothesis in Wetbud - Basic (analytical) Models and Advanced (numerical) Models. Wetbud's Basic Models produced monthly estimates of predicted water levels as the sum of sources and losses of water within the model area, all calculated relative to an approximated wetland bottom elevation. This simple estimate of water table elevation is good for sites without complicated distributions of soils, vegetation, and with direct runoff from an adjacent area. Conversely, Wetbud's Advanced Models are MODFLOW-driven and are intended to be able to handle variations in topography and soil characteristics while making predictions of head elevations in multiple discrete locations throughout a site. While each modeling approach was able to prove that Wetbud was capable of representing different distributions of plant communities, each approach arrived at that conclusion via slightly different tests, and each approach had its own limitations in arriving at those conclusions.

Wetbud's Basic Model was never intended for use in a system as complicated as Huntley Meadows. However, the model was capable of representing the site with the appropriate parameterization. With little effort, the Basic Model was able to accurately represent inputs from precipitation and direct runoff and losses attributed to Penman-Monteith-derived PET and outflows through a variable-height outlet weir. However, one component of the water budget that presented a challenge was the water added from sub-basins one and two, located to the north of the wetland. Wetbud's runoff estimation is based on the Curve Number method, which does not produce runoff when the daily precipitation value is less than the initial abstraction, or minimum precipitation value necessary to create sheet flow. While frequent small precipitation events might not have been creating substantial amounts of runoff that would eventually end up in the wetland, they were contributing to the baseflow discharge flowing through the small channels leaving those sub-basins and entering the wetland. To account for the baseflow observed in the small streams leaving sub-basins one and two and flowing into sub-basin three, a constant user-in flux was added. Adding a user-in flux to account for the baseflow was a critical step towards arriving at accurate predicted water levels.

Another element that presented a challenge was the variable-height outlet weir. Representing the weir itself was not problematic; Wetbud includes an easy routine for varying the outlet height from month to month. However, in a system where inputs are typically greater than outputs and the desired water levels are maintained by adjusting the outlet height, the critical value to evaluate when calibrating the model is the outflow estimate. Without considering the outflow estimate, one might assume the near perfect match of predicted head to observed head at a variable height outlet would mean the model is performing exceptionally well. Head values recorded on the downstream side of the outlet were used to determine how well the model predicted head lost through the outlet each month. If the predicted loss each month was close to the observed head lost each month, then it was assumed the model was properly representing the other losses in the water budget each month. Once the baseflow and outflow components were properly parameterized, the model could be calibrated and used to evaluate the effects of varying ET.

Testing whether or not the calibrated computer model of the area would be capable of modeling changes in the water budget associated with changes in the distributions of plant communities was achieved by assigning monthly crop coefficients (Kc) for each plant community to the model uniformly. The Basic Model predicted outflow was strongly influenced by varying the Kc values by plant community. The predicted outflow increased when emergent vegetation Kc values were applied to the entire site; conversely the predicted outflow values dropped significantly, as did predicted head values, when the forested/shrub vegetation Kc values were applied uniformly. Based on the difference seen in the Kc values for these communities, these differences in outflow values may seem intuitive. However, if one were to model a site with a uniform Kc where the dominant vegetation observed within the model area is emergent, it is possible the outflow value would be significantly underestimated resulting in a particularly dry wetland, as seen in the output from the Forested/shrub wetland model. Operating under this assumption could be particularly problematic during dry years when the predicted head might not be greater than the outlet elevation. For the Huntley model, the solution was to employ an area-weighted monthly Kc. Applying an area-weighted Kc lessened the predicted outflow and decreased the RMSE of the predicted outflow values. The relatively high NSE and low RMSE values of the predicted outflow produced when the area-weighted Kc was applied indicate Basic Model performance is strongly affected by the applied distribution of Kc values. These findings suggest that as the redistribution of plant communities progresses the area-weighted Kc value should be changed to reflect the new area of each plant community. Changes in the area-weighted Kc would in turn affect predicted head elevations. To account for variations in plant communities within areas modeled by Wetbud, future versions of Wetbud could include an area-weighted Kc calculator and suggested Kc values for the plant communities, such as those developed in this and later studies.

The second approach employed to understand the redistribution of plant communities involved using the Advanced Model package in Wetbud to develop a set of numerical models driven by MODFLOW. The series of models used to evaluate whether or not changes in the distribution of plant communities could be modeled revealed that a calibrated model utilizing multiple ET zones would produce higher NSE and lower RMSE values than a model that did not use multiple ET zones. However, there was not a significant difference between the NSE and RMSE values of models that varied the extents of the vegetation within the models based on the observed change in vegetation between two consecutive years. There are three primary factors that likely affected the models' ability to predict significant change: (1) cell size, (2) relatively sparse sampling for determining plant communities, and (3) limitations of Wetbud's graphical user interface.

Determining a cell size for this modelling exercise proved to be challenging. The goal was to predict water levels around the pond with a precision of 0.10 m or less. To achieve this goal, the cells needed to be small enough to represent subtle changes in topography, hydrologic conditions, and vegetative cover, yet they needed to be large enough to allow large amounts of water to flow through the surface layer during a single time step to prevent the model from crashing. Also, there were practical limits on the grid size as Wetbud's grid interface does not allow for cell assignment via polygons. Cells are assigned characteristics by layer, row, column, or creating polygons by selecting single cells. For simple models, which Wetbud was originally intended for, this routine works well. However, for larger, more complex models this routine proved to be less than efficient. The 15.24 x 15.24 m cell size resulted in a grid with more than 9,000 cells per layer; reducing the cell size by half would have resulted in more than 36,000 cells per layer as Wetbud uses a grid with square cells of equal size and does not allow for variable mesh refinement. While this limitation is not necessarily problematic, it does affect grid design. For example, one of the areas that seemed to be routinely affected by grid size was the northern end of transect three. Between wells T3P and T3A there is a small channel that previously had water flowing in it towards the ponded area from outside of the watershed. This ditch was plugged to eliminate the connection to the adjacent watershed during the restoration; however, the ditch still existed within sub-basin three. This relatively small channel was too small to represent as a line of cells with lower elevations; however, the volume of water contained in the ditch was large enough to affect a difference between predicted and observed head values in that area. The model interprets the cell that contains the ditch as an area with a single elevation that is greater than the bottom of the ditch. Therefore, the volume of water contained in the actual ditch was distributed evenly throughout the entire cell and the water table elevation was adjusted to account for the specific yield zone assignment for that cell. In addition to poorly representing ditches within the model, the other issue with cell size was representing microtopography within the wetland. Each cell elevation was the average of the 5 ft (1.52 m) pixel resolution DEM used to generate the 50 ft (15.24 m) aggregated DEM, which was referenced when assigning elevation to the cells in the model. While this routine was a reasonable representation of the relief throughout the park, this routine may not accurately represent the hummocky topography of the wetland itself. The low pools that exist within the wetland would be flat soil surfaces in the model, and the model would not allow small pools to exist within adjacent cells of the same elevation. Rather the model would evenly distribute the water amongst all cells of the same elevation and adjust the predicted head elevation based on the specific yield zone assignment for each cell. While the cells sizes used in this model were the most practical for this exercise, it is likely that utilizing smaller cell sizes would have improved the ability of the model to accurately predict head elevations at discrete locations within the park.

Another consideration in selecting a cell size was the resolution of the data used to assign plant communities. Plant communities within the park were assigned based on the distribution of wetlands shown on the National Wetland Inventory (NWI) maps and adjusted based on the observations of vegetation made at each transect well location by the team from VT. While the transect well locations served nicely as ground truth points for the NWI maps, the transect wells were installed to monitor groundwater levels surrounding the pond itself and were not installed in a uniform grid throughout the park. Also, vegetation was only monitored within 10 ft (~3 m) of each transect well. While the vegetation may have been observed to have changed from 2014 to 2015 at single well locations, it is possible that the areas between wells had not experienced the same changes. Additionally, while these transitions from forested/shrub to emergent may have been taking place, it is not likely that the vegetation had fully, and uniformly, converted in only one growing season. It is possible that the observed head levels were reflective of transitional periods and the model, even with a different vegetation type, was a reasonable approximation of the site, as the vegetation had not fully converted. It would be interesting to use the same set of calibrated parameters in a model that uses weather and vegetation distribution observations from the same site from several years later, once the vegetation is fully converted due to the rise in water levels.

Along with limitations related to cell size and accurately representing the vegetation throughout the park, Wetbud had its own limitations that may have influenced the model's ability to accurately predict head elevations within Huntley Meadows Park. Wetbud's Advanced Model package was designed to include moderately complex inputs into relatively simple groundwater flow models. The main purpose of developing a graphical user interface for MODFLOW was to facilitate the development of wetland water budgets for sloping wetlands, or wetlands with variable topography. Had Huntley Meadows Park been a smaller site, it is likely that the grid interface limitations in Wetbud would have been appropriate for the model; however, as Huntley Meadows was particularly large site for Wetbud, those limitations became more apparent. Additionally, as Wetbud was intended for relatively simple numerical models, there are packages that exist for MODFLOW, such as the lake (LAK) and streamflow-routing (SFR) packages, that would have been useful in modeling a site like Huntley Meadows. While these packages may have been helpful in modeling Huntley Meadows Park, they would not be practical for most of the small wetlands Wetbud was designed to model and therefore were not included in Wetbud.

Despite the limitations of the model, the Calibrated Model designed using Wetbud met the original goals of this project. That model was capable of simulating head values around the pond with approximately 0.10 m accuracy, and it was able to recreate the observed changes in gradient. Additionally, we found that the model that was calibrated using multiple ET zones performed better than the model that was developed without multiple ET zones and without adjusting PET using a crop coefficient. These findings suggest that ET zones play a key role in predicting accurate water levels and models developed using ET zones will likely perform better than those that do not. However, as seen in the differences between the Validation Model and the Test Configuration where vegetation distributions were assigned based on observations made from two consecutive years, it is likely that changes in the water budget would be better represented with sufficient time between transitioning from one plant community to another to avoid attempting to model a change that is not yet significant enough to be modeled.

To better understand the significance of each parameter that was calibrated within the model - specific yield, uniform ET extinction depth, initial head, and hydraulic conductivity - a sensitivity analysis was performed. For the sensitivity analysis, calibrated values from the Calibration Model (Advanced Model Configuration 84) were adjusted by -50%, -25%, 25% and 50% changes; the percent change in RMSE values resulting from each of those configurations, relative to the Calibration Model, were evaluated to determine how sensitive the model was to changes in these parameters (Fig. 36, data in Appendix G). Of the four configurations that employed changes in initial head, three were not able to initialize and resulted in no change in RMSE. This result suggests it is critical that the user select an initial head value that is close to an average anticipated initial head value within the model area. Additionally, changes in ET extinction depth correlated strongly to changes in RMSE. Interestingly, changes in ET extinction depth sometimes caused negative percent changes in RMSE values indicating some RMSE values decreased, meaning predicted head values were more accurate with variation in ET extinction depth. While Wetbud does allow users to apply ET extinction depth on a cell-by-cell basis, ET extinction depth was applied uniformly in our models. Future users should consider incorporating variable ET extinction depth in addition to variable ET zones to increase the predictive abilities of their models.

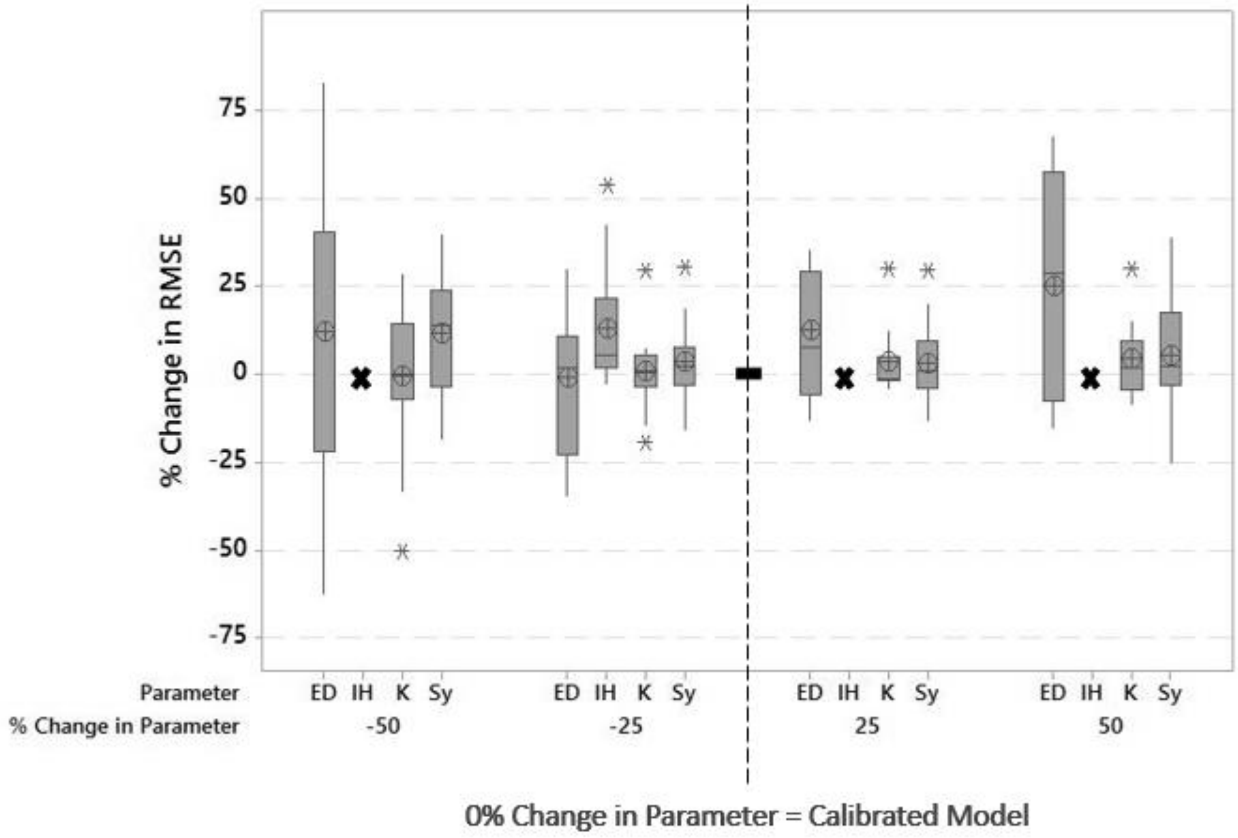

Fig. 36. Advanced Model sensitivity analysis results displayed in a compact box and whisker plot showing the percent change in RMSE of predicted heads across all of the monitoring wells relative to the Calibration Model. Asterisks represent outliers, targets represent the means, horizontal lines represent the medians, boxes represent the interquartile range, and bold x marks indicate models that failed to run. The intersection of the bold black bar and the vertical dashed line represents zero percent change in parameter and output RMSE, as this is the Calibration Model. Output from each of the sensitivity analysis runs were compared to the output from the Calibration Model, with separate models representing changes being made to ET extinction depth (ED), initial head (IH), hydraulic conductivity (K), and specific yield (Sy).

As stated earlier, both the Basic and Advanced Model packages within Wetbud were able to model the effects of varying ET rates and corresponding Kc values throughout the models. Based on the findings presented in this study, there are a few important considerations that future Wetbud users should keep in mind when developing water budget models for site like Huntley Meadows. For Wetbud users developing Basic Models, (1) be sure to include a user-defined influx to account for baseflow from adjacent sub-basins; (2) if the elevation of the outlet weir can change through time be sure to consider the predicted outflow of the model before deeming the model to be calibrated; and (3) depending on the nature and extent of vegetation within the model area, an area-weighted Kc value may be necessary to derive accurate estimates of predicted head. For Wetbud users developing Advanced Models, (1) the findings presented in this study suggest models that incorporate multiple ET zones adjusted with the appropriate Kc values produce more accurate predictions of head than models that use uniform PET estimates not adjusted to account for the observed vegetation.; (2) as with any finite-difference modeling project, careful consideration must be given when deciding on a cell size for Advanced Models in Wetbud; (3) Wetbud applies initial head uniformly, so it is critical that Wetbud users determine the best initial head value for their site and initial conditions; otherwise the model might not initialize, let alone arrive at reasonable predictions of head; and (4) the sensitivity analysis also revealed that root mean square errors of predicted heads in Advanced Models are particularly sensitive to ET extinction depth. While this study did not include spatial or temporal variations in ET extinction depth, spatially-appropriate estimates of ET extinction depth varied with time would likely improve the model’s ability to accurately predict changes in head elevations resulting from wetland expansion.

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APPENDIX A

SOILS MAP AND AUGER-HOLE LOGS

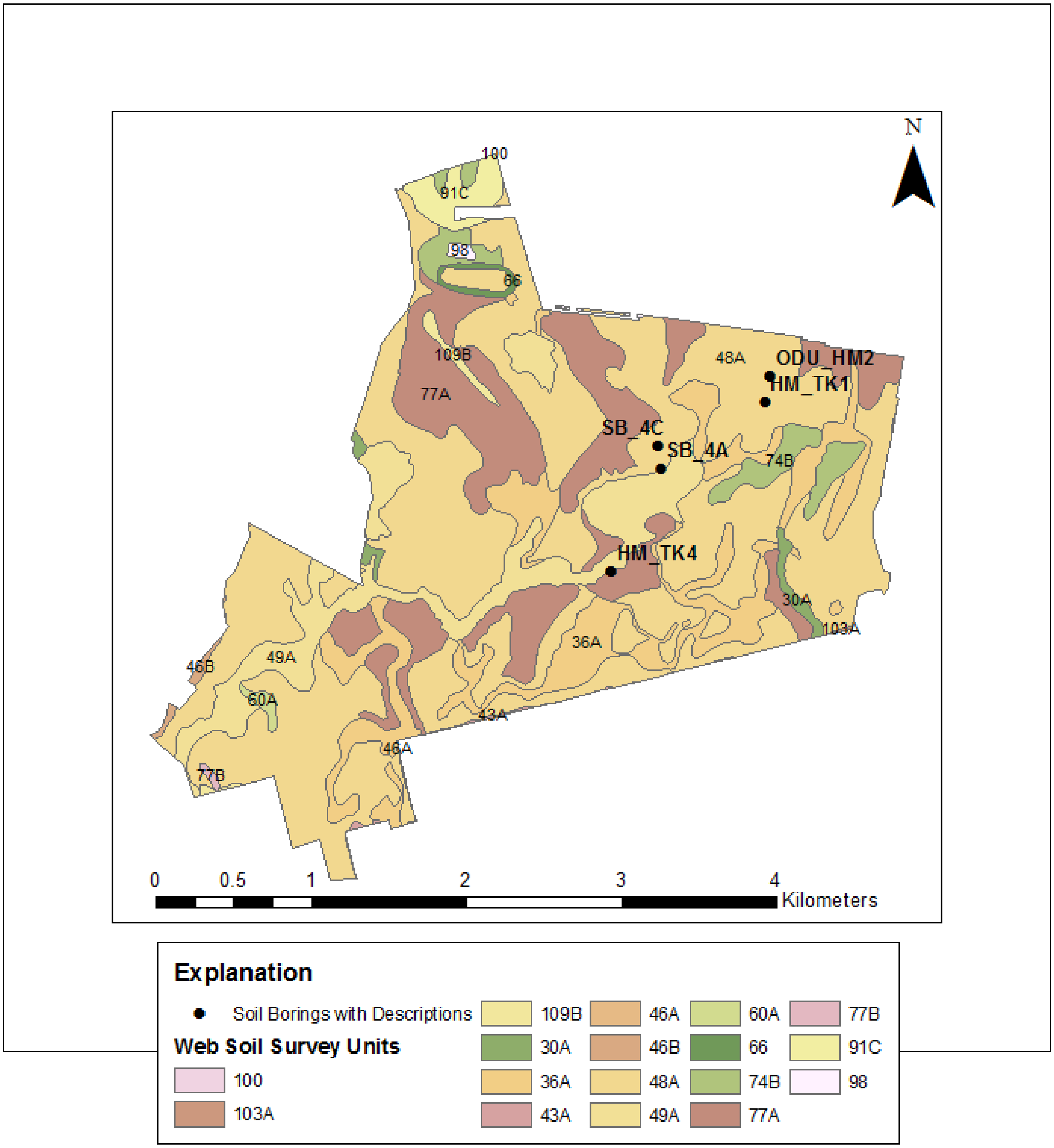


Fig. A-1. Soils units from Web Soil Survey and locations of soils borings with descriptions. Several more borings were performed to confirm the extents of the units shown on the map, however most were not described. Some soils units were labeled on this figure to aide differentiation.

Soils Unit Explanation For Fig. A-1

Unit	Description
100	Urban land-Kingstowne complex
103A	Wheaton-Cordorus complex, 0 to 2 percent slopes
109B	Woodstown sandy loam, 2 to 7 percent slopes
30A	Codorus and Hatboro soils, 0 to 2 percent slopes
36A	Elkton silt loam, 0 to 2 percent slopes
43A	Grist Mill-Gunston complex, 0 to 2 percent slopes
46A	Grist Mill-Mattapex complex, 0 to 2 percent slopes
46B	Grist Mill-Mattapex complex, 2 to 7 percent slopes
48A	Gunston silt loam, 0 to 2 percent slopes
49A	Hatboro silt loam, 0 to 2 percent slopes
60A	Honga peat, 0 to 1 percent slopes
66	Kingstowne sandy clay loam, 0 to 45 percent slopes
74B	Lunt-Marumsco complex, 2 to 7 percent slopes
77A	Mattapex loam, 0 to 2 percent slopes
77B	Mattapex loam, 2 to 7 percent slopes
91C	Sassafras-Marumsco complex, 15 to 25 percent slopes

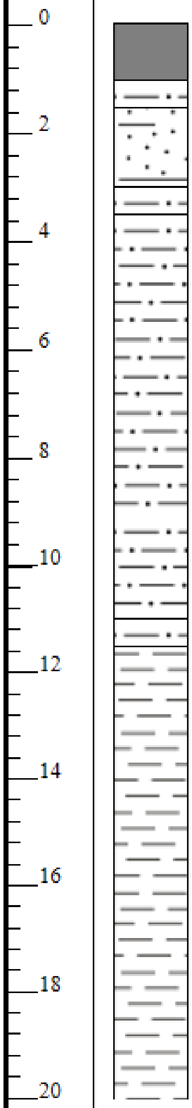
Units and descriptions from Web Soil Survey

Soil Auger Report

Project: Huntley Meadows Water Monitoring
Location: Off of gas line access road
Lat: 38.758867
Long: -77.098823

Name: ODU_HM2
Performed by: S. Stone, B. Hiza
Date: 12/3/14
Auger Type: 4-inch open-bucket hand auger

Scale (ft) **Borehole Information**



0 – 1 ft: dark gray sandy clay, rooty, organics

1 – 1.5 ft: silt loam 7.5YR 6/2

1.5 – 3 ft: sandy clay loam 7.5YR 5/1, some red mottles present in coarse material

3 – 3.5 ft: sandy loam 7.5YR 5/4

3.5 – 10.75 ft: dense silty clay, 7.5YR 5/1, mottles common, mottles 5YR 5/6

10.75 – 11.25 ft: sandy loam 7.5YR 5/4
Encountered water at 11 ft

11.25 – 27 ft: dense dark gray clay 7.5YR 4/1

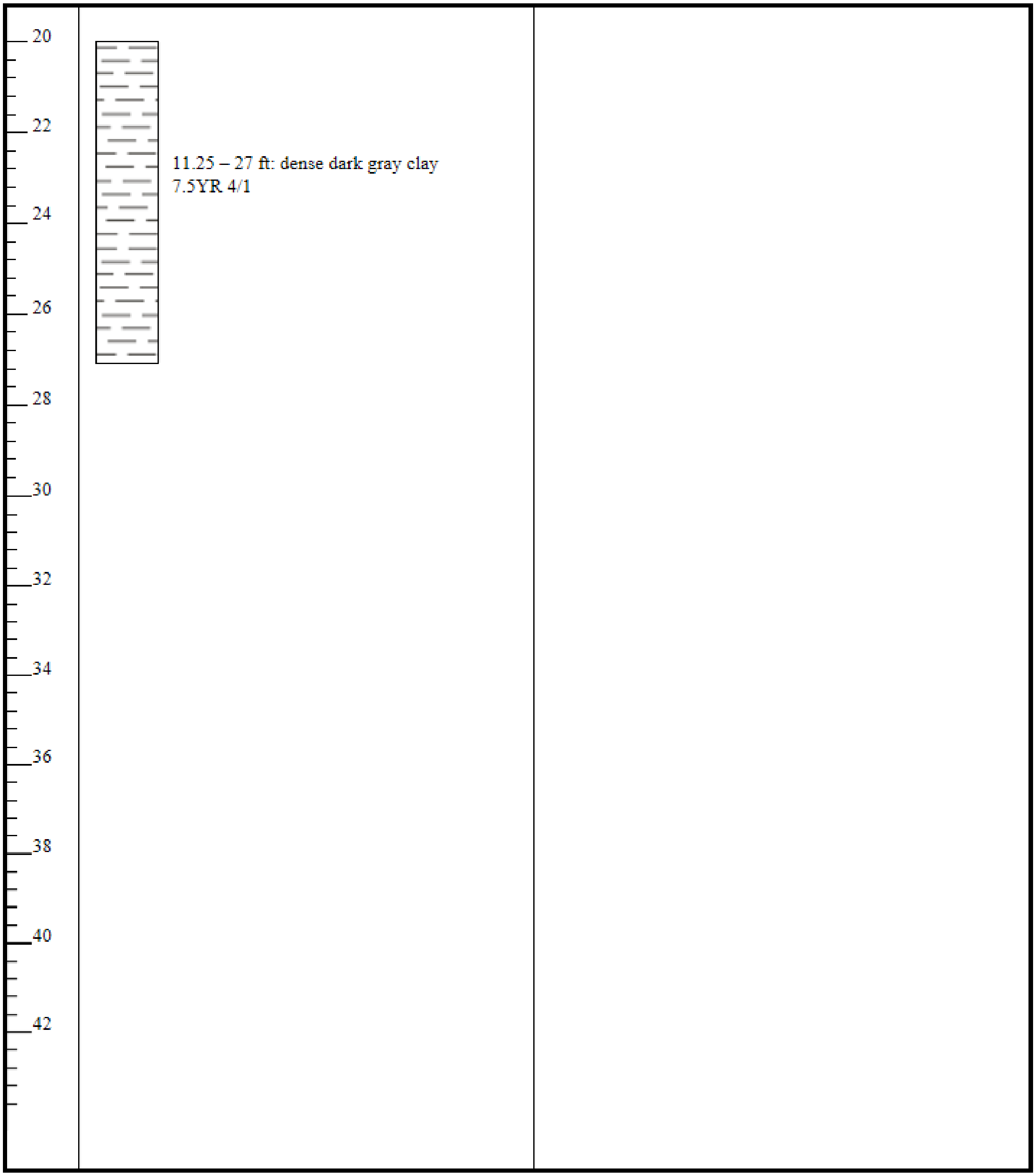
Continued on next page

Soil Auger Report (cont.)

Project: Huntley Meadows Water Monitoring
Location: Off of gas line access road
Lat: 38.751367
Long: -77.108461

Name: ODU_HM2
Constructed by: S. Stone, B. Hiza
Date: 12/3/14
Auger Type: 4-inch open-bucket hand auger

Scale (ft) **Borehole Information**

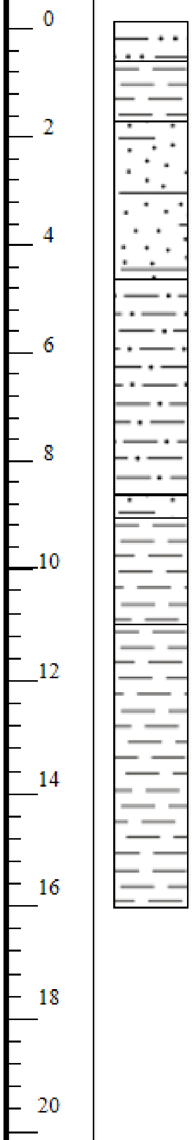


Soil Auger Report

Project: Huntley Meadows Water Monitoring
Location: West of visitor's center parking lot
Lat: 38.75765
Long: -77.099084

Name: HM_TK1
Performed by: S. Stone and B. Hiza
Date: 6/7/14
Auger type: 4-inch open-bucket hand auger

Scale (ft) **Borehole Information**



0-0.5 ft: Light grey-brown loam

0.5-1.5 ft: clay, no mottles, 10YR 5/4

1.5-4.5 ft: sandy clay with mottles, weathered feldspar(?) coarse sand size, 10YR 6/2

4.5-8.5 ft: silty clay, 10YR 7/1, oxidized mottles of slightly more coarse material

8.5-9.0 ft: sandy clay, 10YR 7/1 with mottles

9.0-11.0 ft: clay 10YR 6/2

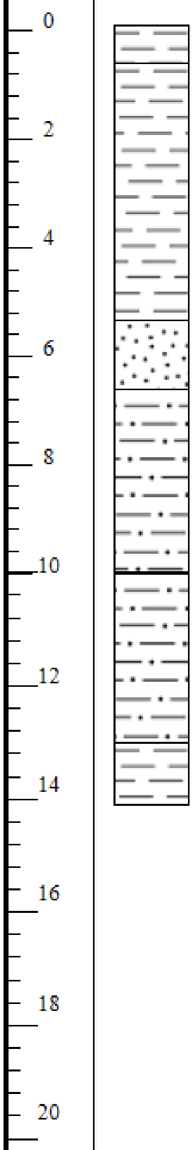
11.0-16.0 ft: dense clay 2.5Y 4/1

Soil Auger Report

Project: Huntley Meadows Water Monitoring
Location: Southwest of subterraneous dam
Lat: 38.750028
Long: -77.108000

Name: HM_TK4
Performed by: S. Stone and B. Hiza
Date: 6/7/14
Auger type: 4-inch open-bucket hand auger

Scale (ft) **Borehole Information**



0-0.5 ft: Light brown clay with organics

0.5-5.5 ft: clay, with mottles, 2.5YR 6/2, mottles were 10YR 5/8

5.5-6.5 ft: medium sand, no mottles, 10YR 5/6

Water at 6.5 ft

6.5-10.0 ft: silty clay, 2.5Y 7/1 with increasing mottles with depth, mottles 7.5YR 5/6

10.0-13.0 ft: silty clay 10YR 4/4, oxidized silt lense 7.5YR 4/6

13.0-14.0 ft: dense clay 10YR 4/2, reduced bands, 10YR 6/1

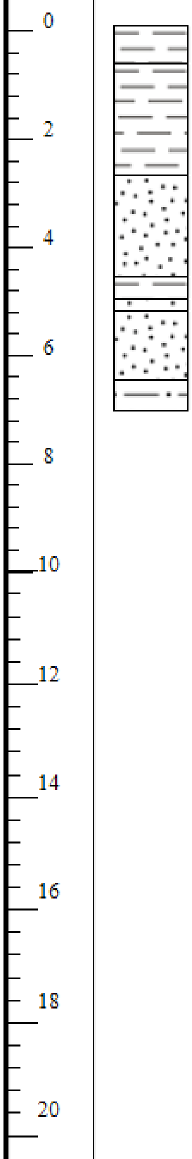
Refusal at 14 ft with hard rock

Soil Auger Report

Project: Huntley Meadows Water Monitoring
Location: Near transect well 4C
Lat: 38.75571
Long: -77.1053

Name: SB_4C
Performed by: S. Stone, B. Hiza, D. Putnam
Date: 8/4/15
Auger type: 4-inch open-bucket hand auger

Scale (ft) **Borehole Information**



0-0.75 ft: Brown clay loam with organics

0.75-2.5 ft: gray clay with orange mottles

2.5-4.5 ft: very coarse deep red sand, iron cemented in places, occasional rounded quartz pebbles

4.5-5.0 ft: gray sandy clay

5.0-5.25 ft: gray clayey sand, v.c. sand, numerous qtz pebbles, some feldspars sub-angular to sub rounded

5.25-6.25 ft: very coarse red sand, more pebbles

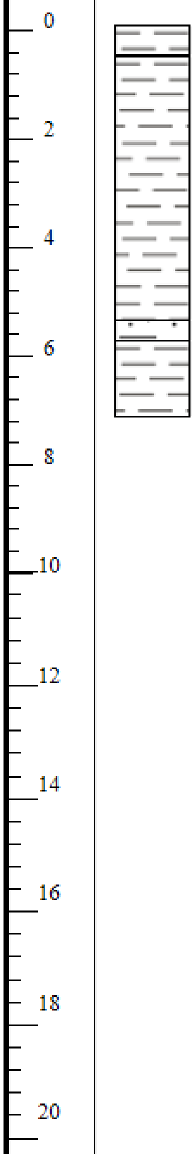
6.25-7.0 ft: clayey sand the transitions to tight gray clay

Soil Auger Report

Project: Huntley Meadows Water Monitoring
Location: Near transect well 4A
Lat: 38.75470
Long: -77.10514

Name: SB_4A
Performed by: S. Stone, B. Hiza, D. Putnam
Date: 8/4/15
Auger type: 4-inch open-bucket hand auger

Scale (ft) **Borehole Information**



0-0.5 ft: light brown clay loam, organics

0.5-5.25 ft: mottled clay, occasional feldspar pebbles at 4.5 ft, < 1 cm, sub angular

5.25-5.75 ft: sandy clay loam, v.c. sand, contains quartz and feldspar pebbles

5.75-7.0 ft: tight clay with mottles, more blocky than soils at depth at SB_4C

APPENDIX B

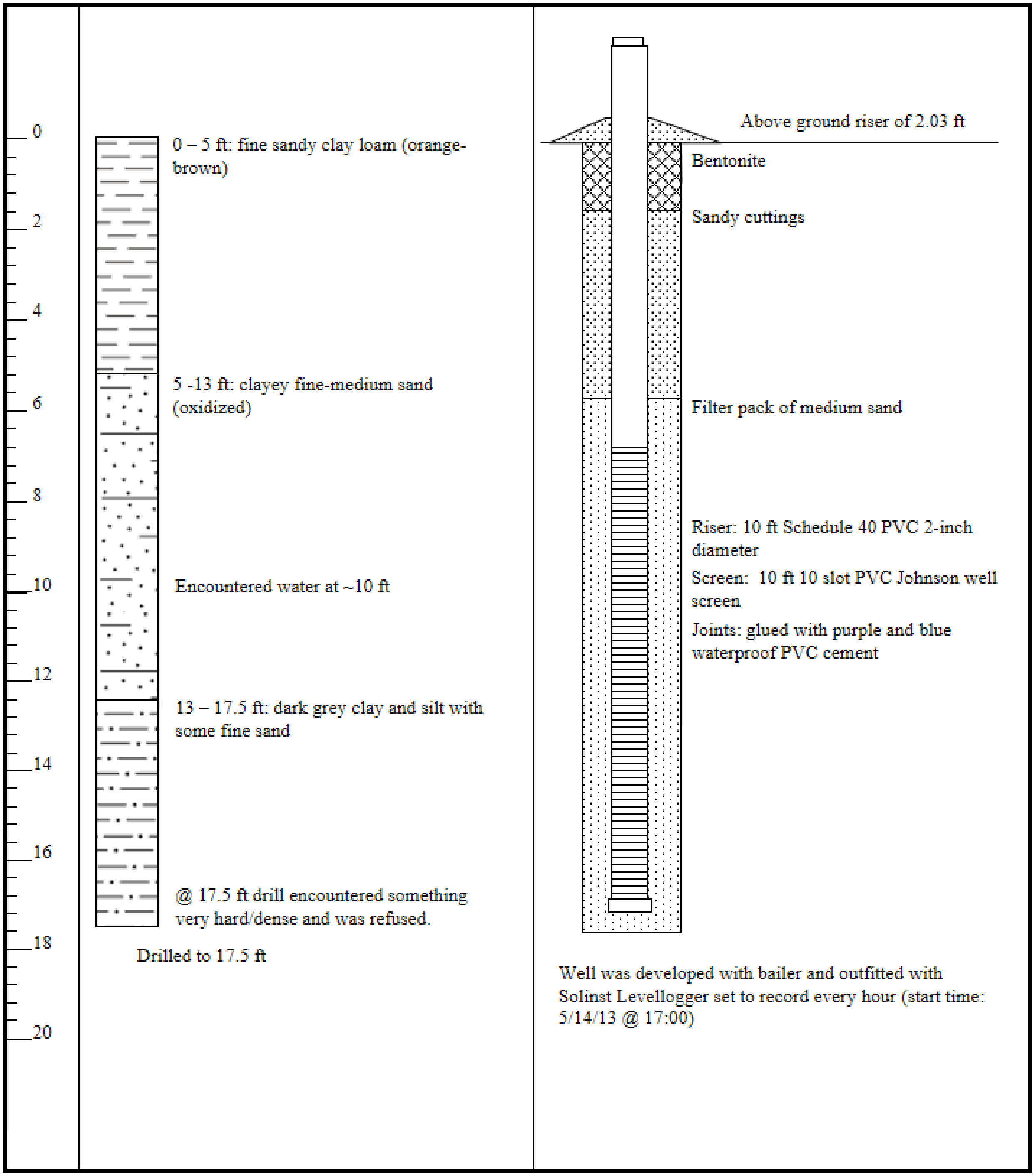
WELL CONSTRUCTION LOGS

Well Completion Report

Project: Huntley Meadows Water Monitoring
Location: Corner of meadow south of HM office
Lat: 38.76001
Long: -77.11718
Top of casing elevation: 48.14 ft

Well Name: VTHD1
Constructed by: S. Nagle, R. Konow, W. Myers
M. Richardson, K. Dobbs, J. Parker
Construction Date: 5/14/13
Auger Type: Drilled with 6-inch hollow-stem auger

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



0 – 5 ft: fine sandy clay loam (orange-brown)

5 -13 ft: clayey fine-medium sand (oxidized)

Encountered water at ~10 ft

13 – 17.5 ft: dark grey clay and silt with some fine sand

@ 17.5 ft drill encountered something very hard/dense and was refused.

Drilled to 17.5 ft

Riser: 10 ft Schedule 40 PVC 2-inch diameter

Screen: 10 ft 10 slot PVC Johnson well screen

Joints: glued with purple and blue waterproof PVC cement

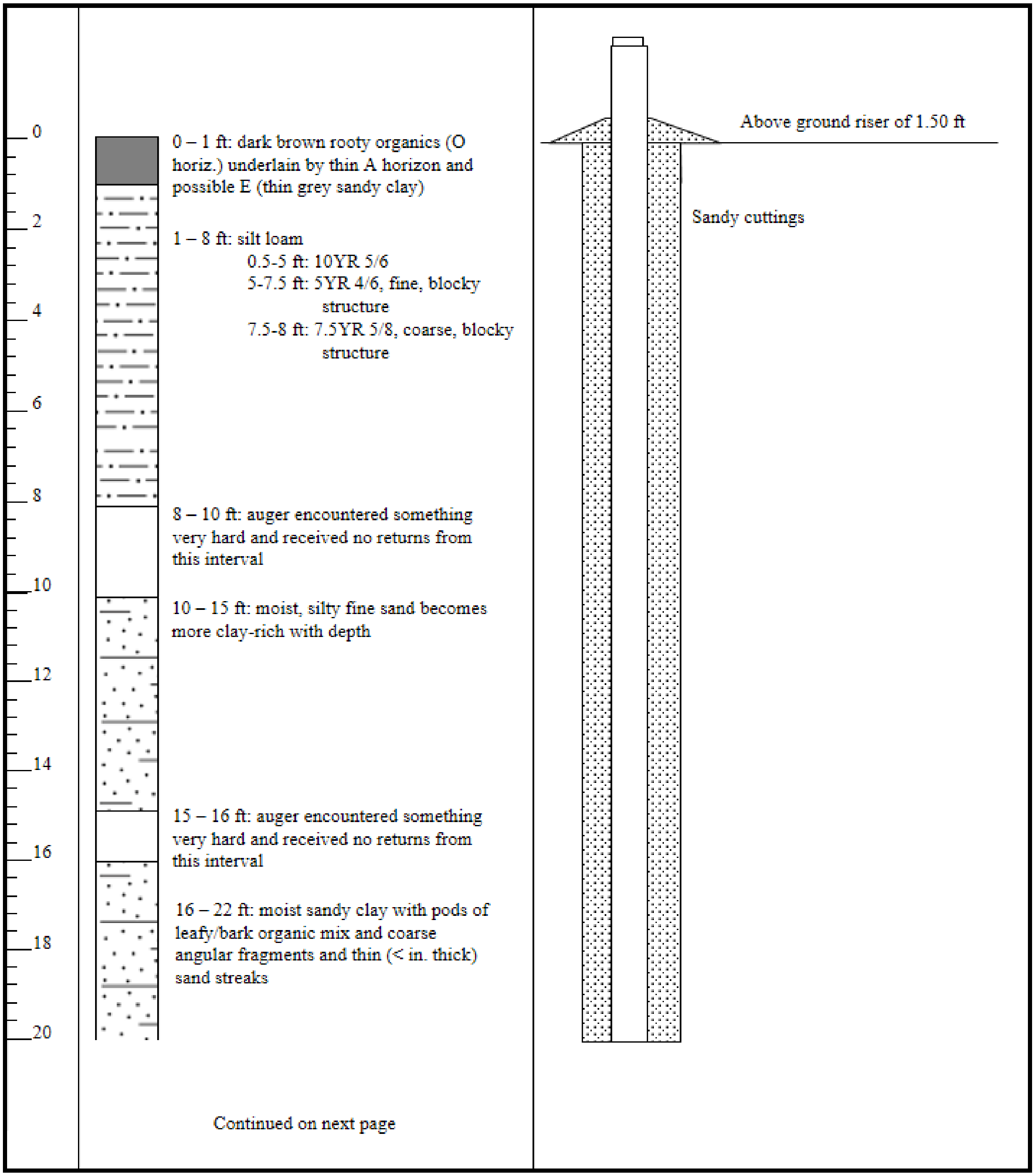
Well was developed with bailer and outfitted with Solinst Levellogger set to record every hour (start time: 5/14/13 @ 17:00)

Well Completion Report

Project: Huntley Meadows Water Monitoring
Location: South end of HM near Muddy Hole Park
Lat: 38.74389
Long: -77.11527
Top of casing elevation: 37.59 ft

Well Name: VTHD2
Constructed by: S. Nagle (Drill operator), W. Myers, K. Dobbs, M. Richardson, J. Parker
Construction Date: 5/14/13
Auger Type: Drilled with 6-inch hollow-stem auger

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



0 – 1 ft: dark brown rooty organics (O horiz.) underlain by thin A horizon and possible E (thin grey sandy clay)

1 – 8 ft: silt loam
  0.5-5 ft: 10YR 5/6
  5-7.5 ft: 5YR 4/6, fine, blocky structure
  7.5-8 ft: 7.5YR 5/8, coarse, blocky structure

8 – 10 ft: auger encountered something very hard and received no returns from this interval

10 – 15 ft: moist, silty fine sand becomes more clay-rich with depth

15 – 16 ft: auger encountered something very hard and received no returns from this interval

16 – 22 ft: moist sandy clay with pods of leafy/bark organic mix and coarse angular fragments and thin (< in. thick) sand streaks

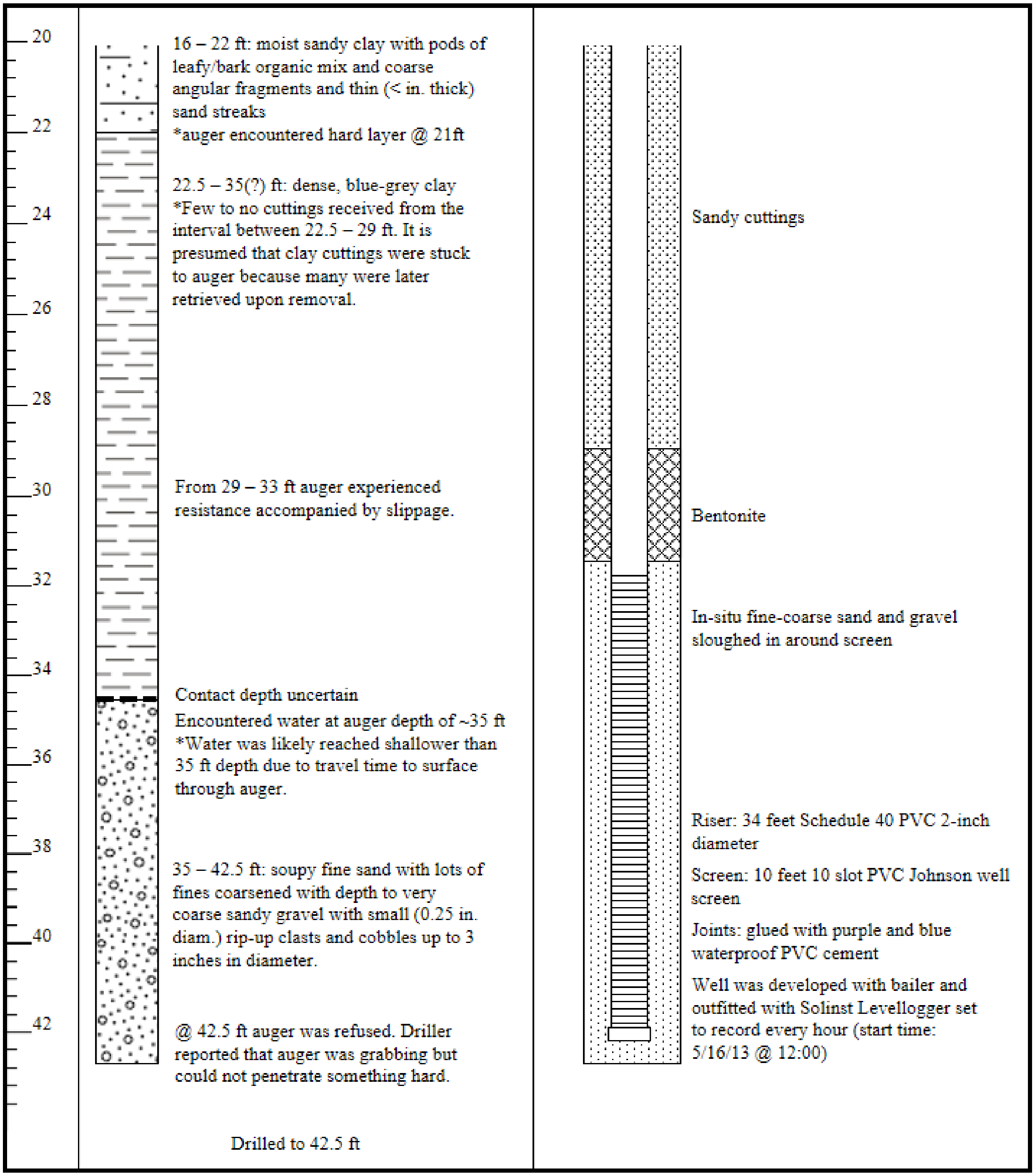
Continued on next page

Well Completion Report (cont.)

Project: Huntley Meadows Water Monitoring
Location: South end of HM near Muddy Hole Park
Lat: 38.74389
Long: -77.11527
Top of casing elevation: 37.59 ft

Well Name: VTHD2
Constructed by: S. Nagle (Drill operator), W. Myers, K. Dobbs, M. Richardson, J. Parker
Construction Date: 5/14/13
Auger Type: Drilled with 6-inch hollow-stem auger

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



16 – 22 ft: moist sandy clay with pods of leafy/bark organic mix and coarse angular fragments and thin (< in. thick) sand streaks
*auger encountered hard layer @ 21ft

22.5 – 35(?) ft: dense, blue-grey clay
*Few to no cuttings received from the interval between 22.5 – 29 ft. It is presumed that clay cuttings were stuck to auger because many were later retrieved upon removal.

From 29 – 33 ft auger experienced resistance accompanied by slippage.

Contact depth uncertain
Encountered water at auger depth of ~35 ft
*Water was likely reached shallower than 35 ft depth due to travel time to surface through auger.

35 – 42.5 ft: soupy fine sand with lots of fines coarsened with depth to very coarse sandy gravel with small (0.25 in. diam.) rip-up clasts and cobbles up to 3 inches in diameter.

@ 42.5 ft auger was refused. Driller reported that auger was grabbing but could not penetrate something hard.

Drilled to 42.5 ft

Sandy cuttings

Bentonite

In-situ fine-coarse sand and gravel sloughed in around screen

Riser: 34 feet Schedule 40 PVC 2-inch diameter

Screen: 10 feet 10 slot PVC Johnson well screen

Joints: glued with purple and blue waterproof PVC cement

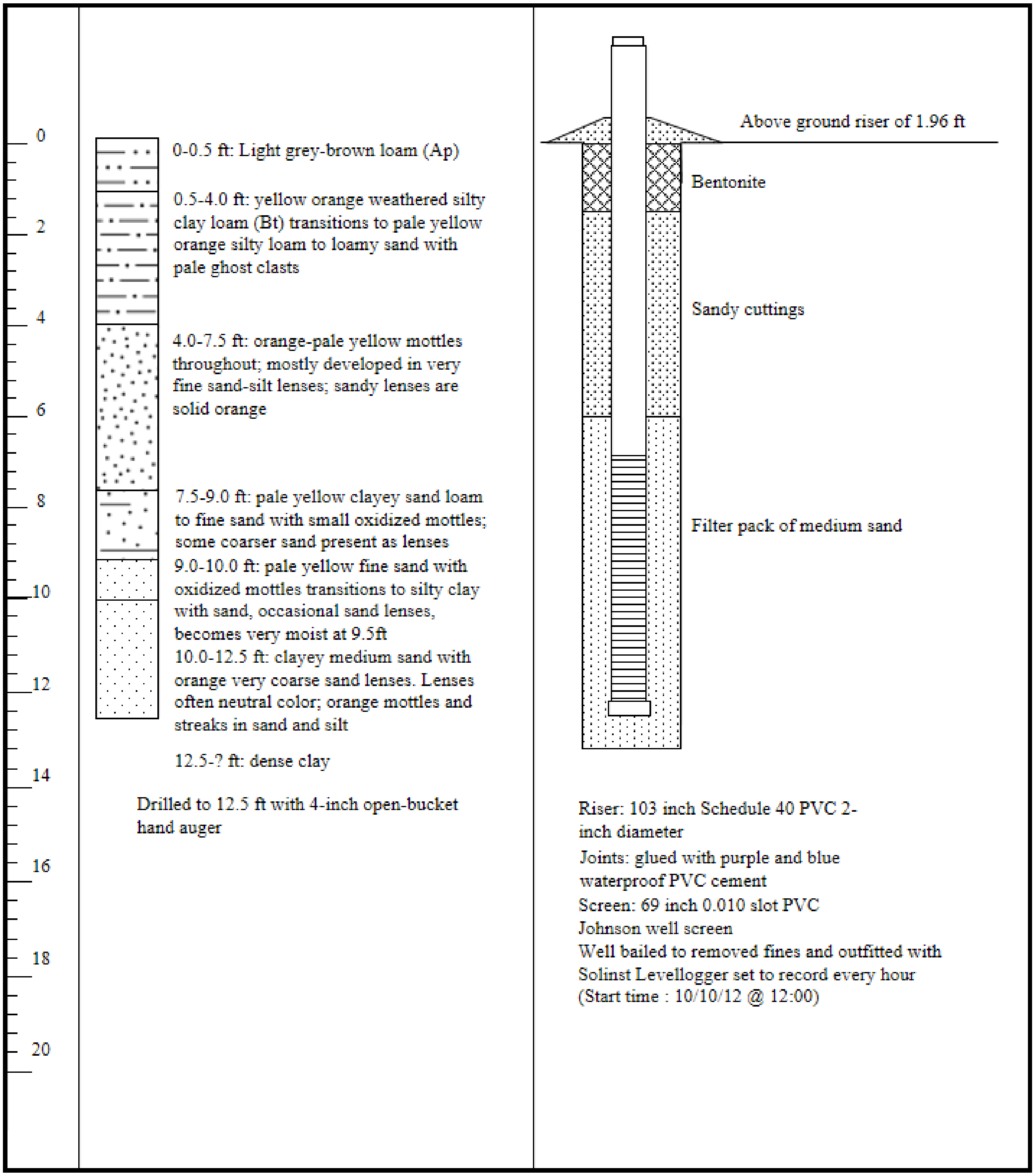
Well was developed with bailer and outfitted with Solinst Levellogger set to record every hour (start time: 5/16/13 @ 12:00)

Well Completion Report

Project: Huntley Meadows Water Monitoring
Location: Huntley Meadows main entrance
Lat: 38.76022
Long: -77.09599
Top of casing elevation: 59.26 ft

Well Name: VTHD3
Constructed by: K. Dobbs and R. Whittecar
Construction Date: 10/9/12
Auger type: 4-inch open-bucket hand auger

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



0-0.5 ft: Light grey-brown loam (Ap)

0.5-4.0 ft: yellow orange weathered silty clay loam (Bt) transitions to pale yellow orange silty loam to loamy sand with pale ghost clasts

4.0-7.5 ft: orange-pale yellow mottles throughout; mostly developed in very fine sand-silt lenses; sandy lenses are solid orange

7.5-9.0 ft: pale yellow clayey sand loam to fine sand with small oxidized mottles; some coarser sand present as lenses

9.0-10.0 ft: pale yellow fine sand with oxidized mottles transitions to silty clay with sand, occasional sand lenses, becomes very moist at 9.5ft

10.0-12.5 ft: clayey medium sand with orange very coarse sand lenses. Lenses often neutral color; orange mottles and streaks in sand and silt

12.5-? ft: dense clay

Drilled to 12.5 ft with 4-inch open-bucket hand auger

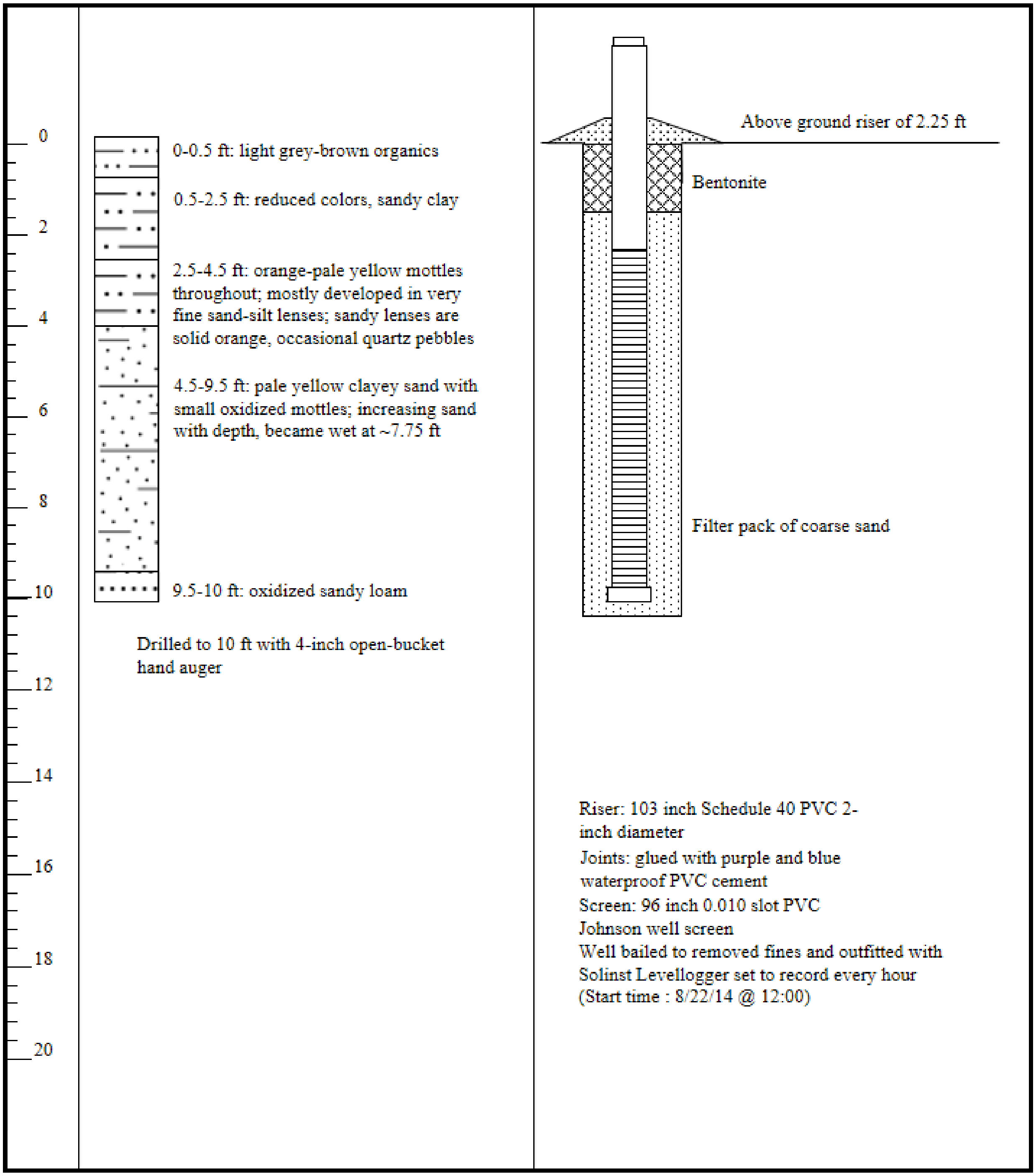
Riser: 103 inch Schedule 40 PVC 2-inch diameter
Joints: glued with purple and blue waterproof PVC cement
Screen: 69 inch 0.010 slot PVC Johnson well screen
Well bailed to removed fines and outfitted with Solinst Levellogger set to record every hour (Start time : 10/10/12 @ 12:00)

Well Completion Report

Project: Huntley Meadows Water Monitoring
Location: Near VT Stream gage east of main entrance
Lat: 38.759517
Long: -77.093433
Top of casing elevation: 58.49 ft

Well Name: ODU_ET1
Constructed by: S. Stone and B. Hiza
Construction Date: 8/19/14
Auger type: 4-inch open-bucket hand auger

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



0-0.5 ft: light grey-brown organics

0.5-2.5 ft: reduced colors, sandy clay

2.5-4.5 ft: orange-pale yellow mottles throughout; mostly developed in very fine sand-silt lenses; sandy lenses are solid orange, occasional quartz pebbles

4.5-9.5 ft: pale yellow clayey sand with small oxidized mottles; increasing sand with depth, became wet at ~7.75 ft

9.5-10 ft: oxidized sandy loam

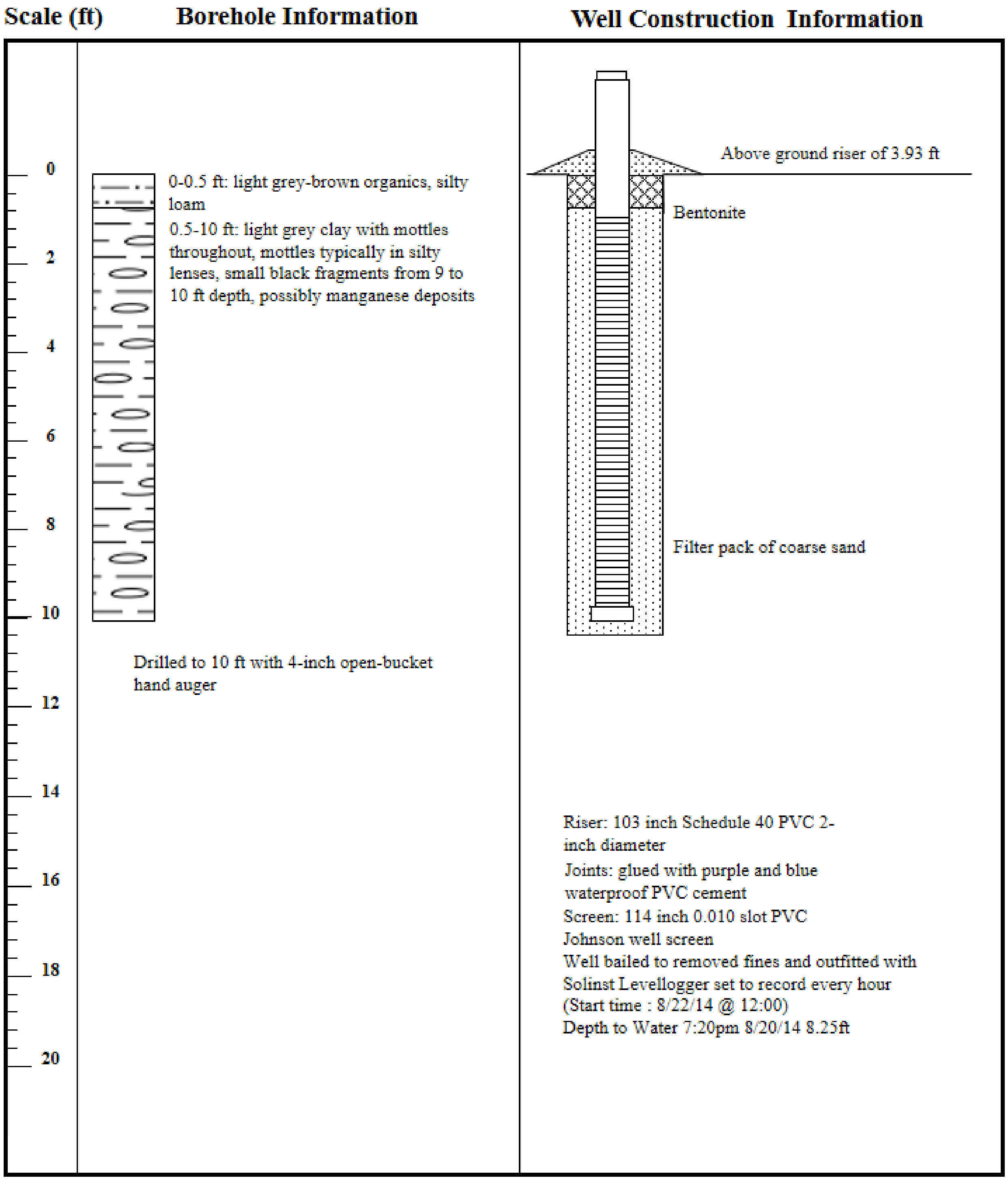
Drilled to 10 ft with 4-inch open-bucket hand auger

Riser: 103 inch Schedule 40 PVC 2-inch diameter
Joints: glued with purple and blue waterproof PVC cement
Screen: 96 inch 0.010 slot PVC Johnson well screen
Well bailed to removed fines and outfitted with Solinst Levellogger set to record every hour (Start time : 8/22/14 @ 12:00)

Well Completion Report

Project: Huntley Meadows Water Monitoring
Location: Near confluence of small streams north of ponded area, mapped as scrub/shrub wetland by NWI
Lat: 38.757609 Long: -77.102559
Top of casing elevation: 41.31 ft

Well Name: ODU_ET2
Constructed by: S. Stone and B. Hiza
Construction Date: 8/20/14
Auger type: 4-inch open-bucket hand auger



0-0.5 ft: light grey-brown organics, silty loam

0.5-10 ft: light grey clay with mottles throughout, mottles typically in silty lenses, small black fragments from 9 to 10 ft depth, possibly manganese deposits

Drilled to 10 ft with 4-inch open-bucket hand auger

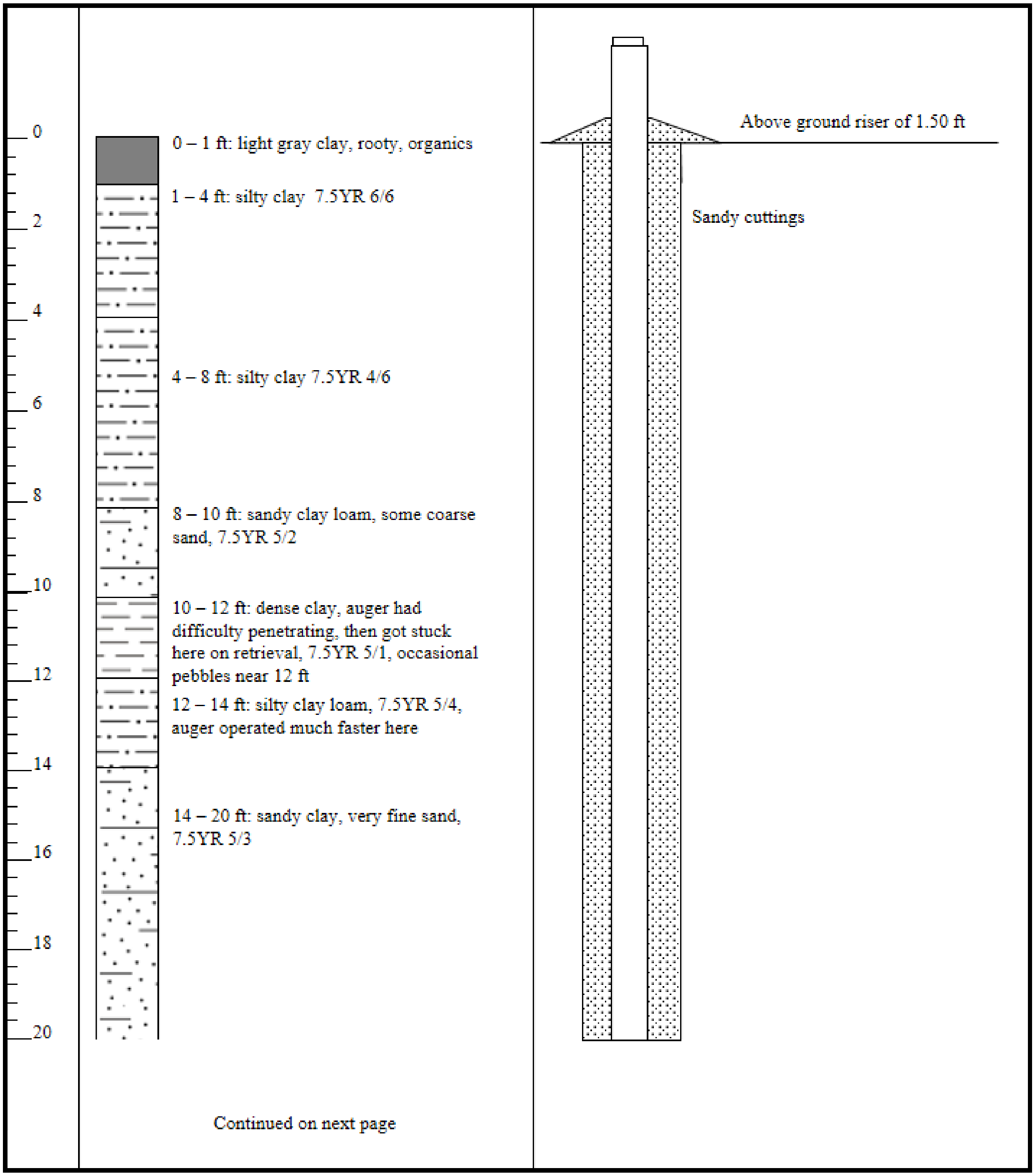
Riser: 103 inch Schedule 40 PVC 2-inch diameter
Joints: glued with purple and blue waterproof PVC cement
Screen: 114 inch 0.010 slot PVC Johnson well screen
Well bailed to removed fines and outfitted with Solinst Levellogger set to record every hour (Start time : 8/22/14 @ 12:00)
Depth to Water 7:20pm 8/20/14 8.25ft

Well Completion Report

Project: Huntley Meadows Water Monitoring
Location: Near variable height outlet
Lat: 38.751367
Long: -77.108461
Top of casing elevation: 40.40 ft

Well Name: ODU_HM1
Constructed by: S. Nagle (Drill operator), S. Stone, B. Hiza
Construction Date: 11/6/14
Auger Type: Drilled with 6-inch hollow-stem auger

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



0 – 1 ft: light gray clay, rooty, organics

1 – 4 ft: silty clay 7.5YR 6/6

4 – 8 ft: silty clay 7.5YR 4/6

8 – 10 ft: sandy clay loam, some coarse sand, 7.5YR 5/2

10 – 12 ft: dense clay, auger had difficulty penetrating, then got stuck here on retrieval, 7.5YR 5/1, occasional pebbles near 12 ft

12 – 14 ft: silty clay loam, 7.5YR 5/4, auger operated much faster here

14 – 20 ft: sandy clay, very fine sand, 7.5YR 5/3

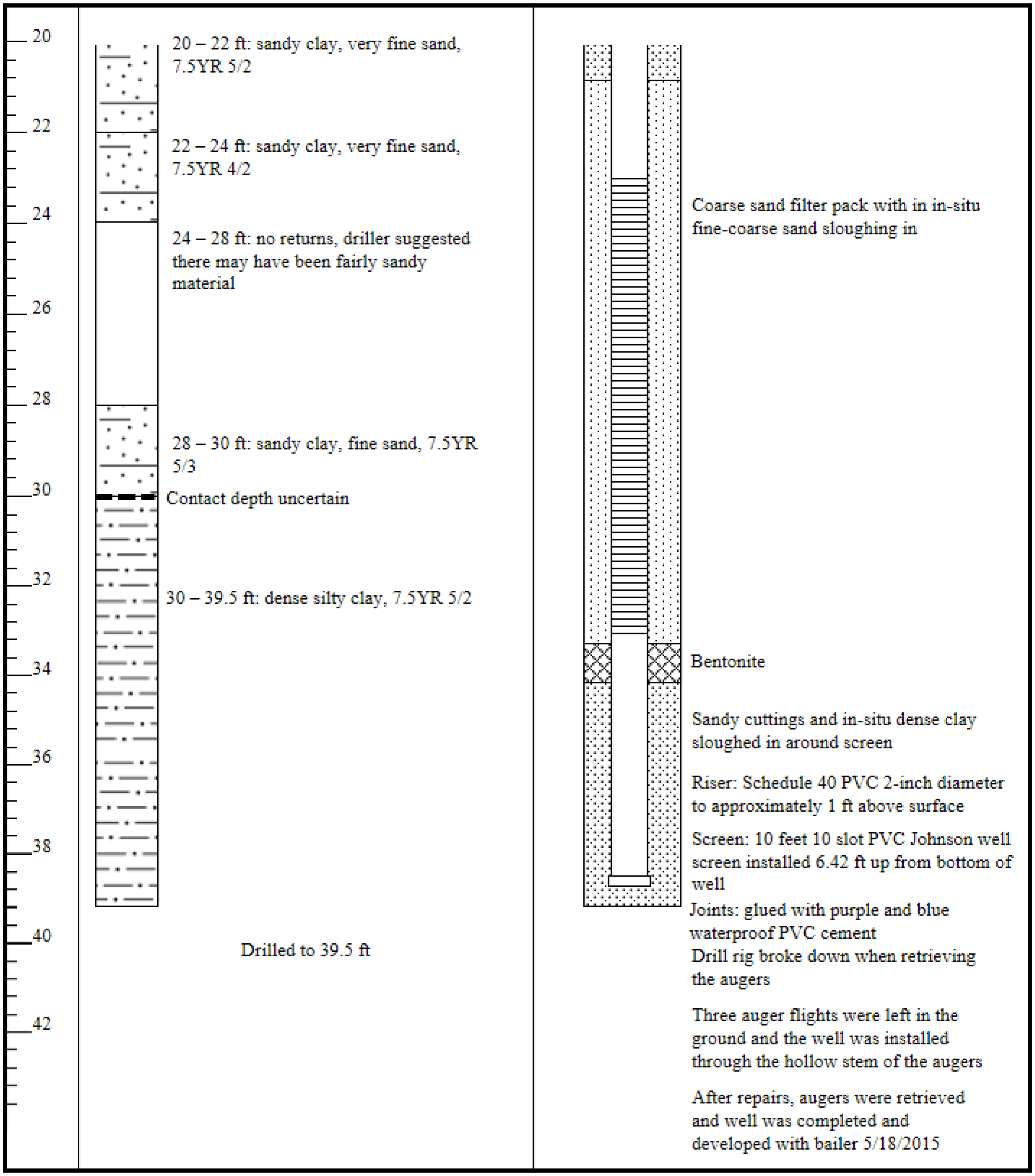
Continued on next page

Well Completion Report (cont.)

Project: Huntley Meadows Water Monitoring
Location: Near variable height outlet
Lat: 38.751367
Long: -77.108461
Top of casing elevation: 40.40 ft

Well Name: ODU_HM1
Constructed by: S. Nagle (Drill operator), S. Stone, B. Hiza
Construction Date: 11/6/14
Auger Type: Drilled with 6-inch hollow-stem auger

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



20 – 22 ft: sandy clay, very fine sand, 7.5YR 5/2

22 – 24 ft: sandy clay, very fine sand, 7.5YR 4/2

24 – 28 ft: no returns, driller suggested there may have been fairly sandy material

28 – 30 ft: sandy clay, fine sand, 7.5YR 5/3

Contact depth uncertain

30 – 39.5 ft: dense silty clay, 7.5YR 5/2

Drilled to 39.5 ft

Coarse sand filter pack with in in-situ fine-coarse sand sloughing in

Bentonite

Sandy cuttings and in-situ dense clay sloughed in around screen

Riser: Schedule 40 PVC 2-inch diameter to approximately 1 ft above surface

Screen: 10 feet 10 slot PVC Johnson well screen installed 6.42 ft up from bottom of well

Joints: glued with purple and blue waterproof PVC cement

Drill rig broke down when retrieving the augers

Three auger flights were left in the ground and the well was installed through the hollow stem of the augers

After repairs, augers were retrieved and well was completed and developed with bailer 5/18/2015

APPENDIX C

SLUG TEST DATA

VTHD1 Slug Test Data

Material Tested: clayey fine and medium sand

Method Used: Hvorslev

Date: 8/21/14	Trial 1		Trial 2		Trial 3	
T (secs)	H (m)	H/H_0	H (m)	H/H_0	H (m)	H/H_0
0	0.36	1.00	0.47	1.00	0.42	1.00
30	0.23	0.65	0.28	0.59	0.27	0.65
60	0.17	0.47	0.20	0.43	0.20	0.47
90	0.12	0.35	0.15	0.32	0.15	0.35
120	0.10	0.26	0.11	0.25	0.11	0.27
150	0.07	0.21	0.09	0.19	0.09	0.21
180	0.06	0.16	0.07	0.15	0.07	0.17
210	0.05	0.13	0.06	0.12	0.06	0.13
240	0.04	0.10	0.04	0.10	0.04	0.11
270	0.03	0.08	0.04	0.08	0.04	0.09
300	0.02	0.07	0.03	0.07	0.03	0.07
330	0.02	0.05	0.03	0.05	0.03	0.06
360	0.02	0.04	0.02	0.04	0.02	0.05
390	0.01	0.04	0.02	0.04	0.02	0.04
420	0.01	0.03	0.02	0.03	0.01	0.03
450	0.01	0.02	0.01	0.03	0.01	0.03
480	0.01	0.02	0.01	0.02	0.01	0.02
510	0.01	0.02	0.01	0.02	0.01	0.02
540	0.01	0.02	0.01	0.01	0.01	0.02
570	0.00	0.01	0.01	0.01	0.01	0.02
600	0.00	0.01	0.01	0.01	0.01	0.01

VTHD2 Slug Test Data

Material Tested: very coarse sand and gravel

Method Used: Hvorslev

Date: 8/21/14	Trial 1		Trial 2		Trial 3	
T (secs)	H (m)	H/H_0	H (m)	H/H_0	H (m)	H/H_0
0	0.39	1.00	0.41	1.00	0.45	1.00
1	0.27	0.70	0.36	0.88	0.32	0.71
2	0.19	0.48	0.24	0.58	0.20	0.45
3	0.13	0.32	0.16	0.38	0.13	0.29
4	0.09	0.22	0.11	0.26	0.09	0.19
5	0.06	0.15	0.07	0.17	0.05	0.12
6	0.04	0.10	0.05	0.11	0.04	0.08
7	0.03	0.06	0.03	0.08	0.02	0.05
8	0.02	0.04	0.02	0.05	0.02	0.03
9	0.01	0.02	0.01	0.03	0.01	0.02
10	0.00	0.01	0.01	0.02	0.01	0.01
11	0.00	0.00	0.01	0.01	0.00	0.00
12			0.00	0.01		

ODU_HM1 Slug Test Data

Material Tested: silty fine sand						
Method Used: Hvorslev						
Date: 8/4/15	Trial 1		Trial 2		Trial 3	
T (secs)	H (m)	H/H_0	H (m)	H/H_0	H (m)	H/H_0
0	0.40	1.00	0.57	1.00	0.30	1.00
5	0.27	0.69	0.29	0.52	0.31	1.01
10	0.19	0.48	0.18	0.33	0.17	0.57
15	0.13	0.33	0.12	0.20	0.10	0.33
20	0.09	0.24	0.07	0.13	0.06	0.19
25	0.07	0.17	0.05	0.08	0.03	0.11
30	0.04	0.10	0.03	0.05	0.02	0.06
35	0.04	0.09	0.02	0.03	0.01	0.04
40	0.03	0.06	0.01	0.02	0.01	0.02
45	0.02	0.05	0.01	0.02	0.01	0.02
50	0.02	0.04	0.01	0.01	0.00	0.01
55	0.01	0.02	0.01	0.01	0.00	0.01
60	0.01	0.02	0.00	0.01	0.00	0.01
65	0.01	0.01			0.00	0.00
70	0.00	0.01				
75	0.00	0.00				

VTHD3 Slug Test Data

Material Tested: clayey fine and medium sand			
Method Used: Bouwer and Rice			
Date: 8/21/14	Trial 1	Trial 2	Trial 3
T (secs)	Drawdown (m)	Drawdown (m)	Drawdown (m)
0	0.46	0.47	0.49
15	0.38	0.35	0.36
30	0.29	0.25	0.26
45	0.21	0.18	0.19
60	0.16	0.13	0.14
75	0.12	0.10	0.10
90	0.09	0.07	0.08
105	0.06	0.06	0.06
120	0.05	0.04	0.04
135	0.04	0.04	0.03
150	0.03	0.03	0.03
165	0.02	0.02	0.02
180	0.02	0.02	0.02
195	0.01	0.02	0.02
210	0.01	0.01	0.01
225	0.01	0.01	0.01
240	0.01	0.01	0.01
255	0.01	0.01	0.01
270	0.00	0.01	0.01
285	0.00	0.01	0.01
300	0.00	0.01	0.01

ODU_ET1 Slug Test Data

Material Tested: clayey fine sand			
Method Used: Bouwer and Rice			
Date:	08/21/2014		11/10/2015
	Trial 1	Trial 2	Trial 3
T (secs)	Drawdown (m)	Drawdown (m)	Drawdown (m)
0	0.45	0.39	0.59
60	0.23	0.23	0.36
120	0.20	0.19	0.33
180	0.17	0.16	0.31
240	0.15	0.14	0.29
300	0.13	0.13	0.28
360	0.12	0.11	0.26
420	0.10	0.10	0.25
480	0.08	0.09	0.24
540	0.08	0.08	0.23
600	0.07	0.06	0.21
660	0.06	0.06	0.20
720	0.06	0.05	0.20
780	0.05	0.04	0.19
840	0.04	0.04	0.18
900	0.04	0.03	0.17
960	0.03	0.03	0.17
1020	0.03	0.03	0.16
1080	0.03	0.02	0.15
1140	0.02	0.02	0.15
1200	0.02	0.01	0.14
1260	0.01	0.01	0.14
1320	0.02	0.01	0.13
1380	0.01	0.01	0.13
1440	0.01	0.00	0.12

ODU_ET2 Slug Test Data

Material Tested: clay with silt lenses			
Method Used: Bouwer and Rice			
Date:	08/21/2014	11/10/2015	
	Trial 1	Trial 2	Trial 3
T (secs)	Drawdown (m)	Drawdown (m)	Drawdown (m)
0	0.35	0.43	
60	0.17	0.26	
120	0.15	0.19	
180	0.15	0.14	
240	0.14	0.11	
300	0.13	0.08	
360	0.13	0.06	
420	0.12	0.05	
480	0.12	0.04	
540	0.11	0.03	
600	0.11	0.02	
660	0.11	0.02	
720	0.10	0.01	
780	0.10	0.01	
840	0.09	0.01	
900	0.09	0.00	
960	0.09	0.00	
1020	0.08	0.00	
1080	0.08	0.00	
1140	0.08	0.00	
1200	0.08	0.00	
1260	0.07		
1320	0.07		
1380	0.06		
1440	0.06		
1500	0.06		
1560	0.06		
1620	0.06		
1680	0.06		
1740	0.05		
1800	0.05		
1860	0.05		
1920	0.05		
1980	0.04		

Note: Initial depth-to-water for trial one was 2.26 m. Initial depth-to-water for trial two was 1.32 m.

APPENDIX D

SPECIFIC YIELD TEST DATA

Key for water table response to precipitation data tables:

Precip = Precipitation

Peak = Observed water table high following precipitation event

Low = Observed water table low immediately prior to precipitation event

ΔWT = Difference between Peak and Low water table elevations

n_d = Drainable porosity

Sy = Specific yield

T1A Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	11/13/2012	12.7	9.95	9.76	0.19	6.6	0.07
2	12/26/2012	36.1	10.16	9.90	0.26	14.0	0.14
3	02/26/2013	15.7	10.14	9.93	0.21	7.6	0.08
4	03/06/2013	26.2	10.16	9.92	0.24	10.9	0.11
5	03/12/2013	21.1	10.15	9.94	0.21	10.1	0.10
6	03/18/2013	8.1	10.06	9.95	0.11	7.4	0.07
7	03/25/2013	13.2	10.09	9.95	0.14	9.7	0.10

T1B Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	10.44	10.14	0.30	5.3	0.05
2	03/06/2013	26.2	10.50	10.22	0.28	9.4	0.09
3	03/12/2013	21.1	10.50	10.34	0.16	13.2	0.13
4	03/18/2013	8.1	10.46	10.31	0.15	5.3	0.05
5	03/25/2013	13.2	10.47	10.29	0.18	7.2	0.07
6							
7							

T1C Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	10.84	10.62	0.22	7.2	0.07
2	03/06/2013	26.2	10.93	10.67	0.26	10.0	0.10
3	03/12/2013	21.1	10.94	10.76	0.18	11.7	0.12
4	03/18/2013	8.1	10.86	10.75	0.11	7.3	0.07
5	03/25/2013	13.2	10.88	10.73	0.15	8.7	0.09
6							
7							

T2A Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	11/13/2012	12.7	9.69	9.65	0.30	27.8	0.28
2	03/18/2013	8.1	9.79	9.76	0.03	30.0	0.30
3							
4							
5							
6							
7							

T2B Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	10.28	9.77	0.49	3.1	0.03
2	03/06/2013	26.2	10.32	9.91	0.41	6.4	0.06
3	03/12/2013	21.1	10.31	10.08	0.23	9.1	0.09
4	03/18/2013	8.1	10.25	9.97	0.28	2.9	0.03
5	03/25/2013	13.2	10.28	9.92	0.36	3.6	0.04
6							
7							

T2C Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	10.81	10.62	0.19	8.3	0.08
2	03/06/2013	26.2	10.89	10.62	0.27	9.9	0.10
3	03/12/2013	21.1	10.85	10.68	0.17	12.1	0.12
4	03/18/2013	8.1	10.79	10.64	0.15	5.2	0.05
5	03/25/2013	13.2	10.83	10.62	0.21	6.4	0.06
6							
7							

T3A Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	11/13/2012	12.7	10.01	9.81	0.20	6.6	0.07
2	12/26/2012	36.1	10.17	9.93	0.24	15.3	0.15
3	02/26/2013	15.7	10.15	9.96	0.19	8.1	0.08
4	03/06/2013	26.2	10.18	9.95	0.23	11.6	0.12
5	03/12/2013	21.1	10.17	9.99	0.18	11.8	0.12
6	03/18/2013	8.1	10.11	9.99	0.12	6.6	0.07
7	03/25/2013	13.2	10.15	9.99	0.16	8.2	0.08

T3B Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	10.36	9.88	0.48	3.3	0.03
2	03/06/2013	26.2	10.74	10.15	0.59	4.4	0.04
3	03/12/2013	21.1	10.76	10.57	0.19	11.1	0.11
4	03/18/2013	8.1	10.76	10.54	0.22	3.8	0.04
5	03/25/2013	13.2	10.77	10.53	0.24	5.6	0.06
6							
7							

T3C Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	11.10	10.91	0.19	8.3	0.08
2	03/12/2013	21.1	11.14	10.96	0.18	12.1	0.12
3	03/18/2013	8.1	11.08	10.93	0.15	5.2	0.05
4	03/25/2013	13.2	11.11	10.91	0.20	6.4	0.06
5							
6							
7							

T4A Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	12/26/2012	36.1	10.30	10.18	0.12	30.0	0.30
2	02/26/2013	15.7	10.29	10.21	0.08	20.7	0.21
3	03/06/2013	26.2	10.30	10.22	0.08	31.6	0.32
4	03/18/2013	8.1	10.28	10.24	0.04	18.4	0.18
5	03/25/2013	13.2	10.29	10.24	0.05	26.9	0.27
6							
7							

T4B Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	10.33	9.84	0.49	3.2	0.03
2	03/06/2013	26.2	10.84	10.23	0.61	4.3	0.04
3	03/01/2015	13	10.84	10.73	0.11	11.6	0.12
4							
5							
6							
7							

T4C Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	02/26/2013	15.7	11.00	10.62	0.38	4.1	0.04
2	03/06/2013	26.2	11.24	10.87	0.37	7.0	0.07
3	03/12/2013	21.1	11.26	11.14	0.12	18.0	0.18
4	03/18/2013	8.1	11.24	11.13	0.11	7.7	0.08
5	03/25/2013	13.2	11.24	11.14	0.10	13.3	0.13
6							
7							

ODU_ET1 Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	01/12/2015	19.1	16.72	16.33	0.39	4.9	0.05
2	01/18/2015	15.2	16.87	16.63	0.24	6.4	0.06
3	03/14/2015	15.2	17.09	16.99	0.10	15.0	0.15
4	03/20/2015	12.4	17.05	16.94	0.11	11.4	0.11
5							
6							
7							

ODU_ET2 Water Table Response to Precipitation Data

Event	Date	Precip (mm)	Peak (m)	Low (m)	ΔWT (m)	n_d (%)	Sy
1	12/16/2014	10.2	11.37	11.25	0.12	8.2	0.08
2	01/12/2015	19.1	11.39	11.23	0.16	12.3	0.12
3	01/18/2015	15.2	11.38	11.27	0.11	13.9	0.14
4	03/20/2015	12.4	11.34	11.23	0.11	10.7	0.11
5							
6							
7							

APPENDIX E

MATLAB SCRIPT FOR AET ESTIMATES

As the script was being developed its output was compared to that of an AET estimate that was determined manually. The script processes a seventy-three point subset of hourly head data saved in a comma-separated values format (.csv). The time span for the subset is noon two days prior to the day of interest through noon of the day after the day of interest; for example, if one were interested in estimating AET on September 7th the subset should contain readings from noon of September 5th through noon of September 8th. The headings for the .csv file are as follows: ID, Date, Time, and Head. The ID column contains a numerical ID for each hourly reading. The numerical ID is an identifier that is used to differentiate each hourly reading for the sake of ease when processing the data. The Date column contains the date the reading was taken in MM/DD/YYYY format. The Time column contains the time the reading was taken in HH:MM:SS format. The Head column contains hourly head readings in meters.

A separate script was saved for each well that was processed containing the specific yield value that was determined for that well by evaluating the water table response to precipitation events. Once the Sy value is established in the script, the .csv file is imported and used to create and populate variables within Matlab. The script then prepares two figures, one figure containing a plot of the raw data within the subset, and a second that is used for estimating ET.

The first step in estimating ET is to apply a five-point moving average to the dataset. It is for this reason that the subset starts and ends at noon. Zhang and others (2016) found that applying a moving average helped to reduce errors introduced by the monitoring equipment. Once the smoothed data are plotted, best fit lines are produced using the linear regression polyfit command set for the points collected during the hours between 00:00 and 06:00 for each of the three nights represented in the subset. The slopes of the best fit lines for these three nights are then averaged and used to represent the rebound rate. The script determines the rate of the twenty-four hour change by determining the slope of the line from midnight of the day of interest to midnight of the following day. The points representing the hours between 00:00 and 06:00 each night are plotted in red and the lines for each of the rebound rates and the twenty-four hour decline rate are plotted for the user to review prior to accepting the AET rate. The AET rate is determined by multiplying the net sum of the averaged rebound rate and the twenty-four hour decline rate by the specific yield the user entered at the start of the script. In this study, in order for a rate to be considered acceptable the sign of all of the rebound slopes had to be the same and a diurnal signal needed to be obvious. The following samples of the script, output, and raw data could be used to recreate, and validate, the MATLAB script for future investigations.

SAMPLE MATLAB SCRIPT

```
%This script is intended to be used to determine the ET rate at a given location from a subset
%of data taken from a pressure transducer at a well screened in the
%ripirian zone

%reset all variables, close figure window(s)
clear all;
close all;

%data should be continuous and taken at hourly intervals
%subset of data should begin at 12 noon two days before the daily rate being calculated and
%continue at least through 12 noon of the last day being evaluated.
%export data from excel as .csv (comma separated values)
%determine specific yield for the well of interest outside of matlab and
%assign it here:
Sy = 0.09

%retrieves comma sep. values from subset csv
[ID, date, time, Headm]=textread('ODU_ET1_Subset_12Jun2015_D.csv','%f %s %s
%f','headerlines',1,'delimiter',',');
%textscan has not been working properly for importing anything other than
%numbers
```

```
figure;
%Plot raw data
subplot(1,2,1);
plot(ID, Headm, '+');
 xlabel('Hours');
 ylabel('Head (m)');
% plot smoothed data (uses 5 day moving average)
head = smooth(Headm);
subplot(1,2,2);
plot(ID, head, '+');
 xlabel('Hours');
 ylabel('head (m)');


 %hold on to use same figure and overlay plots of 12AM to 6AM data from each night
hold on;

%first night
ID1 = ID(13:19);
Headm1 = head(13:19);
plot(ID1, Headm1, 'r+');

    %linear model for first night polyfit(x, y, number of variables)
    %for method info see http://www.mathworks.com/help/matlab/data_analysis/linear-
regression.html
    %output shows p1(1) = slope, p1(2) = y-intercept
    p1 = polyfit(ID1, Headm1, 1)
    %use polyval to use p1 to predict Headm (y) values, saves from writing
    %model eqn yourself
    yfit1 = polyval(p1,ID1);
    %compute the residual values as a vector of signed numbers
    yresid1 = Headm1 - yfit1;
    %square the residual values and total them to obtain residual sum of
    %squares
    SSresid1 = sum(yresid1.^2);
    %compute the total sum of squares of Headm1 by multiplying the variance of
    %Headm1 by the number of observations minus 1
    SStotal1 = (length(Headm1)-1) * var(Headm1);
    %compute r^2, to demonstrate how well the model predicts the variance of
    %Headm1
    rsq1 = 1 - SSresid1/SStotal1
    %plot line of model
    plot(ID1, yfit1);
    %save slope as value in an array
    s1(1) = p1(1,1);
```

```
%second night
ID2 = ID(37:43);
Headm2 = head(37:43);
plot(ID2, Headm2, 'r+');

   %linear model for second night polyfit(x, y, number of variables)
   %for method info see http://www.mathworks.com/help/matlab/data_analysis/linear-
regression.html
   %output shows p2(1) = slope, p2(2) = y-intercept
   p2 = polyfit(ID2, Headm2, 1)
   %use polyval to use p2 to predict Headm (y) values, saves from writing
   %model eqn yourself
   yfit2 = polyval(p2,ID2);
   %compute the residual values as a vector of signed numbers
   yresid2 = Headm2 - yfit2;
   %square the residual values and total them to obtain residual sum of
   %squares
   SSresid2 = sum(yresid2.^2);
   %compute the total sum of squares of Headm2 by multiplying the variance of
   %Headm2 by the number of observations minus 1
   SStotal2 = (length(Headm2)-1) * var(Headm2);
   %compute r^2, to demonstrate how well the model predicts the variance of
   %Headm2
   rsq2 = 1 - SSresid2/SStotal2
   %plot line of model
   plot(ID2, yfit2);
   %save slope as value in an array
   s1(2) = p2(1,1);

%third night
ID3 = ID(61:67);
Headm3 = head(61:67);
plot(ID3, Headm3, 'r+');

   %linear model for third night polyfit(x, y, number of variables)
   %for method info see http://www.mathworks.com/help/matlab/data_analysis/linear-
regression.html
   %output shows p3(1) = slope, p3(2) = y-intercept
   p3 = polyfit(ID3, Headm3, 1)
   %use polyval to use p3 to predict Headm (y) values, saves from writing
   %model eqn yourself
   yfit3 = polyval(p3,ID3);
   %compute the residual values as a vector of signed numbers
```

```
    yresid3 = Headm3 - yfit3;
    %square the residual values and total them to obtain residual sum of
    %squares
    SSresid3 = sum(yresid3.^2);
    %compute the total sum of squares of Headm3 by multiplying the variance of
    %Headm3 by the number of observations minus 1
    SStotal3 = (length(Headm3)-1) * var(Headm3);
    %compute r^2, to demonstrate how well the model predicts the variance of
    %Headm3
    rsq3 = 1 - SSresid3/SStotal3
    %plot line of model
    plot(ID3, yfit3);
    %save slope as value in an array
    s1(3) = p3(1,1);


%24hr change in water table height (s2, slope of the line from midnight of
%the night before to midnight of the day of interest)
    s2 = ((head(61)-head(37))/(ID(61)-ID(37)))


%plot line of 24hr change in water height for visual inspection
    plot([ID(37) ID(61)],[head(37) head(61)]);


%ET rate calculation
    s1av = mean(s1)
    %meters/hr
    ET = Sy * (s1av - s2)
    %mm/day
    ET_mm_per_day = ET * 1000 * 24

%display magnitude and sign of recovery slopes in the Command Window
    s1

%Accept the 'ET_mm_per_day' rate if:
    %the sign of the three recovery slopes is the same
    %there is an obvious diurnal signal
    %the last twenty-four hour period appears to be unaffected by
    %precipitation
```

SAMPLE OF CORRESPONDING GRAPHICAL OUTPUT FROM MATLAB

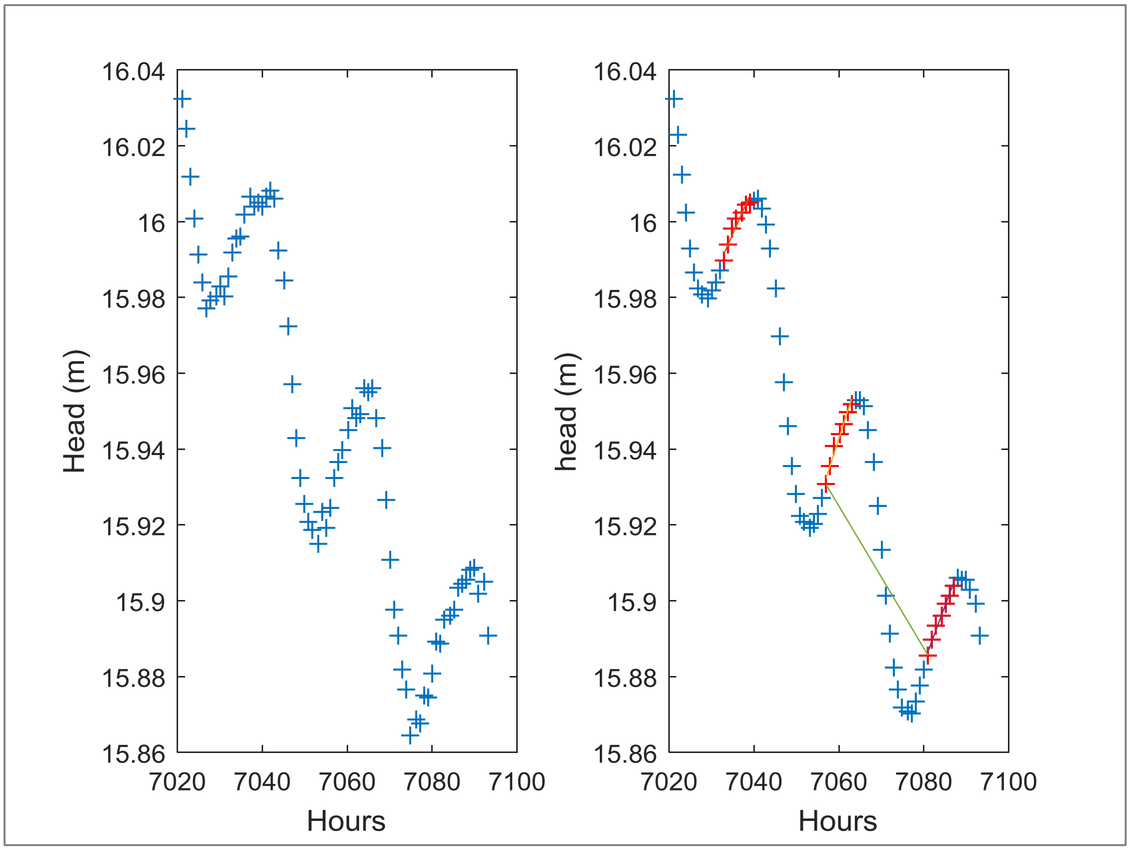


Fig. E-1. Hours correspond to data collected from 12:00:00 06/10/2015 – 12:00:00 06/13/2015 at ODU_ET1. The plot on left side is the raw data. The plot on the right side has had a five-point moving average applied to the same data set as is displayed in the plot of the left side. Red crosses and lines indicate the points used to determine the nightly recovery rates. The green line represents the 24-hour change in head for the period of interest.

SAMPLE OF CORRESPONDING MATLAB COMMAND WINDOW OUTPUT

```
>> Whites_ODU_ET1_D


Sy =

    0.0900


p1 =

    0.0025   -1.7450


rsq1 =

    0.9387


p2 =

    0.0035   -8.5993


rsq2 =

    0.9725


p3 =

    0.0030   -5.3902


rsq3 =

    0.9885


s2 =

   -0.0019


s1av =

    0.0030
```

```
ET =
   4.3889e-04

ET_mm_per_day =
   10.5334

s1 =
    0.0025    0.0035    0.0030
```

HOURLY DATA SET EXAMPLE USED TO DETERMINE AET WITH MATLAB

ODU_ET1_Subset_12Jun2015_D.csv

ID	Date	Time	Head (m)
7021	06/10/2015	12:00:00	16.0326
7022	06/10/2015	13:00:00	16.0243
7023	06/10/2015	14:00:00	16.0119
7024	06/10/2015	15:00:00	16.0006
7025	06/10/2015	16:00:00	15.9915
7026	06/10/2015	17:00:00	15.9841
7027	06/10/2015	18:00:00	15.9773
7028	06/10/2015	19:00:00	15.9792
7029	06/10/2015	20:00:00	15.9803
7030	06/10/2015	21:00:00	15.983
7031	06/10/2015	22:00:00	15.9801
7032	06/10/2015	23:00:00	15.9856
7033	06/11/2015	00:00:00	15.9919
7034	06/11/2015	01:00:00	15.9953
7035	06/11/2015	02:00:00	15.9959
7036	06/11/2015	03:00:00	16.0019
7037	06/11/2015	04:00:00	16.0064
7038	06/11/2015	05:00:00	16.0038
7039	06/11/2015	06:00:00	16.005
7040	06/11/2015	07:00:00	16.0041
7041	06/11/2015	08:00:00	16.0063
7042	06/11/2015	09:00:00	16.0079
7043	06/11/2015	10:00:00	16.0063
7044	06/11/2015	11:00:00	15.9921
7045	06/11/2015	12:00:00	15.9846
7046	06/11/2015	13:00:00	15.9725
7047	06/11/2015	14:00:00	15.9569
7048	06/11/2015	15:00:00	15.9427
7049	06/11/2015	16:00:00	15.9323
7050	06/11/2015	17:00:00	15.9257
7051	06/11/2015	18:00:00	15.9207
7052	06/11/2015	19:00:00	15.9185
7053	06/11/2015	20:00:00	15.915
7054	06/11/2015	21:00:00	15.9236
7055	06/11/2015	22:00:00	15.9192

ODU_ET1_Subset_12Jun2015_D.csv (continued)

ID	Date	Time	Head (m)
7056	06/11/2015	23:00:00	15.9247
7057	06/12/2015	00:00:00	15.9325
7058	06/12/2015	01:00:00	15.9368
7059	06/12/2015	02:00:00	15.9399
7060	06/12/2015	03:00:00	15.9448
7061	06/12/2015	04:00:00	15.9509
7062	06/12/2015	05:00:00	15.9482
7063	06/12/2015	06:00:00	15.9491
7064	06/12/2015	07:00:00	15.9561
7065	06/12/2015	08:00:00	15.9549
7066	06/12/2015	09:00:00	15.9558
7067	06/12/2015	10:00:00	15.9483
7068	06/12/2015	11:00:00	15.9405
7069	06/12/2015	12:00:00	15.9267
7070	06/12/2015	13:00:00	15.9106
7071	06/12/2015	14:00:00	15.8979
7072	06/12/2015	15:00:00	15.891
7073	06/12/2015	16:00:00	15.8816
7074	06/12/2015	17:00:00	15.8766
7075	06/12/2015	18:00:00	15.8645
7076	06/12/2015	19:00:00	15.8689
7077	06/12/2015	20:00:00	15.8677
7078	06/12/2015	21:00:00	15.875
7079	06/12/2015	22:00:00	15.8747
7080	06/12/2015	23:00:00	15.8808
7081	06/13/2015	00:00:00	15.8892
7082	06/13/2015	01:00:00	15.8885
7083	06/13/2015	02:00:00	15.8948
7084	06/13/2015	03:00:00	15.8961
7085	06/13/2015	04:00:00	15.8978
7086	06/13/2015	05:00:00	15.9036
7087	06/13/2015	06:00:00	15.9045
7088	06/13/2015	07:00:00	15.9055
7089	06/13/2015	08:00:00	15.908
7090	06/13/2015	09:00:00	15.9087
7091	06/13/2015	10:00:00	15.9017
7092	06/13/2015	11:00:00	15.905
7093	06/13/2015	12:00:00	15.891

APPENDIX F

ADVANCED MODEL SETUP DATA

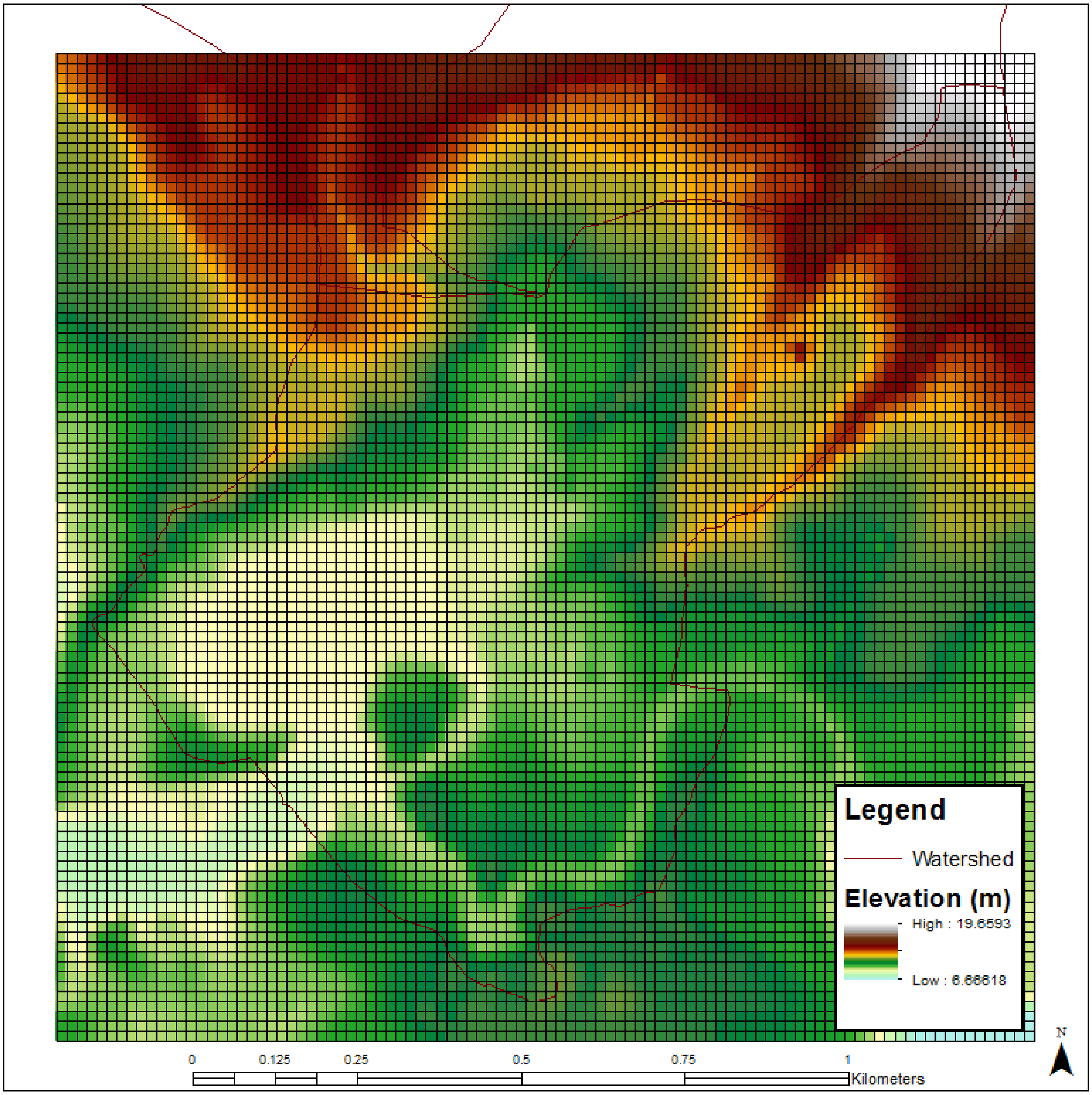
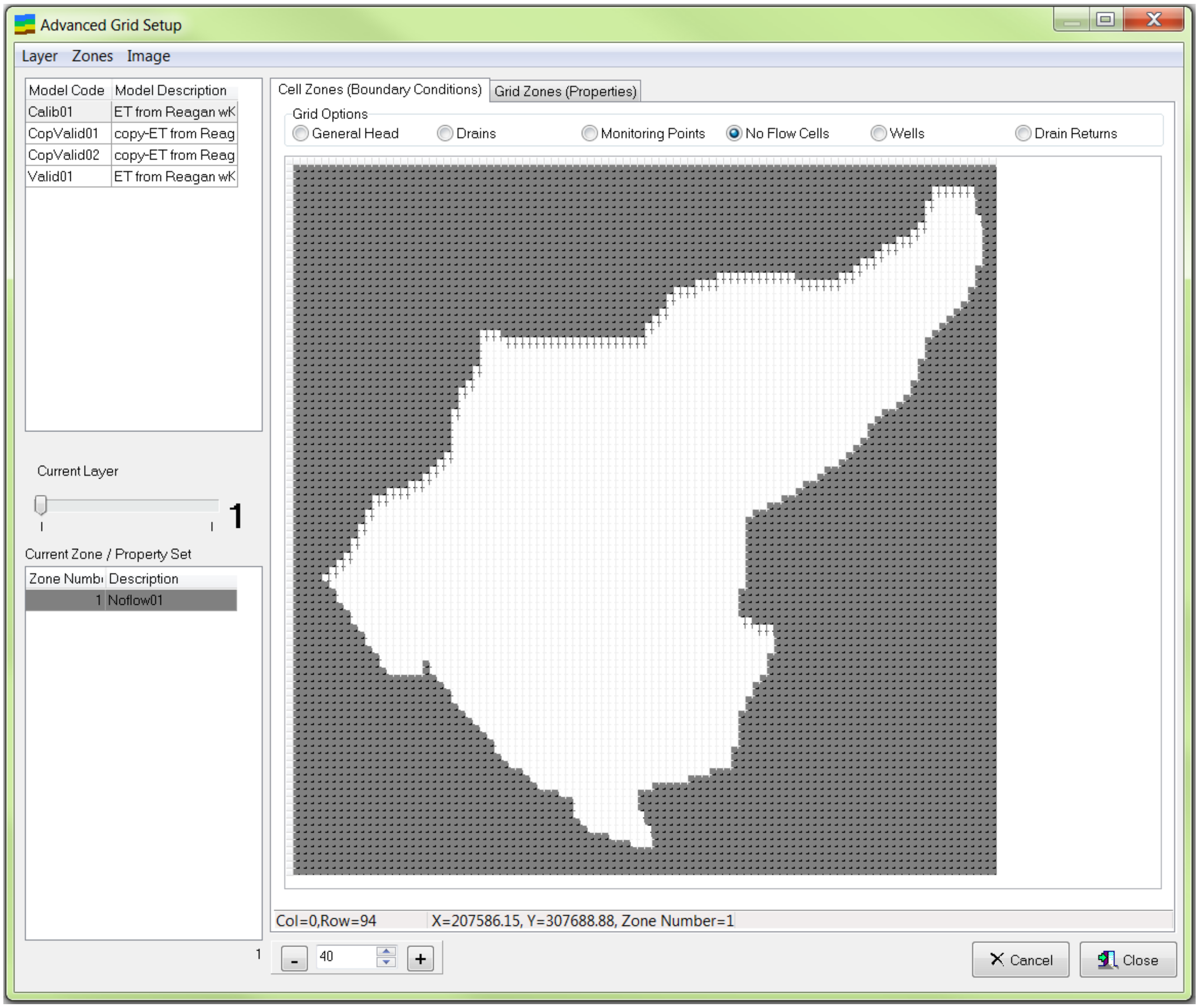


Fig. F-1. Elevation data from ArcGIS used to represent ground surface in Advanced Scenarios. Grid dimensions match those used in Wetbud.

BEGIN SCREENSHOTS FROM WETBUD



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

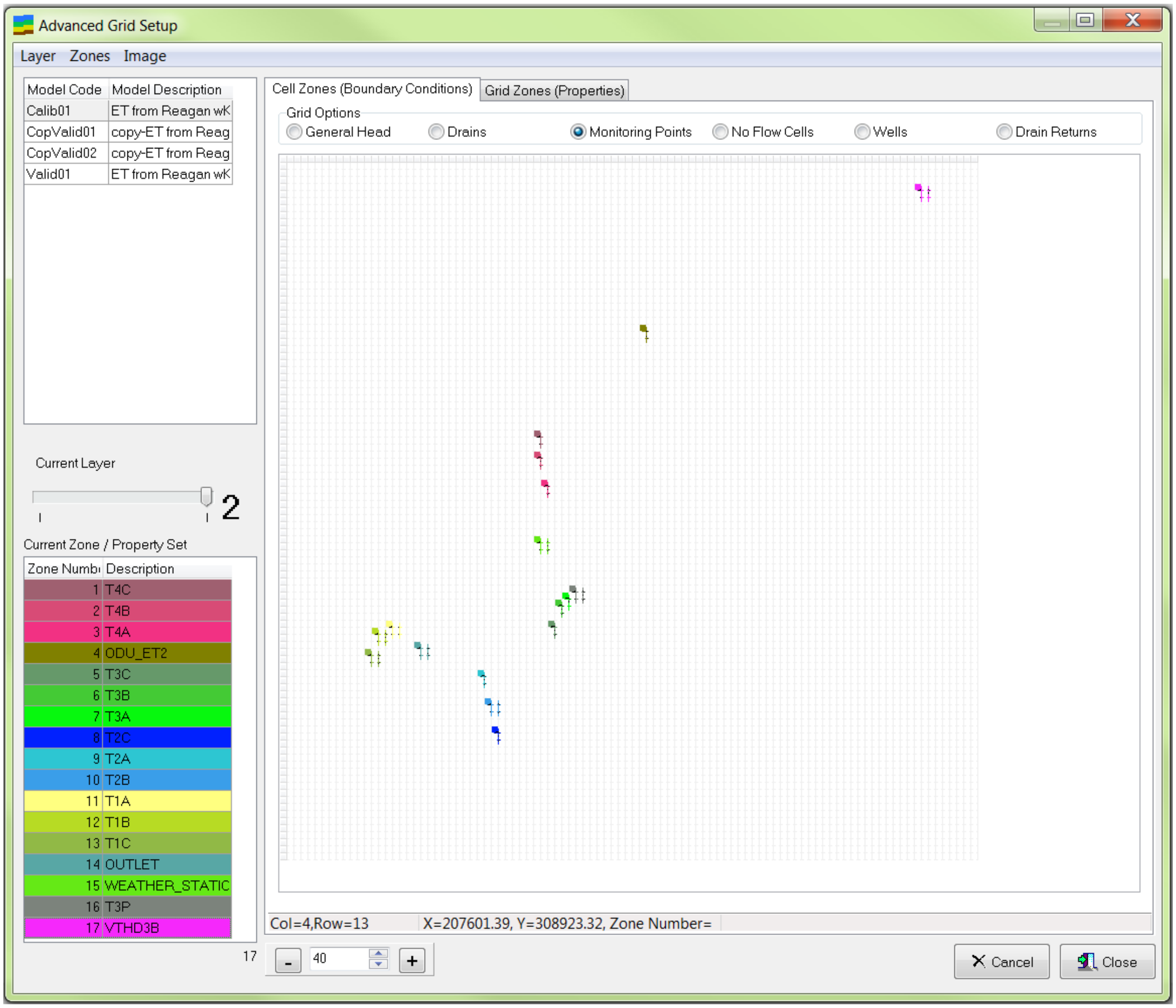
Grid Options
○ General Head ○ Drains ○ Monitoring Points ● No Flow Cells ○ Wells ○ Drain Returns

Zone Numb	Description
1	Noflow01

Col=0,Row=94 X=207586.15, Y=307688.88, Zone Number=1

40

Fig. F-2. No-flow boundary used in all Advanced Scenarios.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

○ General Head ○ Drains ● Monitoring Points ○ No Flow Cells ○ Wells ○ Drain Returns

Current Layer: 2

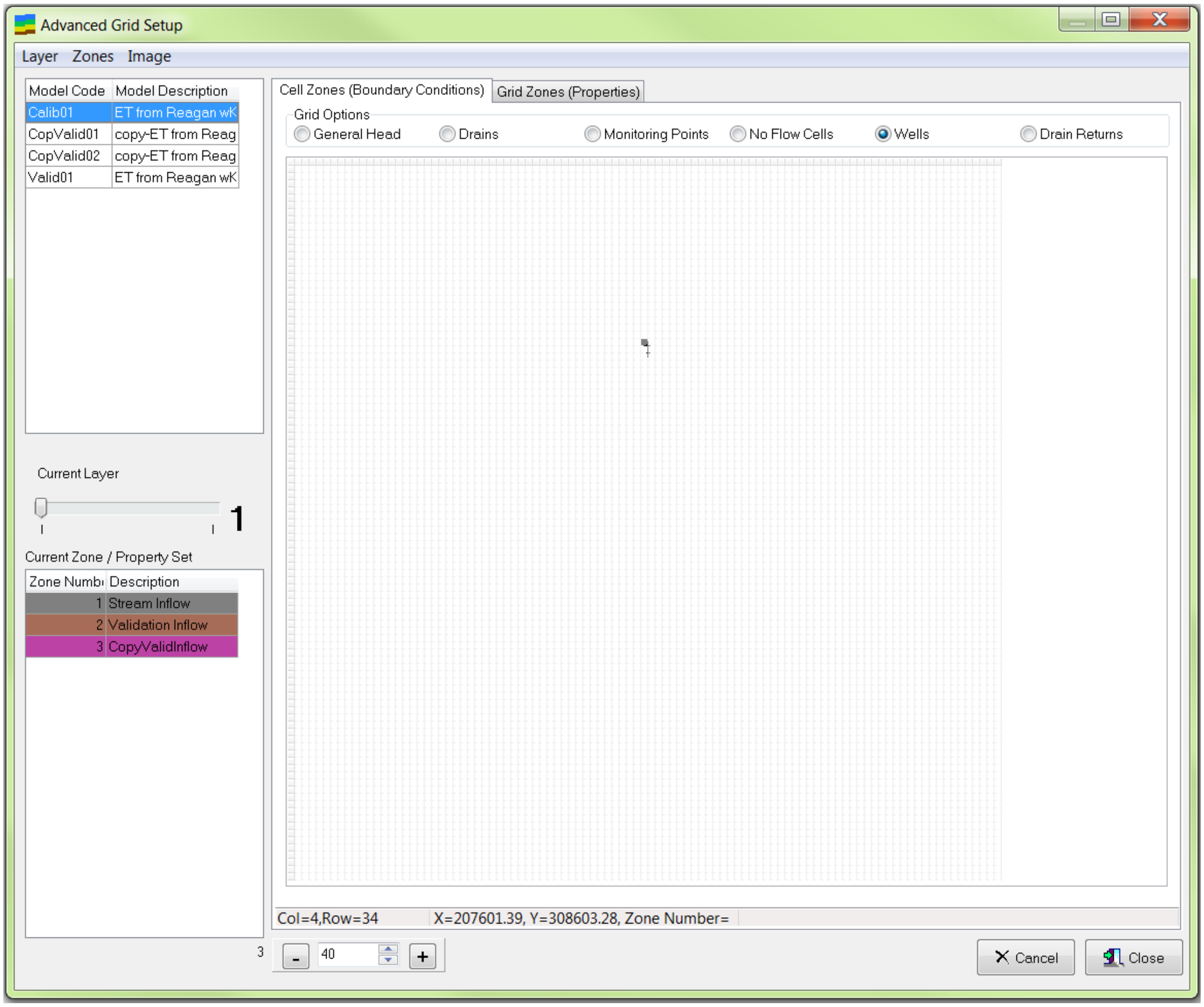
Zone Numb	Description
1	T4C
2	T4B
3	T4A
4	ODU_ET2
5	T3C
6	T3B
7	T3A
8	T2C
9	T2A
10	T2B
11	T1A
12	T1B
13	T1C
14	OUTLET
15	WEATHER_STATIC
16	T3P
17	VTHD3B

17

Col=4,Row=13 X=207601.39, Y=308923.32, Zone Number=

40

Fig. F-3. Monitoring point locations used in all Advanced Scenarios.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

Current Layer 1

Current Zone / Property Set

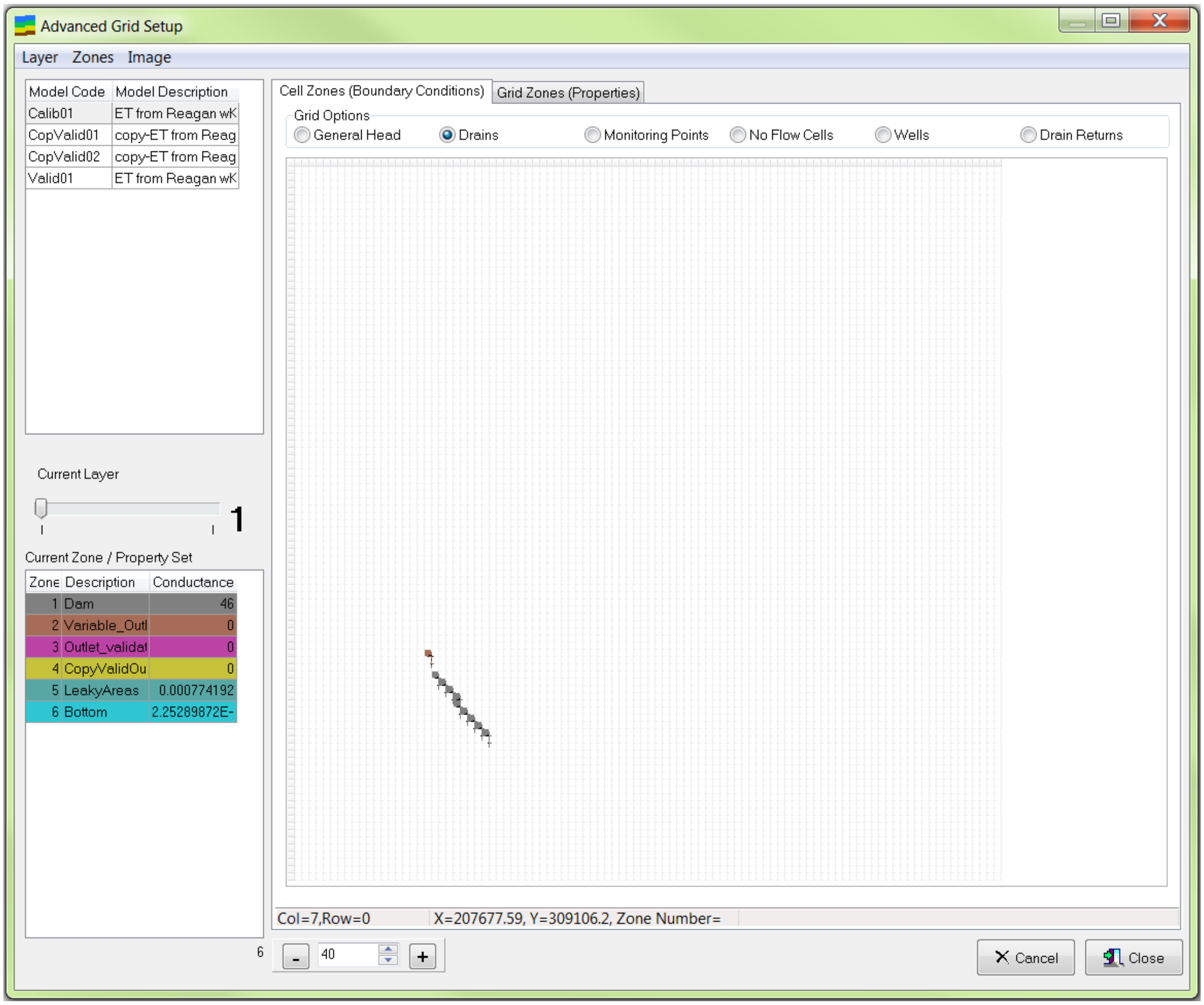
Zone Numb	Description
1	Stream Inflow
2	Validation Inflow
3	CopyValidInflow

Grid Options: ○ General Head ○ Drains ○ Monitoring Points ○ No Flow Cells ● Wells ○ Drain Returns

Col=4,Row=34 X=207601.39, Y=308603.28, Zone Number=

3 40

Fig. F-4. Location of well used to add water from sub-basins 1 and 2. Location was the same for all Advanced Scenarios. Zone number changed depending on the time period that was modeled.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

Current Layer 1

Current Zone / Property Set

Zone	Description	Conductance
1	Dam	46
2	Variable_Outl	0
3	Outlet_validat	0
4	CopyValidOu	0
5	LeakyAreas	0.000774192
6	Bottom	2.25289872E-

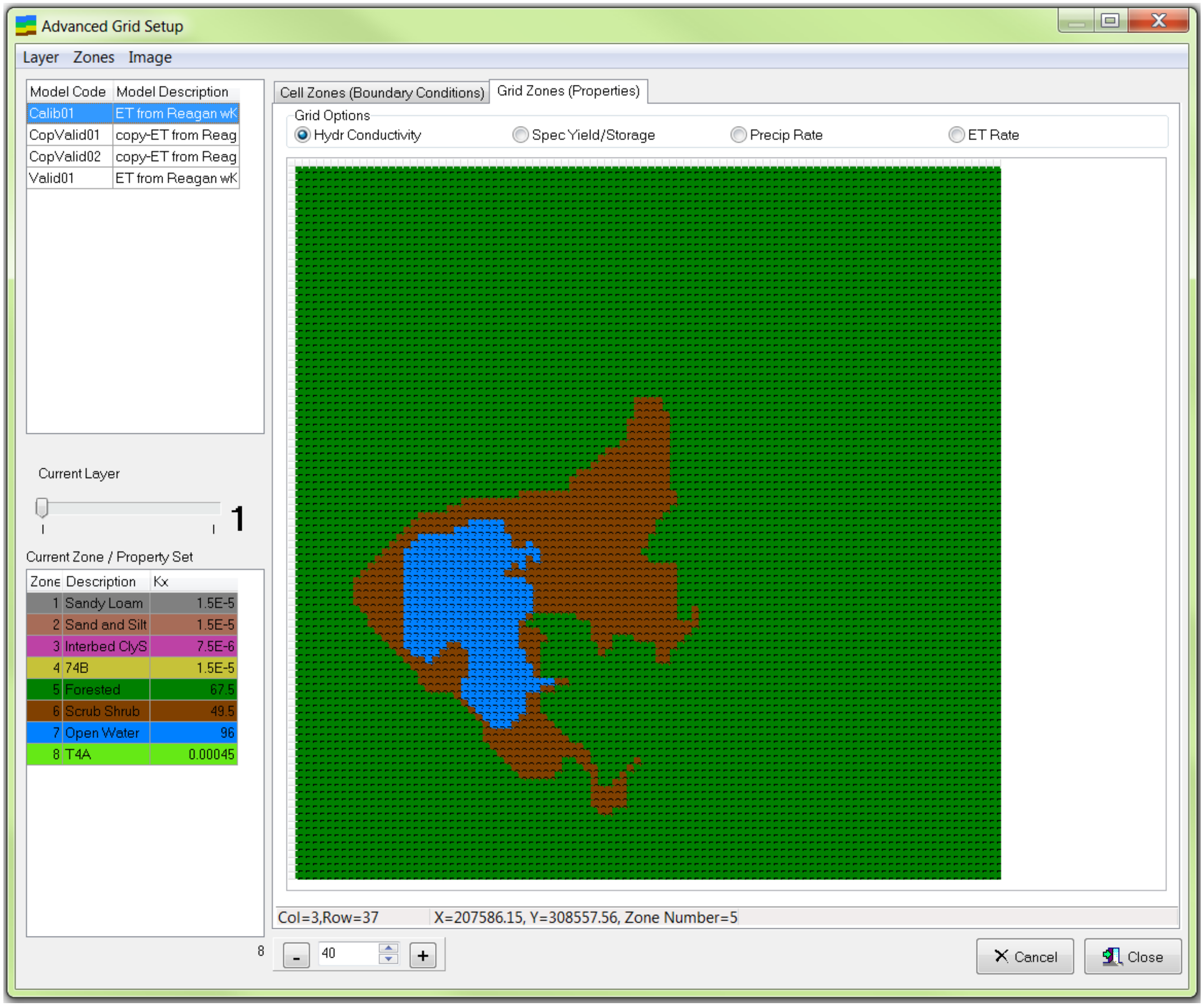
Grid Options

○ General Head ● Drains ○ Monitoring Points ○ No Flow Cells ○ Wells ○ Drain Returns

Col=7,Row=0 X=207677.59, Y=309106.2, Zone Number=

- 40 +

Fig. F-5. Locations of drains within Advanced Scenarios. ‘Leaky Areas’ and ‘Bottom’ were not used in the final versions of the models. The only drains used in the final models were at the location of the variable height outlet and the vinyl piling dam. Zone numbers changed depending on the time period that was modeled.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

Grid Options
● Hydr Conductivity ○ Spec Yield/Storage ○ Precip Rate ○ ET Rate

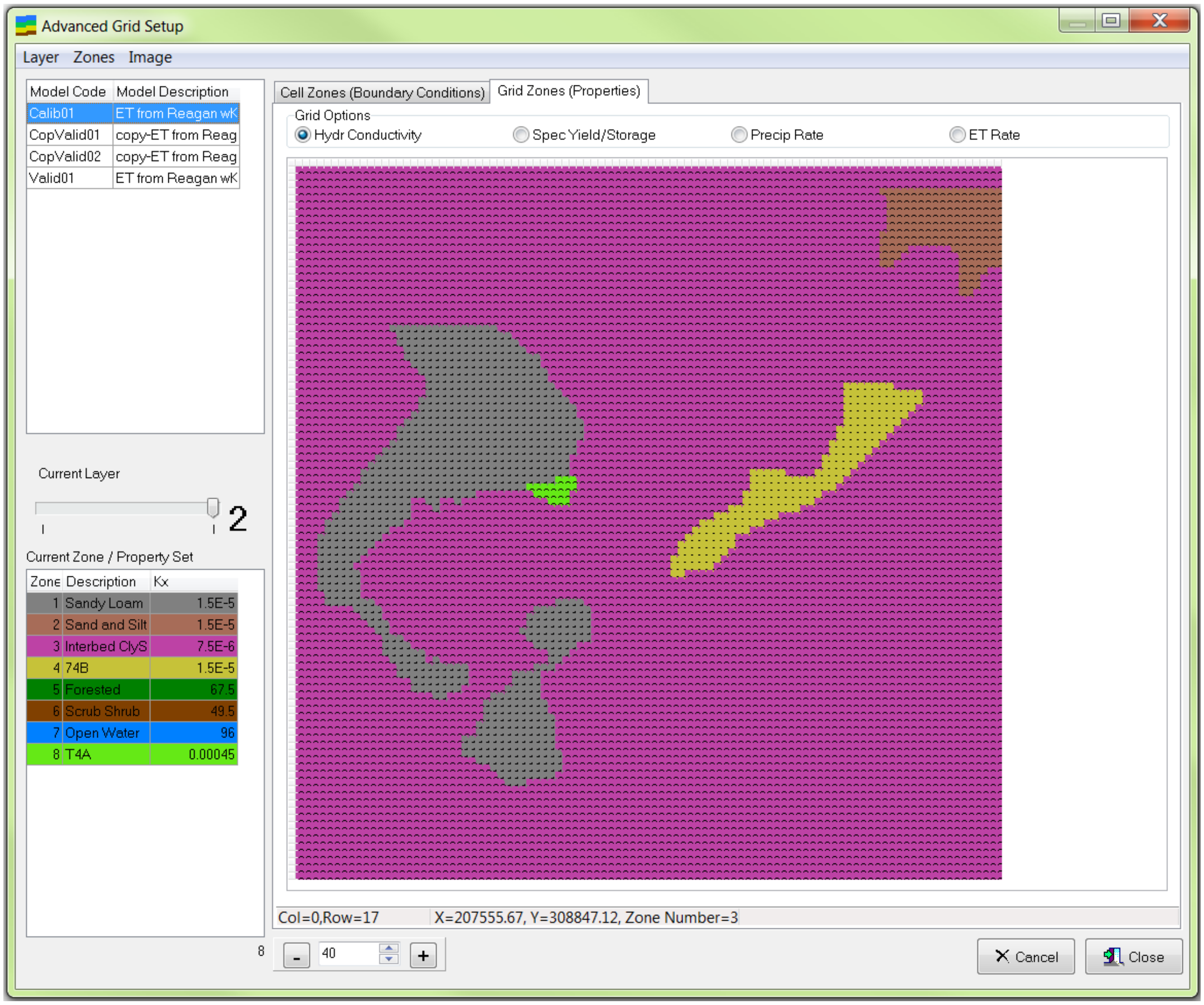
Current Layer 1

Current Zone / Property Set

Zone	Description	Kx
1	Sandy Loam	1.5E-5
2	Sand and Silt	1.5E-5
3	Interbed ClyS	7.5E-6
4	74B	1.5E-5
5	Forested	67.5
6	Scrub Shrub	49.5
7	Open Water	96
8	T4A	0.00045

Col=3,Row=37 X=207586.15, Y=308557.56, Zone Number=5

Fig. F-6. Surface layer hydraulic conductivity used in all Advanced Scenarios. Specific yield and Specific storage zone assignments match hydraulic conductivity zone assignments for this layer.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

● Hydr Conductivity ○ Spec Yield/Storage ○ Precip Rate ○ ET Rate

Current Layer 2

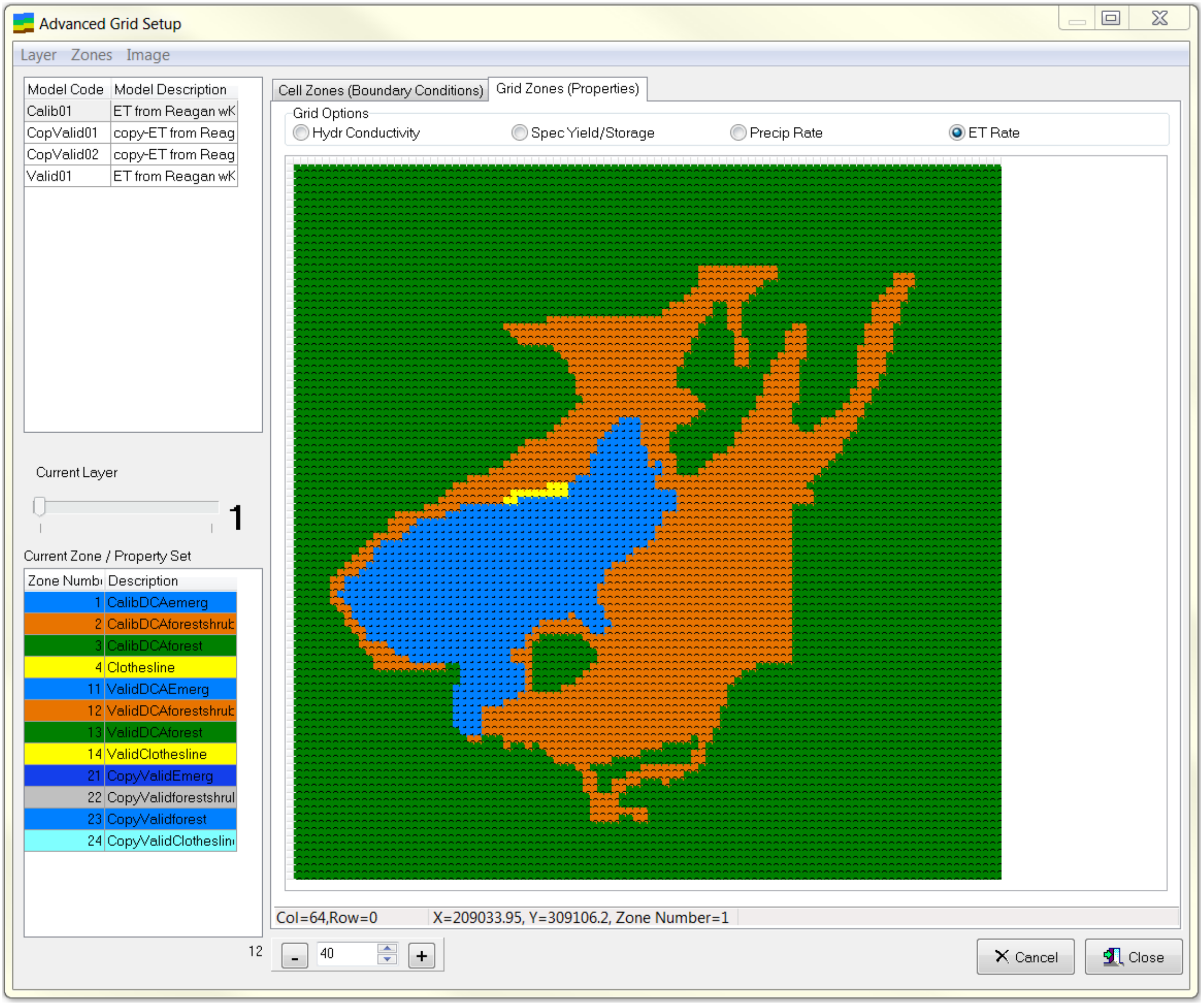
Current Zone / Property Set

Zone	Description	Kx
1	Sandy Loam	1.5E-5
2	Sand and Silt	1.5E-5
3	Interbed ClyS	7.5E-6
4	74B	1.5E-5
5	Forested	67.5
6	Scrub Shrub	49.5
7	Open Water	96
8	T4A	0.00045

Col=0,Row=17 X=207555.67, Y=308847.12, Zone Number=3

- 40 +

Fig. F-7. Soil layer hydraulic conductivity used in all Advanced Scenarios. Specific yield and Specific storage zone assignments match hydraulic conductivity zone assignments for this layer.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

Current Layer 1

Current Zone / Property Set

Zone Numb	Description
1	CalibDCAemerg
2	CalibDCAforestshrub
3	CalibDCAforest
4	Clothesline
11	ValidDCAEmerg
12	ValidDCAforestshrub
13	ValidDCAforest
14	ValidClothesline
21	CopyValidEmerg
22	CopyValidforestshrul
23	CopyValidforest
24	CopyValidClotheslin

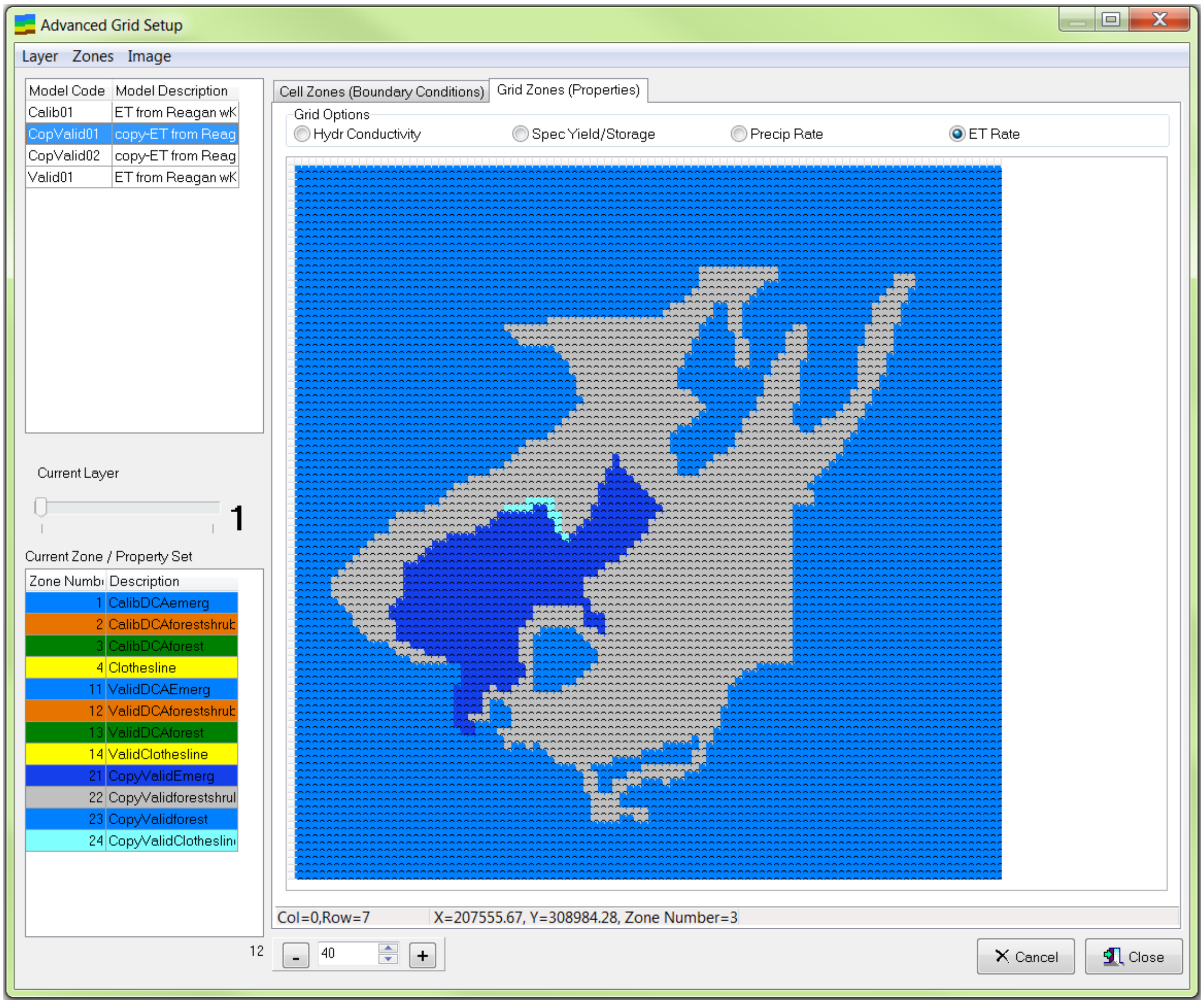
12

Grid Options ○ Hydr Conductivity ○ Spec Yield/Storage ○ Precip Rate ● ET Rate

Col=64,Row=0 X=209033.95, Y=309106.2, Zone Number=1

- 40 +

Fig. F-8. ET Zone assignments used in Calibration Model.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

Grid Options

○ Hydr Conductivity ○ Spec Yield/Storage ○ Precip Rate ● ET Rate

Current Layer 1

Current Zone / Property Set

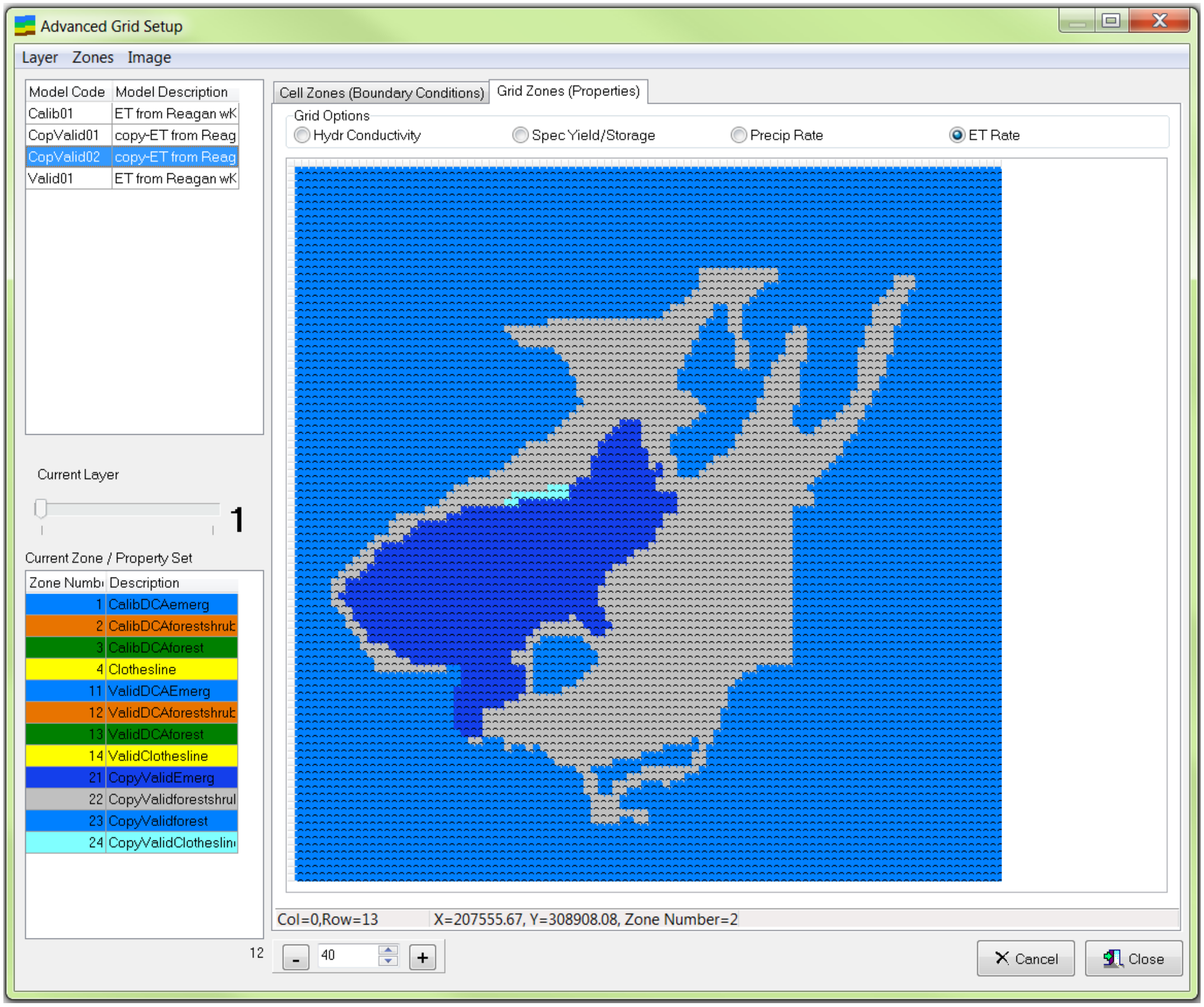
Zone Numb	Description
1	CalibDCAemerg
2	CalibDCAforestshrub
3	CalibDCAforest
4	Clothesline
11	ValidDCAEmerg
12	ValidDCAforestshrub
13	ValidDCAforest
14	ValidClothesline
21	CopyValidEmerg
22	CopyValidforestshrul
23	CopyValidforest
24	CopyValidClotheslin

12

Col=0,Row=7 X=207555.67, Y=308984.28, Zone Number=3

- 40 +

Fig. F-9. ET Zone assignments used in Validation Model.



Model Code	Model Description
Calib01	ET from Reagan wK
CopValid01	copy-ET from Reag
CopValid02	copy-ET from Reag
Valid01	ET from Reagan wK

Grid Options
○ Hydr Conductivity ○ Spec Yield/Storage ○ Precip Rate ● ET Rate

Current Layer 1

Current Zone / Property Set

Zone Numb	Description
1	CalibDCAemerg
2	CalibDCAforestshrub
3	CalibDCAforest
4	Clothesline
11	ValidDCAEmerg
12	ValidDCAforestshrub
13	ValidDCAforest
14	ValidClothesline
21	CopyValidEmerg
22	CopyValidforestshrul
23	CopyValidforest
24	CopyValidClotheslin

12

Col=0,Row=13 X=207555.67, Y=308908.08, Zone Number=2

40

Fig. F-10. ET Zone assignments used in Test Configuration.

APPENDIX G

ADVANCED MODEL SENSITIVITY ANALYSIS DATA

Calibrated Model - Configuration 84 (0% change in parameters)

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

Calibration Model - Configuration 84 - Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.54	0.45	1.96	2.39
ODU_ET2	367	0.22	0.57	0.50	2.26
Outlet	367	0.86	0.08	0.61	0.86
T1A	273	0.54	0.11	0.94	0.73
T1B	367	0.74	0.19	1.67	1.024
T2A	228	0.82	0.08	0.57	0.83
T2B	190	0.41	0.22	1.25	1.23
T2C	226	0.77	0.21	2.13	1.40
T3P	340	-0.23	0.20	1.34	0.98
T3A	319	0.27	0.16	1.44	0.69
T3B	200	0.49	0.25	1.75	1.05
T3C	225	0.69	0.28	1.81	1.51
T4A	263	0.22	0.20	1.80	0.83
T4B	176	0.01	0.37	2.33	1.28
T4C	242	0.55	0.37	2.41	1.77

50% Decrease in Specific Yield Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.075
2	Loam 2	1.00E-05	1.00E-03	0.050
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.150
4	Sandy Loam	1.00E-05	1.00E-03	0.100
5	Vegetation - Forested	4.50E+01	9.80E-01	0.490
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.450
7	Open Water	6.40E+01	9.90E-01	0.495
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.175
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

50% Decrease in Specific Yield Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.68	0.37	2.85	2.39
ODU_ET2	367	0.27	0.55	0.71	2.26
Outlet	367	0.84	0.08	0.63	0.86
T1A	273	0.50	0.12	1.02	0.73
T1B	367	0.83	0.16	1.90	1.024
T2A	228	0.76	0.10	0.58	0.83
T2B	190	0.46	0.21	1.29	1.23
T2C	226	0.66	0.26	2.52	1.40
T3P	340	-1.41	0.29	1.73	0.98
T3A	319	-0.12	0.20	1.80	0.69
T3B	200	0.30	0.29	2.15	1.05
T3C	225	0.54	0.34	2.42	1.51
T4A	263	0.12	0.21	2.03	0.83
T4B	176	-0.28	0.42	2.56	1.28
T4C	242	0.21	0.49	2.69	1.77

25% Decrease in Specific Yield Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.113
2	Loam 2	1.00E-05	1.00E-03	0.075
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.225
4	Sandy Loam	1.00E-05	1.00E-03	0.150
5	Vegetation - Forested	4.50E+01	9.80E-01	0.735
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.675
7	Open Water	6.40E+01	9.90E-01	0.743
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.263
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

25% Decrease in Specific Yield Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.62	0.41	2.34	2.39
ODU_ET2	367	0.24	0.56	0.58	2.26
Outlet	367	0.86	0.08	0.62	0.86
T1A	273	0.53	0.11	0.97	0.73
T1B	367	0.82	0.16	1.79	1.024
T2A	228	0.77	0.10	0.57	0.83
T2B	190	0.45	0.21	1.26	1.23
T2C	226	0.79	0.20	2.24	1.40
T3P	340	-0.74	0.24	1.51	0.98
T3A	319	0.10	0.18	1.60	0.69
T3B	200	0.42	0.26	1.93	1.05
T3C	225	0.67	0.29	2.06	1.51
T4A	263	0.17	0.21	1.90	0.83
T4B	176	-0.07	0.38	2.42	1.28
T4C	242	0.47	0.40	2.51	1.77

25% Increase in Specific Yield Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.188
2	Loam 2	1.00E-05	1.00E-03	0.125
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.375
4	Sandy Loam	1.00E-05	1.00E-03	0.250
5	Vegetation - Forested	4.50E+01	9.80E-01	1.000
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	1.000
7	Open Water	6.40E+01	9.90E-01	1.000
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.438
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

25% Increase in Specific Yield Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.45	0.49	1.79	2.39
ODU_ET2	367	0.20	0.57	0.45	2.26
Outlet	367	0.87	0.07	0.61	0.86
T1A	273	0.58	0.11	0.89	0.73
T1B	367	0.66	0.22	1.54	1.024
T2A	228	0.77	0.10	0.56	0.83
T2B	190	0.43	0.22	1.20	1.23
T2C	226	0.67	0.25	2.03	1.40
T3P	340	0.07	0.18	1.18	0.98
T3A	319	0.43	0.14	1.29	0.69
T3B	200	0.51	0.24	1.59	1.05
T3C	225	0.64	0.30	1.68	1.51
T4A	263	0.28	0.19	1.68	0.83
T4B	176	-0.02	0.37	2.25	1.28
T4C	242	0.53	0.38	2.31	1.77

50% Increase in Specific Yield Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.225
2	Loam 2	1.00E-05	1.00E-03	0.150
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.450
4	Sandy Loam	1.00E-05	1.00E-03	0.300
5	Vegetation - Forested	4.50E+01	9.80E-01	1.000
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	1.000
7	Open Water	6.40E+01	9.90E-01	1.000
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.525
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

50% Increase in Specific Yield Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.36	0.53	1.66	2.39
ODU_ET2	367	0.18	0.58	0.42	2.26
Outlet	367	0.87	0.07	0.61	0.86
T1A	273	0.56	0.11	0.86	0.73
T1B	367	0.58	0.25	1.45	1.024
T2A	228	0.77	0.10	0.56	0.83
T2B	190	0.42	0.22	1.18	1.23
T2C	226	0.56	0.29	1.93	1.40
T3P	340	0.31	0.15	1.07	0.98
T3A	319	0.53	0.13	1.18	0.69
T3B	200	0.53	0.24	1.46	1.05
T3C	225	0.60	0.32	1.58	1.51
T4A	263	0.34	0.19	1.58	0.83
T4B	176	-0.06	0.38	2.17	1.28
T4C	242	0.49	0.39	2.22	1.77

50% Decrease in ET Extinction Depth Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			1.50

50% Decrease in ET Extinction Depth Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	-0.55	0.82	1.60	2.39
ODU_ET2	367	0.16	0.59	0.40	2.26
Outlet	367	0.83	0.09	0.59	0.86
T1A	273	0.32	0.13	0.69	0.73
T1B	367	0.23	0.34	1.08	1.024
T2A	228	0.76	0.10	0.56	0.83
T2B	190	0.29	0.24	0.86	1.23
T2C	226	0.55	0.29	1.29	1.40
T3P	340	0.83	0.08	0.84	0.98
T3A	319	0.56	0.13	0.87	0.69
T3B	200	0.33	0.28	1.10	1.05
T3C	225	0.37	0.40	1.17	1.51
T4A	263	0.66	0.13	1.01	0.83
T4B	176	0.67	0.21	1.31	1.28
T4C	242	0.45	0.40	1.39	1.77

25% Decrease in Extinction Depth Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			2.25

25% Decrease in ET Extinction Depth Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.25	0.57	1.81	2.39
ODU_ET2	367	0.19	0.57	0.45	2.26
Outlet	367	0.85	0.08	0.60	0.86
T1A	273	0.48	0.12	0.83	0.73
T1B	367	0.59	0.24	1.42	1.024
T2A	228	0.77	0.10	0.56	0.83
T2B	190	0.39	0.23	1.07	1.23
T2C	226	0.79	0.20	1.73	1.40
T3P	340	0.47	0.13	1.12	0.98
T3A	319	0.65	0.11	1.19	0.69
T3B	200	0.44	0.26	1.47	1.05
T3C	225	0.61	0.31	1.49	1.51
T4A	263	0.56	0.15	1.43	0.83
T4B	176	0.41	0.28	1.85	1.28
T4C	242	0.65	0.33	1.93	1.77

25% Increase in Extinction Depth Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.75

25% Increase in ET Extinction Depth Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.47	0.48	2.24	2.39
ODU_ET2	367	0.23	0.56	0.54	2.26
Outlet	367	0.88	0.07	0.62	0.86
T1A	273	0.61	0.10	1.01	0.73
T1B	367	0.80	0.17	1.86	1.024
T2A	228	0.77	0.10	0.57	0.83
T2B	190	0.48	0.21	1.35	1.23
T2C	226	0.59	0.28	2.47	1.40
T3P	340	-1.17	0.27	1.48	0.98
T3A	319	-0.34	0.22	1.61	0.69
T3B	200	0.50	0.24	1.97	1.05
T3C	225	0.66	0.29	2.07	1.51
T4A	263	-0.23	0.25	2.07	0.83
T4B	176	-0.49	0.45	2.73	1.28
T4C	242	0.25	0.47	2.83	1.77

50% Increase in Extinction Depth Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			4.50

50% Increase in ET Extinction Depth Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.17	0.60	2.41	2.39
ODU_ET2	367	0.24	0.56	0.57	2.26
Outlet	367	0.88	0.07	0.63	0.86
T1A	273	0.61	0.10	1.07	0.73
T1B	367	0.81	0.16	2.02	1.024
T2A	228	0.77	0.10	0.57	0.83
T2B	190	0.50	0.20	1.45	1.23
T2C	226	0.36	0.35	2.75	1.40
T3P	340	-2.09	0.32	1.61	0.98
T3A	319	-1.05	0.27	1.76	0.69
T3B	200	0.51	0.24	2.15	1.05
T3C	225	0.61	0.31	2.27	1.51
T4A	263	-0.73	0.30	2.31	0.83
T4B	176	-0.96	0.52	3.09	1.28
T4C	242	-0.13	0.58	3.19	1.77

50% Decrease in Initial Head Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			5.20
	ET Extinction Depth (m)			3.00

MODEL CRASHED, NO OUTPUT TO SHOW

25% Decrease in Initial Head Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			7.80
	ET Extinction Depth (m)			3.00

25% Decrease in Initial Head Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.06	0.64	1.80	2.39
ODU_ET2	367	0.22	0.57	0.50	2.26
Outlet	367	0.67	0.12	0.90	0.86
T1A	273	0.48	0.12	0.93	0.73
T1B	367	0.76	0.19	1.67	1.024
T2A	228	0.77	0.10	0.69	0.83
T2B	190	0.44	0.22	1.23	1.23
T2C	226	0.72	0.23	1.99	1.40
T3P	340	-0.37	0.22	1.32	0.98
T3A	319	0.24	0.17	1.43	0.69
T3B	200	0.30	0.29	1.75	1.05
T3C	225	0.53	0.34	1.76	1.51
T4A	263	0.20	0.20	1.78	0.83
T4B	176	-0.09	0.39	2.28	1.28
T4C	242	0.50	0.39	2.37	1.77

25% Increase in Initial Head Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			13.00
	ET Extinction Depth (m)			3.00

MODEL CRASHED, NO OUTPUT TO SHOW

50% Increase in Initial Head Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.00E-05	1.00E-03	0.150
2	Loam 2	1.00E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	5.00E-06	1.00E-03	0.300
4	Sandy Loam	1.00E-05	1.00E-03	0.200
5	Vegetation - Forested	4.50E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	3.30E+01	9.00E-01	0.900
7	Open Water	6.40E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.00E-04	1.00E-03	0.350
	Initial Head (m)			15.60
	ET Extinction Depth (m)			3.00

MODEL CRASHED, NO OUTPUT TO SHOW

50% Decrease in Hydraulic Conductivity Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	5.00E-06	1.00E-03	0.150
2	Loam 2	5.00E-06	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	2.50E-06	1.00E-03	0.300
4	Sandy Loam	5.00E-06	1.00E-03	0.200
5	Vegetation - Forested	2.25E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	1.65E+01	9.00E-01	0.900
7	Open Water	3.20E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	1.50E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

50% Decrease in Hydraulic Conductivity Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.39	0.51	2.05	2.39
ODU_ET2	367	0.21	0.57	0.39	2.26
Outlet	367	0.87	0.07	0.61	0.86
T1A	273	0.55	0.11	1.00	0.73
T1B	367	0.70	0.21	1.88	1.024
T2A	228	0.77	0.10	0.57	0.83
T2B	190	0.49	0.21	1.46	1.23
T2C	226	0.66	0.26	2.34	1.40
T3P	340	0.70	0.10	1.19	0.98
T3A	319	0.68	0.11	1.37	0.69
T3B	200	0.58	0.22	1.77	1.05
T3C	225	0.71	0.27	2.08	1.51
T4A	263	0.23	0.20	1.93	0.83
T4B	176	-0.30	0.42	2.51	1.28
T4C	242	0.37	0.43	2.56	1.77

25% Decrease in Hydraulic Conductivity Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	7.50E-06	1.00E-03	0.150
2	Loam 2	7.50E-06	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	3.75E-06	1.00E-03	0.300
4	Sandy Loam	7.50E-06	1.00E-03	0.200
5	Vegetation - Forested	3.38E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	2.48E+01	9.00E-01	0.900
7	Open Water	4.80E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	2.25E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

25% Decrease in Hydraulic Conductivity Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.51	0.46	1.98	2.39
ODU_ET2	367	0.21	0.57	0.46	2.26
Outlet	367	0.87	0.07	0.61	0.86
T1A	273	0.55	0.11	0.96	0.73
T1B	367	0.74	0.20	1.72	1.024
T2A	228	0.77	0.10	0.57	0.83
T2B	190	0.47	0.21	1.32	1.23
T2C	226	0.74	0.23	2.23	1.40
T3P	340	0.20	0.17	1.29	0.98
T3A	319	0.47	0.14	1.42	0.69
T3B	200	0.53	0.24	1.77	1.05
T3C	225	0.71	0.27	1.92	1.51
T4A	263	0.15	0.21	1.85	0.83
T4B	176	-0.12	0.39	2.42	1.28
T4C	242	0.49	0.39	2.48	1.77

25% Increase in Hydraulic Conductivity Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.25E-05	1.00E-03	0.150
2	Loam 2	1.25E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	6.25E-06	1.00E-03	0.300
4	Sandy Loam	1.25E-05	1.00E-03	0.200
5	Vegetation - Forested	5.63E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	4.13E+01	9.00E-01	0.900
7	Open Water	8.00E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	3.75E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

25% Increase in Hydraulic Conductivity Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.52	0.46	1.97	2.39
ODU_ET2	367	0.25	0.55	0.67	2.26
Outlet	367	0.87	0.08	0.61	0.86
T1A	273	0.58	0.11	0.90	0.73
T1B	367	0.74	0.19	1.62	1.024
T2A	228	0.77	0.10	0.56	0.83
T2B	190	0.42	0.22	1.16	1.23
T2C	226	0.76	0.21	2.04	1.40
T3P	340	-0.57	0.23	1.35	0.98
T3A	319	0.11	0.18	1.43	0.69
T3B	200	0.45	0.26	1.73	1.05
T3C	225	0.65	0.30	1.76	1.51
T4A	263	0.29	0.19	1.72	0.83
T4B	176	0.05	0.36	2.24	1.28
T4C	242	0.56	0.36	2.34	1.77

50% Increase in Hydraulic Conductivity Configuration

Zone	Material	KSAT (m/s)	Ss	Sy
1	Loam	1.50E-05	1.00E-03	0.150
2	Loam 2	1.50E-05	1.00E-03	0.100
3	Interbedded Clay, Silt, and Sand	7.50E-06	1.00E-03	0.300
4	Sandy Loam	1.50E-05	1.00E-03	0.200
5	Vegetation - Forested	6.75E+01	9.80E-01	0.980
6	Vegetation - Scrub Shrub	4.95E+01	9.00E-01	0.900
7	Open Water	9.60E+01	9.90E-01	0.990
8	T4A - Loam with Gravels	4.50E-04	1.00E-03	0.350
	Initial Head (m)			10.40
	ET Extinction Depth (m)			3.00

50% Increase in Hydraulic Conductivity Model Evaluation Statistics

Well	n Observed	NSE	RMSE (m)	Predicted Range (m)	Observed Range (m)
VTHD3	367	0.45	0.49	1.98	2.39
ODU_ET2	367	0.28	0.54	0.77	2.26
Outlet	367	0.87	0.08	0.61	0.86
T1A	273	0.58	0.11	0.88	0.73
T1B	367	0.73	0.20	1.57	1.024
T2A	228	0.77	0.10	0.56	0.83
T2B	190	0.41	0.22	1.11	1.23
T2C	226	0.75	0.22	1.96	1.40
T3P	340	-0.64	0.24	1.35	0.98
T3A	319	0.08	0.18	1.43	0.69
T3B	200	0.42	0.26	1.70	1.05
T3C	225	0.63	0.31	1.75	1.51
T4A	263	0.35	0.18	1.67	0.83
T4B	176	0.09	0.35	2.16	1.28
T4C	242	0.57	0.36	2.28	1.77

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