# Evaluation of a Water Budget Model for Created Wetland Design and Comparative Natural Wetland Hydroperiods.

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ABSTRACT

Wetland impacts in the Mid-Atlantic USA are frequently mitigated via wetland creation in former uplands. Regulatory approval requires a site-specific water budget that predicts the annual water level regime (hydroperiod). However, many studies of created wetlands indicate that post-construction hydroperiods frequently are not similar to impacted wetland systems. My primary objective was to evaluate a water budget model, *Wetbud* (Basic model), through comparison of model output to on-site water level data for two created forested wetlands in Northern Virginia. Initial sensitivity analyses indicated that watershed curve number and outlet height had the most leverage on model output. Addition of maximum depth of water level drawdown greatly improved model accuracy. I used Nash-Sutcliffe efficiency (NSE) and root mean squared error (RMSE) to evaluate goodness of fit of model output against site monitoring data. The Basic model reproduced the overall seasonal hydroperiod well once fully parameterized, despite NSE values ranging from -0.67 to 0.41 in calibration and from -4.82 to -0.26 during validation. For RMSE, calibration values ranged from 5.9 cm to 12.7 cm during calibration and from 8.2 cm to 18.5 cm during validation. My second objective was to select a group of "design target hydroperiods" for common Mid-Atlantic USA wetland types. From > 90 sites evaluated, I chose four mineral flats, three riverine wetlands, and one depressional wetland that met all selection criteria. Taken together, improved wetland water budget modeling procedures (like Wetbud) combined with the use of appropriate target hydroperiod information should improve the success of wetland creation efforts.

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GENERAL AUDIENCE ABSTRACT

Wetlands in the USA are defined by the combined occurrence of wetland hydrology, hydric soils, and hydrophytic vegetation. Wetlands serve to retain floodwater, sediments and nutrients within their landscape. They may serve as a source of local groundwater recharge and are home to many endangered species of plants and animals. Wetland ecosystems are frequently impacted by human activities including roadbuilding and development. These impacts can range from the destruction of a wetland to increased nutrient contributions from storm- or wastewater. One commonly utilized option to mitigate wetland impacts is via wetland creation in former upland areas. Regulatory approval requires a site-specific water budget that predicts the average monthly water levels (hydroperiod). A hydroperiod is simply a depiction of how the elevation of water changes over time. However, many studies of created wetlands indicate that post-construction hydroperiods frequently are not representative of the impacted wetland systems. Many software packages, called models, seek to predict the hydroperiod for different wetland systems. Improving and vetting these models help to improve our understanding of how these systems function. My primary objective was to evaluate a water budget model, *Wetbud* (Basic model), through comparison of model output to on-site water level data for two created forested wetlands in Northern Virginia. Initial analyses indicated that watershed curve number (CN) and outlet height had the most influence on model output. Addition of a maximum depth of water level drawdown below the ground surface greatly improved model accuracy. I used statistical analyses to compare model output to site monitoring data. The Basic model reproduced the overall seasonal hydroperiod well once inputs were set to optimum values (calibration). Statistical results for the calibration varied between excellent and acceptable for our selected measure of accuracy, the root mean squared error. My second objective was to select a grouping of "design target hydroperiods" for common Mid-Atlantic USA wetland types. From > 90 sites evaluated, I chose four mineral flats, three riverine wetlands, and one depressional wetland that met all selection criteria. Taken together, improved wetland water budget modeling procedures (like *Wetbud)* combined with the use of appropriate target hydroperiod information should improve the success of wetland creation efforts

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## 1. Introduction

Wetlands are defined based on three general factors, hydrology, hydric soils, and hydrophytic vegetation. Explained in more detail later, the Army Corps of Engineers (USCOE) is tasked with regulating potential impacts to wetland ecosystems in the United States; their official definition of a wetland is used as the basic definition throughout this thesis. The USCOE requires landowners to submit permits for disturbances to wetlands and engages with them as a regulatory body for wetlands in the United States; more on this a bit later. As wetlands have gained recognition for their importance for provision of ecosystem functions and socioeconomic values, regulations have been promulgated to presumably limit net loss of wetland ecosystems via a range of impact mitigation measures. Regulatory oversight and debate over mitigation effectiveness have led to the need for research into more effective means of creating wetlands. Creation is just one aspect of the overall mitigation process described below.

The Clean Water Act (CWA) of 1972 (Public law 92-500) included protections for wetlands within Section 404, which regulates the discharge of dredge and fill materials which might impact the quality of navigable waters of the United States. Wetlands protected by these regulations must be tied hydrologically, chemically, or biologically to the water quality of their downstream waterbody (USCOE, 2010). As discussed later, sections of the CWA gave regulatory authority to the USCOE along with other federal agencies via an advisory role (NRC, 2001). Section 404 of the CWA allowed for the increased use of created wetlands to compensate for losses where minimizing impacts or avoidance was impossible. Avoidance is the practice of changing project goals or structure so as to circumvent impact to a wetland system. The National Research Council (NRC, 2001) provided a critique of section 404 of the CWA guidelines and its implementation at that

time. Associated NRC guidance addressed issues with consistency of created wetlands so as to improve replacement procedures. When it is either cost prohibitive or otherwise impossible to avoid a wetland impact, provisions have been made within the CWA guidance applied by USCOE to allow for replacement of lost wetland acreage in accordance with their "no net loss" policy.

Compensation permits are based on many variables and each permit is site-specific. These plans are comprehensive and need to include all requirements relevant to each project. Generally speaking, the four main components of an application are: Notification of adjacent property owners, conceptual construction plans, wetland and water boundary delineations, and a functional assessment of the wetland to be impacted. Site plans include various components related to construction: proposed grading plans, planting plans, monthly hydroperiod predictions, reference wetland information, pre-construction and post construction monitoring plans. Site maps and plans for each aspect of construction must be submitted. All of this is done before anything is started on the project, and this permit is then submitted for review by the USCOE along with the relevant state authority (e.g. Virginia Department of Environmental Quality – DEQ).

During the 404 permit review process for proposed wetland impacts, the USCOE and other cooperating federal (e.g. EPA and FIW) and state agencies (e.g. DEQ) rank wetlands proposed for impacts based on the system's function and exceptionality. These rankings are then used at the discretion of the USCOE to create replacement ratios for the wetlands which will be lost. Nine studies reviewed by the NRC (2001) found that stated permit goals were not met in any of the replacement sites evaluated. With successful "functional replacement" occurring so infrequently, ratios for mitigation are needed to presumably assure long term overall replacement. For example,

ratio guidelines used by the California Department of Fish and Wildlife may require that for every 1.0 ha of impact to a low-value habitat, permittees need to create 1.0 ha of new wetlands (NRC, 2001). In contrast, impacts to 1 ha of endangered species habitat may require the permittee to create up to 5 ha of new wetlands. These ratios are designed to help assure the creation of an adequate area of functional wetland replacement under prevailing assumptions of wetland creation success. In some cases, these ratios are also used in a punitive manner to protect unique ecosystems which may be impossible to reproduce (NRC, 2001).

Wetland impact permits commonly employ relatively simplified water budget predictions. These budgets involve procedures to estimate wetland water inputs and outputs in order to derive a prediction of the annual overall range of ponding or soil saturation (e.g. the "hydroperiod"; Mitsch & Gosselink, 2000). The hydroperiod of a given wetland is controlled by various water inputs and outputs which can be expressed using a water balance or budget. This is an algorithm which attempts to account for the hydrologic variables of a system, in this case a wetland. The primary user output for a wetland water budget is typically shown as the change in the overall water level (or water storage) within the wetland over time (typically one year). This change in storage is controlled largely by several factors such as evapotranspiration (ET), precipitation (P), groundwater flux, and surface water inflow vs. outflow. All of these variables are specified by on-site data or estimated via computations and applied to site-specific factors such as the wetland soil area, contributing watershed runoff, wetland soil depth, soil hydraulic conductivity and porosity to determine a predicted hydroperiod for the site in question under varying climatic and seasonal conditions.

With increased scrutiny of the success of wetland systems in terms of functional replacement, standardized methods of construction and design have become more important. For example, the NRC (2001) recommended that target (design) wetland hydroperiods have seasonal variations similar to natural systems. Variations in wetland water levels over time may impact various aspects of wetland vegetation. Hydroperiods have been shown to have an effect on litter breakdown, wetland plant growth success, and seedbank composition (Battle and Golladay, 2001; Slusher et al., 2014; Correa-Araneda et al., 2012; Poiani and Johnson, 1989).

In this study, I evaluated the basic version of a newly developed wetland water budget model (Wetbud; http://landrehab.org/WETBUD) for created wetland design at one site in Northern Virginia. This program was designed with the needs of wetland designers, consultants and regulators in mind. Wetbud is intended to be used as a design prediction model, and is a compilation of accepted methods for constructed wetland design (Stone, 2017; Agioutantis et al., 2016). Within Wetbud, generally accepted equations for site-watershed interactions have been linked to available climatic data to provide a consistent and defensible analysis of created wetland design variations as they would influence a site-specific water budget. Additionally, we have developed an associated library of "target hydroperiods" for three types of common mid-Atlantic non-tidal wetlands that can be used to underpin water budget modeling inputs and assumptions to improve the ability of these models to accurately reproduce appropriate hydrologic conditions.

1.1. Overall Objectives

> To evaluate the accuracy of daily and monthly versions of the Basic model of Wetbud through comparison to monitoring well data from two created wetland cells. This evaluation included sensitivity analysis of parameters within the Wetbud Basic model.

> To produce a set of target Mid-Atlantic wetland hydroperiod examples for use in created wetland design of mineral flats, riverine, and depressional wetlands.

## 2. Literature Review

Throughout the history of the United States, wetlands have often been regarded as roadblocks to land development (Dahl, 1990). Starting with European colonization, wetland drainage and conversion was common and continued as more of the United States was explored (Dahl and Allord, 1996). Practices which were harmful to wetlands came under USCOE jurisdiction in 1972 with passage of the Clean Water Act (CWA; Public law 92-500). The CWA placed regulation on waste management, agricultural runoff, discharge of chemicals, and placement of dredge and fill materials into waters of the United States. Section 404(b) (1) and Section 403(c) of the CWA provide the most far-reaching power for USCOE regulation and of wetlands (NRC, 2001). This section (404b) gives the USCOE the ability to regulate dredge and fill materials that could impact quality of traditional navigable waters of the United States. When a project might alter or degrade a wetland and impact downstream waters, USCOE oversight and permitting is required. Section 401 of the CWA also requires that prior to receiving a federal permit, any applicant must first receive certification from the state. Via these parallel regulations, state and other local water authorities may be more stringent than USCOE permit requirements (Public law 92-500; Federal

Water Pollution Control Act Amendments). For example, Virginia also regulates "isolated wetlands" while USCOE does not.

## 2.1. Wetland Characteristics

Wetland ecosystems are as diverse as the landscapes they occur on. They vary in greatly in size, landscape position, and based on their differing water sources (Mitsch & Gosselink, 2000). Three characteristics which are universal in historic and current definitions of wetlands are wetland hydrology, hydric soils, and hydrophytic vegetation. From a regulatory standpoint, the most universally important definition is the current USCOE definition:

*"Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstance do support, a prevalence of vegetation typically adapted for life in saturated soil conditions"* (USCOE, 2010).

Hydrology is the driving force for wetland occurrence on any landscape (Richardson and Vepraskas, 2001), but differences in landforms, geology and local hydrologic conditions generate a wide diversity of wetland types. Continuously saturated and inundated hydroperiods are presumed to lead to development of hydric soils and support the dominance of hydrophytic vegetation in wetlands. Development of the term 'hydric soil' began in 1979 when the NRCS was tasked with defining hydric soils and developing associated criteria (Richardson and Vepraskas, 2001). The NRCS guidelines and criteria are complementary to the regulations provided by the USCOE Wetland Delineation manual and associated regional supplements (e.g. USCOE, 2010). Jurisdictional wetlands are required to satisfy at least one characteristic criterion typical of wetlands in each of three categories: vegetation, soil, and hydrology (USCOE, 2010).

## 2.2. Wetland Vegetation

Anaerobic soil conditions are key for the development of hydric soils and act as a controlling factor for the development of hydrophytic plant species (Richardson and Vepraskas, 2001). Within a wetland system, water levels range from partial saturation to complete inundation year-round (Richardson and Vepraskas, 2001). Wetland vegetation is spatially organized by hydrologic stressors with water depth and duration of saturation or ponding, creating preference for wetland adapted vegetation (Cronk and Fennessy, 2001). As noted earlier, the pattern of the depth to which wetlands are saturated or flooded throughout a year is known as the hydroperiod (Richardson and Vepraskas, 2001). These variations in water levels cause vegetative zonation within the wetland system, which largely accounts for the diversity of plants in wetland ecosystems (Bornette and Amoros, 1996; Collins and Battaglia, 2001).

Wetland plant species are able to survive the stress associated with variable hydroperiods through specific morphological adaptations (Mitsch and Gosselink; 2000; USCOE, 2010). Wetland and upland plants are broken into five hydrophytic indicator groups: obligates (OBL), facultative wet (FACW), facultative (FAC), and facultative upland (FACU) and upland obligates (UP) (Lichvar and Minkin, 2008). Being well adapted to extended inundation, most wetland obligates are found in the deepest and most commonly inundated or saturated sections of the wetlands (Cronk and Fennessy, 2001). Hydrology is also a driving factor for the overall net primary productivity of wetland species (Cronk and Fennessy, 2001). Significant differences occur between plant species composition when compared based on water depth and the change in surface water levels (Magee and Kentula, 2005). For the wetlands analyzed, Magee and Kentula (2005) also found that plants were likely to group spatially based on hydrophytic indicator group, with obligates occupying the

deepest sections of ponding or the shallowest depths to soil saturation. As the depth to the water table increases, plant composition changes from species tolerant of anaerobic conditions (OBL & FACW) into FAC and FACU plants (Magee and Kentula, 2005). Slusher et al. (2014) used a greenhouse trial to look at the differences in four wetland tree species ability to grow during varied periods of inundation. An example of this are species bald cypress **(***Taxiodium distichum***)** and sweet bay (*Magnolia virginiana*) which can survive 100 days of continuous ponding while pond pine (*Pinus serotina*), considered FACW, and swamp chestnut oak (*Quercus michauxii Nutt.*), are unable to survive this length of continuous ponding (Slusher et al., 2014).

Within a given wetland system there is often more than one hydrologic regime. For example, in the deepest parts of a wetland, plants may experience inundation for most of the growing season. In fringe areas, there may be saturation but no flooding. Poiani and Johnson (1989), using the seedling emergence method described by Van der Valk and Davis (1978), found that differences in seed bank propagule density (# $m^{-2}$) may have been related to differences in hydroperiod. The authors hypothesized that differences in the number of short-lived annual seeds were due to various source plants' abilities to maximize seed production during longer drawdown periods. This has implications for wetland creation, since reproducing multiple types of vegetation across a given site may require transitional elevations and associated grading practices. Whittecar and Daniels (1999) suggested wetland creation plans provide for these transitional areas between upland and hydric soils. However, these transitional areas may not meet permit requirements and thus may not receive replacement credit. Producing tiered wetness regimes could be attained by grading at different elevations. By using a flexible design for manipulations of water budget components,

such as manipulating outlet elevations and varying slope forms, one can adjust water levels as needed (Whittecar and Daniels, 1999).

## 2.3. Water Budgets

Water budgets are used for created wetland design proposals and permitting. The actual hydroperiod of a created or restored site is considered a major determinant of how effective created wetland are for impact compensation (Cole, 2016; NRC, 2001). Important issues for accurate water budget development include finding and utilizing appropriate weather data for a given site, estimating net groundwater inputs/outputs, and other factors such as how to consistently determine Wet, Normal, and Dry (WND) years for an appropriate site design. However, for a wide variety of reasons, these estimated a priori water budgets may not adequately depict the water budget for an actual natural or created wetland site, regardless of the intent of the designer (Whittecar and Daniels, 1999).

Gary Pierce was one of the first wetland scientists to promote the idea that during wetland creation, properly specifying site hydrology is paramount to the success of a created wetland. A technique he developed has been commonly used in wetland construction and is known as the "Pierce Method". This approach involves shaping the landscape to limit groundwater fluxes coupled with berms and outlet controls to produce an accurate water budget for site location so as to promote the optimum water level for wetland plant communities (Pierce et al., 2015). Most water budgets in use today for wetland design owe their origins and rationale to this method although many alternative approaches have also evolved (e.g. those based on DRAINMOD; Skaggs, 1982).

A water budget is "…an accounting of the inflow to, outflow from, and storage change in a hydrologic unit such as an aquifer or drainage basin" (Driscoll and Carter, 2001). These are conceptual models which attempt to account for the mass balance associated with water flows into, within, and out of a wetland system. A water budget for a given wetland or wetland creation project area can be itemized using a common model (Equation 2.1) which was expressed by Richardson and Vepraskas (2001) as:

Equation 2.1. $$\mathrm{P} + \mathrm{Ho} + \mathrm{Gwd} = \mathrm{Gwr} + \mathrm{ET} + \mathrm{So} + \mathrm{Gwr} \pm \Delta S$$

where, precipitation (P) is all atmospheric inputs including rain and snow; surface water inflow (Ho) is runoff from adjacent uplands and stream overbank flow; groundwater inflow (Gwd) is subsurface discharge from up the hydrologic gradient into the wetland; evapotranspiration (ET) is water loss caused from combined soil and water direct evaporation and plant transpiration; surface water outflow (So) is the total hydraulic loss of overland flow through an outlet or berm; and groundwater outflow (Gwr) is the total subsurface water recharge (loss) from the wetland. In this equation, the change in water levels with time is reflected by changes of the $\Delta S$ parameter expressed as the relative height of the saturated or ponded zone (hydroperiod). Other water budget equations such as those provided by Mitsch and Gosselink (2000) display tidal flux as another variable within the budget; this represents the contribution of diurnal local tidal influences on the water level of a given wetland.

A factor which is not commonly expressed in water budgets that is important to understanding a wetland's hydroperiod is the residence time of water within a wetland. This is the amount of time

which it takes a unit of water to move through a wetland system and be replaced by water from its uplands. Residence times vary based on the geomorphic landscape on which wetlands occur, soil texture, underlying geology, and vegetation (Mitsch and Gosselink, 2000). Precipitation can be defined as the total amount of rain and snowfall which a site, including its watershed, receive over the period of interest. Some precipitation is collected by vegetation in a wetland, and thus becomes intercepted, and is likely to be lost through direct evaporation. Water that isn't lost in this way is considered throughfall or stemflow depending on how it reaches the wetland surface (Mitsch and Gosselink, 2000).

Topography creates hydrologic pressures which have drastic effects on the elements of a wetland water budget and can affect which factors in Equation 2.1 contribute most to a wetland's hydroperiod. Slope gradient and length and watershed size are the three largest factors in determining the runoff coming into a wetland (Quinn and Planchon, 1991; Desmet et al., 1999). Based on the amount of precipitation a site receives, runoff inputs can be calculated by using the watershed size and a runoff coefficient, such as via the NRCS curve number (CN) method (Mishra and Singh, 2003). The CN is determined primarily by landuse/impermeable cover, vegetation, and presumed soil texture/infiltration as these variables affect how wetting fronts will move over the land surface or through surface soil pores and into the underlying soil (Mitsch and Gosselink, 2000). Water moving through larger soil macropores that are open at the surface can be called bypass flow (Bouma, 1990) and can greatly increase infiltration rates which would decrease local runoff.

Groundwater can be very influential to water levels within wetlands, although this is not true for all wetland types (Siegel, 1988). When local up-gradient water tables are higher in elevation than a wetland and the water is moving into the wetland, this is considered a discharge wetland. These types of wetlands are also associated with springs or seeps, often occurring as slope wetlands. These may also occur where there are abrupt soil textural changes or impermeable geologic layers outcrop on a slope (Mitsch and Gosselink, 2000; Richardson and Vepraskas, 2001). A recharge wetland is the opposite situation, where a wetland is above the local or downgradient water table, and is losing water to the surrounding landscape. Wetlands often have a combination of these conditions where one side of the wetland has discharge and the other has recharge characteristics; this is called a throughflow wetland, where the residence time is enough to create wetland hydrology (Mitsch and Gosselink, 2000).

Evapotranspiration is the last important component of water budgeting which has received considerable attention over the years, with many authors creating equations to estimate it. Commonly used methods include the Penman-Monteith (Equation 2.2), Thornthwaite (Equation 2.3), the White method, Hamon method, and the Hammer and Kadlec equation (White, 1932; Thornthwaite, 1948; Hamon, 1962; Hammer and Kadlec, 1986; Jensen et al., 1990; Allen et al., 1998).

All of these variables (Eq. 1.1) contribute to the water level in a given wetland at any point in time, and help to explain why different geomorphic settings will create differing wetland hydrology. Differing levels of each of these variables can produce a large range of daily, monthly, and yearly water levels. For example, tidally influenced wetlands will have drastically different water levels

up to four times every day, while a groundwater discharge driven system may have nearly the same water level year-round and only dry up after extended periods of drought (Mitsch and Gosselink, 2000; Richardson and Vepraskas, 2001).

Equation 2.2. Penman-Monteith evapotranspiration model:

$$E_{mass} = \frac{mR_n + p_a\, c_p(\delta \mathrm{e}) g_a}{\lambda \mathrm{v}\ (\mathrm{m} + \gamma)}$$

m = Slope of the saturation vapor pressure curve (Pa $K^{-1}$)

$R_n$ = Net irradiance (W $m^{-2}$)

$\rho_a$ = density of air (kg $m^{-3}$)

$c_p$ = heat capacity of air (J $kg^{-1}$ $K^{-1}$)

$g_a$ = momentum surface aerodynamic conductance (m $s^{-1}$)

$\delta e$ = vapor pressure deficit (Pa)

$\lambda_v$ = latent heat of vaporization (J $kg^{-1}$)

$\gamma$ = psychrometric constant (Pa $K^{-1}$)

Equation 2.3. Thornthwaite potential evapotranspiration:

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_\alpha}{I}\right)^\alpha$$

$T_a$ = the average daily temperature (degrees Celsius)

N = the number of days in the month being calculated

L = the average day length (hours) of the month being calculated

I = the heat index based on monthly mean temperatures

Multiple studies have produced conceptual water budgets for various wetland types including low lying forested wetlands in the SC coastal plain (Harder et al., 2007), Carolina Bays (Caldwell et al., 2007; Pyzoha et al., 2008), and northern prairie wetlands (Voldseth et al., 2007). Harder et al. (2007) used three simplified water budgets, along with variations based on three evapotranspiration equations: Thornthwaite, Penman-Monteith, and Hamon. These models ignored lateral groundwater flux, surface flow, and deep seepage for the site. Harder et al. (2007) used similar goodness-of-fit statistics to those recommended by the American Society of Civil Engineers (ASCE) (1993) similar to this study as described later. Their resulting water budgets were analyzed based on comparisons of outflow and predicted water surplus, and they found that models did a relatively good job of predicting actual site conditions. Another model applied to wetland systems, DRAINMOD (Skaggs, 1982) is a relatively complex water balancing software requiring more input variables than Wetbud Basic model, particularly with respect to local site soil and drainage conditions. DRAINMOD is designed for poorly or artificially drained soils with shallow water tables (Caldwell et al., 2007) and was originally designed to model local agricultural drainage ditch and tile influences on the water table. Caldwell et al. (2007) used it to model the water table and cumulative drainage for a Carolina Bay located near Plymouth North Carolina. Using data from 1993-1994 to calibrate their model, they achieved “good” to “excellent” goodness of fit statistics for their model (Caldwell et al., 2007). The years 1995 and 1996 were used as a verification period, which I describe later as the “validation period” for my study. During 1995 and 1996, Caldwell et al. (2007) achieved “good” statistical fit of their modeled water levels to their observed data.

Many studies use a water budget modeling approach to determine residual values that may be unaccounted for in the budget and/or use them to represent variables which may be difficult or cost prohibitive to measure. One example of this is reported by Claessens et al. (2006) who used water withdrawals and streamflow for the Ipswitch river basin to create a water budget which accounted for all inputs and outputs from the municipal system. Subsequently, Claessens et al. (2006) calculated residuals, the unexplained losses, to represent the overall ET for their watershed to corroborate their ET calculations which were done via the physically based CRAE model (Morton, 1983). Residuals are whatever quantity remains after all other variables have been subtracted or accounted for.

## 2.4. Wetland Creation

As touched on in the introduction, compensation wetlands are commonly constructed under Section 404 of the CWA as a permit condition to compensate for draining or filling an existing natural wetland. Constructed wetlands in the US are used for a wide array of uses such as wastewater treatment, municipal water treatment, urban stormwater detention and treatment, as well as for treating agricultural and industrial runoff (Hammer, 1989). They are also commonly used to compensate for wetland impacts at other locations, generally within the same watershed. Constructed wetlands are defined by the NRC as "…the conversion of a persistent upland or shallow water area into a wetland by human activity" (NRC, 2001). Assuming creation is allowed as a mitigation alternative, the Section 404 CWA permit places specific requirements on the construction and monitoring plans for these sites. The NRC (2001) remarked that these conditions are not always consistent and vary depending on the scope of a project and its impact. These sites are often achieved through altering elevation in an upland soil, such that the hydrologic regime

can be molded to support a seasonally saturated hydrology, thus presumably producing a jurisdictional wetland area. In an effort to propagate wetland vegetation, created wetlands (or zones therein) are sometimes designed to mimic a specific wetland hydroperiod (e.g. continuously ponded, periodically saturated/flooded, etc…) which can be based on a nearby reference wetland similar to that being created or the original impact site. Replacement ratios for lost wetland conditions that define successful replacement are determined on a case-by-case basis during CWA 404 permit negotiations with the USCOE and local regulators. For example, the Virginia DEQ usually requires ratios of 2:1 (Creation:Impact area) for forested and 1:1 for emergent wetlands with a presumption of type-for-type functional replacement (Daniels, personal communication).

The functional condition of wetlands is based upon the complex inter-relationships of hydrology, vegetation, and hydric soils. A recent wetland hydrology assessment in Pennsylvania found that across the wide range of constructed wetlands analyzed, all except one created wetland clustered separately from their presumed comparative natural wetlands (Cole, 2016). This reinforced the idea that constructed wetlands often fail to reflect hydrology consistent with natural wetlands. Additionally, all of the created sites were considered to be wetter sites in comparison with natural wetlands in the large (n = 42) review data set (Cole, 2016). Whittecar and Daniels (1999) also found discrepancies (excess wetness) between target water regimes and actual water regimes of constructed wetlands. As previously stated, this can lead to the establishment of non-target plant species such as replacement of forested wetland impacts by mixed shrub/scrub and emergent wetland systems. Therefore, an accurate assessment of proposed site hydrology is crucial for implementation of soil reconstruction and overall site grading plans (Daniels and Whittecar, 2004).

Permitting and constructing effective wetlands is a costly process. Daniels and Whittecar (2004) found that constructing, planting, and monitoring a created wetland can cost upwards of $100,000 $ha^{-1}$. Pre-planning is crucial to reducing these costs. Mitsch and Wilson (1996) suggest an ecosystem approach be used to better achieve markers of success. This approach hinges on understanding wetland functions, allowing time to reach steady-state, and creating a flexible design that allows for altering hydrology to some extent over initial periods to achieve appropriate conditions.

## 2.5. Common Non-Tidal Wetland Types in the Mid-Atlantic

Hydrogeomorphic (HGM; Brinson, 1993) setting classification is a widely accepted method used to group wetlands based on common hydrologic and landscape settings. These classes are: mineral soil flats, depressional, riverine, slope, organic soils flats, estuarine fringe, and lacustrine fringe. For the purposes of this study, we will be focusing on mineral soil flats, depressions, and riverine wetlands. However, the Cowardin et al. (1979) wetland nomenclature is still the most widely used by wetland regulators and consultants and for setting permit conditions. The Cowardin classification terms (e.g. palustrine forested, emergent, etc.) differ for a given wetland vs. HGM classes. HGM classes are centered on two factors, wetland geomorphic setting and hydrology; each HGM wetland type has a unique combination of these and they describe both landscape setting and hydrologic drivers for a given wetland type.

### 2.5.1. Mineral Soil Flats (Pocosins; wet pine flatwoods)

Often mineral flats occur "…on interfluves, relic lake bottoms or large floodplain terraces…" (Brinson et al., 1995). These wetlands are common to the Mid-Atlantic lower and middle Coastal

Plain and are similar in classification to “hardwood mineral flats” (Brinson, 1993). One common type of mineral flat wetland is a pocosin. This term has its roots in the Native American Algonquian language, meaning “swamp on a hill” (Tooker, 1899). Pocosins lack well-defined alluvial surface features as they are not typically adjacent to rivers or streams. Pocosins may contain subtle, poorly developed surface drainage features and portions may also be very gently concave in surface topography. These wetlands are found on low relief and are precipitation driven systems (Weakley and Schafale, 1991). The combination of low relief and lateral distance from incised drainage generates a distinctive hydroperiod driven by seasonal differences in precipitation vs. ET. Depending on the study, pocosins are often separated based on depth of organic matter, size, and vegetation types (Weakley and Schafale, 1991). More specifically, the term pocosin has be used to describe short (scrub-shrub) pocosins and tall (pine dominated) pocosins (Richardson, 2003). Mineral flats are subjected primarily to vertical flow of water due to differences in precipitation vs. ET, but may also lose water to local groundwater recharge (Brinson, 1993). Tall pocosins are characterized by nutrient deficient and high pH soils, while short pocosins have been reported to be driven by the water table which is “perched above the regional water table” (Richardson, 1983).

2.5.2. Depressional (Isolated depression/vernal pool/Carolina bay)

Depressional wetlands occur in areas of lower topographic relief which hold water for longer than their surroundings (Brinson et al., 1995). These are often topographically isolated wetlands such as prairie potholes, Carolina bays, or Delmarva bays. Rarely is it the case that depressional wetlands are completely hydrologically or ecologically isolated; however, this requires a more detailed inventory to assess (Tiner, 2003). Carolina bays are typically elliptical or oval in nature,

having a sand rim, and generally oriented northwest/southeast (Stolt and Rabenhorst, 1987b; Lide, 1997) with a higher rim to the southeast. These isolated depressions are primarily rainwater fed, but may also have some limited groundwater interactions with surrounding uplands or wetlands. Stolt and Rabenhorst (1987a) state that most Carolina bays they studied had no evidence of an outlet. Most mid-Atlantic Coastal Plain depressions are typically considered to be Carolina bays or other isolated depressions with similar characteristics. Soils commonly described in Carolina bays vary and may include clay-based, sandy, and organic soils (Stolt and Rabenhorst, 1987a). Hydroperiods of these bays also range from permanently flooded in the center to seasonally saturated soils. Vegetation in each of these systems is variable based on length and depth of saturation. These patterns also influence the soil development along the hydrologic gradient presented in Carolina bays (Sharitz, 2003; Stolt and Rabenhorst, 1987a). Recently, they have been theorized to be formed by prevailing winds from the NW creating waves and circular scour patterns within depressional waterbodies (Lide, 1997; Folkerts, 1997). Stolt and Rabenhorst (1987b) describe Carolina bays occurring on the eastern shore of Maryland, covering their soils, distribution, and origin. They discuss how their soil analysis generated inconsistencies with many of the theories surrounding the genesis of the bays. Finding a lack of evidence for dissolution and subsidence, meteoric or other types of impact, as well as having a distribution unlikely to have been effected by coastal processes. They proposed various landscape progressions which would support their findings. They hypothesized that windblown material accumulated in dunes and inter-dune areas or that unvegetated patches had been “blown out”. Having been derived from wind deposited materials (e.g. aeolian Pleistocene loess over sands), these bays then underwent pedogenic processes due to their ability to accumulate water. They eventually formed into the

sandy rim and finer textured inner bowl characteristic of the bays we find now (Stolt and Rabenhorst, 1987b).

Within Carolina bay wetlands, Collins and Battaglia (2001) and Battaglia and Collins (2006) found that plants ranged from wetland obligates near bay centers and deeper wetter pockets out to facultative species on the drier fringes or on windthrow mounds. With an increase in the hydroperiod variation, Collins and Battagalia (2001) found there was an increase in species richness associated with seedbank germination. Brinson (1993) described depressional wetlands as having vertical hydrologic flow, dominantly driven by precipitation with minimal groundwater and surface water interactions. In areas where karst features dominate, it is common to find sinkhole depressional wetlands (Tiner, 2003). Depressions in karst topography are often heavily influenced by groundwater with dissolution of underlying bedrock as a driving force in their occurrence (O'Driscoll and Parizek, 2008).

2.5.3. Riverine (Emergent/scrub-shrub/forested)

For the purpose of this thesis, the Cowardin et al. (1979) combined classes of palustrine forested, scrub-shrub, and emergent non-tidal wetlands will all be considered as "riverine" within the HGM system (Cowardin, 1979; Brinson, 1993). Dominant water sources for these systems include groundwater flows to and from the stream channel depending on surrounding water table height; this often produces a more uniform hydroperiod which is less buffered against precipitation and seasonal variations. Other non-dominant water sources for these types of wetlands include periodic overbank flow, precipitation, and inputs from adjacent upland runoff and local groundwater discharge (Brinson, 1993). While riverine systems do experience drawdown during

the dry season, they tend to stay saturated closer to the surface for longer durations due to their strong groundwater interactions (Brinson et al., 1995).

Within riverine systems, a wide range of plant communities exists based on topographic relief and local hydrologic regime. Within the zone where riparian systems shift from deepwater habitat to wetland habitat, there is an abundance of aquatic vegetation adapted to withstand being saturated and flooded for most of the year (Cronk and Fennessy, 2001). Landward, there is then a shift from aquatic hydrophytes to emergent herbaceous vegetation adapted to resist water saturation for much of the year. Seed germination and recruitment for many species in this zone requires water table drawdown (Cronk and Fennessy, 2001). Moving upgradient, the next subsequent vegetation stratum would be scrub-shrub and then forested wetlands would occur in the driest zones of this wetland landscape. Each zone of vegetation can be sensitive to minor changes in water level, causing a shift in vegetation type (Magee and Kentula, 2005) if hydrologic conditions change. Thus, a precursor to a forested wetland system may be an earlier elevation zone with a combination of perennial herbaceous plants as well as woody vines, shrubs and small trees (< 6 m) (Cowardin et al., 1979) which then accumulates sediment, raising effective elevation above saturation, etc.

## 2.6. Wetbud

Wetbud is a new water budget computer program for assistance in the design of created wetlands that was developed and verified through collaboration between industry professionals, software designers, hydrologists, and soil scientists. The intent of this program is to allow for more uniform and unbiased water budget calculations for planning and permitting of created wetlands that can be readily performed on a personal computer. There are two models with varying levels of

complexity with different input parameters in Wetbud. The two models are (a) Basic and (b) Advanced, but the program includes a wizard option for creating a Basic model with simplified parameter presets. My primary focus was given to the Wizard option and regular parameterized Basic models for the purpose of model evaluation. While not the focus here, the Advanced Model utilizes 3-D multi-layer flow modeling though the addition of a MODFLOW interface (Harbaugh et al., 2005). Wetbud is freeware and currently available at http://landrehab.org/WETBUD.

The Wizard application of the Basic model is the simplest option to quickly produce an estimated water budget using limited site data within a few minutes. The Wizard option is accessed through a button on the home screen of Wetbud (Figure 2.1). The Basic model water budget produced by the Wizard option has two levels of specification: project level and scenario level. Project level specifications include the size of the wetland, the size of the watershed, the location of the project in decimal degrees, and the elevation of the wetland bottom. Within projects, a user has the ability to create multiple independent models of the same project, known as scenarios (Figure 2.2).

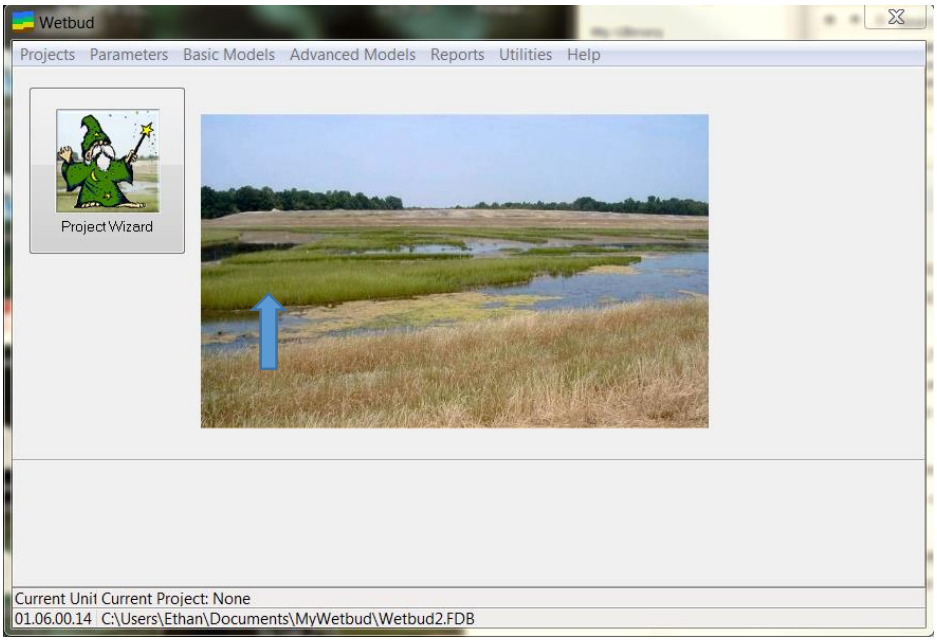


Figure 2.1. Wetbud Home Screen: This is the dialog box which apears when wetbud is launched, it has options to view projects, parameters, Basic models, Advanced models, reports, utilities, and a button to launch a Wizard for creating Basic models using default values.

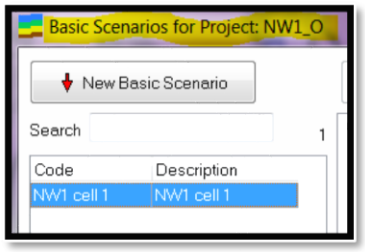


Figure 2.2. Wetbud interface where one can create more scenarios with identical project parameters.

Utilizing the Wizard automatically creates a Basic model with various parameters held constant. The Basic model incorporates scenario alterations as the next step in module complexity. The Basic model (and the Wizard option) calculates a water budget for a flat-bottomed basin with a set outlet height and capacity; there is no wetland surface or water level slope included in this calculation. The full Basic model interface allows for considerably more input complexity than

the Wizard, allowing the user to create a 1-D formulation where groundwater flux can be predicted using Darcy's Law (groundwater) and stream overbank can be calculated using dimensionless unit hydrograph calculations based on precipitation or stage discharge data.

Wetbud calculates the water budget on a daily time step and aggregates it into a monthly report (Figure 2.3) for the Basic model output. Precipitation is imported from daily weather data collected either manually by a user or from the preloaded weather stations. A web retrieval method also exists for building new weather stations. The overbank flow is currently calculated through user input data and is not required to produce a Basic model water budget, but may be appropriate for riverine systems. Runoff input to the wetland ($H_o$) is calculated through the NRCS curve number method (Mishra and Singh, 2003) with the CN and watershed area provided by the user. This parameter is also commonly called "run-on", however, Wetbud uses the term "runoff" for direct local surface water additions. Groundwater discharge and groundwater recharge is provided by the user via a simple application of Darcy's Law or may be set to a user defined level that may vary over time or remain fixed. Potential evapotranspiration (PET) is estimated through either Penman-Monteith or the Thornthwaite method (dependent on the availability of solar data). Surface water out ($S_o$) is determined by the program based on the capacity of the basin as controlled by the outlet height; once the volume of the basin is filled to capacity, $S_o$ is calculated as any water above that amount on a given day. Total water for the budget output is calculated as a mass balance and presented in terms of absolute depth/mass of water in the system. Total water is then used to calculate actual water level, which is equal to total water divided by the soil storage factor (Figure 2.4) or the specific yield (Sy) (Equation 2.4.). Specific yield is the ratio of volume of water which a saturated rock or soil will yield by gravity to the total volume of the rock or soil (Johnson, 1963).

This parameter is also equivalent to "gravitational water" as defined by soil scientists. Specific yield is often expressed as a percentage; however, in this application, Wetbud represents Sy as a decimal. For example, 0.25 would mean 25% of the soil is available to Wetbud as water storage. As used in Wetbud, this approach assumes that water will not be withdrawn from the soil at potentials lower (drier) than field capacity (-10 to -33 kPa), which is obviously a conservative assumption since wetland plants certainly extract water below this water potential point. This assumption underlies the daily water budget calculation, and thus contributes to how much water will be "lost" from the system through outflow.

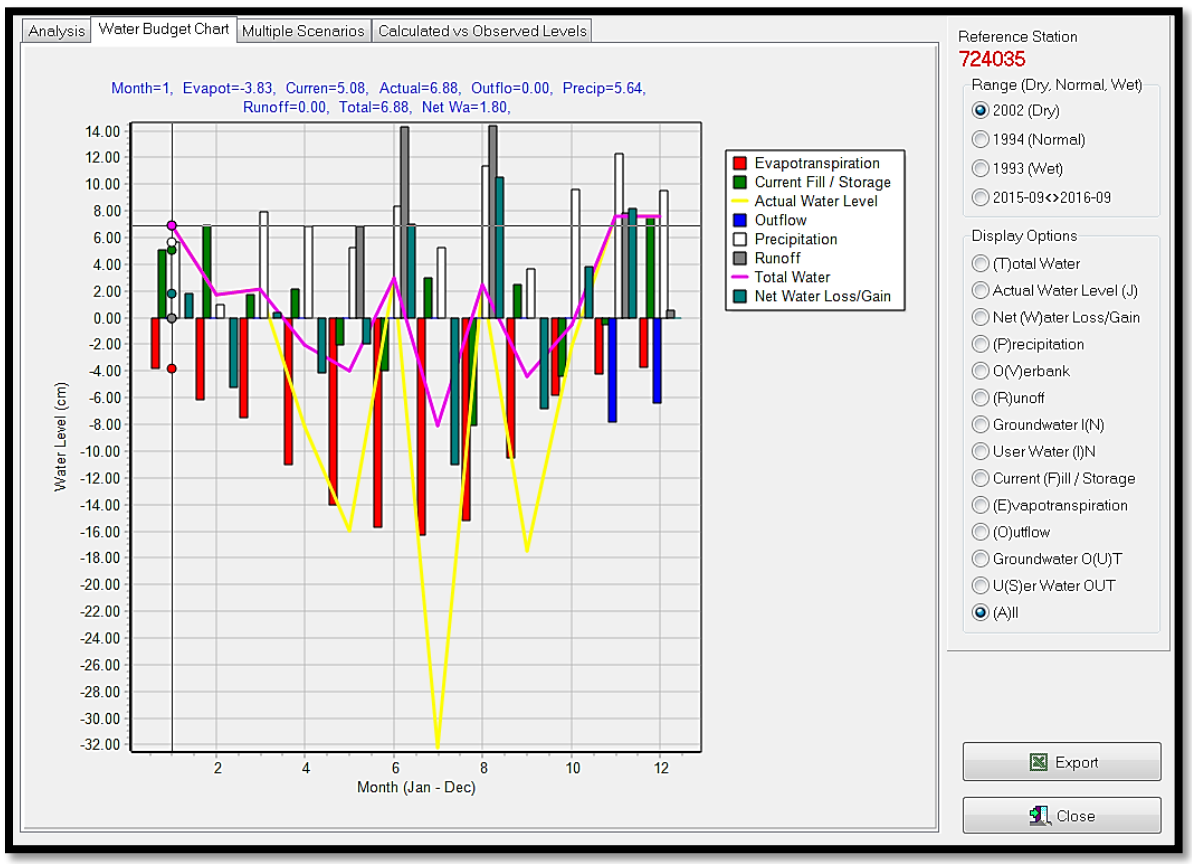


Figure 2.3. Water budget basic scenario analysis output (all parameters).

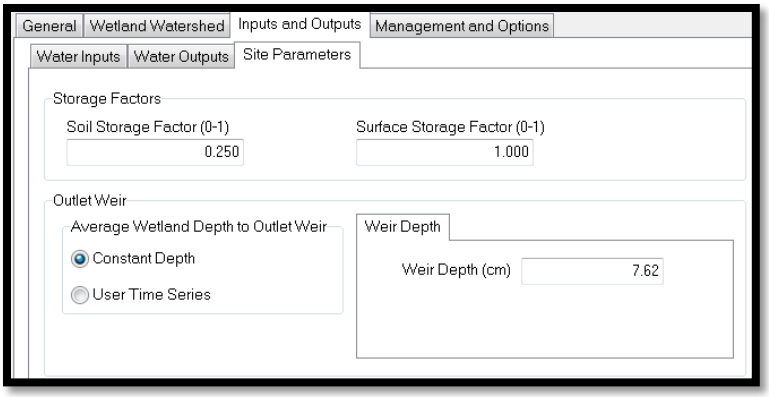


Figure 2.4. Basic model user interface – Inputs and Outputs; site parameters: On this screen soil storage factor (Sy) and surface storage factors as well as weir depth can be input.

Equation 2.4. $$S_y = (\frac{V_{wd}}{V_T})$$

Where $V_{wd}$ = volume of water at field capacity and $V_t$ = volume of water at saturation.

Producing a basic scenario begins with determining the appropriate weather stations: National Oceanic and Atmospheric Administration (NOAA) or National Climatic Data Center (NCDC), and associated Natural Resource Conservation Service - Wetland Tables (NRCS-WETS). Wetbud populates a list and a map with available stations based on user defined distance from the site (Figure 2.5). Next, the average surface elevation is input for the wetland surface elevation, represented graphically as zero (Figure 2.6). All water level data is calculated and represented relative to the surface elevation as influenced by Sy, etc. (Figure 2.4).

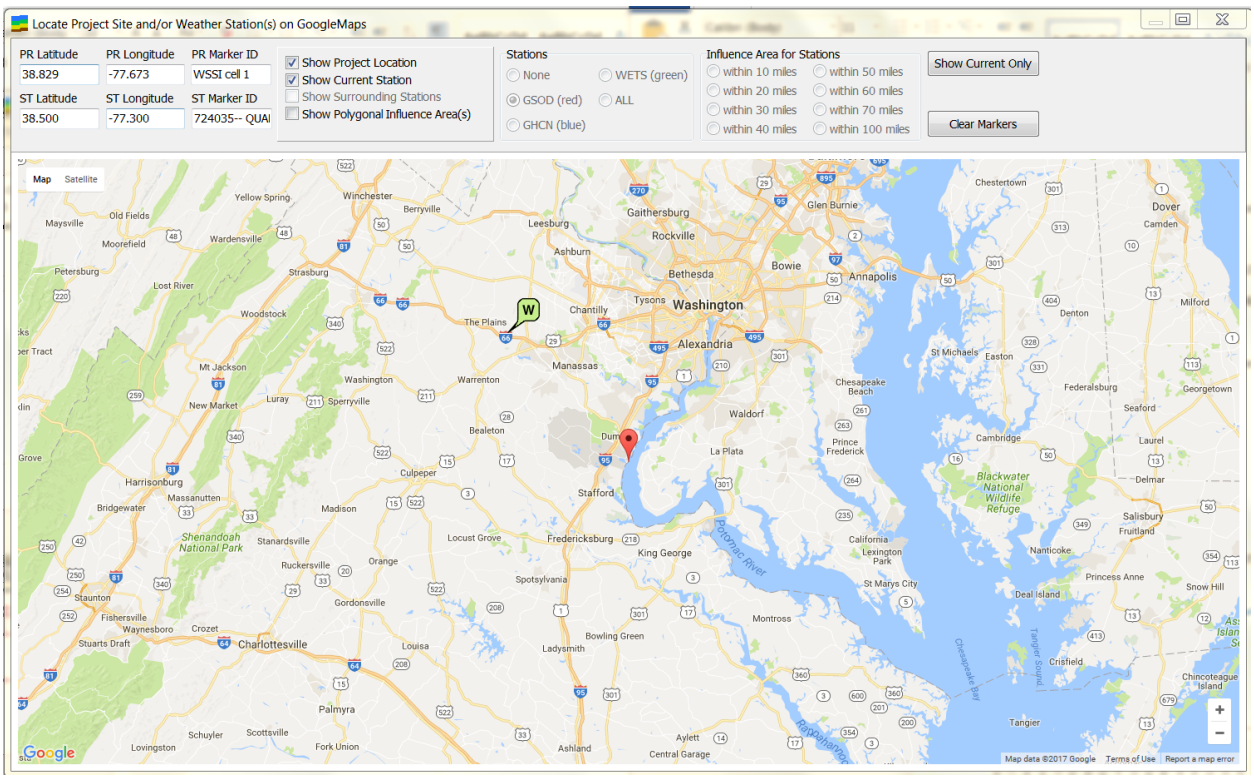


Figure 2.5. Example of weather station location map. 'W' denotes the research site location and the pin is the weather station available as pre-loaded data.

Estimation of $H_o$ is based on the NRCS curve number methodology (Mishra and Singh, 2003). This method calculates the amount of overland flow which an area is subjected to after soil infiltration capacity (a.k.a. the "initial abstraction") is reached. To make this calculation, Wetbud needs wetland watershed area and the estimated watershed NRCS curve number (Figures 2.7). These inputs allow the program to calculate $H_o$ driven by rainfall data associated with the pre-selected weather station. Wetbud will then calculate PET using either the Penman-Monteith or Thornthwaite equations (Equation 2.2 & 2.3) based on available data and user preference (Jensen et al., 1990; Allen et al., 1998; Thornthwaite, 1948). As a user option, it is also possible to calculate PET values externally and import the data. This may be useful in the case of applying crop

coefficients (e.g. Kc; Stone, 2017). Users requiring specific time periods or preferred resolutions may need to import additional site- and time-specific ET data (Figure 2.8).

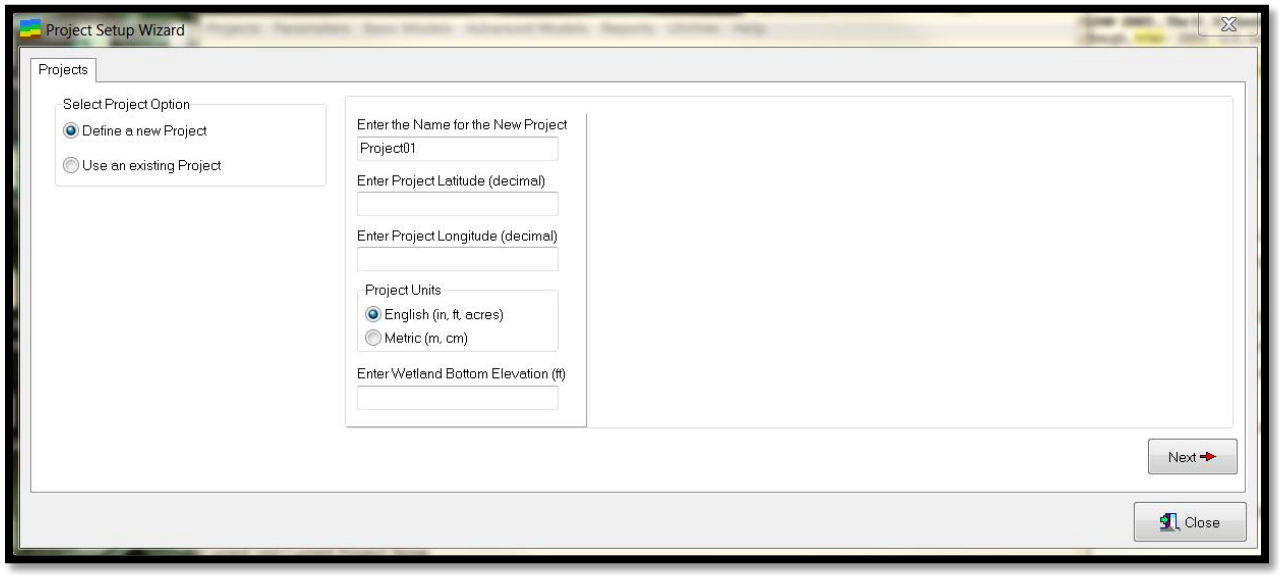


Figure 2.6. Wizard button dialog box- This is the first step of parameter input when creating a Basic model using the Wizard.

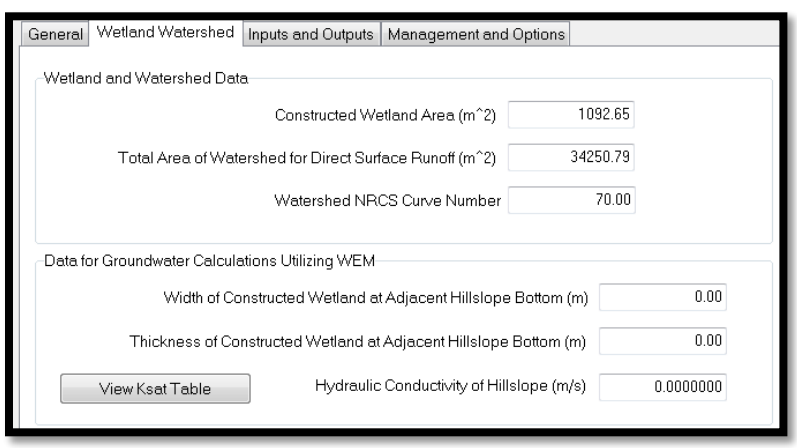


Figure 2.7. Basic model user interface - Wetland Watershed: Here the user can alter the size of their wetland area, total watershed area, NRCS curve number, as well as the part of the WEM interface.

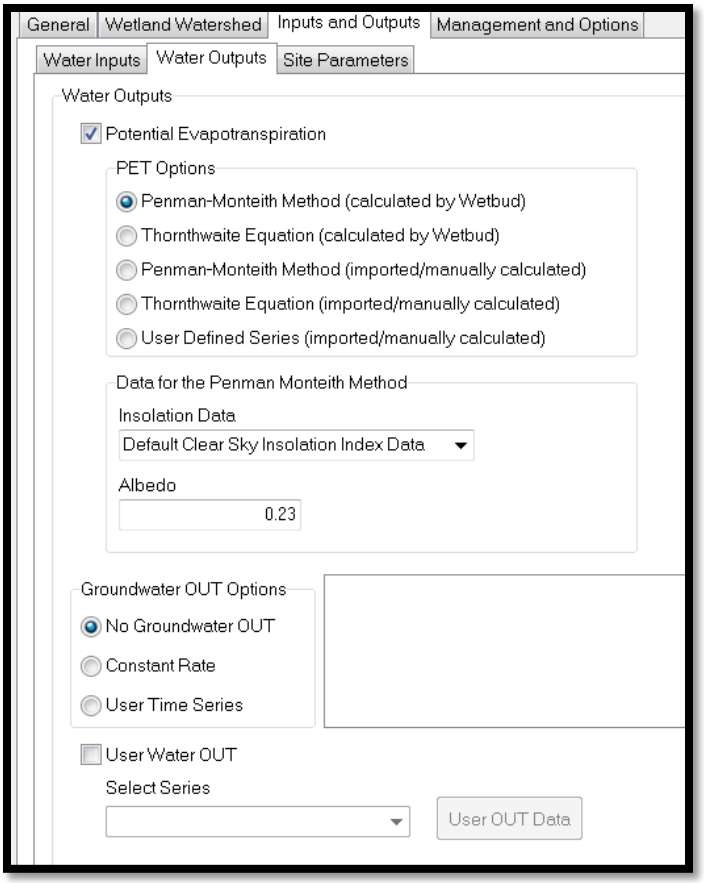


Figure 2.8. Basic model - Inputs and Outputs; Water outputs: this allows for the user to select their preferred PET calculation method, as well as to take water out of the system (i.e. to simulate pumping).

When produced in the Wizard, Wetbud's Basic model assumes a number of values: an initial "full pond" fill level of 5.08 cm (2 in.) (Figure 2.9), a presumed net groundwater loss of 2.54 cm (1 in./month), and an outlet weir height of 7.62 cm (3 in.) above the wetland bottom elevation. A soil storage factor (Sy) of 0.25 (25%) is assumed for below ground level and ponded zones above ground level are assumed to have a storage factor (Sy) of 1.0 (100%) (Figure 2.4).

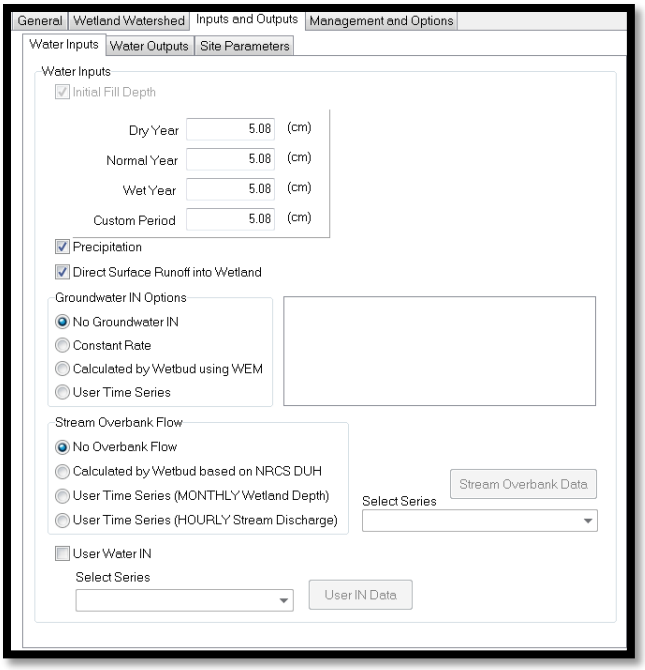


Figure 2.9. Basic model interface - Inputs and Outputs; Water inputs: This interface allows for variation of inputs of initial fill depths as well as enabling precipitation, direct surface runoff, groundwater, and stream overbank options in the model.

## 2.7. The Process of Simulation Model Evaluation

Model evaluation is a method used to assess performance in models seeking to model variations of similar systems. Evaluation is often a composite approach involving calibration, validation, verification, and sensitivity analysis. Sensitivity analysis is a term used to describe the impact which parameter alterations have on model output (Norton, 2015). Verification, calibration, and validation are all aspects of model and associated software development, often used in tandem with one another. For the purpose of this program, we have used these definitions:

### 2.7.1. Verification

Verification of a model is the process of confirming that various components of the model/software perform the governing equations correctly and output data accordingly. Verification is often done

through expert consultation on the governing principles and by making a general comparison of model output to data sets generated separately for an identical system. Ideally, a program would be tested and most program defects removed (Sargent, 2009) before moving to calibration.

### 2.7.2. Calibration

Calibration is the alteration of model parameters and comparing the resulting model output for a given set of assumed conditions to observed data (Moriasi et al., 2007). Model output and observed data are compared using various goodness of fit measures; for hydrologic models it is common to use the coefficient of determination ($R^2$), root mean squared error (RMSE) (Equation 2.5), Nash-Sutcliffe efficiency (NSE) (Equation 2.6) and various other statistics (Nash and Sutcliffe, 1970). RMSE and NSE are often used in combination due to the nature of NSE. Statistically, the RMSE is equal to the amount of unexplained deviation from the mean divided by the total variation (explained + unexplained variation) from the mean. So in the case of a linear regression model, it is similar to an $R^2$ value. NSE evaluates the ability of a model to simulate observed values through time. The results range from $-\infty$ to 1.0, with a value of 1.0 implying a perfect fit, and a value below zero denoting that the model provides a poorer estimate than the mean of the observed points (ASCE, 1993). Because NSE compares model output to the mean observed value, it is most appropriate for models with large variations in absolute values (Arnold et al., 2012; Gupta et al. (2009). The wetland analyzed in this study showed relatively small variations in water level over the study period, so RMSE was prioritized over NSE for evaluating model calibration and validation.

Previous studies on Wetbud have used an NSE threshold of >0.5 and RMSE threshold of $\pm$10 cm to judge “relative success” (Stone, 2017). Previous work on another commonly used model,

DRAINMOD, under a variety of conditions, has employed similar statistics and thresholds to those used here. For example, Caldwell et al. (2007) proposed ranges of acceptable, good and excellent ratings for NSE and mean absolute error (MAE). MAE is the average of the residual differences between two datasets and is similar to the results for RMSE. When calculated on the same data set, the RMSE will always be the same value or higher than the MAE, and they both range from 0 to ∞. Due to this relationship, we felt that using MAE model accuracy standards used in these other studies with the RMSE estimator would provide as good (or actually stricter) a threshold for acceptability of statistical results. Given that regulatory standards are concerned with length of occurrence of saturation of the zone above -30 cm (-15 cm in sandy soils), a wetland system model with an RMSE greater than 15 cm would create doubt in the validity of the predictions. Therefore, to address jurisdictional wetland hydrology criteria, we concluded that a model with an RMSE less than 10 cm would be much more reliable for the prediction of water within the upper 30 cm of the wetland soil.

Equation 2.5.

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

| | | | |
|---|---|---|---|
| Where: | RMSE | = | Root Mean Squared Error (m) |
| | $Q_m$ | = | Modeled water level (m) |
| | $Q_o$ | = | Observed water level (m) |
| | N | = | Number of calculated residuals |

Equation 2.6.

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

| | | | |
|---|---|---|---|
| Where: | NSE | = | Nash-Sutcliffe Efficiency (dimensionless) |
| | $Q_o$ | = | Observed water level, at a given time, t |
| | $Q_m$ | = | Modeled water level, at a given time, t |

### 2.7.3. Validation

Validation is the process of confirming that a calibrated model is sufficiently accurate in its representation the natural system it seeks to model (Sargent, 2009; Refsgaard, 1997). This is usually accomplished using data for the same or a similar system to the one used for model calibration. Ideally, the data used in validation wasn't used for calibration; this data is then modeled using the calibrated model parameters. Model validation is deemed successful when the validated model performs with sufficient accuracy (Refsgaard, 1997). Model value can be assessed multiple ways, one of which is accuracy. Other assessments are based in the core uses of the model and what it can contribute to its users (Bennett et al., 2013). Sargent et al. (2009) stated that model accuracy should be determined individually for each model prior to analysis. Here we have used RMSE as our statistical measure of accuracy.

## 2.8. Sensitivity Analysis

A variety of sensitivity analysis (SA) techniques exist and will vary depending on the model being evaluated. These techniques all function with the same basic principle of altering input parameter values and measuring the change in model output (Norton, 2015). A commonly employed method is known as one-at-a-time permutations (OAT), employed when iterative model runs are time-consuming or costly. Other methods of sensitivity analysis employ statistical sampling techniques

which can be used to create a response surface. These response surfaces are used to assess parameters within the model which are more sensitive than others based on the degree of output change. Common parameter metrics used during OAT SA are the absolute and relative sensitivity ($S_a$ and $S_r$). These two, $S_a$ and $S_r$, are used in initial SA to gauge the most volatile parameters in the model, as they can be used to rank which parameters have the greatest effect on model output. $S_a$ is reported as the output units over the input units while $S_r$ is dimensionless since it is proportional to the change in the input parameters (Haan et al., 1995). Equations for $S_a$ and $S_r$ are shown in Equation 2.7:

Equation 2.7.

$$S_a = \frac{\delta O}{\delta I} \qquad S_r = \frac{\delta O}{\delta I} \cdot \frac{I}{O}$$

Where:

$\delta$ = change in

$S_a$ = absolute sensitivity

$S_r$ = relative sensitivity

O = particular output

I = particular input

## 2.9. Wetbud Work to Date

Wetbud evaluation and validation has been a multi-disciplinary process involving the various collaborating investigators at Virginia Tech (W.L. Daniels and T.W. Thompson), Old Dominion University (G.R. Whittecar) and the University of Kentucky (Z. Agioutantis). This approach has yielded improvements for practical application and greater functionality of the user interface.

Previous research work has involved verification of various input components and develop additional databases. Both the Basic and Advanced models have been compared with observed water level data in multiple wetland scenarios (Gloe, 2011; Dobbs, 2013; Neuhaus, 2013; and Stone, 2017). Dobbs (2013) worked on and evaluated the Effective Monthly Recharge ($W_{em}$) Model, which uses hydrologic head pressure to calculate groundwater inputs, on two toe-slope wetlands in the central Piedmont. Work done by Gloe (2011) compared the accuracy of Wetbud's PET equations for a given site. Gloe (2011) performed the first evaluations of Wetbud using statistical analysis of the model in comparison to observed wetland water levels. Models produced by Gloe (2011) were not calibrated to the observed data which they were compared against. Gloe compared results using the Basic model with Thornthwaite vs. the Penman-Monteith method as well as models run with the Advanced Model GUI for MODFLOW. Gloe (2011) found that Thornthwaite equation based Basic models were the least accurate and the MODLFOW based Advanced models were the most accurate. Penman based Basic models fell just short of the Advanced model. Gloe (2011) also performed sensitivity analysis on input parameters for Wetbud, ET, and the hydraulic conductivity of two levels of vegetative stem density. He found that the hydraulic conductivity alterations were not a sensitive parameter except at extreme alterations in their values and that at a modest 10% shift in ET produced a stronger variation in the model output.

In a subsequent study, Neuhaus (2013) expanded on Gloe's (2011) research and compared both the Advanced and Basic models and their ability to predict seasonal drawdown as well as the effectiveness of weather data. He also looked at the implications of using data which might not represent the site area's actual weather patterns. Neuhaus (2013) confirmed that using the Penman-Monteith ET equation would provide better results than the Thornthwaite equation and was

advisable whenever comprehensive solar data is available. Stone (2017) focused on the ability of Wetbud to predict changes in water budgets given changes in hydrologic control structures at an altered/enhanced wetland site. The site in question was a natural wetland which was slated to be expanded by raising its outlet elevation by installation of a dam and a weir. Stone (2017) was able to observe wetland water levels prior to and after installation of the new dam, which effectively increased the area of land subjected to wetland hydrology. Surprisingly, he found that the Basic model did an acceptable job of predicting overall water level fluctuations in this very large wetland complex and associated mixed urban/forested watershed. Additionally, Stone (2017) compared Wetbud Basic model outputs with varying Crop coefficients (Kc) to observed values for the same constructed wetland expansion in northern Virginia. He also found that using a Kc appropriate for actual local vegetation improved model performance.

## 3. Research Methods

### 3.1. Wetbud evaluation

Field Site Description (North Fork Wetland) for Basic model Validation/Calibration:

The study site is located in the northwest corner of the North Fork mitigation bank located in Prince William County, Virginia (Figures 2.1, 2.2, 2.3, and 2.4). This created wetland site has an underlying truncated high clay soil/saprolite layer over hard diabase bedrock which was graded and compacted from the underlying Bt, Btss, Btg, and C horizon materials during wetland construction in 2000. This presumably largely isolates the cells from groundwater flow for the series of created wetlands used in this study. For this study, there were four wetland cells evaluated, three of which were inter-connected and subject to local watershed runoff, while the fourth was an isolated cell designed as a "vernal pool". The first three of these sites were a series of inter-connected cells that received surface water input via a swale (0 order stream) from the adjacent upland watershed. The three connected cells (Figure 3.3) in the upper portion of the site were 1092 $m^2$ (0.27 ac), 1174 $m^2$ (0.31ac), and 1335 $m^2$ (0.33 ac) in size, respectively. These cells were separated by low embankments with water flow between them controlled via "rock weirs" which allowed for a certain amount of permeable flow through the weir structure itself. The fourth cell (Figure 3.4) is 28,044 $m^2$ (6.93ac) in size, entirely precipitation driven, and does not interact hydrologically with the other three sites. Here, Wetbud was not calibrated for rock weirs; this option is not yet integrated into the program. This project used a constant flat elevation for the weir and assumed all water which could overtop the weir left the system on a daily basis.

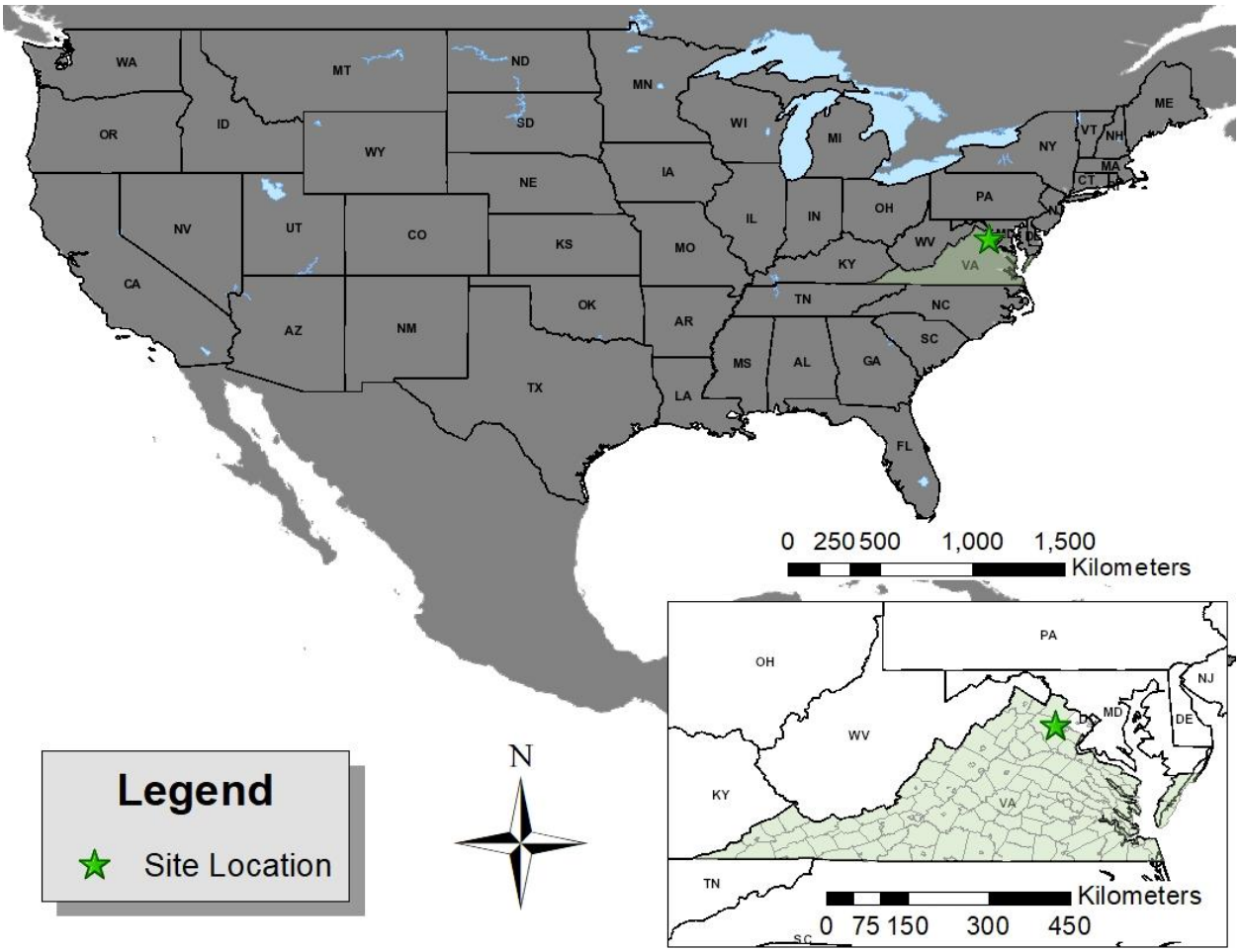


Figure 3.1. General site location map.

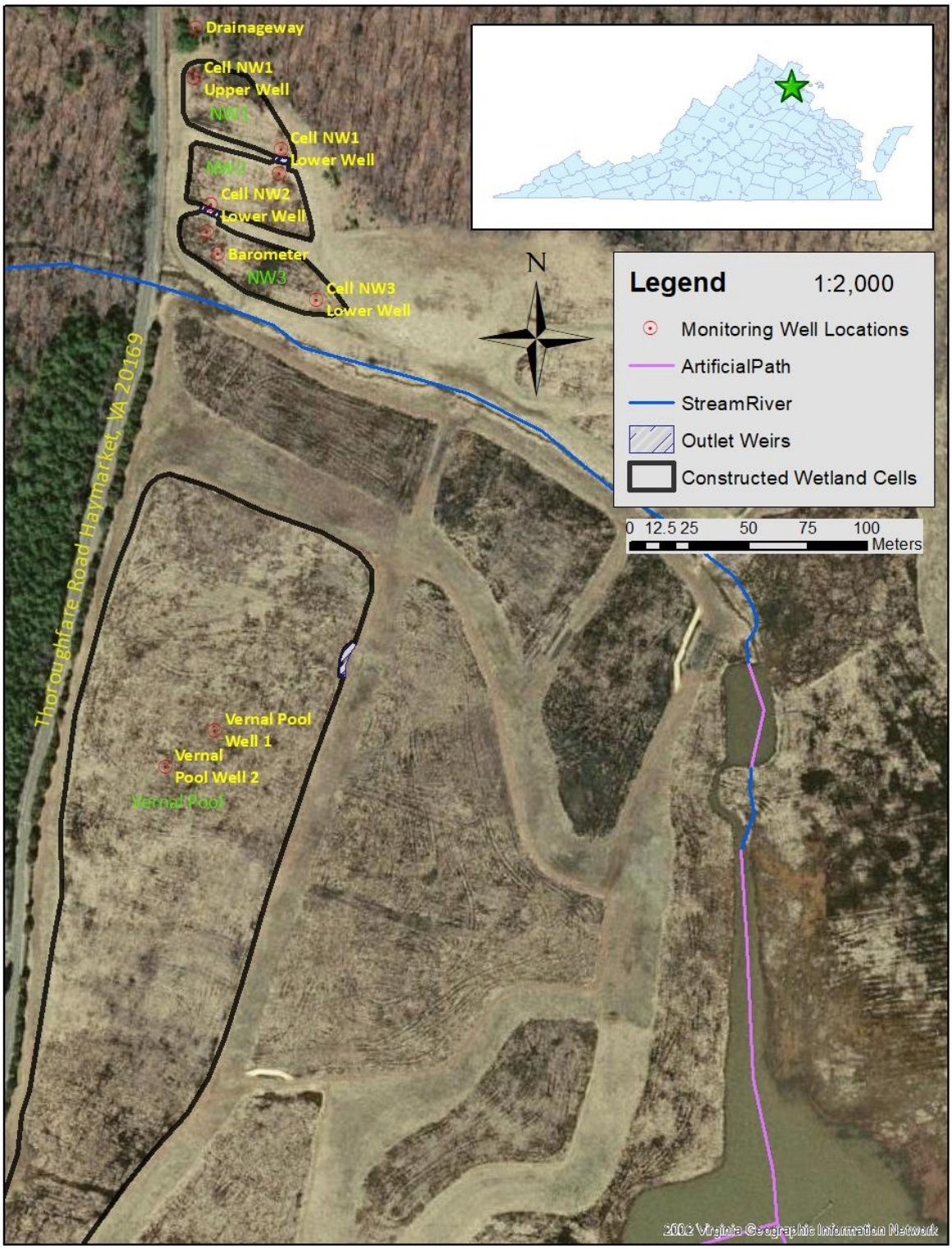


Figure 3.2. Site overview map. Interstate 66 is just to the south of this image. Located at approximately 38°49'35.2"N 77°40'23.1"W.

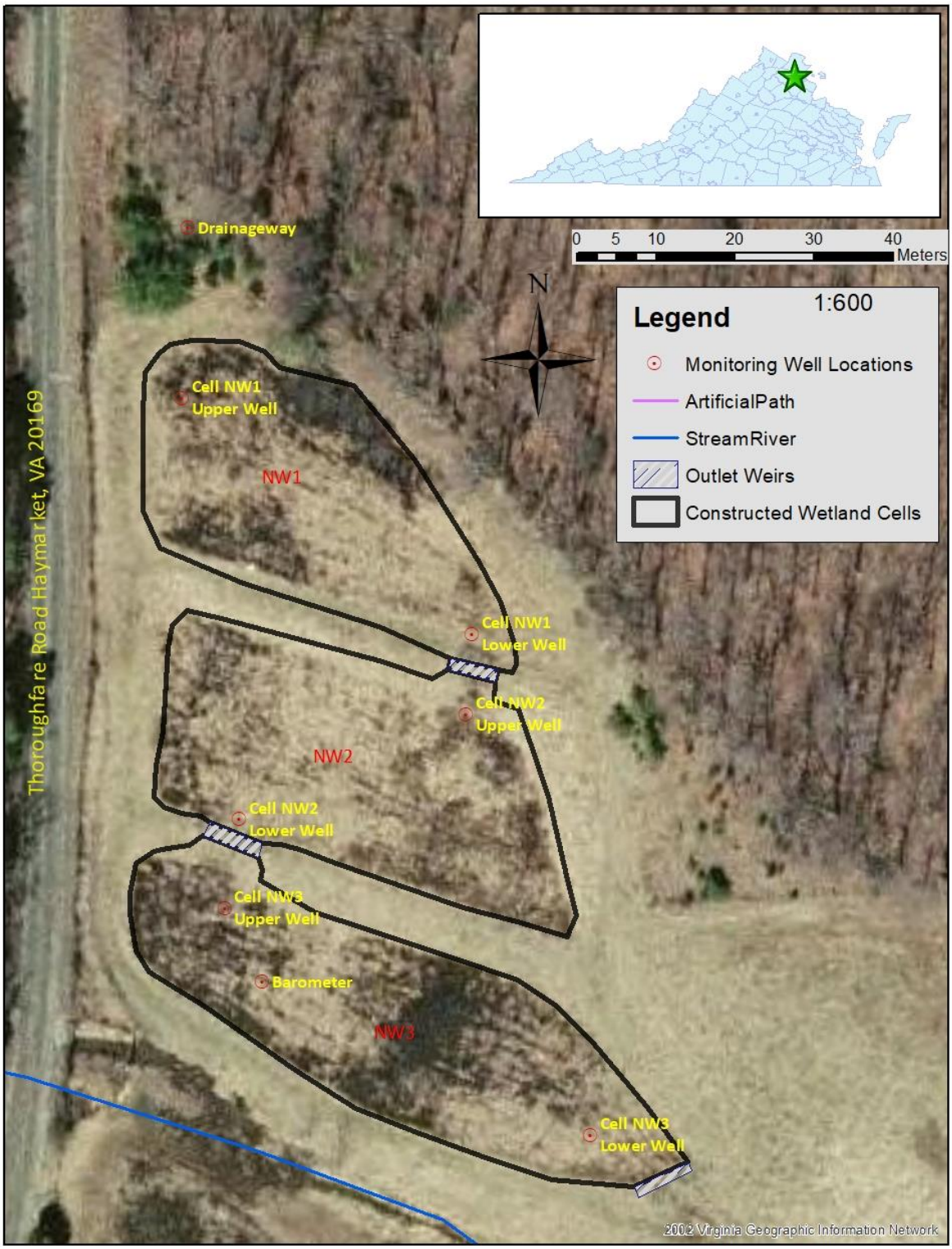


Figure 3.3. Three northernmost cells of the North Fork Mitigation Bank.

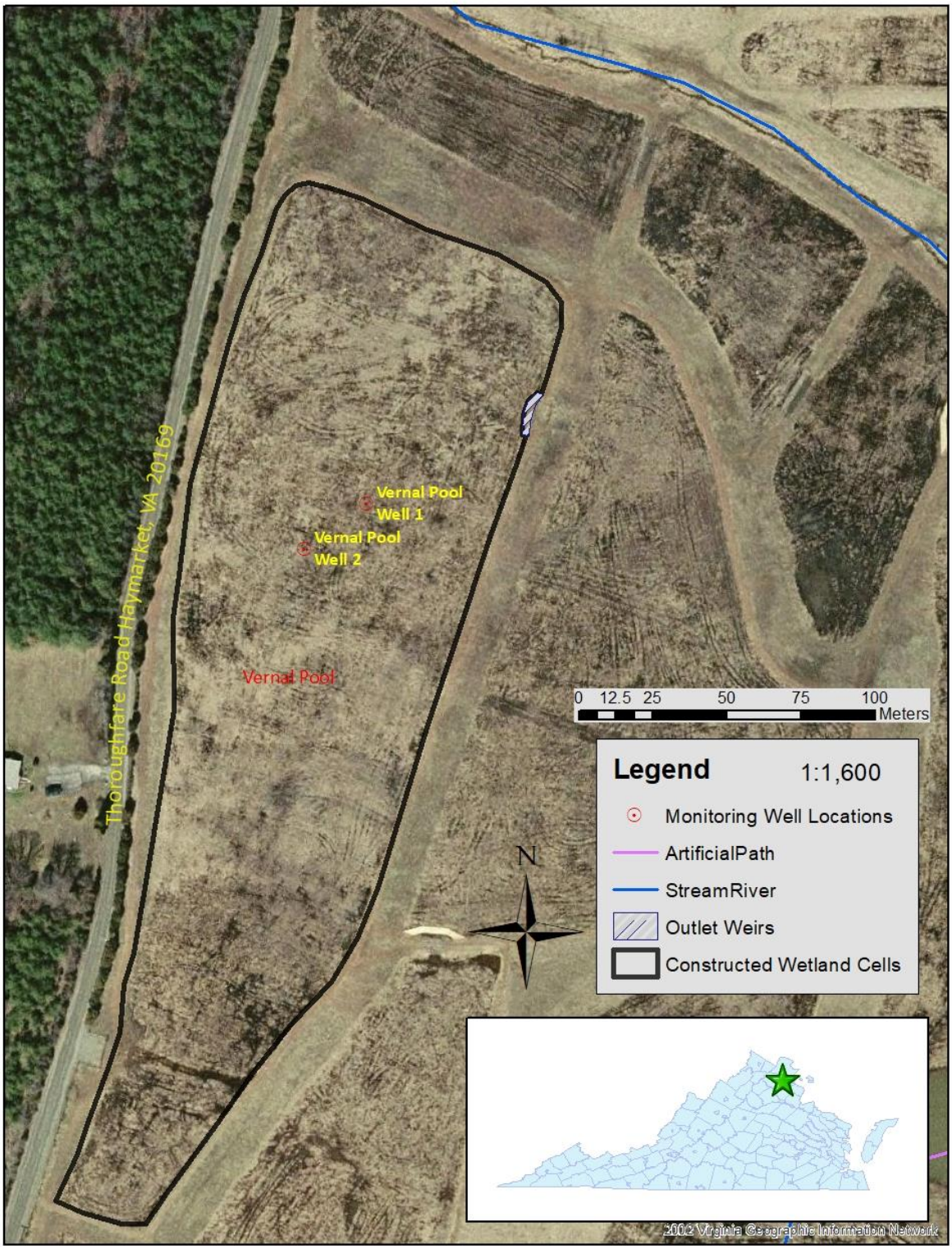


Figure 3.4. Vernal pool site located in the North Fork Mitigation Bank.

The WSSI mitigation bank in question is located within the Culpeper Triassic basin, containing sedimentary and igneous rocks from the Mesozoic period. This site is contained within a section of the basin which was filled in with mostly micaceous silty and sandy materials which have undergone metamorphism to produce micaceous and calcareous silt/sandstones. The area beneath the research site underwent subsequent magmatic intrusions into the silt/sandstones creating local areas of diabase bedrock as well as baked country rock contact areas of metamorphosed (heat altered) sediments identified as Hornfels (Shelton and Carpenter, 1999). Soil survey reports (NRCS, 2010) state the original site soils were a mix of the Waxpool series, Fine, smectitic, mesic Aeric Epiaqualfs; Jackland series, Fine, smectitic, mesic Aquic Hapludalfs; Albano series, Fine, mixed, active, mesic Typic Endoaqualfs; Oakhill series, Loamy-skeletal, mixed, mesic Typic Hapludalfs; and Legore series, Fine-loamy, mixed, active, mesic Ultic Hapludalfs. Textures present onsite were silt loam dominated A horizons over argillic Bt and Btg horizons with clay and clay loam textures. The C horizons consisted of sandy loam textures with paralithic skeletal material with lithic contacts ranging from 61 to 109 cm. A more detailed geotechnical pre-construction report of soils located onsite indicated between 15.24 cm - 30.48 cm (6-12 inches) of topsoil present (Shelton and Carpenter, 1999). They also determined pre-existing soils ranged from 0.6 m - 2.4 m (2 to 8 feet) in thickness and were composed of silts, clays and fine sandy silts with varying amounts of mica. Locally, most of the soils were low-moderately plastic and grain size increased with depth below the B horizon. The soils transition into saprolitic bedrock and then into very hard consolidated unweathered material. Highly plastic and expansive clayey subsoil is common in areas where weathered diabase bedrock contacts Hornfels formations (Shelton and Carpenter, 1999).

This cluster of sites was selected for evaluating the capacity of Wetbud's Basic model to calculate and graphically express predicted water budgets for design purposes. They were chosen because of presumed limited groundwater interaction and historical knowledge of the site (via the research sponsor) coupled with their similarity of design assumptions to the Basic model. With this approach, we evaluated the relative ability of Wetbud to calculate a water budget in both the simplified Wizard version and the also with a calibrated Basic model.

The North Fork Mitigation bank plans were developed in March 1999 by Wetland Studies and Solutions Inc. (WSSI) and this site was constructed preemptively to generate mitigation credits for future development. Construction was initiated shortly thereafter and continued until September, 2000. The site was separated into the subdivided cells for the mitigation bank based on the 1999 plans. After the subsoil was graded, clay liner material was delivered and this layer was graded and compacted to form the cells and embankments. Stored topsoil was then spread back over the site followed by a final grading. The site was then seeded and had its first growing season initiated in the fall of 2000. The site underwent monitoring before construction to determine site groundwater patterns. Ground surface exploration seepage observations were made using soil test pits dug during excavation; groundwater seepage was not observed in any test pits. Shelton and Carpenter (1999) noted that the analysis was not performed during late winter early spring months when the water tables would be at their highest, and so these observations may not have been fully representative of the site hydrology with respect to groundwater. Due to the site's geology, Shelton and Carpenter (1999) expected that watershed runoff inputs and rainfall would have the greatest effect on groundwater levels due to the perching effect which shallow refusal depths have on groundwater flow.

### 3.1.1. Well Installation

Shallow groundwater monitoring wells for this study were installed in October 2015 following USCOE (2005) standard wetland monitoring well installation guidelines. Using a hand auger, wells were installed to a depth of 45 cm (18 in) where possible using 5 cm (2 in) PVC with an open well screen 30 cm (1 ft.) in length (where possible) in the lower portion. To prevent siltation, sand was backfilled around the well screen and the surface was sealed from rainfall using a bentonite clay plug. The 5 cm pipe was required for the use of automated water level loggers as outlined in USCOE (2005). Wells were instrumented with Onset HOBO$^{tm}$ water level loggers which recorded water levels at 15 min intervals. These loggers were downloaded monthly. One logger was placed in a tree central to the study site to provide barometric correction for the loggers. Wells were placed near the inlets and outlets of the three connected cells (NW1, NW2, and NW3). Within the vernal pool, wells were intentionally installed in an area with varying local microtopography. A slightly concave position was used for Vernal Pool 1 and Vernal Pool 2 was installed in a slightly convex micro-topographic position. The wells have an average depth of 38 cm (15 in.) with a minimum of 24.1 cm (9.5 in.) and maximum of 48.3 cm (19 in.). During installation, a variety of soil conditions and depths to bedrock were encountered (Table 3.1). Field soil textures in the open screened horizons/layers included SiL, L, SiCL, CL, and C textures.

Well maintenance was conducted every other month, ensuring good condition of the loggers and wells by clearing debris from around the pipes, cleaning the loggers and sealing/securing any loose wells. Additionally, well readings were confirmed using manual methods to confirm logger

accuracy. Monitoring well NW2 Upper was installed as a shallow stilling well due to shallow bedrock and was quickly ice-heaved and abandoned.

Table 3.1. Summary of soil depth data for monitoring well installation.

| **Monitoring Well ID** | **Depth from Surface** (cm) | **Dominant Soil Texture at Well Screen** | **Depth to hard rock Refusal** (cm) |
|---|---|---|---|
| **Cell NW1 Upper** | 27.9 | Loam | 27.9 |
| **Cell NW1 Lower** | 30.5 | Silt loam | None |
| **Cell NW2 Upper** | 24.1 | Silt loam | 24.1 |
| **Cell NW2 Lower** | 40.6 | Gravelly clay | 40.6 |
| **Cell NW3 Upper** | 27.9 | Clay loam | 27.9 |
| **Cell NW3 Lower** | 27.9 | Silt loam | None |
| **Vernal Pool 1** | 48.3 | Silt loam | 48.3 |
| **Vernal Pool 2** | 48.3 | Silt loam | 48.3 |
| **Drainageway** | 48.3 | SiL over clay | None |

3.1.2. Water budget components

As described earlier, the Wetbud Basic model uses a simplified water budget as required by federal and state agencies for constructed wetland mitigation permit review. This budget is best expressed as:

Equation 2.1. $$\mathrm{P} + \mathrm{SWI} + \mathrm{GWI} = \mathrm{ET} + \mathrm{SWO} + \mathrm{GWO} \pm \Delta\mathrm{S}$$

Within the Wetbud programming and User's Manual, some of these terms are described using different terminology and in some cases are controlled by more than one program feature:

### 3.1.3. Precipitation (P)

Precipitation data was obtained through two sources, publicly collected data stored in Wetbud from Washington/Dulles International Airport, DC (Dulles, VA 20166) and the local research weather monitoring station in the vernal pool. Within Wetbud, precipitation data is automatically collected and included in your model based on your selection of a weather station. Available stations are suggested based on proximity to your site or may be chosen manually.

The onsite weather station was equipped with sensors which measured:

Temperature using a Campbell Scientific HC2S3 Temperature and Relative Humidity probe.

Wind speed/direction using a Campbell Scientific Met One 034B wind set.

Rainfall using a Campbell Scientific TE525 (metric) tipping bucket rain gage.

Barometric pressure using a Campbell Scientific CS106 barometric pressure sensor (by Vaisala).

Net solar radiation using a Campbell Scientific NR01 four-component net radiation sensor.

The data were relayed in near real time data using a Raven XTV cellular modem using the Verizon network. All of these sensors were powered with an SP50 50W solar panel with a group 27 marine deep cycle battery and Morningstar SunSaver charge regulator and were mounted on a Campbell Scientific CM 110 tripod.

### 3.1.4. Evapotranspiration (ET)

Evapotranspiration was estimated through the Penman-Monteith (Equation 2.2) calculation when site data for solar radiation was available. When certain data were unavailable, Wetbud calculated ET using the less accurate Thornthwaite Method (Equation 2.3).

### 3.1.5. Surface water inputs and Outputs (SWI, SWO)

Surface water inputs were calculated by Wetbud using the original curve number method (Mishra and Singh, 2003). There were no surface water inputs for the vernal pool site; water table fluctuations were presumed to be the result of direct precipitation vs. ET. Surface water outputs were calculated on a daily basis and were taken as any water which would overtop the designated local weir elevation.

### 3.1.6. Groundwater Input and output (GWI, GWO)

Groundwater inputs were assumed to be minimal for all of these sites as they overlie a compacted clayey shrink-swell subsoil and are shallow to hard bedrock. Groundwater output was assumed initially to be a constant loss of a 2.54 cm (1.0 in.) per month based on previous applications of the "Pierce Approach" as described earlier. However, during model calibration it was noted that adjusting groundwater loss was required to achieve better model fit.

### 3.1.7. Soil water holding analysis

Multiple intact soil cores were taken from the soil surface and subsurface in each modeled cell at North Fork during the summer of 2017 near selected monitoring wells. Three cores per two depths (10 cm & 20 cm or refusal) were sampled at each well in the system. Following Soil Survey Methods, moisture release curves down to -100 kPa (1 bar) were developed using standard water potential pressure plate apparatus and intact cores (Veerman and Stolte, 1997). Specific yield (Sy) was estimated as the difference between saturation (0 kPa) and three different water content

desorption points: -10 kPa (1/10$^{th}$ bar), -33 kPa (1/3$^{rd}$ bar), and -100 kPa (1bar). Bulk density was determined with the intact core method (Dane et al., 2002).

### 3.2. Evaluation of Wetbud

The Wetbud Basic model was designed to be used primarily as an uncalibrated design modeling software. A goal for this model is to provide an appropriate balance of relative model accuracy vs. user input demands for a priori prediction of created wetland water levels. This hopefully allows for minimal site data requirements to achieve relatively accurate design predictions. My overall evaluation of the Wetbud Basic model involved sensitivity analysis as well as site-specific calibration and validation of the model. Sensitivity of the model parameters was calculated for four of the user inputs (NRCS curve number, weir elevation, soil specific yield, and surface storage factor) within the Basic model by varying parameters along a realistic range followed by analysis of relative sensitivity in comparison to an initially calibrated model. In an effort to validate the Basic model, I then statistically compared onsite well data to the modeled values to quantify its accuracy at predicting the actual water levels over time (e.g. the hydroperiod). This was done using a cross-validation method as discussed by Bennett et al. (2013), whereby the observed data was separated into two equal groups (e.g. two different years) then calibration and validation were performed sequentially on the two respective datasets. Various goodness of fit statistics were used to quantify the ability of Wetbud to compute onsite conditions based on methods and criteria recommended by the ASCE (1993). Thus, the initial step in model evaluation was sensitivity analysis followed by calibration and then validation based on calibrated parameters.

### 3.2.1. Sensitivity Analysis of Wetbud

In order to better inform the calibration of Wetbud, sensitivity analysis allowed for the ranking of parameters based on their relative sensitivity (Equation 3.1). To determine sensitivity of the model output to varying input parameters, this analysis was performed on the four user inputs listed above. Sensitivity testing intervals for parameters were based on Equation 3.2. Relative sensitivity (SR) was analyzed using uncalibrated parameters that were based on initial models of the Upper and Lower wells located in Cell NW1.

Equation 3.1. $$Sr = \frac{\frac{\delta O}{O}}{\frac{\delta P}{P}}$$

Where O is output value, and P is the parameter value.

Equation 3.2. $$P = Xmin + \left(\frac{Xmax - Xmin}{2}\right) F$$

Where: F is a scaling factor that can range from 0 to 2 (0.0, 0.5, 1.0, 1.5, 2.0) and X*min* and X*max* represent the realistic limits of the parameter P.

Sensitivity analysis was performed initially on an uncalibrated model and those results were consistent with the results presented here. Values presented here resulted from SA of models calibrated using the initial sensitivity analysis results, so I refer to this as "initial calibration". After initial calibration was completed using the secondary SA, the models unfortunately determined to be invalid due to an issue with the original ET data used. Once the dataset was repaired, final calibration was performed and those are the final models which are presented here. However, SA

was only run on the completely uncalibrated and the "initially calibrated" versions of the various models.

Four parameters were analyzed: curve number, weir elevation, soil specific yield, and surface storage factor. Monthly average water level was used for the output O. Sr values were considered to rank parameter sensitivity. Gloe (2013) and Byne (2000) stated |Sr values| greater than 1.0 indicate an exaggerated model response to a parameter alteration. Sr for the 'monthly average water level' was the absolute value of Sr calculated separately for each month's 'average predicted water level' (calculated separately) and those values were aggregated to produce one value for parameter thresholds as defined by Equation 3.2. Parameter interactions were not considered in this sensitivity analysis.

### 3.2.2. Calibration

The Basic model package was run to generate a water budget for two test cells at the North Fork Mitigation Bank, cells NW1 and VP. NW1 was selected for evaluation due its similarities to the original Pierce model, which was the original simple water budget approach that early iterations of the Basic model were based on. Models assumed limited groundwater interaction and no direct adjacent watershed runoff inputs. VP was selected due to its absence of a watershed or overbank inputs, making it optimal for observing the effect of preloaded regional vs. onsite weather data on a precipitation driven system.

The water budgets generated by Wetbud were then compared to the observed well data for their respective cells. The monitoring wells described earlier were installed near the inlet and outlet of

the first cell influenced by watershed runoff. Water levels from the two wells of NW 1 were averaged together to achieve a "flat" water surface which the calibrated Basic model was able to represent. Calibration was first accomplished with iterative runs of the Basic model with statistical comparisons to observed data, ranked by NSE and RMSE. Manual alterations based on observed patterns were performed until alterations did not produce a better model fit. These iterations were done in order of parameter sensitivity, with the most sensitive being altered first, then refining the model fit with following parameters. Daily comparisons calculated as the measured actual daily average water levels were compared to those produced by the Basic model for each corresponding day. Basic model dates were removed from statistical comparisons when monitoring wells were dry. Monthly comparison were made using average observed monthly water levels against average monthly predicted water levels. These averages were calculated using Wetbud output. Observed dates with dry well readings were removed from the analysis, as were months with less than a third of a month's wet monitoring dates/points.

During the calibration phase, the parameters of interest were curve number, depth of soil in the wetland, specific yield of the soil, maximum depth for drawdown, surface storage factor, and estimated default rate of groundwater seepage losses. During calibration, adjustments to input variables and Basic model assumptions were considered based on their ability to affect the accuracy of model predictions. Several internal model adjustments that resulted were the addition of a limiting maximum soil depth for actual water level drawdown and the use of more conservative groundwater seepage loss estimates (e.g. 0 - 2.54 cm/month). Additionally, Sy was estimated at three water retention potential points, -10 kPa, -33 kPa, and -100 kPa, and both site models were calibrated at these varying levels of Sy.

### 3.2.3. Validation.

To validate the calibrated model, I used a combination of visual comparisons, various goodness of fit statistics, along with a focus on outputs which had regulatory permit review implications. These criteria included continuous days saturated during the growing season as well as the relative timing of spring drawdown and fall recharge (water level rebound) for our modeled constructed wetland. Earlier versions of the Basic model have been validated using expert review in tandem with statistical and visual measures (Neuhaus, 2013; Dobbs, 2013). Models designed in this evaluation had constrained water level ranges (<1 m). This results in poor NSE values due to the tendency for the average water level, to which NSE compares predicted values, to be closer to monitoring data. Thus, the use of common statistical validation thresholds may tend not to be as informative as other semi-quantitative and subjective measures (Sargent, 2009; Refsgaard, 1995). While we did employ and utilize goodness of fit statistics as a guide for how well the model performed during calibration, we did not use them as our sole measure of "model accuracy". In the case of Wetbud, the most important attribute of the Basic model is its ability to generate an estimated hydroperiod that is similar in (a) overall range of saturation/ponding depth, (b) length of near surface saturation, and (c) timing of spring water level drawdown vs. the actual on-site comparative data.

### 3.2.4. Statistical Analyses

We used three basic statistical measures for model evaluation, Sr, NSE and RMSE (Equations. 3.1, 2.5, and 2.6). The Sr was used to rank the sensitivity of user input parameters; this informed the parameterization stage of the calibrated model. As discussed above, ASCE (1993) suggests

goodness of fit statistics for the analysis of continuous hydrologic models, of which we used NSE and RMSE (Equation 2.5 and 2.6).

3.3. Selection of typical hydroperiod patterns for use in created wetland design.

The development of a library of presumably "typical" hydroperiod patterns was based on a detailed review of both published and non-published water level and associated site datasets. Datasets were solicited from a range of sources around Virginia and North Carolina. The wetlands were defined with respect to their HGM classification and generally fit within depressional (Isolated depression/vernal pool/Carolina Bay), riverine (Emergent/scrub-shrub/forested), or mineral flats (pocosins). The complete list of reviewed sites found in Appendix A. The secondary objective of this effort was to provide a range of hydroperiod data for these differing non-tidal wetland types that could be used by wetland creation and restoration design teams to set appropriate "hydroperiod targets". Thus, we developed the following minimum criteria for the datasets for inclusion in our review process:

- At least two full years of data.
- Full annual data sets with at least one reading per month, with higher resolutions being considered preferred data sets.
- Candidate sites needed to be relatively undisturbed via ditching and/or immediately surrounding development and should support an appropriate vegetative cover for their type. All sites for these wetland types were presumed to be dominantly forested wetlands.
- Candidate sites needed to be associated with soil map units dominated by hydric soils and be on appropriate HGM class landforms.

- Where possible, confirming data on vegetation and overall jurisdictional status was highly preferred.

Regional hydroperiod data were obtained from a wide array of published studies, agency (USCOE, DEQ), non-governmental sourced monitoring data (e.g. The Nature Conservancy), other unpublished data associated with various Virginia Department of Transportation (VDOT) projects, and mining industry research programs known to Virginia Tech, Old Dominion University and other cooperators and colleagues. Our final selection was done in an effort to provide a minimum of three appropriate sites for each of the three wetland settings described above. Ideally, the sites were sufficiently well-documented to allow them to be used as future test sites for both Basic and Advanced model runs by Wetbud.

Final selection of "typical sites" for each of these three wetland types was made based primarily on their hydroperiod graphics combined with local detailed topographic maps, soil maps and aerial imagery. Additional metadata on vegetation assessments and jurisdictional determinations was also utilized where/when available. At a future date (beyond the completion of this M.S. thesis) site visits will be conducted by the research team leaders (W.L. Daniels and G.R. Whittecar) and other colleagues to make on-site confirmation of important soil, hydrologic and vegetation indicators and status.

After final site visits for each wetland type are completed, our research group will propose them for agency review and confirmation as being "typical" with respect to their hydroperiods for their mix of dominant vegetation combined with their HGM settings. Our objective here was to produce

a set of “target hydroperiods” for each wetland type that can be used to improve created wetland design via application of improved water budget estimation procedures. Thus, there is clear linkage between this portion of the research project and the testing and validation of the basic Wetbud model as described earlier.

### 3.3.1. Examination Process

Appendix A includes a list of all evaluated sites and whatever preliminary data was collected for every site available for review. Each site was then analyzed using ArcMap 10.2 to view topography, orthoimagery, and soils data in an effort to categorize wetland characteristics which led to our estimation of each wetland type. We used all companion data available for each site under consideration. Companion data here refers to a range of resources including: soil pit data, wetland determination forms, mitigation permits, mitigation executive reports, site maps, wetland characteristics and other miscellaneous data available for each site.

## 4. Model Evaluation Results and Discussion

### 4.1. Overall Approach to Model Validation and Calibration

The evaluation of the Wetbud Basic model was tailored for this research project by following recommendations for model statistical analysis as summarized by Willmott et al. (1985) and ASCE (1993). This research effort was also consistent with previous Wetbud research efforts (Gloe et al., 2011; Dobbs et al., 2013; Neuhaus et al., 2013; Stone, 2017).

The first step in this evaluation was to assess parameter sensitivity of four user-definable parameters which were not rigorously assessed by previous researchers working on Wetbud (Gloe et al., 2011; Dobbs et al., 2013; Neuhaus et al., 2013; Stone, 2017). Prior to model calibration, Wizard models were run for cell NW1 and the VP. Next, relative sensitivities were used to prioritize parameterization of the Basic model for calibration of the model with corresponding field data from the North Fork wetland. As stated in the methods section, the two years of well data were split; the first year was used as the calibration period and the second year was the validation period for each model.

The initial phase of calibration consisted of creating a model using the Wizard and comparing its predictive ability before moving into parameterization of the model. Creating a project with the Wizard application automatically creates a Wetbud Basic model project and scenario set to the Wizard specifications. This Wizard produced a Basic model with weather data collected onsite and not the preloaded weather station. This was used to produce output and statistically rate the model Wizard. With this Basic model project, a scenario was created for eight models, differentiated by two site locations, two weather stations, and two parameter settings for an impermeable layer

(with/without). Iterative alterations beginning with the most sensitive parameters and moving to the less sensitive were performed with statistical comparisons made against well data from fall 2015 to fall 2016. These alterations were conducted for each parameter within each model scenario until parameter adjustments no longer yielded a better model fit. At this point, the calibrated model parameters were used to validate the model performance using the fall 2016 to fall 2017 field water level data. The results of this comparison constituted the validation phase of the project. It is important to note that the effective sensor depth of our water monitoring gauges was not ideal (~20 cm; due to shallow depths to rock and sensor standoff height above well bottom) and this depth caused the hydroperiod to "flat line" once saturation reached this depth. This made it difficult to show the full range of the hydroperiod and likely had a negative effect on the statistics employed since all monitoring points/date pairs below this depth were removed from analysis.

Thus, as a first step, the Wetbud Wizard application (simplified Basic model), was compared to measured well data in order to determine the general level of model accuracy given approximated parameters (Table 4.1). Model accuracy was assessed using NSE and RMSE to evaluate how well the model was able to predict the daily or monthly average water levels. The fixed parameters used by the Wizard are groundwater out and/or in, soil Sy, and weir elevation. Initially, the Wizard model assumed a default groundwater out of 2.54 $cm \cdot month^{-1}$, groundwater in of 0.0 $cm \cdot month^{-1}$, an outlet weir elevation of 7.62 cm (3 in), and no impermeable layer to restrict downward water table drop.

Table 4.1. Parameters generated by the Wizard application in Wetbud for initial model runs. With the exception of the NRCS curve number, all of these parameters are specified defaults by Wetbud.

| Parameter | Vernal Pool | NW1 |
|---|---|---|
| Groundwater out | 2.54 cm·month$^{-1}$ | 2.54 cm·month$^{-1}$ |
| Ground water in | 0 cm·month$^{-1}$ | 0 cm·month$^{-1}$ |
| Curve number | No Contributing Watershed | 70 |
| Soil Specific yield | 0.25 (25%) | 0.25 (25%) |
| Surface storage factor | 1.0 | 1.0 |
| PET Equation | Penman-Monteith | Penman-Monteith |
| Weir Depth | 7.62 cm | 7.62 cm |
| Depth To Impermeable layer | none | none |

Regulatory wetland permit review standards generally require average monthly water budgets on proposed constructed wetland sites for a wet (W), normal (N) and dry (D) year. Wetbud was designed to select appropriate WND years and then produce these monthly water budgets using its suite of formulae, user parameters, and imported weather data. Wetbud operates internally on a daily timestep, so for this project, we statistically evaluated Wetbud's ability to produce daily as well as monthly water budgets. However, as discussed later, it is not recommended that the Wetbud Basic model be used on a daily timestep because of issues with its inability to predict water movement within the wetland on a daily basis.

Table 4.2 shows the statistical results from the initial Wizard model runs before any calibration efforts. As stated in Chapter 2, NSE was used to assess overall model accuracy during calibration. However, since Wetbud is intended to be used in wetland design it was also compared using RMSE. As reviewed earlier, ranges established by Caldwell et al. (2007) have been applied here: acceptable, good, and excellent NSE values ranges are, in order, >0.4, >0.6, >0.75. For MAE Caldwell et al. (2007), used <20 cm, <15 cm, and <10 cm, so I used these thresholds for RMSE. The initial Wizard runs did not produce results with acceptable NSE values (Table 4.2). The model for cell NW1 achieved the only "good" RMSE of 13.5 cm on a daily basis and 13.7 cm on a monthly

basis. Figure 4.1 Shows the Output from a Basic model run within Wetbud. On a daily basis, the NW1 model hydroperiod (Figures 4.1 and 4.2) did not accurately estimate the summer low water levels in either 2016 or 2017. The daily NW1 Wizard models did reasonably reproduce the 2016 winter high water levels, but failed to reasonably estimate the summer low water levels in 2017 (Figure 4.2). The monthly comparison for the NW1 Wizard model (Figure 4.3) did relate well to the actual 2016 summer low water and the 2016 winter high levels, however, it was unable to successfully repeat this for the second year of data.

Table 4.2. Comparison results of NSE and RMSE calculated for the Wizard model of Cell NW1 and vernal pool. These values are calculated prior to any manual calibration and do not include the limiting layer.

| **Statistical Parameter** | | **2015-2017** | |
|---|---|---|---|
| | | NSE | RMSE (cm) |
| **Daily Time-Step** | NW1 Wizard | -2.5 | 13.5 |
| | Vernal Pool Wizard | -155.6 | 137.8 |
| **Monthly Time-Step** | NW1 Wizard | -2.4 | 13.7 |
| | Vernal Pool Wizard | -203.7 | 144.4 |

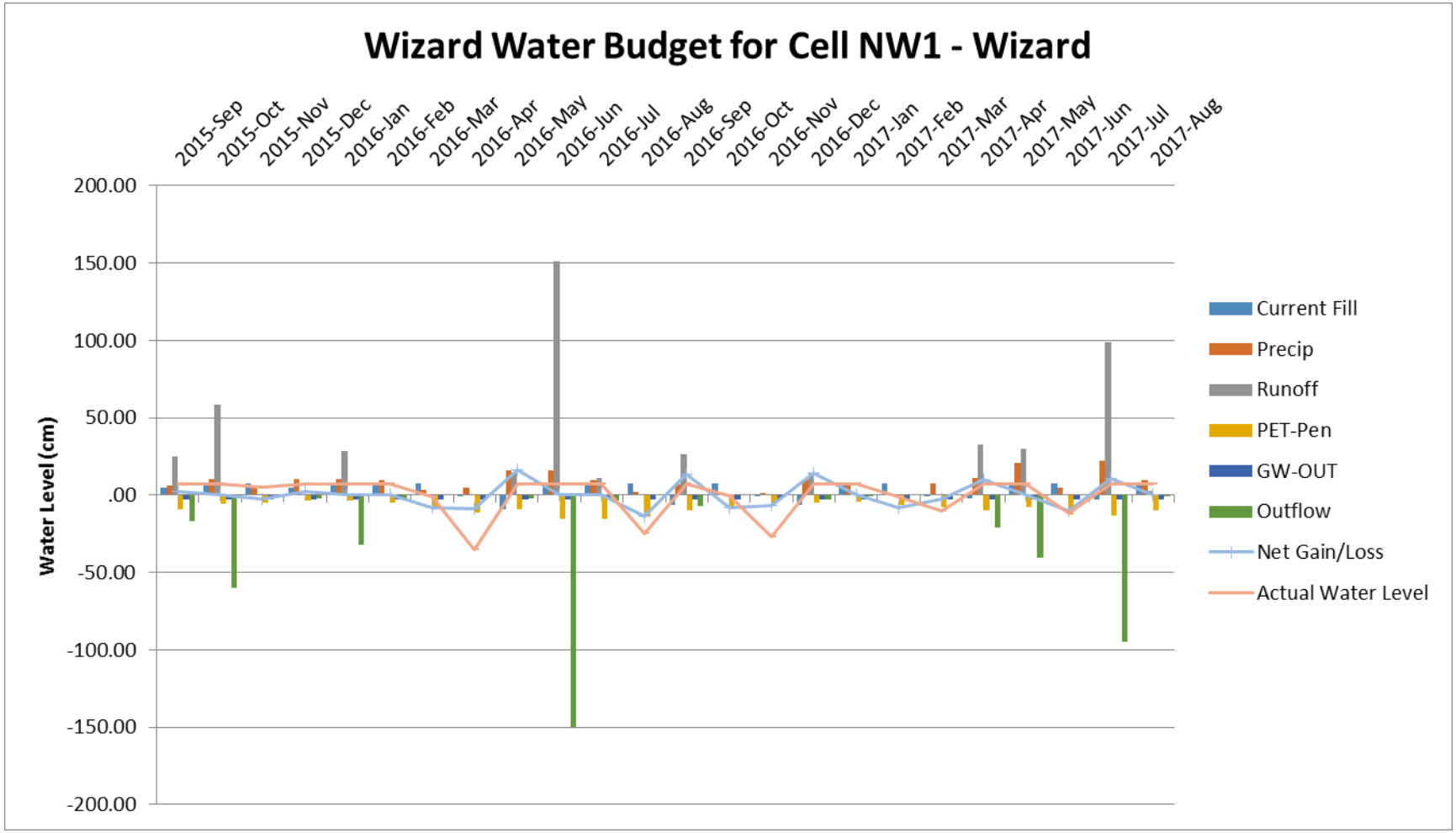


Figure 4.1. The Monthly output of the NW1 Wizard model shown with model inputs and outputs for 2015-2017. The Wizard model represents a completely unaltered and uncalibrated model for the site.

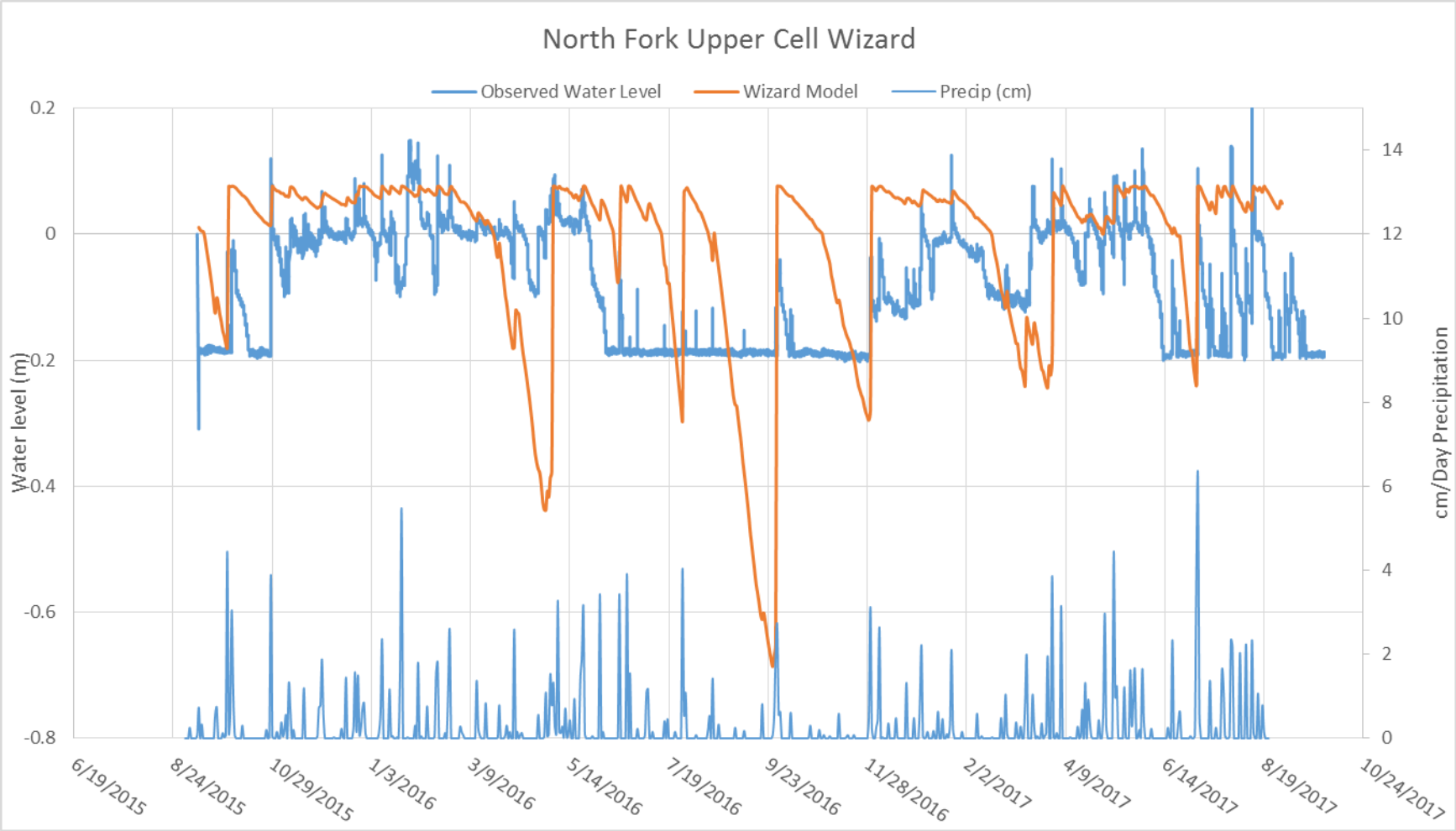


Figure 4.2. The daily output of the NW1 Wizard model compared with the onsite monitoring data from 2015-2017. The observed water level represents the average of two monitoring wells installed in the cell. The precipitation reported is from the onsite weather monitoring station. The Wizard model represents a completely unaltered and uncalibrated model for the site.

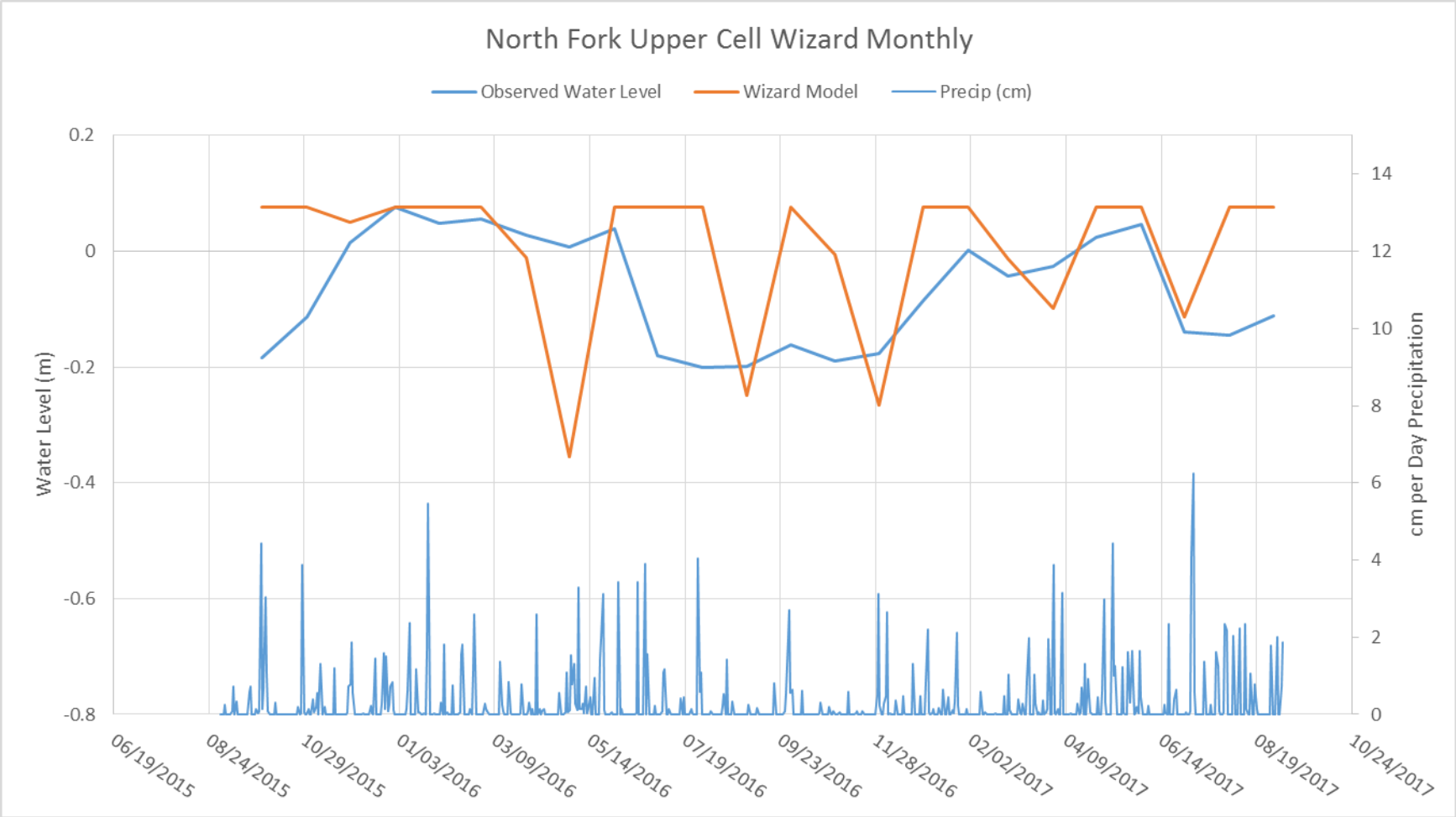


Figure 4.3. The Monthly output of the NW1 Wizard model compared with the onsite monitoring data from 2015-2017. The observed water level represents the average of the two monitoring wells installed in the cell. The precipitation reported is from the onsite weather monitoring station. The Wizard model represents a completely unaltered and uncalibrated model for the site.

Models for the vernal pool produced with the Wizard (Figures. 4.4, 4.5, 4.6) were unable to accurately predict the actual water level given that an option for the impermeable layer was absent in this initial simulation. The vernal pool, which was entirely precipitation-fed, was predicted by the Wizard model to have a very low and unrealistic water level during the first summer. This low initial value then prohibited recovery of the water table in the following winter, producing a very poor statistical fit. This was a result of having no limiting layer to stop the drawdown beyond the actual bottom of the cell (e.g. hard rock) coupled with also losing 2.54 cm of groundwater out each month which pulled the modeled water table even deeper during dry periods. On a monthly basis (Figures 4.4, 4.5), the vernal pool model behaved in the same fashion, indicating a constantly dropping water table that became too deep for normal winter season rebound to occur. Subsequently, these models served as the baseline from which the calibration phase proceeded where impermeable layers were added to combat this deep drawdown. Over the course of the two study years, the vernal pool was generally saturated close to the surface, but became innundated only following rainfall events. During calibration, a groundwater loss adjustment was needed for the vernal pool model so that it wouldn't remain ponded for extended periods.

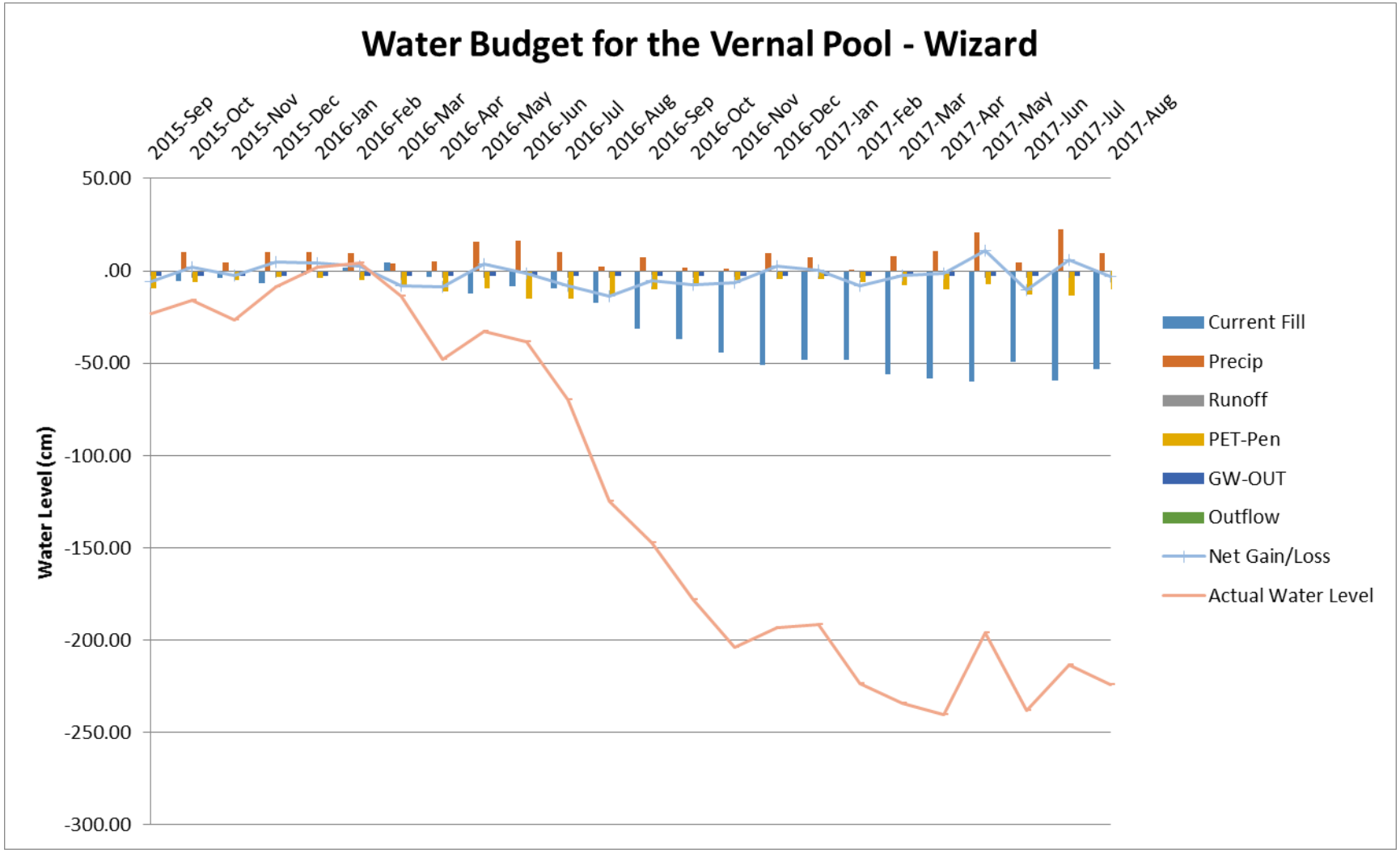


Figure 4.4. Monthly output of the Vernal Pool model graphed alongside the model inputs and outputs for 2015-2017. The Wizard model represents a completely unaltered and uncalibrated model for the site.

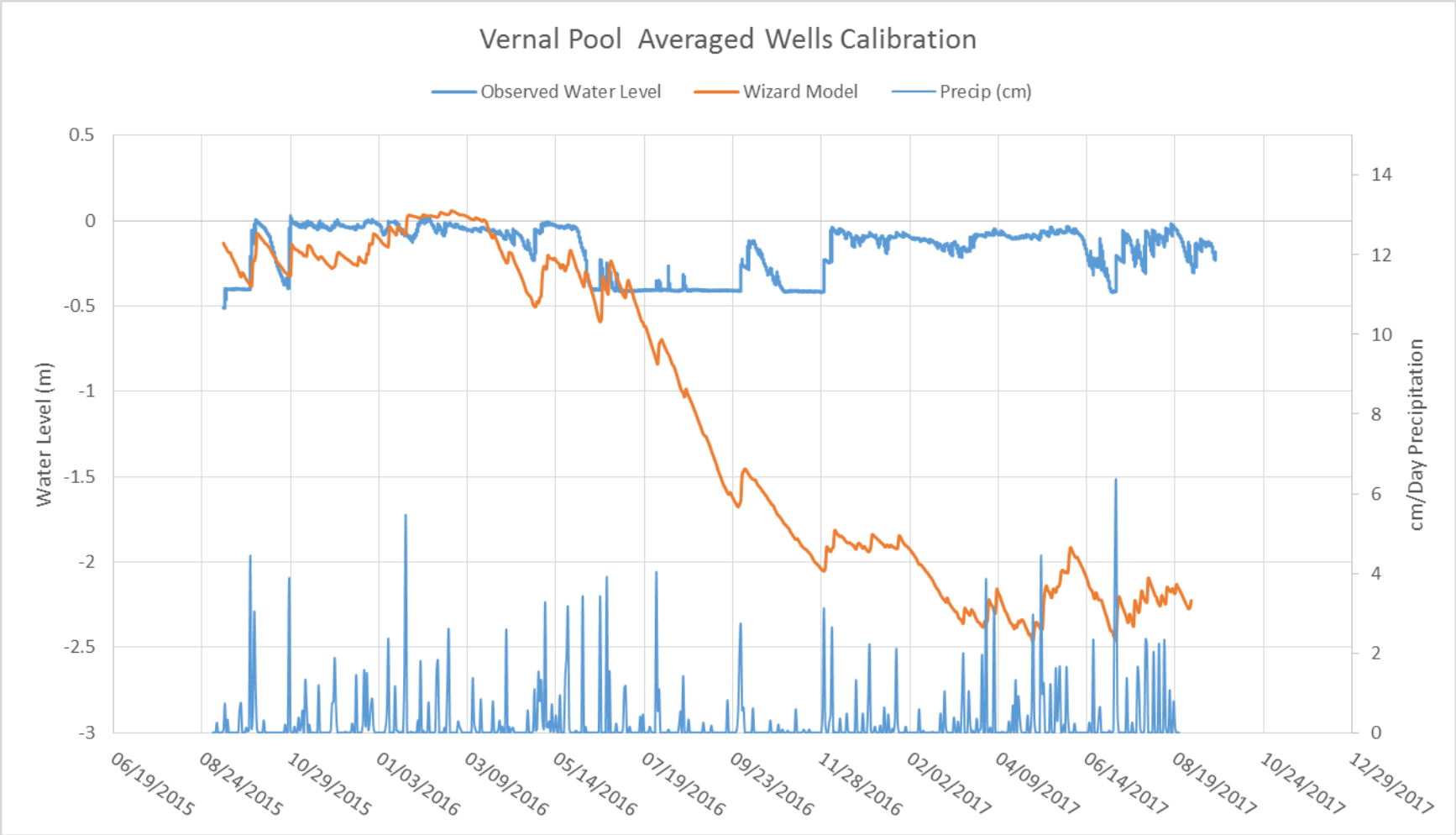


Figure 4.5. The daily output of the vernal pool Wizard model compared with the monitoring data from 2015-2017. The observed water level represents the average of our two monitoring wells installed in the cell. The precipitation reported is from the onsite weather monitoring station. The Wizard model represents a completely unaltered and uncalibrated model for the site.

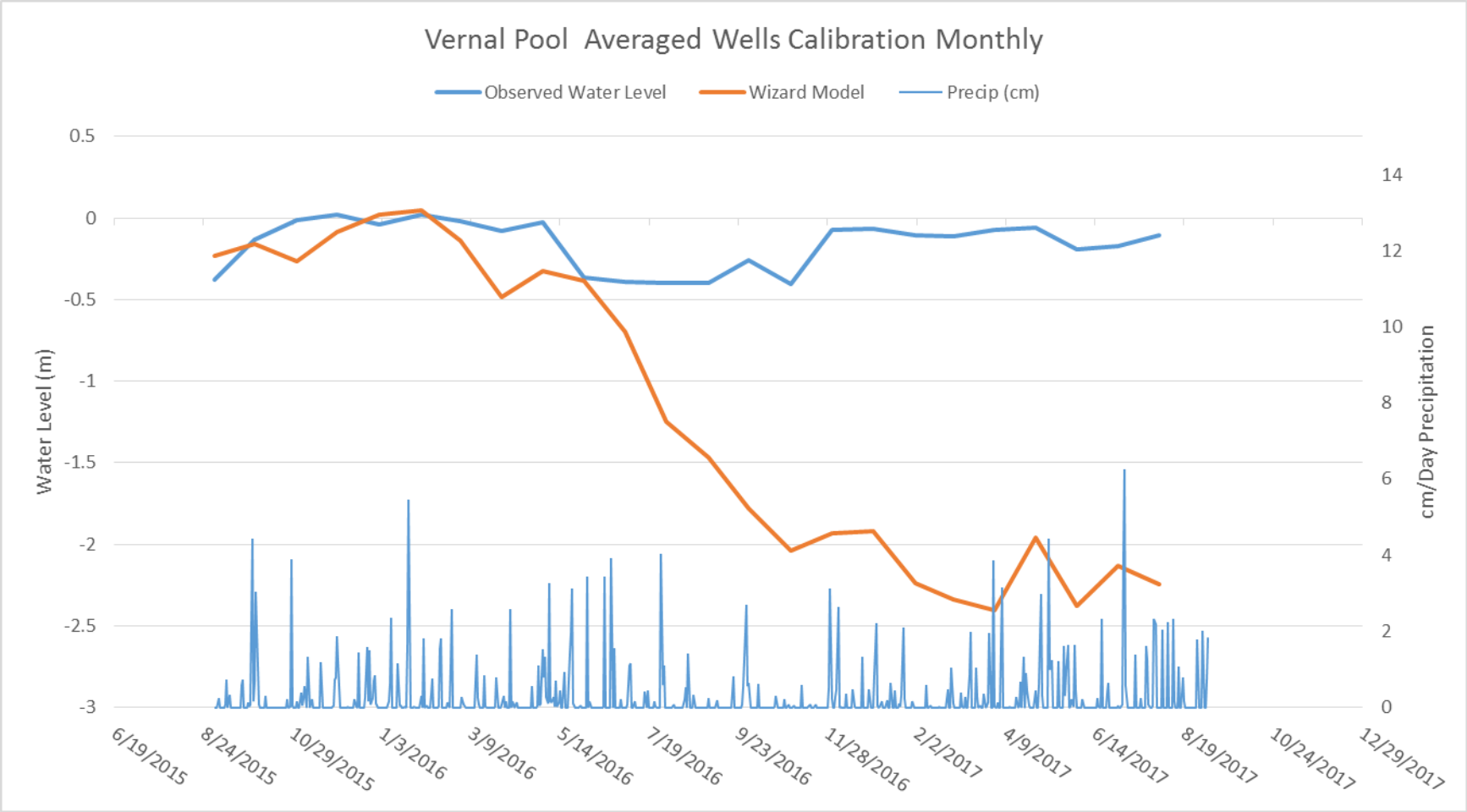


Figure 4.6. The Monthly output of the vernal pool Wizard model compared with the onsite monitoring wells from 2015-2017. The observed water level represents the monthly average of the two wells which were installed onsite. The precipitation reported is from the onsite weather monitoring station. The Wizard model represents a completely unaltered and uncalibrated model for the site.

## 4.2. Relative Sensitivity Analyses

Relative sensitivities (Sr) were calculated using parameter settings based on Equation 3.2. Figure 4.7 shows the absolute value of the Sr graphed against the realistic parameter range (F ratio) for each model run. Sensitivity analysis using this approach is recommended in cases where it is not feasible or practical to measure parameter interactions due to model limitations (Haan et al., 1995). During sensitivity analysis, the most influential variable analyzed was the NRCS Runoff curve number (CN; Figure 4.7). The second most influential parameter was the weir elevation, followed by the surface storage factor, and then finally soil specific yield (Sy). The CN is an integral coefficient in calculating the amount of water entering a site for rainfall events, thus the large effect it had on the model output was not unexpected. Weir elevation directly changes the amount of water storage and the average maximum elevation of the water level. The surface storage had a lower influence on the overall model while soil specific yield (Sy) had a very minimal impact on the overall modeled water levels throughout the year.

## 4.3. Calibrated Model Variations vs. Model Accuracy

Within the original model wizard project eight separate Basic models were produced; these are considered individual Basic models. Through iterative model parameterization, "best fit" parameters (Table 4.3) were established for the two wetland cells, NW1 and the vernal pool. The calibrated model was derived at the point where parameter alterations were unable to achieve a better statistical fit. Four models were derived for each cell, using two different weather data sets (on-site and Dulles) and the presence or absence of an impermeable layer. In order to validate the Basic model's reproducibility as well as its relative accuracy at simulating water levels, two steps were performed. "Best fit" model parameters created during calibration were statistically rated

based on their goodness of fit to field conditions. Subsequently, these calibrated parameters were used to produce models for evaluation against the second year of data to validate model performance vs. observed water level data. Thus, these two steps formed the basis for model evaluation and to provide future users with information to better assist in parameterization. This provided a determination of the relative accuracy for a fully parameterized Basic model within Wetbud.

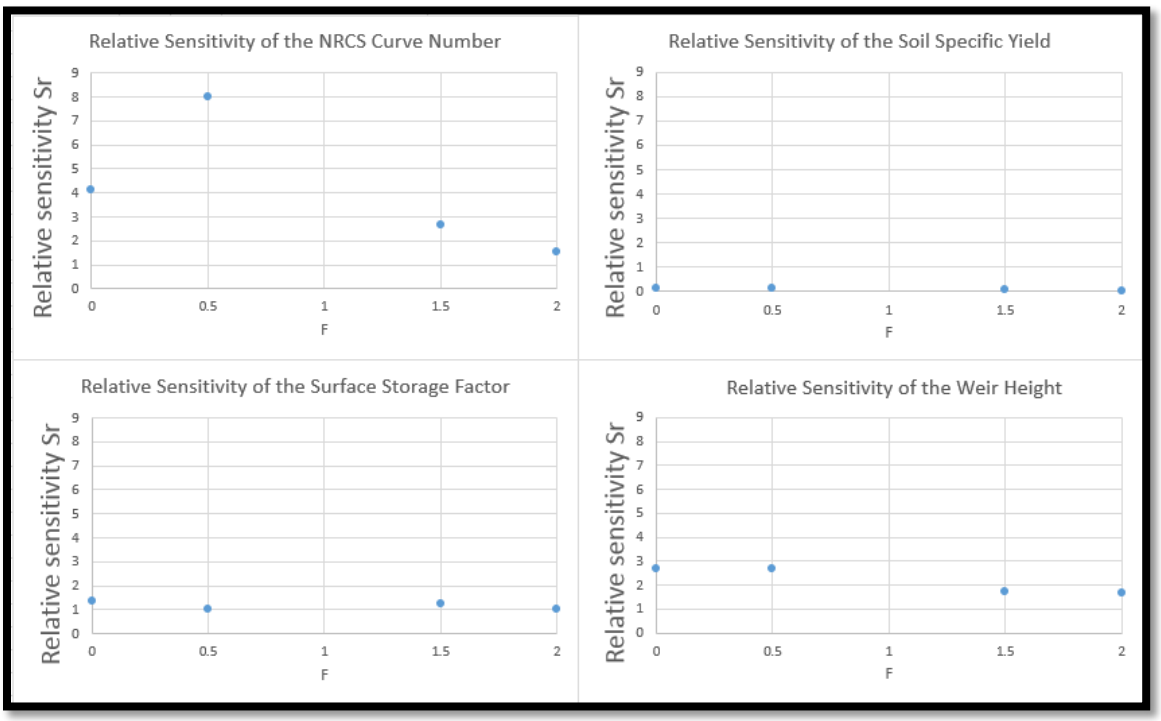


Figure 4.7. Relative sensitivity (Sr) (Equation 3.1) for four parameters (Curve number (CN), soil storage factor or Specific yield (Sy), Surface storage factor, and weir height) vs. F, the USCOEfficient from Equation 3.2 which relates to the magnitude of the parameter.

As described earlier in Methods, model output using onsite weather data set was compared to the Washington/Dulles weather data. The two data sets (model vs. actual) were compared using NSE

and RMSE during calibration and then validation. NSE and RMSE were calculated using all valid points for the daily and monthly comparison. Excluding months with too few valid points (n < 9), monthly comparisons used the monthly average water levels. Dry dates for the water levels sensors were removed for comparison since points modeled for these days were unverifiable. Removal of dry monitoring days reduced the number of points compared and increased the relative effect of minor water level differences. This is due to the statistical power of NSE being limited by small sample size and a limited range of absolute values (actual water depth).

Table 4.3. Final “best fit" parameters used for each calibrated model. Any experimental alterations beyond these are expressed in their respective analysis tables.

| Parameter | Vernal Pool Onsite Weather | Vernal Pool Dulles Weather | NW1 Both-Weather Stations |
|---|---|---|---|
| Groundwater out | 3.9 cm/month | 2.25 cm/month | 0 cm/month |
| Groundwater in | 0 cm/month | 0 cm/month | 0 cm/month |
| Curve number | No Contributing Watershed | No Contributing Watershed | 80 |
| Soil Specific yield | 0.117 (11.7%) | 0.117 (11.7%) | 0.13 (13%) |
| Surface storage factor | 1.0 | 1.0 | 1.0 |
| PET Equation | Penman-Monteith | Penman-Monteith | Penman-Monteith |
| Weir Depth | 11cm | 11 cm | 4 cm |
| Depth To Impermeable layer | 40 cm | 40 cm | 30 cm |

## 4.4. Specific Yield Variations vs. Model Accuracy

Specific yield was calculated at three water holding water potential thresholds for “field capacity” and “readily available water” as the difference between saturated water content and water retained at -10 kPa, -33 kPa and -100 kPa. These first two thresholds are commonly used (Weil and Brady, 2017) to define “field capacity” for sandy vs. fine-textured soils, respectively. Water retained

down to –100 kPa is considered to be "readily available" for plant uptake, but is held against gravitational loss and therefore not part of conventional Sy estimates. Table 4.4 shows the average and median values calculated from the water retention analyses on intact cores taken from each cell. These values were applied to the models during calibration for both sites as part of the iterative process. The relative effects on NSE and RMSE of varying these parameters on model accuracy for cell NW1 (0.1 ha) and vernal pool (2.8 ha) are shown in table 4.5. These values were all used in the calibration process to find the "best fit". Comparisons and associated statistics (Tables 4.4, 4.5, 4.6, and 4.7) were generated during calibration to illustrate the effects of Sy on model output.

Table 4.4. Mean and median specific yield values calculated from three different water retention potential points for NW1 and the vernal pool.

| | Water retention point and resulting Sy $\Theta_V$ | | | | | |
|---|---|---|---|---|---|---|
| | -10 kPa | | -33 kPa | | -100 kPa | |
| Site | Mean | Median | Mean | Median | Mean | Median |
| NW1 | 8.7% | 8.8% | 10.6% | 10.5% | 13.0% | 12.5% |
| Vernal Pool | 7.6% | 6.9% | 9.2% | 8.0% | 11.7% | 10.6% |

Table 4.5. Model comparison results of NSE and RMSE for the Cell NW1 and the vernal pool varying weather data and levels of specific yield.

| **Daily model comparison results of NSE and RMSE for the model of Cell NW1 using onsite weather data and varying levels of specific yield** | | | | | | |
|---|---|---|---|---|---|---|
| **Water Retention Curve Pressure** | -10 kPa (1/10th bar) | | -33 kPa (1/3rd Bar) | | -100 kPa (1 bar) | |
| **Specific Yield of Soil** | 8.8% $S_y$ $\Theta_V$ | | 10.5% $S_y$ $\Theta_V$ | | 13% $S_y$ $\Theta_V$ | |
| **Statistical Parameter** | NSE | RMSE (cm) | NSE | RMSE (cm) | NSE | RMSE (cm) |
| **Calibrated model with onsite weather data** | -0.81 | 6.44 | -0.68 | 6.23 | -0.59 | 6.05 |
| **Monthly comparison results of NSE and RMSE calculated for the model of Cell NW1 using onsite weather data and varying levels of specific yield** | | | | | | |
| **Water Retention Curve Pressure** | -10 kPa (1/10th bar) | | -33 kPa (1/3rd Bar) | | -100 kPa (1 bar) | |
| **Specific Yield of Soil** | 8.8% $S_y$ $\Theta_V$ | | 10.5% $S_y$ $\Theta_V$ | | 13.0% $S_y$ $\Theta_V$ | |
| **Statistical Parameter** | NSE | RMSE (cm) | NSE | RMSE (cm) | NSE | RMSE (cm) |
| **Calibrated model with onsite weather data** | -0.37 | 5.23 | -0.38 | 5.24 | -0.39 | 5.28 |
| **Daily comparison results of NSE and RMSE calculated for the model of the vernal pool using onsite weather data and varying levels of specific yield** | | | | | | |
| **Water Retention Curve Pressure** | -10 kPa (1/10th bar) | | -33 kPa (1/3rd Bar) | | -100 kPa (1 bar) | |
| **Specific Yield of Soil** | 7.6% $S_y$ $\Theta_V$ | | 9.2% $S_y$ $\Theta_V$ | | 11.7% $S_y$ $\Theta_V$ | |
| **Statistical Parameter** | NSE | RMSE (cm) | NSE | RMSE (cm) | NSE | RMSE (cm) |
| **Calibrated model with onsite weather data** | -0.29 | 12.7 | -0.12 | 11.21 | 0.002 | 10.52 |
| **Monthly comparison results of NSE and RMSE calculated for the model of the vernal pool using onsite weather data and varying levels of specific yield.** | | | | | | |
| **Water Retention Curve Pressure** | -10 kPa (1/10th bar) | | -33 kPa (1/3rd Bar) | | -100 kPa (1 bar) | |
| **Specific Yield of Soil** | 7.6% $S_y$ $\Theta_V$ | | 9.2% $S_y$ $\Theta_V$ | | 11.7% $S_y$ $\Theta_V$ | |
| **Statistical Parameter** | NSE | RMSE (cm) | NSE | RMSE (cm) | NSE | RMSE (cm) |
| **Calibrated model with onsite weather data** | 0.45 | 11.1 | 0.061 | 9.29 | 0.68 | 8.53 |

Table 4.6. Daily comparison results of NSE and RMSE statistics for calibrated models and validation of cell NW1. The four comparisons include the two weather station locations with and without a limiting layer.

| **Statistical Parameter** | **Calibration 2015-2016** | | **Validation 2016-2017** | |
|---|---|---|---|---|
| | NSE | RMSE cm | NSE | RMSE cm |
| **Calibrated model using onsite weather data** | 0.052 | 6.73 | -0.40 | 8.26 |
| **Calibrated model using offsite weather data** | -0.67 | 8.93 | -0.75 | 9.22 |
| **Calibrated model using onsite weather data and no limiting layer** | 0.052 | 6.73 | -0.41 | 8.27 |
| **Calibrated model using offsite weather data and no limiting layer** | -0.81 | 9.31 | -1.71 | 11.48 |

Table 4.7. Monthly comparison results of NSE and RMSE statistics for the calibrated models and validation of Cell NW1. These four models compared weather station location and presence/absence of a limiting layer.

| **Statistical Parameter** | **Calibration 2015-2016** | | **Validation 2016-2017** | |
|---|---|---|---|---|
| | NSE | RMSE cm | NSE | RMSE cm |
| **Calibrated model using onsite weather data** | 0.22 | 5.92 | -0.47 | 9.55 |
| **Calibrated model using offsite weather data** | -0.24 | 7.35 | -0.44 | 9.47 |
| **Calibrated model using onsite weather data and no limiting layer** | 0.22 | 5.92 | -2.00 | 13.66 |
| **Calibrated model using offsite weather data and no limiting layer** | -0.33 | 7.71 | -1.10 | 11.41 |

Previous related research by Stone et al. (2017) used Sy calculated using intact cores at – 33 kPa for field capacity; for this project we measured Sy on intact cores down to -100 kPa (1bar) to determine the potential effect of extra available water release to Sy. There was little effect of

altering Sy for both the daily and monthly (Table 4.5) comparisons in cell NW1. Changing the Sy from -10 kPa to -100 kPa resulted in less than 0.4 cm difference in the RMSE for a calibrated model analyzed on a daily basis (Table 4.5). This response is consistent with relative parameter sensitivity (Sr) results given the low Sr determined earlier. The calibrated vernal pool Basic model showed a slightly greater effect of Sy on model output relative to cell NW1. Changing the Sy from -10 kPa to -100 kPa resulted in a 2.2 cm difference for daily analysis (Table 4.5) and a 2.5 cm difference for monthly analysis in RMSE.

## 4.5. North Fork Upper Cell Model Accuracy

Daily models of cell NW1 where both weather station data sets were run with and without the limiting layer and relative statistical comparisons are reported in Table 4.6. Calibration of these models was accomplished iteratively using model fit analysis of output, and then comparisons of various parameter changes resulted in a final selected model having the "best fit" to the observed data. These "best fit" models were then used as the calibrated models for further analyses for each combination. During calibration, the groundwater loss was added and adjusted iteratively until it yeilded no further improvement to NSE and RMSE. The groundwater loss rate was varied independently for the onsite and the offsite weather stations, with the best onsite weather-driven model losing more water through GWO, 3.9 cm month$^{-1}$, versus the best offsite weather-driven model losing 2.25 cm month$^{-1}$. However, this addition made the model without a limiting layer much more susceptible to a very deep and inaccurate water table drop. Thus, models lacking a limiting layer failed to model water level accurately.

The model using onsite weather data and a limiting layer predicted water levels the most accurately out of the four comparisons, generating an NSE value of 0.052 and RMSE of 6.73 cm (Table 4.6). Local weather patterns and topography can lead to differences in rainfall timing and amounts vs. regional data (e.g. Dulles for this study). The "best fit" daily models for NW1 using onsite and offsite weather data with/without a defined depth limiting layer are shown in figures 4.8, 4.9 and 4.10. So, the increased accuracy of the calibrated model using onsite weather data was expected as was the improvement due to the limiting layer better estimating actual water storage volume and actual summer drawdown. Figures 4.11 and 4.12 represent the days when the actual onsite water level was saturated or ponded (> -30cm), and the corresponding points predicted by the models for cell NW1. These figures (4.11 and 4.12) show points for the first six months of the growing season during both the calibration and validation year. During calibration the site was saturated for 102 days, and 148 during validation. During calibration, the Wizard model had the poorest predictions (86 days), but still matched closely the days saturated for the site. Next, the two models using offsite weather data were not as continuously saturated as the actual onsite water level data, and predicted 97 days without a limiting layer and 98 with one. Lastly, the onsite weather data with or without the limiting layer had the best fit during calibrations and predicted 99 days in both cases. During validations, the worst predicting models were in fact based on the offsite weather data, both predicting 144 days versus the actual 148 days. The Wizard and two onsite weather data models all correctly predicted all 148 days saturated during this time period. It should be noted this is likely because the Wizard model used the onsite weather data, and the limiting layer in the NW1 models validation year played very little role in the difference.

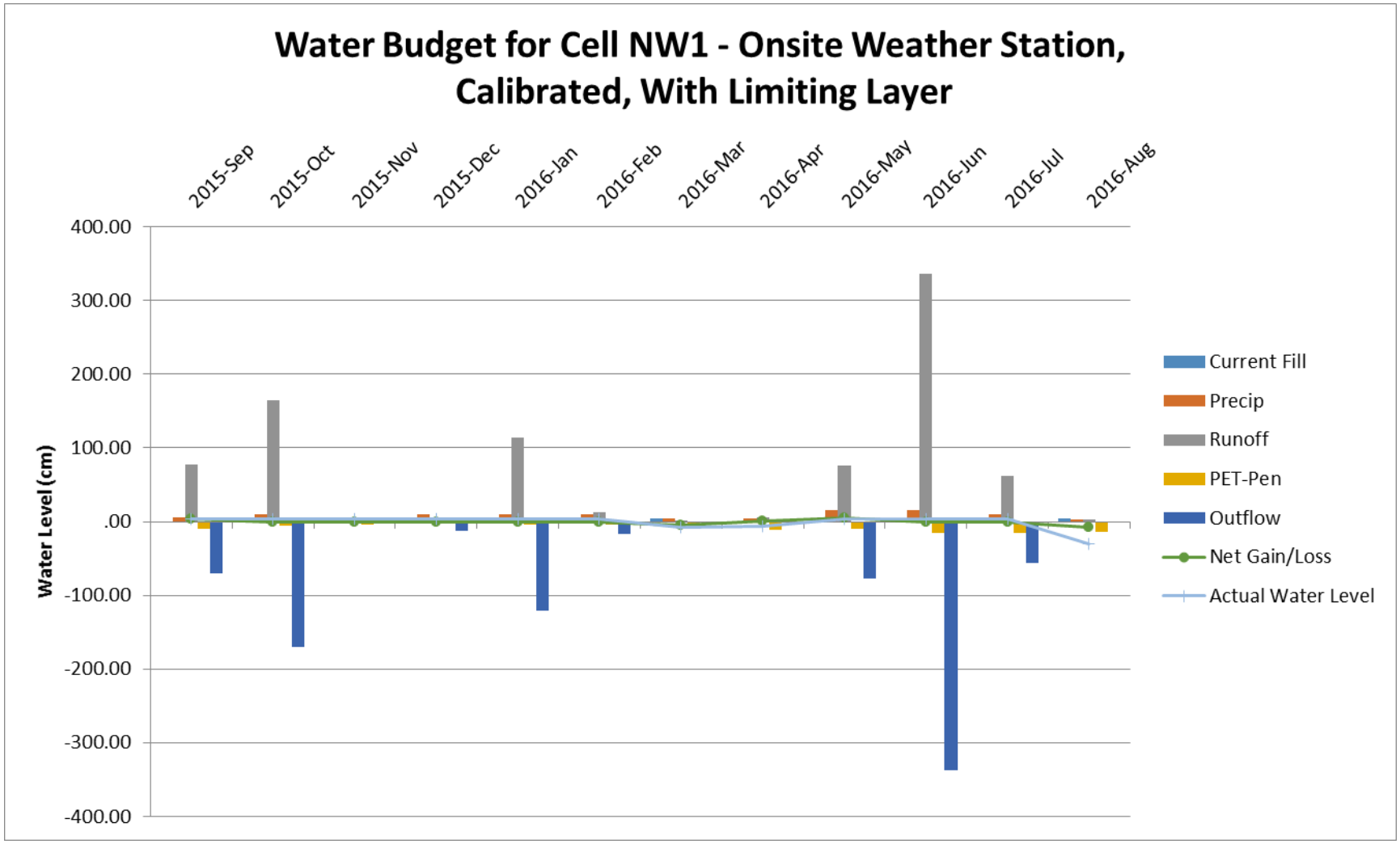


Figure 4.8. The monthly output of the NW1 calibrated onsite weather model with a limiting layer shown with model inputs and outputs for 2015-2016.

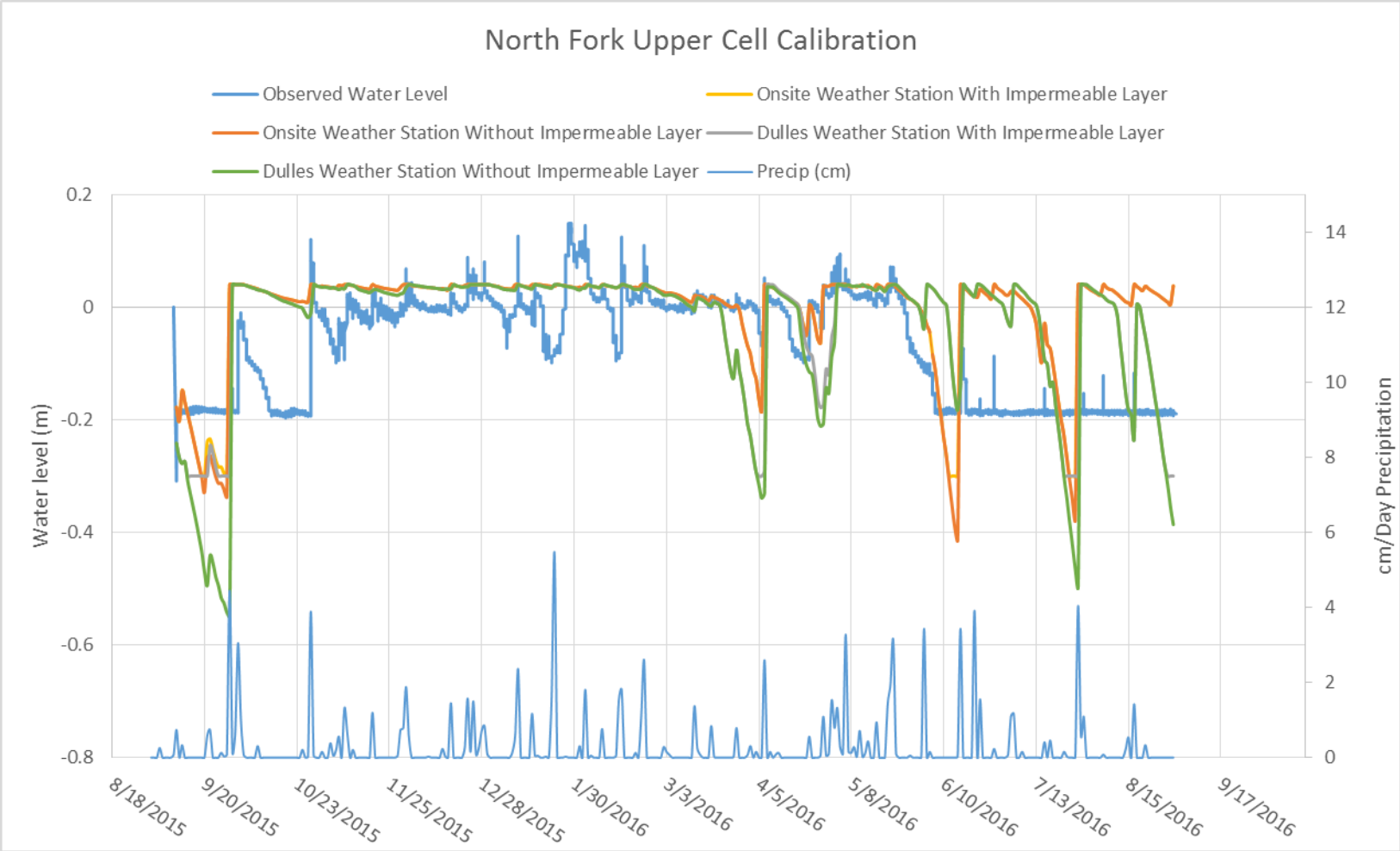


Figure 4.9. Daily hydroperiod of the calibrated models for cell NW1 with well monitoring data from 2015-2016 shown along with precipitation. Statistical comparison of the models is show in Table 4.6. Data for dates where the onsite wells were dry were removed from statistical comparisons.

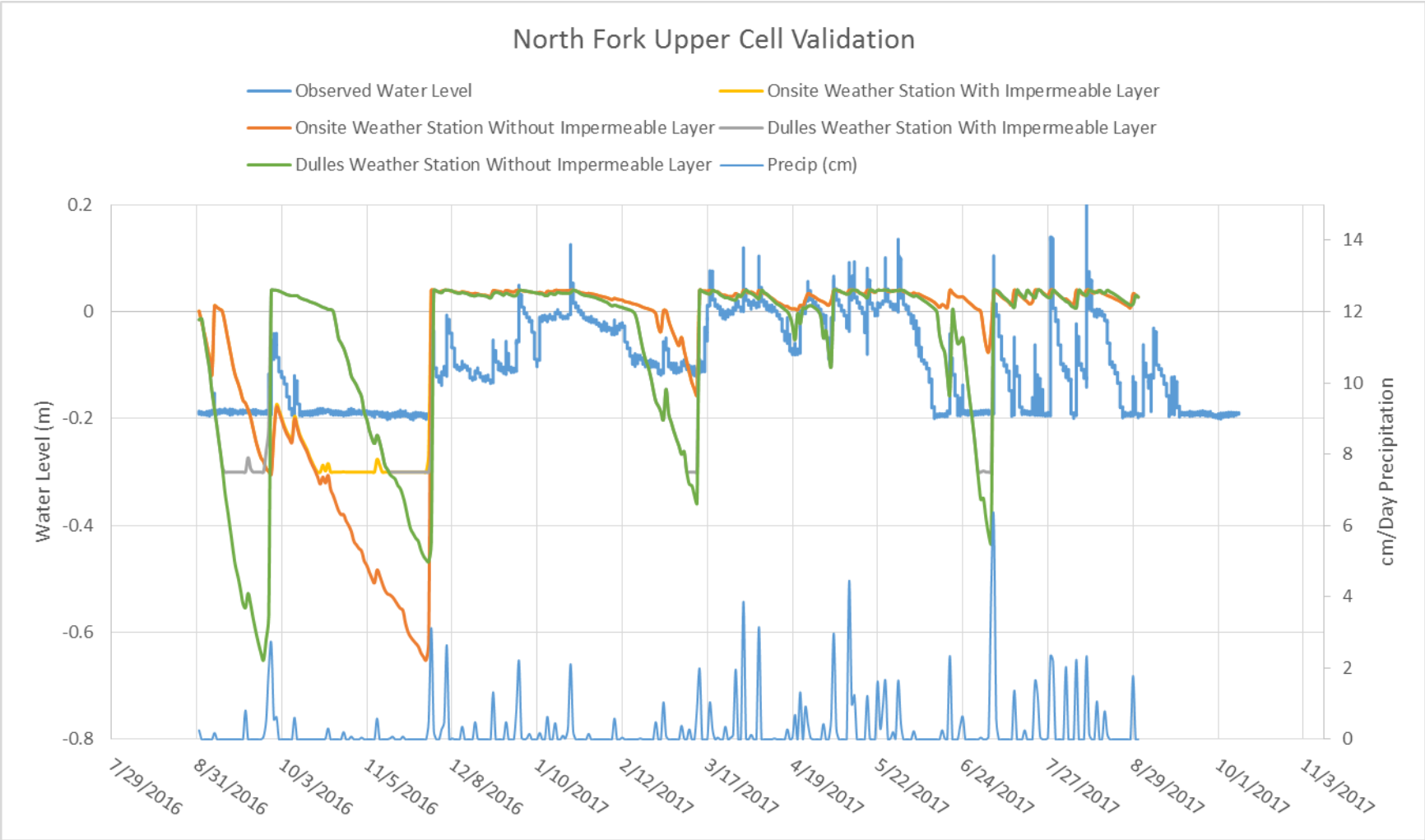


Figure 4.10. Daily hydroperiod of the validation models for cell NW1 with well monitoring data from 2016-2017 shown along with precipitation. Statistical comparison of the models is show in Table 4.6. Data for dates where the onsite wells were dry were removed from statistical comparisons.

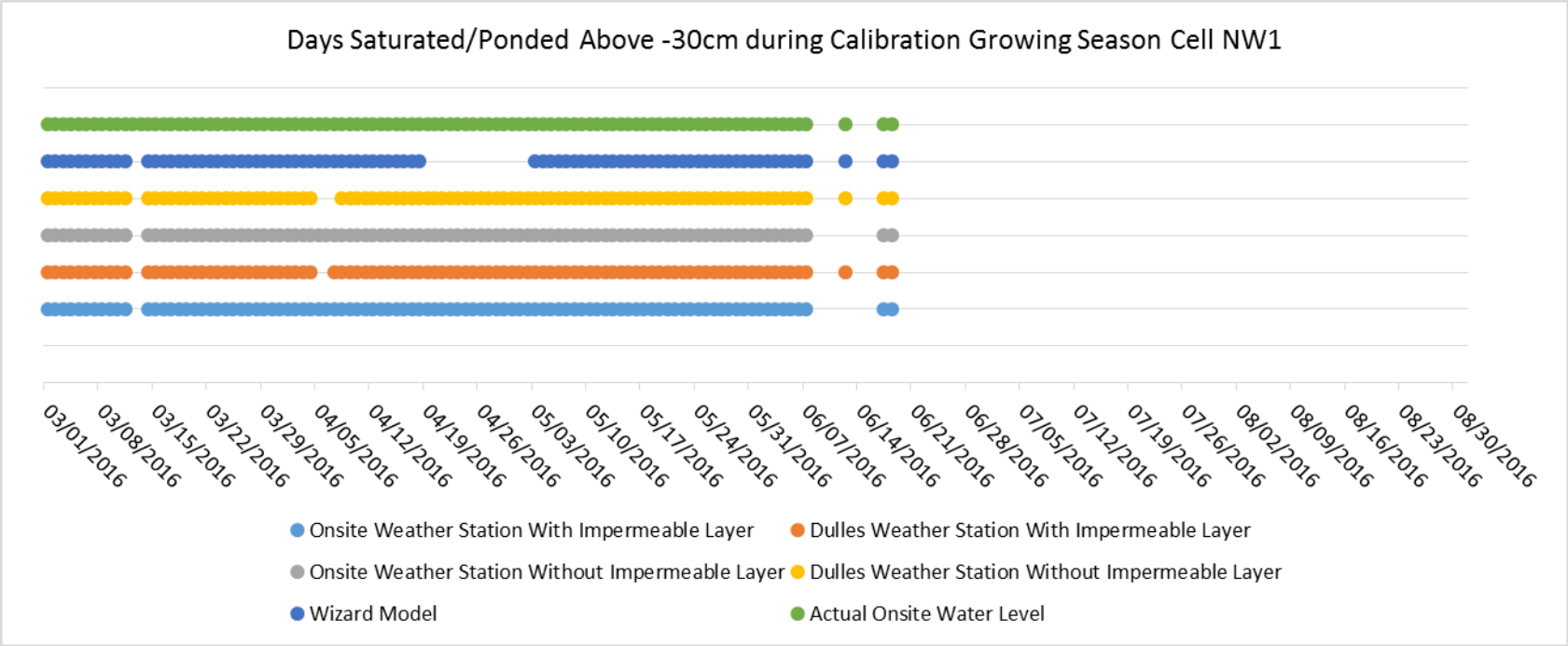


Figure 4.11. Graphical chart of days saturated or ponded above -30 cm during the calibration period partial growing season (3/1 to 8/31) for cell NW1. All six series for each model combination are reported. Blanks indicate no actual or predicted saturation or ponding above -30 cm. Data shown for spring through late summer portion of growing season. Jurisdictional hydrology criteria are usually evaluated in early spring through mid-summer.

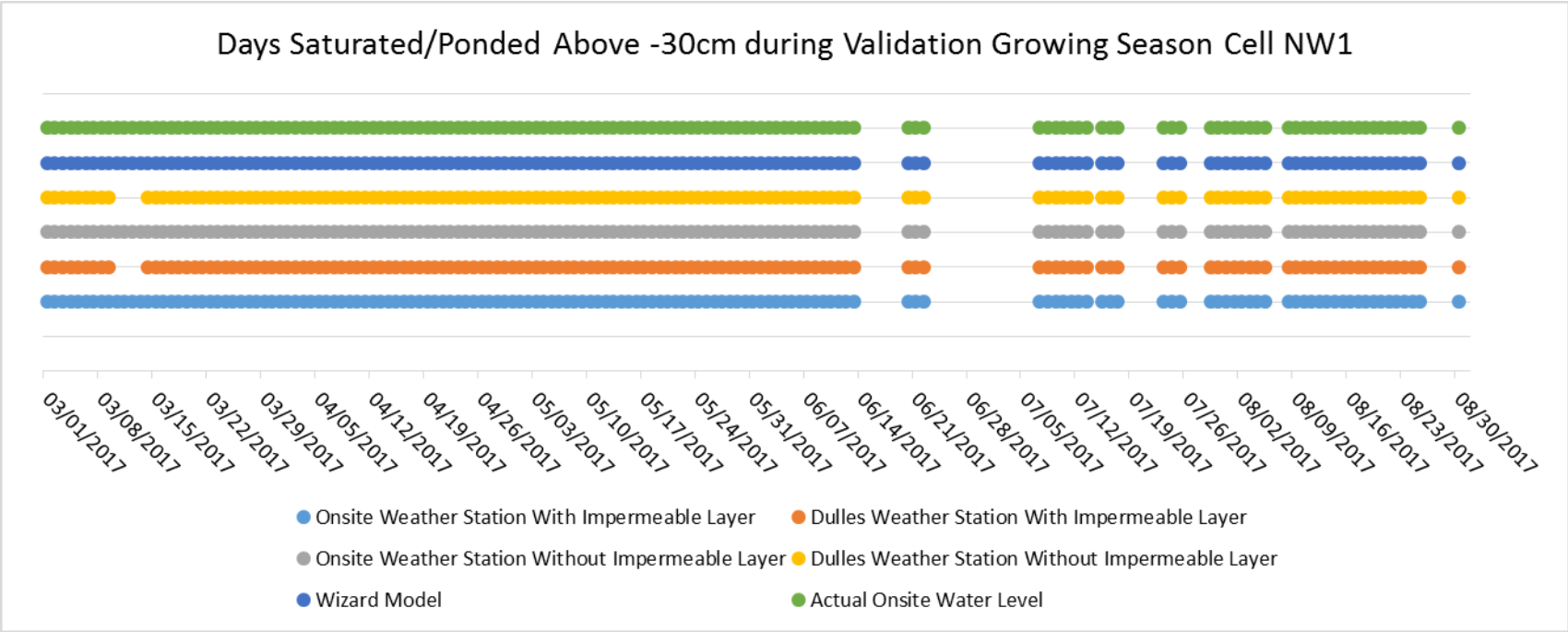


Figure 4.12. Graphical chart of days saturated or ponded above – 30 cm during the validation period partial growing season (3/1 to 8/31) for cell NW1. All six series for each model combination are reported. Blanks indicate no actual or predicted saturation or ponding above -30 cm. Data shown for spring through late summer portion of growing season. Jurisdictional hydrology criteria are usually evaluated in early spring through mid-summer.

The calibrated model using offsite weather data (Dulles) generated a lower NSE and higher RMSE relative to the onsite weather (Table 4.6). Removal of the limiting layer during calibration did not affect the onsite weather based models' abilities to predict actual water levels. The difference for the offsite weather model was very minimal when the limiting layer was removed. This is because dry monitoring points were removed from comparison, which is when the limiting layer would likely be most influential. For the validation model runs, using onsite weather data resulted in an excellent RMSE with or without the limiting layer. Similarly, the offsite weather data produced a validated model which achieved an excellent RMSE with a limiting layer. However, without the limiting layer, the RMSE was only "good" (Table 4.6) by our criteria. Overall, between the calibration year and validation year, there was a drop in accuracy for all models. This was likely due to the nature of the second year weather data compared to the first (Figures 4.9 and 4.10). During the second year, there were smaller and less intense rain events in the early part of the part of the year with longer dry periods interspersed with large rainfall events in the later part of the year. This pattern likely lowered the day-to-day accuracy of the model and thus negatively affected both the daily model and the monthly model output.

When the daily hydroperiods for the calibration period (Figure 4.9) for NW1 are analyzed visually, the model based on onsite weather estimated the late summer drawdown more accurately than the offsite weather model, which stayed wetter longer. All four models predicted a rise in the water table far in advance to the actually observed late fall to early winter rise in onsite wells. Models based on the onsite weather data with and without the impermeable layer responded similarly for the calibration year and tended to vary only when the models without the impermeable layer dropped below that depth. Calibrated models with and without the limiting layer had the same

predictive ability when using onsite weather data however when using offsite weather data, the model with the impermeable layer resulted in a better model fit. The calibrated onsite weather data model adequately predicted water levels above the limiting layer for wet parts of the year, but once it predicted dry soil conditions the monitoring well data had already dropped below the observable depth. Both the calibrated and validation models predicted a similar winter water level increase in mid-September due to a large precipitation event, however, the site was not consistently saturated until early October. The offsite weather based models did a better job of predicting the late summer drawdown of the site in late May when compared to the onsite weather data models which kept the surface wetter for longer.

Table 4.7 shows the monthly comparison of the NW1 models shown in Figures 4.13 and 4.14. The monthly analysis of all four models produced similar NSE and RMSE values to the daily analyses. As in the daily comparisons, the effect of the limiting layer was obscured by the removal of dry points in the monthly analysis. The onsite weather data resulted in the best model fit during calibration with and without the limiting layer, but all models produced at least acceptable statistical results. During the validation model runs, the offsite weather data fit the onsite data best and all models again resulted in excellent RMSE's (< 10 cm). From Figure 4.13 it is clear that the monthly model predicted the general trends of the observed water levels well, however, none of the models were able to accurately model the late summer low water levels. In all cases, calibrated monthly average hydroperiods (Figures 4.13 and 4.14) were able to predict the measured water level data with an RMSE < 10 cm; thus all models were excellent with regard to our established statistical thresholds for RMSE. For NSE, no models of NW1 were able to produce an acceptable value. With a limiting layer, the onsite weather data had an RMSE of 5.92 cm vs offsite with 7.35

cm. During validation however, the offsite weather model with the limiting layer was similar with an RMSE of 9.47 cm vs. the onsite weather model with an RMSE of 9.55 cm; both results were considered excellent by our criteria. Models with and without the limiting layer produced unacceptable NSE, but good RMSE values in the validation year, presumably for weather related reasons discussed earlier.

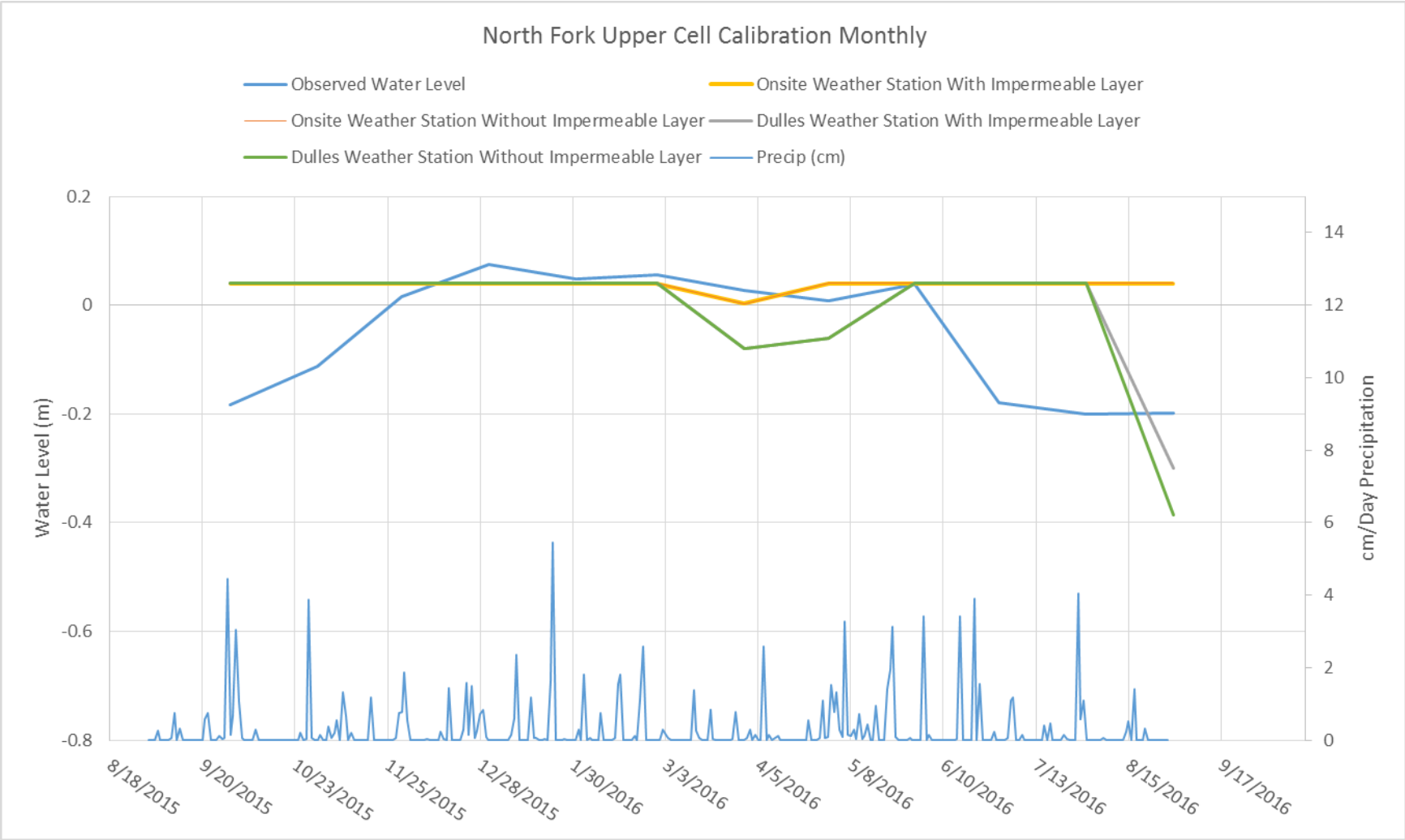


Figure 4.13. Monthly hydroperiod of the calibrated models for cell NW1 with well monitoring data from 2015-2016 shown along with precipitation. Statistical comparison of the models is show in Table 4.7. Data for dates where the onsite wells were dry were removed from statistical comparisons.

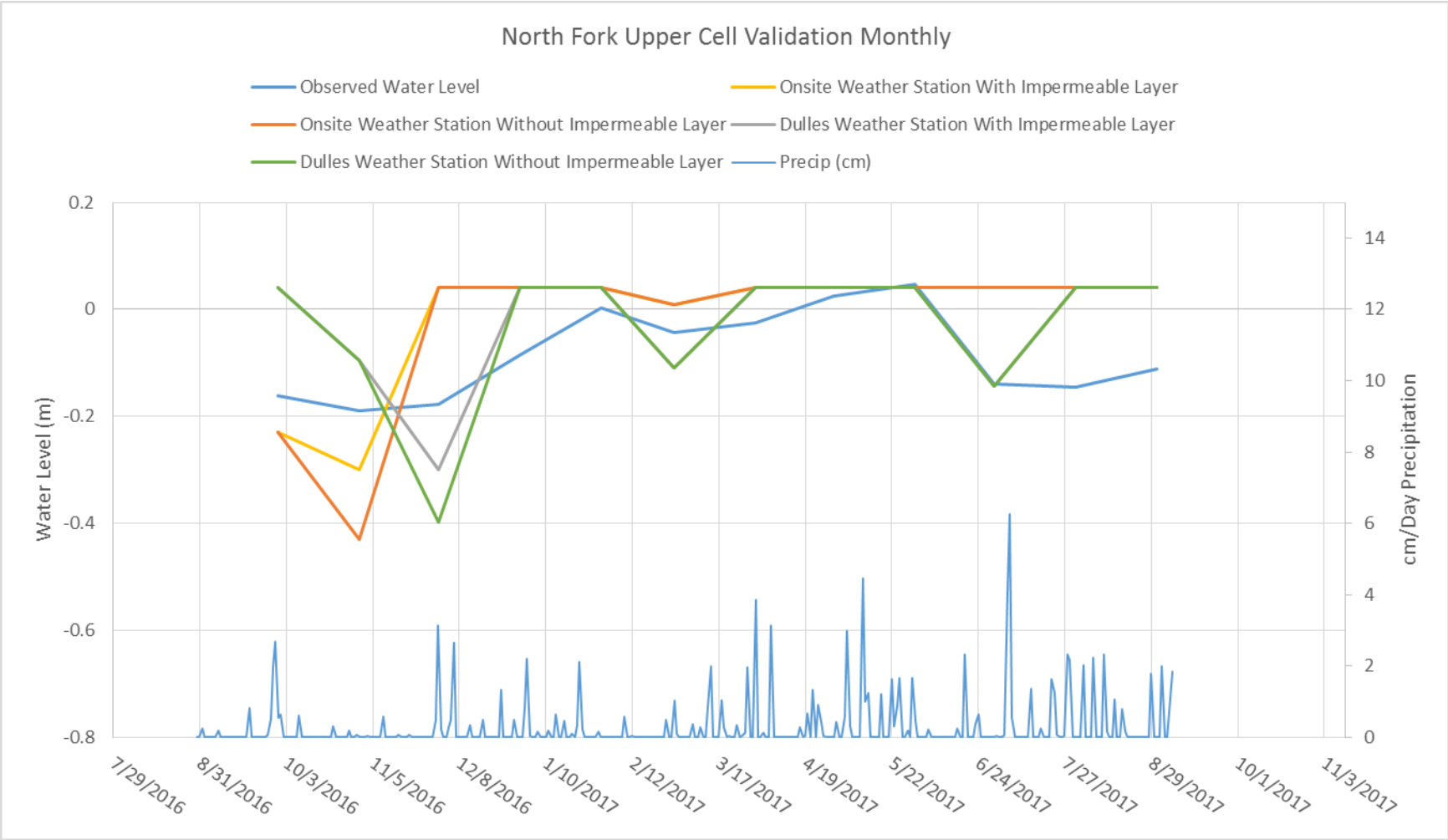


Figure 4.14. Monthly hydroperiod of the validation models for cell NW1 with well monitoring data from 2016-2017 shown along with precipitation. Statistical comparison of the models is show in Table 4.7. Data for dates where the onsite wells were dry were removed from statistical comparisons.

## 4.6. North Fork Vernal Pool Cell Model Accuracy

Figure 4.15 shows the monthly output for the calibrated vernal pool model with the onsite weather station with all inputs and outputs. Figures 4.16 and 4.17 show daily hydroperiods for the four calibrated and validated vernal pool daily models, along with the onsite monitoring well data, which are all statistically compared in Table 4.8. For daily model comparisons, the calibrated model for the vernal pool (Table 4.8) using onsite weather data and a limiting layer produced the most accurate model with an acceptable RMSE (e.g. RMSE <20 cm), however, it still failed to produce an acceptable NSE (e.g. NSE > 0.4). During calibration, the daily onsite weather driven model visually (e.g. qualitatively) predicted winter high water levels and summer low water periods reasonably well and responded to precipitation events reflected in the monitoring data (Figure 4.16). The calibrated model using offsite weather data also qualitatively predicted winter high water levels well; however, it stayed ponded long into the summer when actual water levels had already receded.

Figures 4.18 and 4.19 show the days saturated or ponded (> -30cm) for the vernal pool during the first six months of the growing season of the calibration and validation year. The actual onsite data for the vernal pool showed 100 days saturated/ponded during calibration and 176 for validation. During calibration, the models without the limiting layer performed the worst (onsite predicted 43 days, offsite predicted 53 days), with the Wizard model providing a better representation of the growing season saturation at 77 days. The two models with limiting layers, with onsite weather data (93 days) and offsite weather data (97 days), were the best fit to the actual onsite monitoring data both. This emphasizes the need for the limiting layer in the mainly precipitation driven models; this is likely because without continuous local surface water inputs, the model is more

likely to dry down unrealistically deep. During validation, all models without a limiting layer (Wizard, onsite/offsite weather data without limiting layer) were unable to produce any corresponding points during the growing season. However, models with onsite/offsite weather data and limiting layers were able to model the days saturated very well, predicting the exact same numbers of days saturated (141), but with different timing.

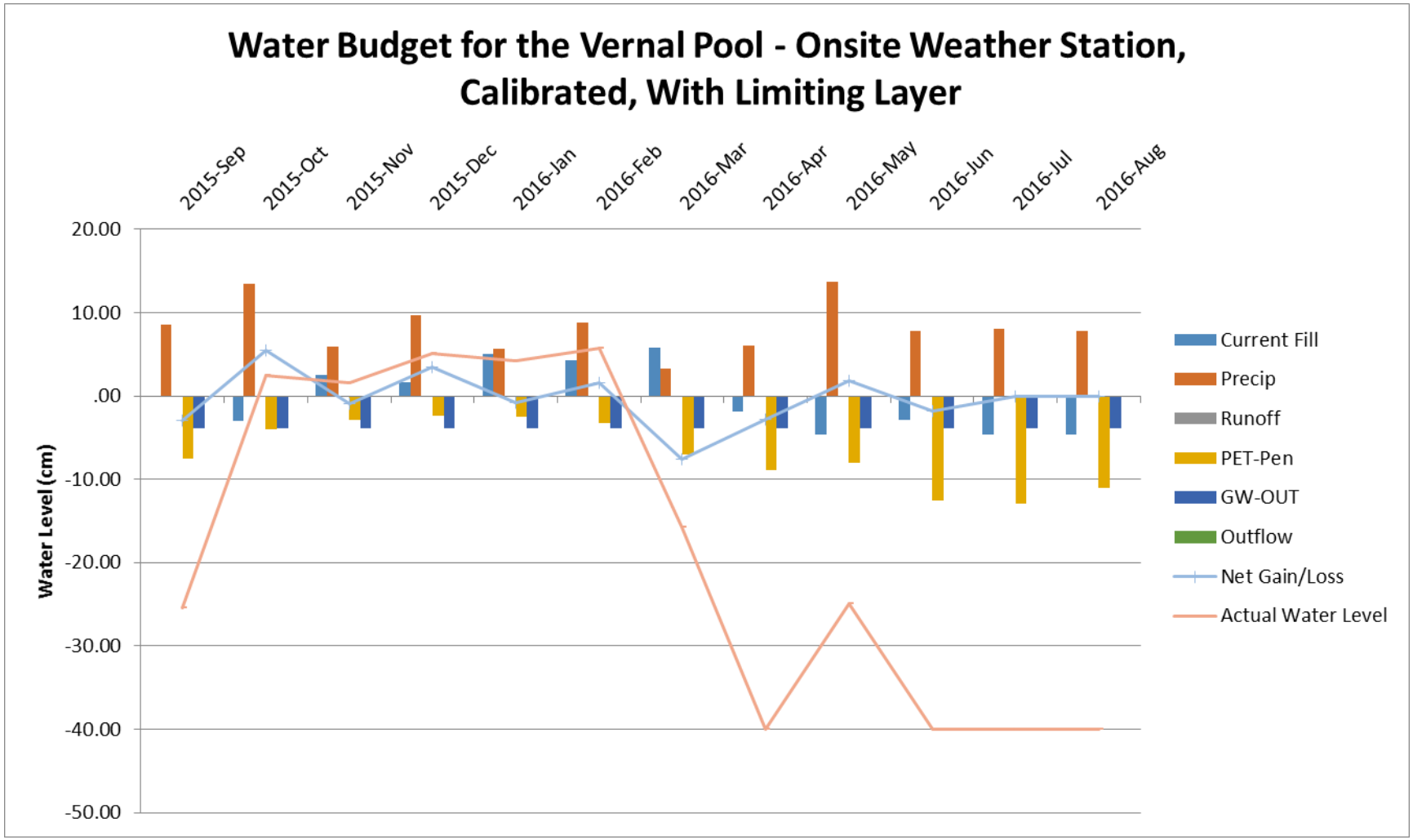


Figure 4.15. The monthly output of the vernal pool calibrated onsite weather model with a limiting layer graphed alongside the model inputs and outputs for 2015-2016.

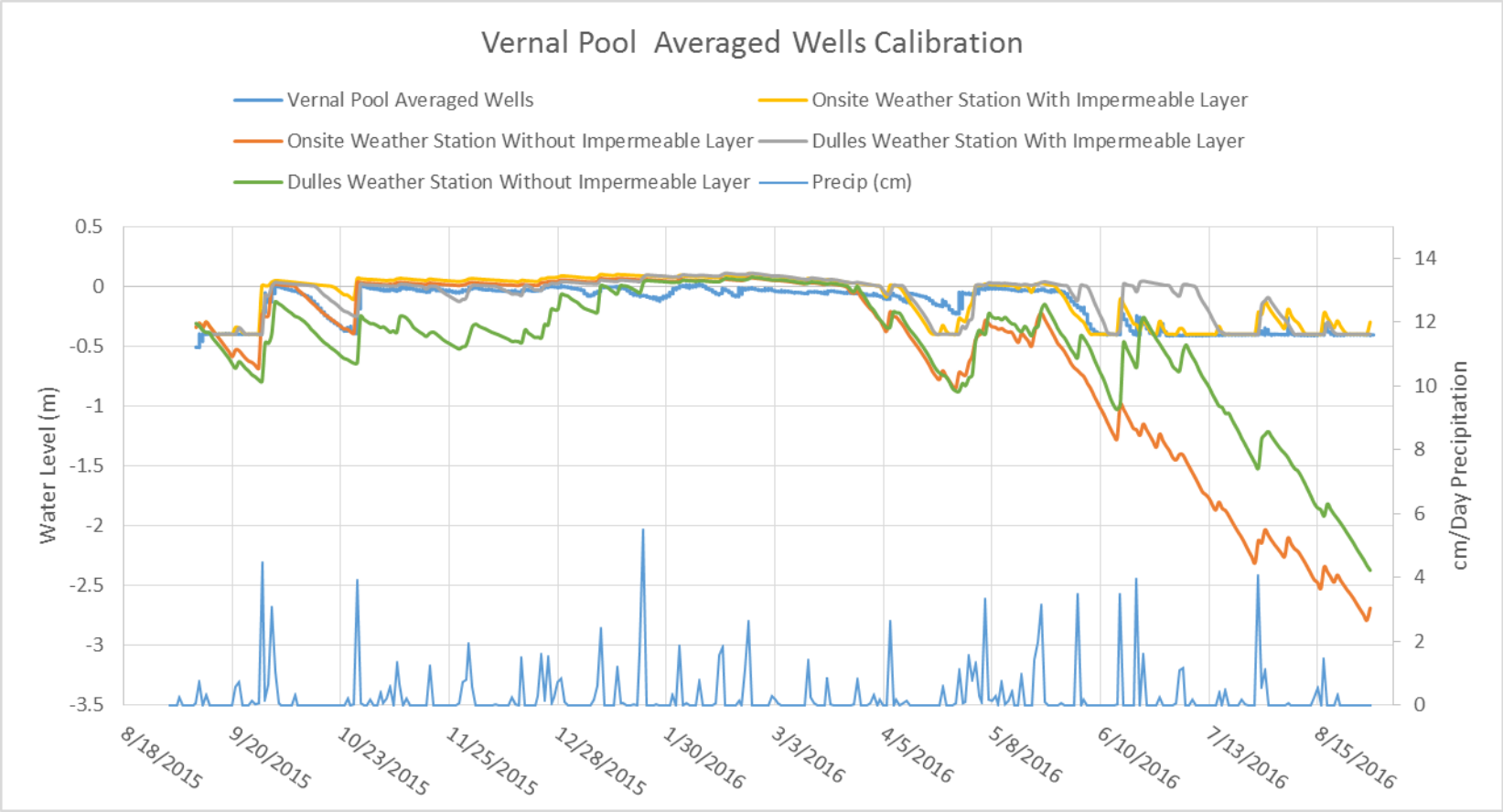


Figure 4.16. Daily hydroperiod of the calibrated models for the vernal pool along with well monitoring data from 2015-2016 and precipitation data. Statistical comparison of the models is show in Table 4.8. Data for dates where the onsite wells were dry were removed from statistical comparisons.

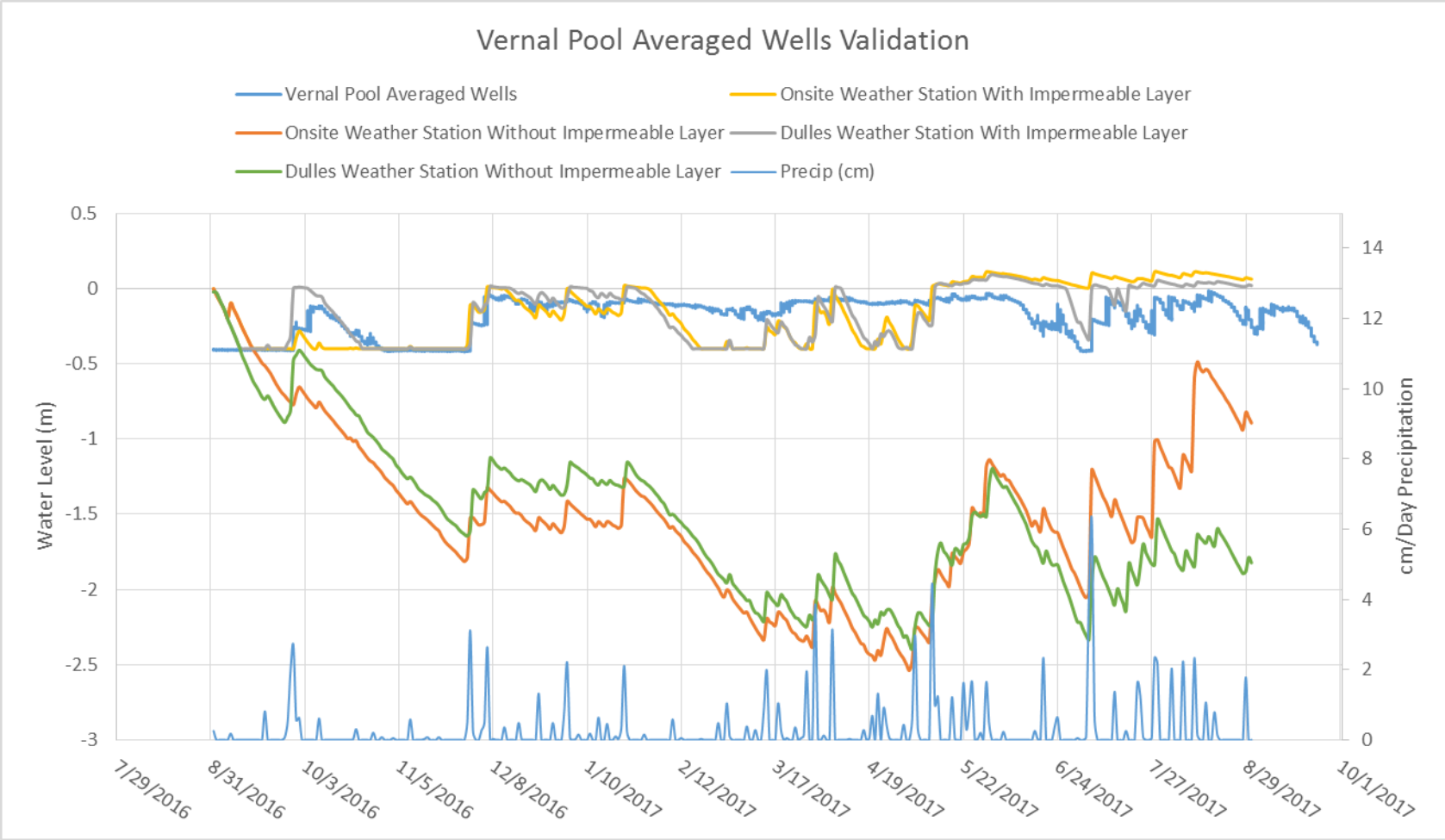


Figure 4.17. Daily hydroperiod of the calibrated models for the vernal pool along with well monitoring data from 2016-2017 and precipitation data. Statistical comparison of the models is show in Table 4.8. Data for dates where the onsite wells were dry were removed from statistical comparisons.

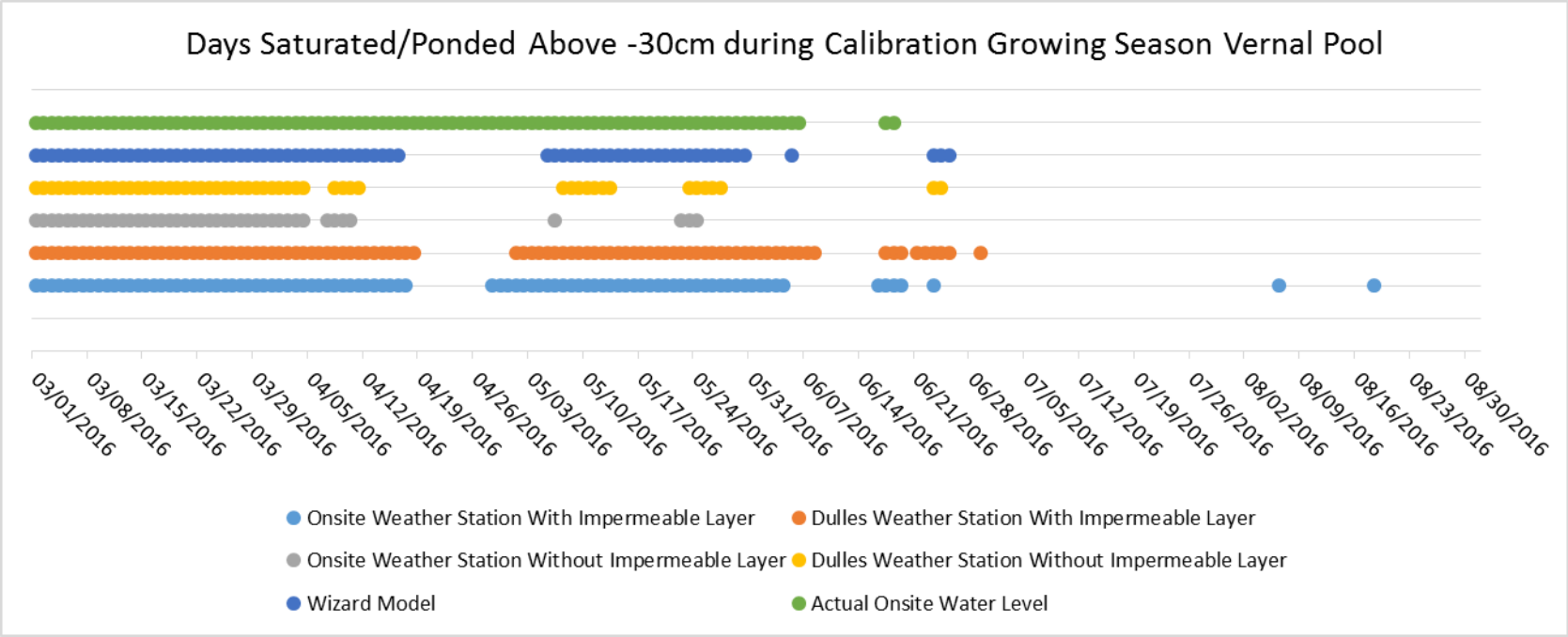


Figure 4.18. Graphical chart of days saturated or ponded above – 30 cm during the calibration period partial growing season (3/1 to 8/31) for the vernal pool. All six series for each model combination are reported. Blanks indicate no actual or predicted saturation or ponding above -30 cm. Data shown for spring through late summer portion of growing season. Jurisdictional hydrology criteria are usually evaluated in early spring through mid-summer.

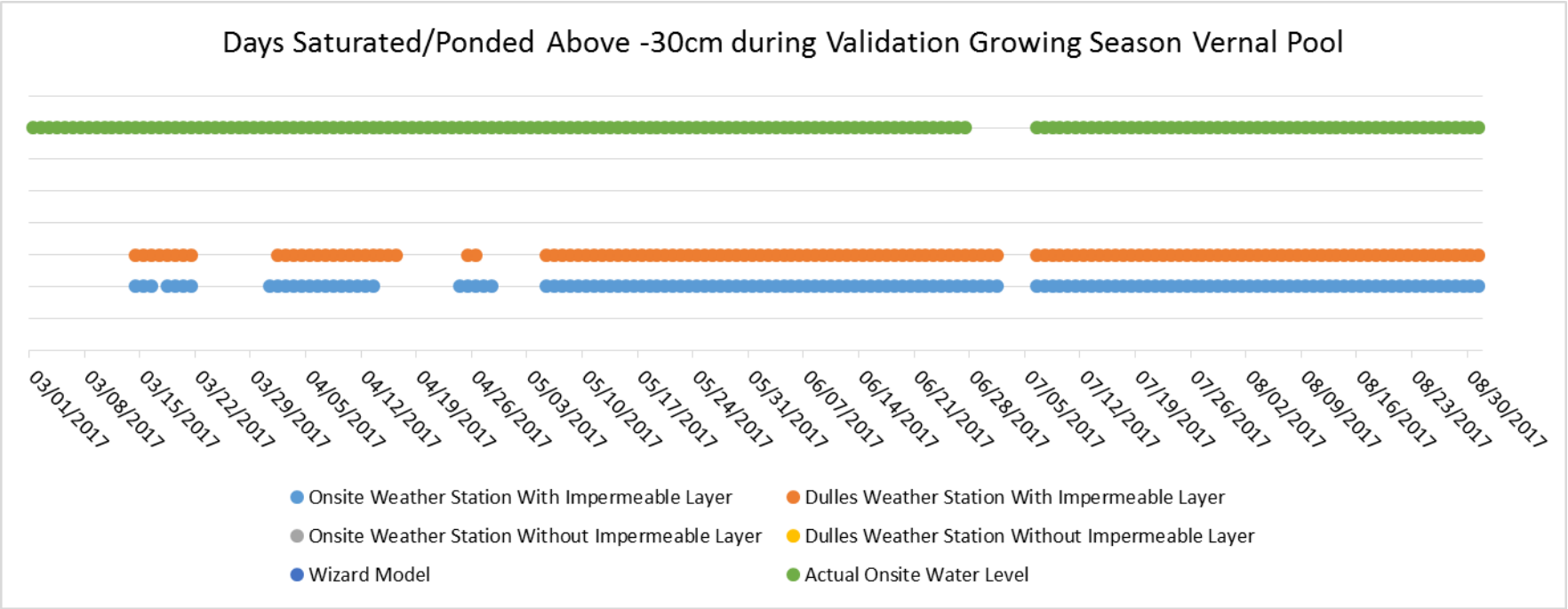


Figure 4.19. Graphical chart of days saturated or ponded above – 30 cm during the validation period partial growing season (3/1 to 8/31) for the vernal pool. All six series for each model combination are reported. Blanks indicate no actual or predicted saturation or ponding above -30 cm. Data shown for spring through late summer portion of growing season. Jurisdictional hydrology criteria are usually evaluated in early spring through mid-summer.

Table 4.8. Daily comparison results of NSE and RMSE statistics for calibrated models and validation of the vernal pool. Models compare weather station location and presence of a limiting layer.

| **Statistical Parameter** | **Calibration 2015-2016** | | **Validation 2016-2017** | |
|---|---|---|---|---|
| | NSE | RMSE cm | NSE | RMSE cm |
| **Calibrated model using onsite weather data** | 0.06 | 11.40 | -4.82 | 18.54 |
| **Calibrated model using offsite weather data** | -0.14 | 12.55 | -3.68 | 16.64 |
| **Calibrated model using onsite weather data and no limiting layer** | -12.47 | 43.11 | -411.63 | 156.54 |
| **Calibrated model using offsite weather data and no limiting layer** | -8.70 | 36.57 | -419.40 | 157.61 |

During daily model analyses the validation models without limiting layers were unable to produce acceptable NSE or RMSE values (Table 4.8). Validation models with limiting layers conformed to the onsite data best, but both on- and offsite weather based models under-predicted actual observed water levels during the late winter and over-predicted them during the drier summer months. Both daily models with the onsite and offsite weather data we able to produce good model fit during calibration and acceptable fit during validation. During validation, the offsite weather data did statistically (and visually) correspond better than the onsite data (Table 4.8 and Figure 4.17); however, none of these models were successful based on NSE. This was likely due to the bias effect which a low range of absolute values has on NSE combined with the lowered sample size from dry date removal. During calibration, the modification of the groundwater out component strongly improved the fit of the calibrated model for the first year. During validation, however, this addition may have exacerbated the effect of lowered rainfall and drawn the water

table down too far in models without a limiting layer. This further reinforces the need for correctly specifying a limiting layer when there is a subsurface impermeable layer which may perch water and/or greatly slow infiltration losses to lower than the default of 2.54 cm per month.

Figures 4.20 and 4.21 show the hydroperiods for the calibrated and validated monthly models, which are statistically compared in Table 4.9. When compared on a monthly scale, the results are similar to the daily models with respect to NSE and RMSE values. Averaging water levels by month for this analysis resulted in slight improvements across the board in NSE and RMSE compared to daily analyses. The calibrated onsite weather data model with a limiting layer was the only model that achieved acceptable success levels with a NSE at 0.41, which was barely above the "acceptable threshold" of 0.40. This model also produced a good RMSE of 10.31.

During the monthly calibration period for the vernal pool, the removal of the limiting layer from the model with offsite weather data resulted in a very poor model fit to the data. During calibration, the onsite weather data model with a limiting layer did visually (qualitatively) predict the actual observed water levels reasonably well. Once the limiting layer was removed from the onsite weather data model, its accuracy became very poor and the visual fit suffered as well (Table 4.9 and Figure 4.20). The models with limiting layers were considered "good" in terms of their RMSE. During validation, the onsite weather station was considered "acceptable" and the offsite weather resulted in a good RMSE. Via both visual and statistical analyses, the hydroperiods for the offsite weather data models were not very different from each other, so this improvement was likely due to a minor difference in predicted monthly average water levels (Figure 4.20). During the validation period (2016-2017), all models without a limiting layer experienced too much

drawdown to rebound normally in late-fall/early-winter, while the water level quickly rose in the onsite monitoring well's. The best performing model during validation period was the offsite weather station model with a limiting layer; however, no model was able to produce an acceptable NSE. These results might be a reflection of the lower amounts of rainfall during the beginning of the year and high intensity storms in the later part of the validation year.

Table 4.9. Monthly comparison results of NSE and RMSE statistics for calibrated models and validation of the vernal pool. Models compare weather station location and presence of a limiting layer.

| **Statistical Parameter** | **Calibration 2015-2016** | | **Validation 2016-2017** | |
|---|---|---|---|---|
| | NSE | RMSE cm | NSE | RMSE cm |
| **Calibrated model using onsite weather data** | 0.41 | 10.31 | -0.76 | 15.67 |
| **Calibrated model using offsite weather data** | 0.10 | 12.71 | -0.26 | 13.24 |
| **Calibrated model using onsite weather data and no limiting layer** | -19.71 | 60.24 | -149.54 | 145.06 |
| **Calibrated model using offsite weather data and no limiting layer** | -7.48 | 39.19 | -151.63 | 146.07 |

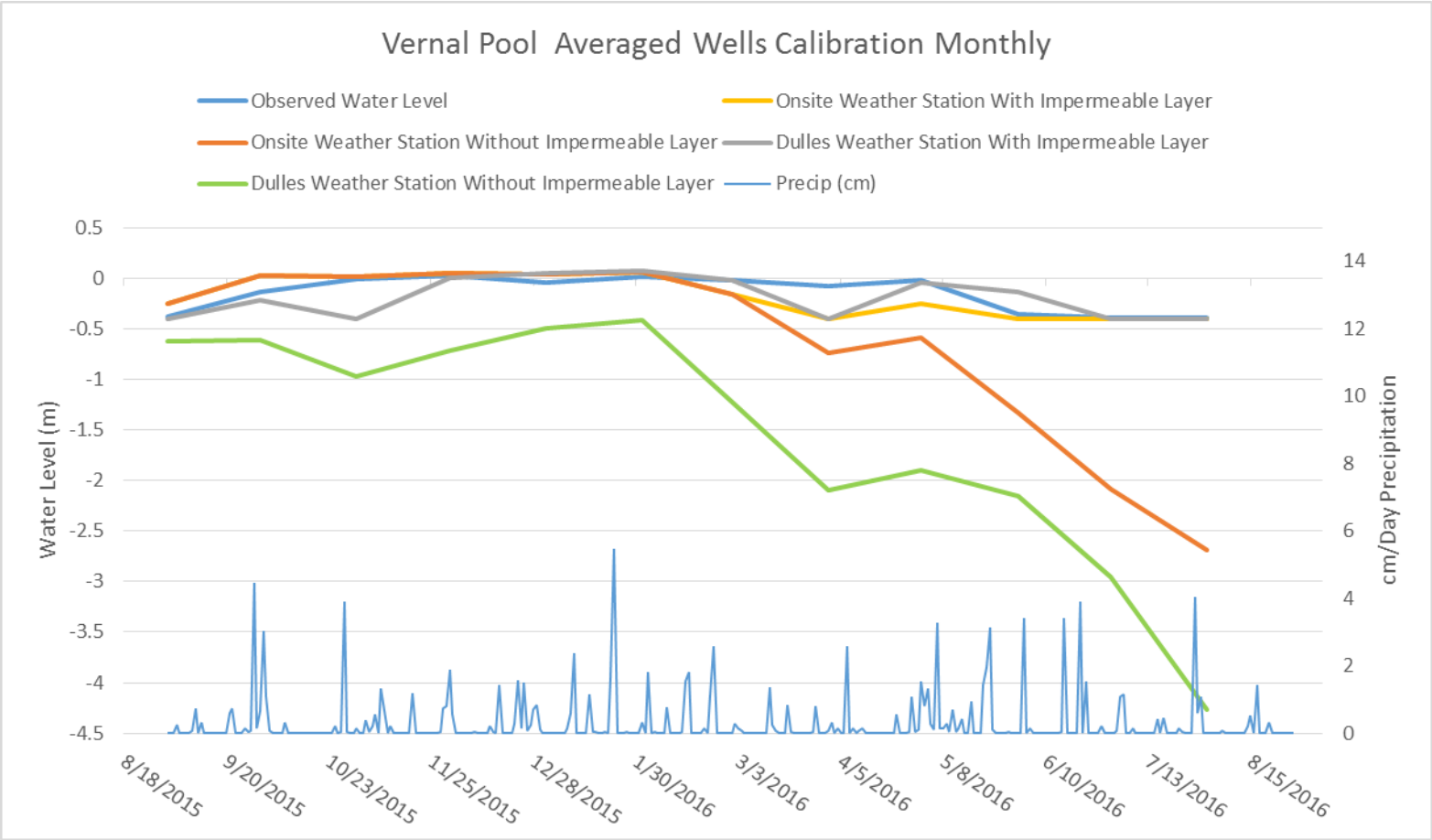


Figure 4.20. Monthly hydroperiod of the calibrated models for the vernal pool along with well monitoring data from 2015-2016 and precipitation data. Statistical comparison of the models is show in Table 4.9. Data for dates where the onsite wells were dry were removed from statistical comparisons.

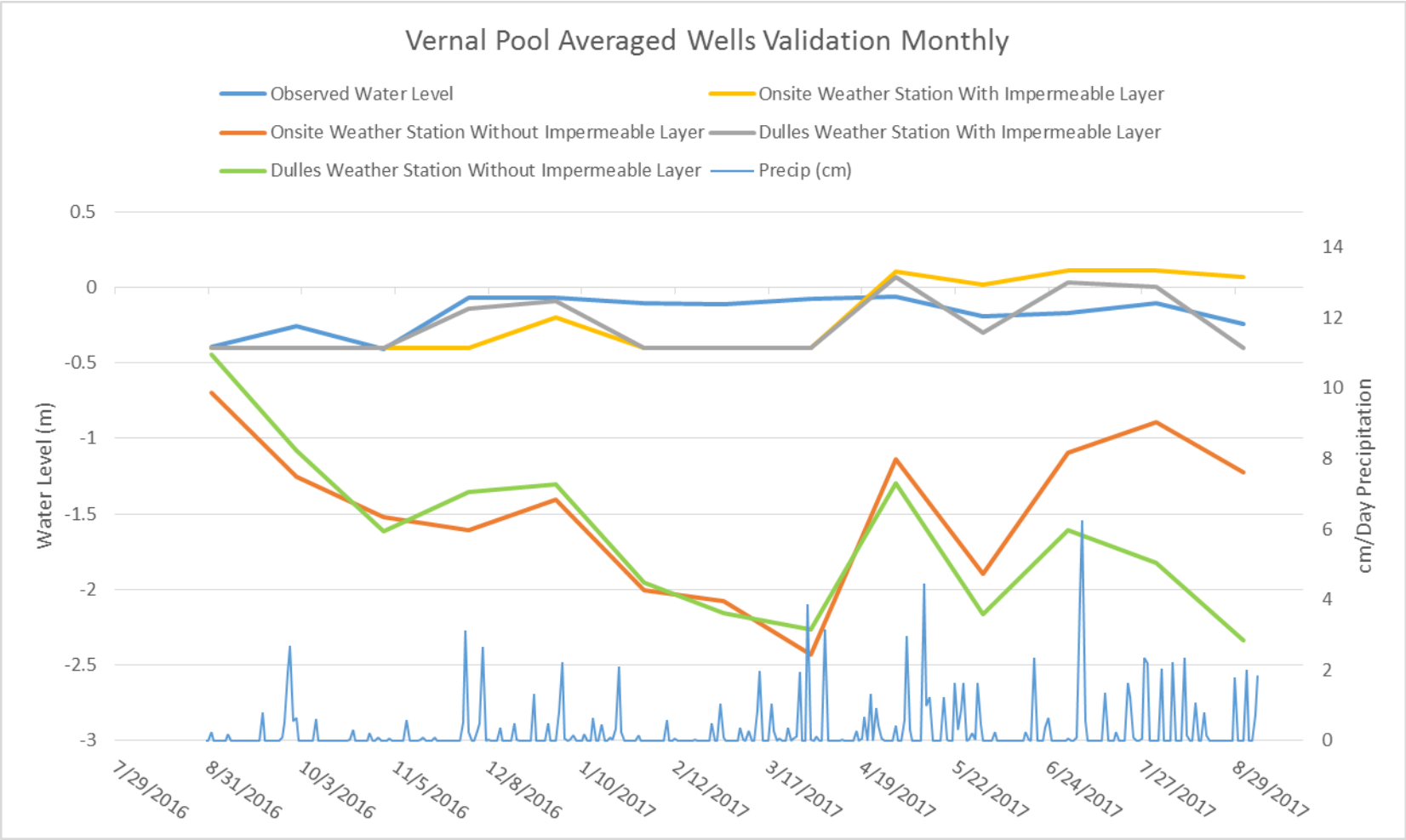


Figure 4.21. Monthly hydroperiod of the calibrated models for the vernal pool along with well monitoring data from 2016-2017 and precipitation data. Statistical comparison of the models is show in Table 4.9. Data for dates where the onsite wells were dry were removed from statistical comparisons.

## 4.7. Discussion

The assumptions within the Wizard application are broad and should be varied and manipulated in situations where Wetbud is used for any specific constructed wetland design when it is clear that the adjustments are appropriate based on actual site conditions. However, the Wizard does provide a good way to review the influence of changes in precipitation patterns as well as what primary input parameters (e.g. curve number or outlet weir elevation) might need to be adjusted within a fully specified Basic model scenario.

Much more complex models such as the calibrated DRAINMOD model used by Caldwell et al. (2007) reproduced water budgets resulting in an average absolute deviation of about 4 cm from the actual observed water levels. As a less complex model, the Wetbud Basic model as applied in this study, and calibrated with one year of data, produced an RMSE between 6.73 cm and 12.55 cm (excellent to good). During the following validation period, it produced RMSE's ranging between 8.26 cm and 16.64 cm (excellent to acceptable) for models containing all parameters. Models of the vernal pool without impermeable layers were unable to achieve success in all cases.

My overall efforts were focused on the Basic model within Wetbud and not surprisingly demonstrated the need for accurate parameterization to improve model accuracy. Wetbud is intended as a design model and so it is assumed that parameterization will be based on proposed "as built" site conditions. My sensitivity results suggest that accurate curve number determination will prove beneficial for accurate model output and eventual site sizing and design considerations. Due to the large impact that weir elevation can have on extent/period of flooding, total basin volume, discharge timing/rate as well as maximum water elevation, it is also a parameter that

should be properly specified and considered carefully in the constructed wetland design process. The use of a variable elevation weir to regulate maximum water levels could promote the correct hydroperiod for site vegetation. Variable height weirs could be used in the short term to help establish vegetation, but then need to be set permanently to qualify for permit requirements as a fully passive system. As stated in the methods section, the weirs in this study were flow-through rock weirs located at breaks in the cell berms. This style of weir has variable flow rates which are stage dependent and will vary over time as stones shift, they fill with debris, and vegetation grows into the area. This may have resulted in a decreased level of accuracy in our analysis via NSE and RMSE statistics.

For NW1 and the vernal pool, the Wetbud Basic model provided a reasonably accurate prediction of site hydroperiods with a properly parameterized model. Site models where weather data is available in close proximity will have increased accuracy in most cases when compared to weather data which is sourced from farther away. This also is not surprising, but was reconfirmed in this study. Figures 4.11 and 4.12, demonstrate Wetbud's ability to predict saturation/ponding during the growing season for the watershed runoff and precipitation fed cell, NW1. These models were able to very accurately predict how many days would be saturated as well as when they would be. During validation of the NW1 models these results were replicated with an increased level of accuracy. Figures 4.18 and 4.19 also showed the strength of Wetbud at predicting days saturated, this time in an entirely precipitation fed model (vernal pool). However, these models emphasized the importance of the limiting layer as the models without this layer performed far worse than the models with this parameter invoked. Within the Validation year, the models without the limiting layer were unable to produce even one corresponding point within the growing season.

Wetbud's Basic model output should be considered more critically as the level of uncertainty in any important input parameter increases. The models for Cell NW1 and the vernal pool reflect the level accuracy which could be expected of the Wetbud Basic model. When properly parameterized, all calibrated models for Cell NW1 produced an excellent RMSE of less than 10 cm, and only one validation run failed to meet this criterion (offsite weather, no limiting layer, RMSE = 11.48). The calibrated models for the vernal pool with impermeable layers and varied amounts of GWO (2.25 cm month$^{-1}$ for offsite weather station and 3.9 cm month$^{-1}$ for the onsite weather station) all achieved good RMSE's during calibration and during validation they achieved good to acceptable RMSE values. The vernal pool results highlight the need to properly specify the impermeable depth since models without that parameter produced NSE's and RMSE's far below acceptable thresholds. In general, the models tended to over-predict the number of days ponded; the validation year being slightly better than the calibration year. Seasonal drawdown was accurately predicted in the calibrated model with minor drops in accuracy during validation. However, due to the large water level fluxes in the summer of 2017, the model was less reliable at predicting time of drawdown than in 2016.

Users looking to employ Wetbud as intended as a design model should develop accurate design parameters based on projected site conditions which will hopefully produce reasonably accurate representations of target systems. Accurate parameterization is critical as the model is only as good as the data we can give it. Important site conditions include soil types, depth to limiting layers, intended vegetation, contributing watershed size, basin configuration, nearby weather data, and outlet weir elevations. Neuhaus (2013) also recommended using the highest resolution PET

estimations available, which means the preloaded Wetbud option for Penman-Monteith is the most accurate. Stone (2017) highlighted the importance of accurate crop coefficient (Kc) values in adjusting PET, but this adjustment is currently not available in Wetbud. A more advanced user can adjust the Wetbud PET output values by the appropriate Kc externally and then reload the corrected ET estimates into a Basic model. These corrected values for the actual plant communities present would likely produce a better estimate how water levels will change over time.

The main differences between Cell NW1 and the vernal pool were watershed contributions, and the overall size of the sites (with Cell NW1 being a fraction the size of the vernal pool). Results from the suite of NW1 models were more successful during validation when compared to the suite of vernal pool validation models. This suggests that an entirely precipitation based system (e.g. the vernal pool) may be harder to accurately model when compared to a smaller system which has watershed contributions regulating input water flow. Also, due to the large size of the vernal pool and some differences in elevation and microtopography, we cannot rule out that surface water was redistributed to or away from our well locations when the site was ponded. We attempted to address this via installing our two wells on nearby but different microtopographic positions, but some level of uncertainty on this potential source of model error persists. Finally, while our interpretation of local site conditions and underlying geologic conditions led us to conclude that groundwater inputs to both cells were very minimal, we did not install sufficient instrumentation on site to confirm this and if in fact these were positive, they certainly would have affected our relative comparative results.

As with all models, there are always concerns which must be taken into consideration since Wetbud is still an amalgamation of its underlying formulae. Because of this, Wetbud will only function as well as the equations allow and will be directly impacted by the quality of input site data.

## 5. Selection of Target Seasonal Hydroperiods for Three Typical Types of Mid-Atlantic Wetlands

### 5.1. Introduction

As discussed earlier, the term "hydroperiod" was first coined by William Mitsch and appeared in print in the original version of the classic textbook, *Wetlands* (Current version is Mitsch and Gosselink, 2015). In their book, these authors assembled a set of annual hydroperiod graphics for a wide range of USA and global wetland types that have been frequently cited by others over time. However, further publications that show detailed site-specific continuous (full season) hydroperiods over multiple years are exceedingly rare. One example for wetland landscapes in southeastern Virginia was provided by Genthner et al. (1998) for an upland/wetland toposequence, but data were only presented for one "typical year" (although the authors had four years of data). Furthermore, going into this study, we were not aware of any published data sets for the Mid-Atlantic region of interest (e.g. MD/NC/VA) that provided continuous water level data for multiple seasons.

Therefore, the intent of this study was to evaluate all readily available data sets for three typical wetland types in the Mid-Atlantic region via the methods described in Chapter 2 (Methods). As stated earlier, our overall objective in this effort was to select at least three sites for each wetland type whose associated hydroperiods could potentially be used as "design targets". These targets would be for wetland professionals involved in the initial permit preparation process for wetland creation. Presumably, wetland professionals could improve their application and execution of water budgeting procedures and models (like Wetbud) by being able to compare their model output against actual regional examples of these typical hydroperiods. While we have diligently pursued

applicable regional hydroperiod data sets for this study, we do acknowledge that additional suitable site data may exist that we were not able to acquire and analyze, particularly with private sector organizations involved with monitoring. However, the results and site data presented here represent our best effort to analyze all data sets (n > 90) that we could reasonable acquire over an approximate two-year study period. We have carefully selected a suite of well-characterized sites that we believe are "typical" or "central concept" for their wetland type and that appear to display appropriate characteristics based on the available scientific literature along with our (e.g. E.P. Sneesby, W.L. Daniels and G.R. Whittecar) collective experience.

In this chapter, we further explain the data collection and selection process. Our objective was to identify and characterize three primary sites for each of our selected wetland types (mineral flats, depressional and riverine). Due to data and site limitations, depressional wetlands were underrepresented; but we were able to select one small Carolina bay. However, we were able to select and propose four mineral soil flats and three riverine wetland systems for use as "target hydroperiods". We also have several other mineral flats that could be used as additional reference areas if needed for future applications.

During the process of selecting hydroperiod records for final inclusion, we applied a set of criteria sequentially to select our final candidate site hydroperiod data sets. Candidate sites were solicited from various groups and agencies including: The Nature Conservancy, The Army Corps of Engineers, The North Carolina Department of Environmental Quality, as well as scientists from Old Dominion University and Virginia Tech. Additional inquiries were made to wetland soils faculty at other universities in Delaware, North Carolina, and Maryland. However, while these

scientists have all published heavily, multi-year data sets meeting our full criteria for inclusion in this study are quite rare and none were available from these sources.

## 5.2. Site Selection Process and Criteria Employed

Only reference or natural wetland data sets were included in the final data set; constructed sites were removed at the outset. However, some sites had been in previous agricultural or commercial forest land uses and then restored via ditch plugging and other practices. All wetland data sets available were analyzed for continuity, with preference given to those with continuous annual data that were at least two years in length. This removed many of the candidate sites as it is very common practice so only record well data during the late winter and early growing season for jurisdictional determination to confirm the technical standard (USCOE, 2005). Exceptions were made for partially missing data if seasonal water level changes were clearly shown. When sites appeared to be heavily impacted or urbanized, they were removed from site selection. Data sets where the logger's bottom depth varied from year to year and/or appeared unusual were also removed. When the deepest observed water level "bottoms out" at different depths year-to-year, it may indicate an issue with data correction (for riser height etc.) or logger placement unless the well records clearly indicate the well was removed and replaced. In the case of the Level Ponds site, there is one questionable year; however, there were two continuous years prior to this. Notes from the USCOE indicates that they clean/move wells as well as relocate loggers regularly, this may explain the issues with Level ponds. After the removal of sites per the process described above, there were 34 sites remaining for final assessment (Appendix A). Our next criterion sorted for well data showing seasonal water changes for at least two years with a minimum monthly

monitoring frequency. These data sets varied in their resolution, ranging from twice per month manual well readings to electronically logged 15-minute interval data.

The final selections were made with input and review from W. Lee Daniels (Virginia Tech) and G. Richard Whittecar (Research Co-P.I.; Old Dominion University). Final sites were selected based on their conformance to the assumptions for the three HGM classes and associated hydroperiods of interest: (a) mineral soil flats, (b) depressional (including Carolina bays), and (c) riverine systems. During this final review process, orthoimagery, topography, soil types/series, and NWI classification criteria were compared along with detailed well location data to get as complete a characterization of the sites as possible. These maps, images and associated data sets were then reviewed to determine whether the sites conformed to the topographic, vegetative and other characteristics of their wetland type (e.g. a mineral flat). Recent aerial imagery was reviewed for signs of disturbance such as mining, agriculture, drainage or other obvious land alterations. Once sites deemed unsatisfactory were removed, the remaining data sets that contained at least two years of monitoring data were characterized based on soils. Imagery and associated field data sets (if available) was then also reviewed to confirm the more general Cowardin classification and the presence of hydric soils at or near the monitoring wells.

All sites considered had been previously delineated as jurisdictional wetlands and this would have included an on-site vegetation assessment. However, it is the intent of this research program that each final site will have vegetation and other local site factors vetted in the field to assess their level of disturbance and reconfirm approximate age and composition. This work will occur after the completion of this thesis, however. Finally, for the purpose of our analysis, we used the start

of the growing season as March 1st based on personal communication (W.L. Daniels, 2018) with several wetland delineation professionals. Generalized locations of each site can be seen on Figure 5.1.

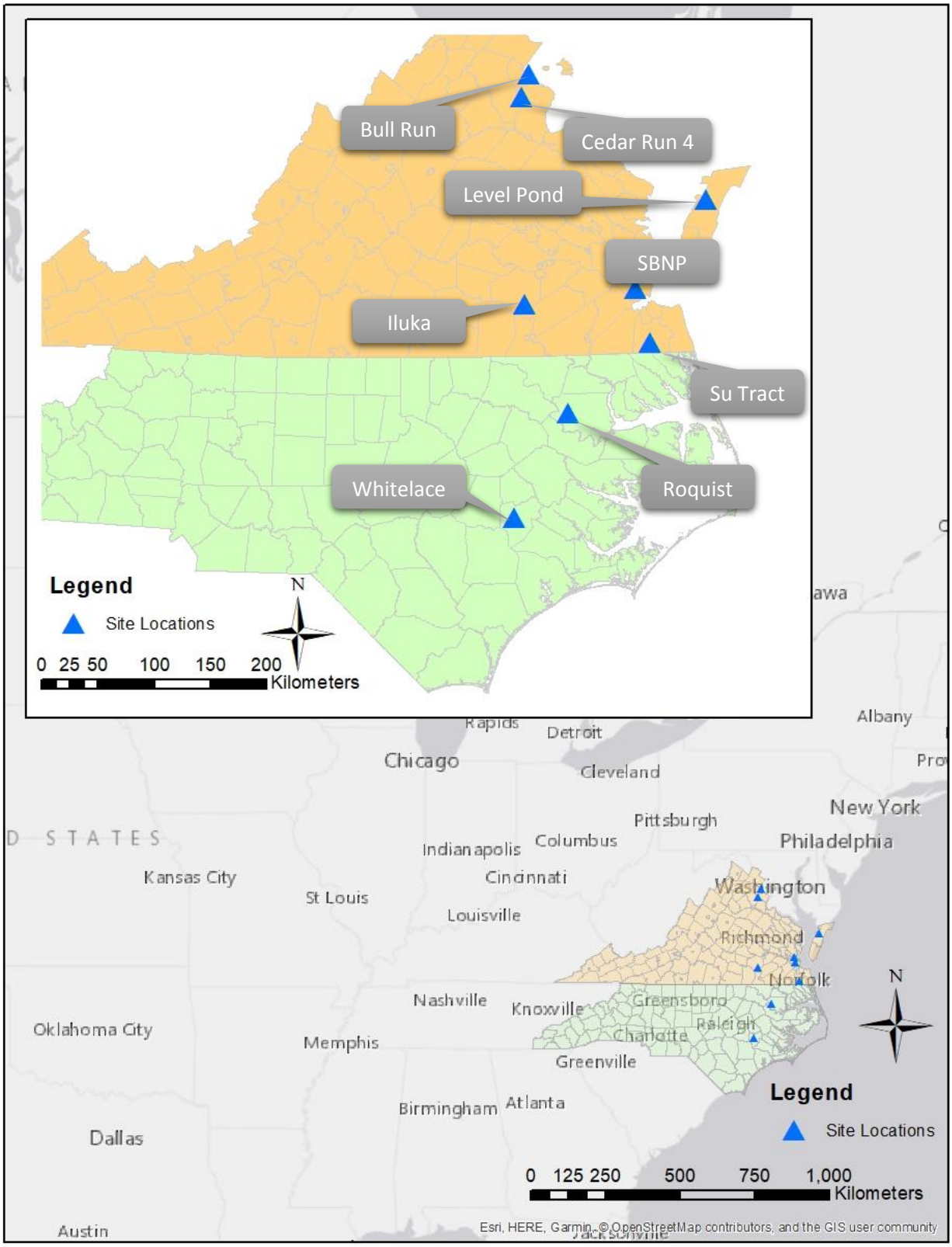


Figure 5.1. Generalized location map for the final nine sites.

To determine whether years were dry, normal, or wet, precipitation data was sourced from Natural Resource Conservation service (NRCS) weather stations, (Remote Automatic Weather Stations) RAWS weather stations, and National Oceanic Atmospheric Administration (NOAA) regional weather stations and then compared to the NRCS WETS table averages established for 1971-2002. Each year of data is also clearly labeled with their dry (D), normal (N), or wet (W) year determination.

## 5.3. Mineral Flats

The final selected sites for the mineral flat category include data from sites provided by the Norfolk District USCOE, Virginia Tech, and Old Dominion University. Geomorphic landscape position and soil type were the most important parameters for site selection within this HGM class.

### 5.3.1. Su Tract:

This site is located on the Tabb formation and overlies the Sedgefield member, which is older than the Lynnhaven member, but is made up of the same major constituents. Soils in this unit are also pebbly and cobbly with fine to coarse sand grains grading into clayey and silty fine sand and sandy silt. This site is located on a broad flat landform and is not associated with any well-defined waterways (Figure 5.2). Soils located on this site (Table 5.1, Figure 5.3) are a mixture of Dragston - Coarse-loamy, mixed, semiactive, thermic Aeric Endoaquults; Nimmo - Coarse-loamy, mixed, semiactive, thermic Typic Endoaquults; Tomotley - Fine-loamy, mixed, semiactive, thermic Typic Endoaquults; and Betire Series - Fine-loamy, mixed, semiactive, thermic Aeric Endoaquults; all with 0-2 slopes (NRCS, 2010) (Figure 5.3). These soils range from somewhat poorly drained to

poorly drained and are all hydric. This area has been mapped as various forms of PFO's by the NWI (Figure 5.4).

This wetland has one of the largest data sets analyzed and was provided by a combination of the VA USCOE (2009-2017) and The Nature Conservancy (2002-2005). The data set includes continuous data for 2002-2005, and excluding 2012, the rest of the data (2009 – 2017) spans the winter through spring (Figures 5.5 and 5.6). All wells indicate similar winter high water levels and show consistent near-surface saturation well into the growing season with some minor year-to-year variation. Water levels typically drop in May and June and rebound in December and January. This site appears to have limited groundwater buffering with quick short-term response to rainfall events.

Limited lateral groundwater interaction is typical of flats (Vepraskas and Craft, 2016) and the topography also doesn't support concentration of overland flows. This hydroperiod consistently shows a high winter and early spring water level, due to low ET and high regional precipitation in the form of snow and rain, and there is evidence of significant winter/spring ponding. High water levels do not persist, and as typical of mineral flats, there is a large seasonal drawdown once late spring hits. From 2003 through 2005, the sensors only confirmed drawdown to -80 cm (lower well depth). However, looking at the later 2009-2017 data (Figure 5.6), we can see the drawdown was as deep as or deeper than -1.8 m.


Figure 5.2. Topographic map for Su Tract with well locations for the TNC monitoring wells. This wetland is located near Chesapeake City.

Table 5.1. Su Tract location, soil map unit symbols and names.

| Chesapeake City, Virginia (VA550) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| 1 | Acredale silt loam, 0 to 1 percent slopes |
| 16 | Deloss-Tomotley-Nimmo complex, 0 to 1 percent slopes |
| 20 | Dragston-Tomotley complex, 0 to 2 percent slopes |
| 25 | Munden fine sandy loam, 0 to 2 percent slopes |
| 30 | Nawney silt loam, 0 to 1 percent slopes, frequently flooded |
| 41 | Tomotley fine sandy loam, 0 to 1 percent slopes |
| 42 | Tomotley-Bertie complex, 0 to 2 percent slopes |
| 45 | Tomotley-Nimmo complex, 0 to 1 percent slopes |


Figure 5.3. Soil and imagery map for Su Tract with well location for the TNC/COE monitoring wells. Soil Key in appendix 4.2. This wetland is located near Chesapeake City.


Figure 5.4. NWI and imagery map for Su Tract with well location for the TNC/COE monitoring wells. This wetland is located near Chesapeake City.

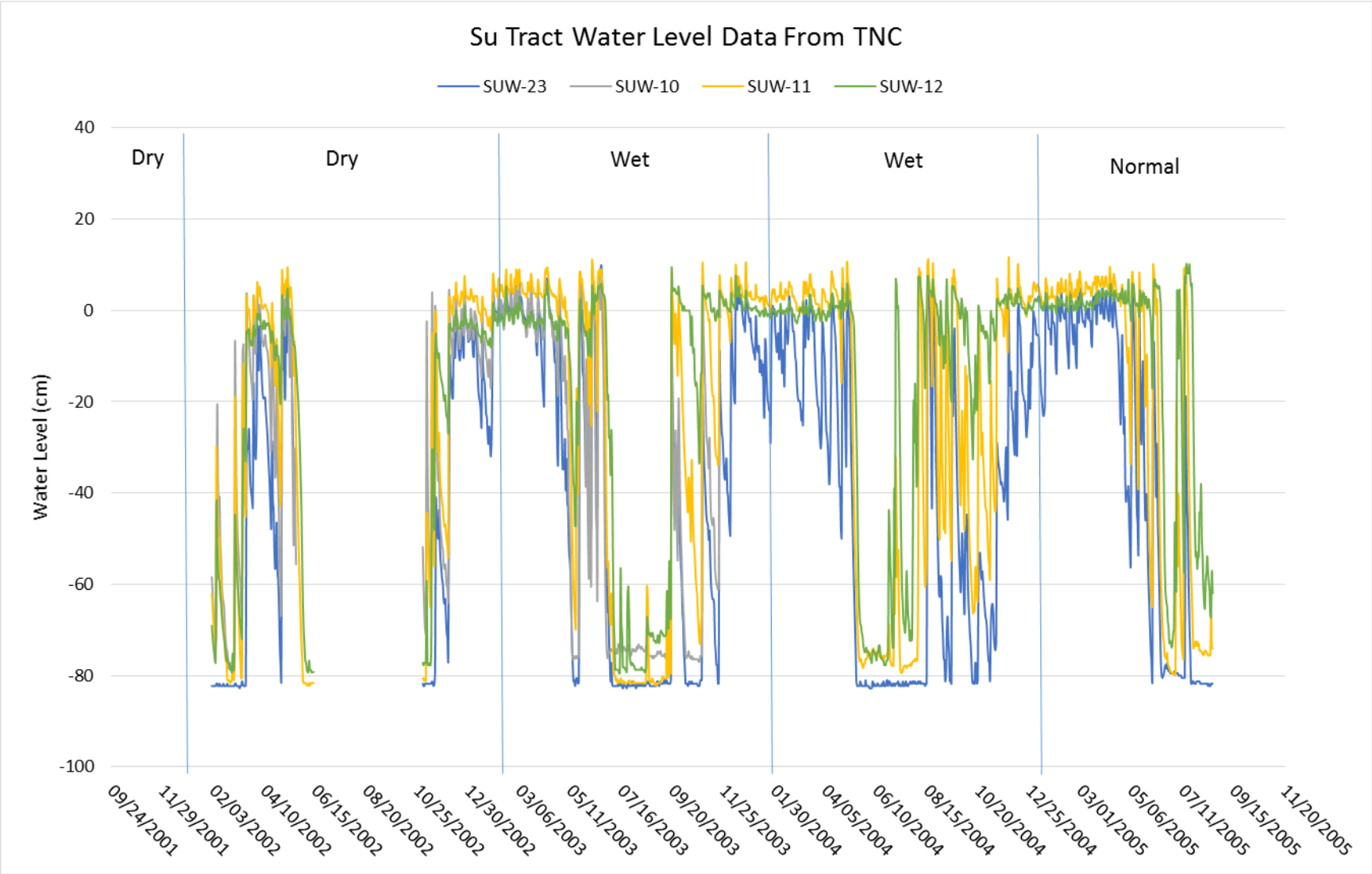


Figure 5.5. Water level monitoring data for well SUW-10, SUW-11, SUW-12, and SUW-23, from 2001- 2005.

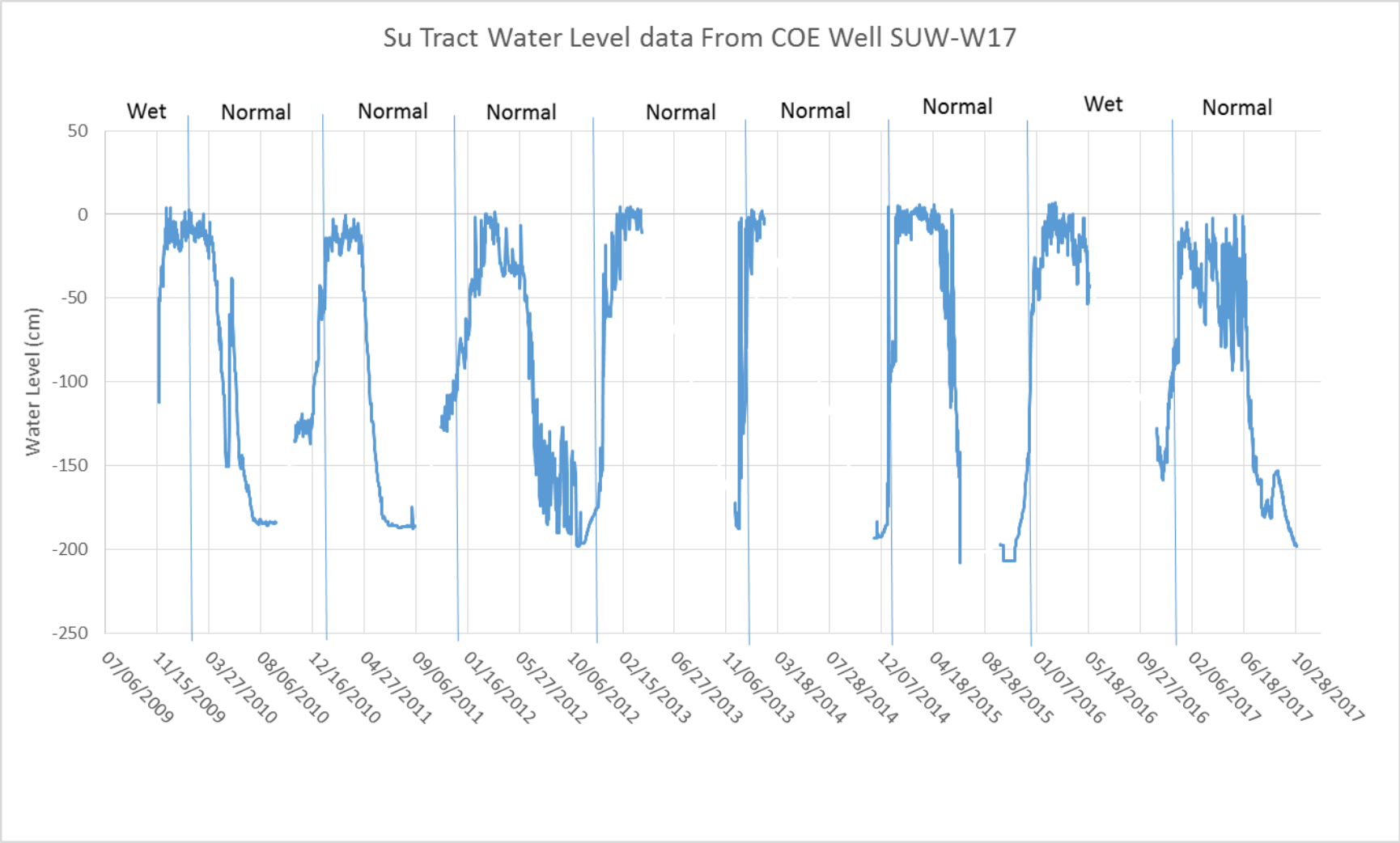


Figure 5.6. Water level monitoring for a USCOE well located next to SUW-10, in the Su tract wetland (with fall removal); the data spans 2009-2017.

5.3.2. Sandy Bottom Nature Park (SBNP)

This wetland has continuous bimonthly Data points from May 1993 through November 1995 taken by Virginia Tech in conjunction with a study funded by VDOT in support of onsite wetland creation. The site is located in Hampton Virginia between the Bethel Scarp and the Harpersville Scarp on Todds Flat. Todds Flat is underlain by the Sedgefield unit, the oldest member of the Tabb formation. Sediments in this member are derived from the Piedmont, Blue Ridge, and Valley and Ridge (Johnson, 1974). Geology onsite was observed from three 30.5 m (100 ft.) deep bore holes, within 30.5 m (100 ft.) there are four different members present, approximately the first 9 m (30 ft.) is within the Tabb Formation, and then the logs indicate there is a 0-3.5 m (10 ft.) Section of the Shirley Formation. The Shirley contains a mix of organic mineral/peat facies with some silt and gravelly sand at its base. Deeper, there is a 23 m – 24.5 m (60 – 70 ft.) thick section from the Yorktown Formation; the Mogart's Beach Member – a compact silty sand with many shells. Finally, at a depth of about 30.5 m (100 ft.), the Rushmere member became dominant - a fine to medium sand.

Data was collected by Virginia Tech and ODU in an effort to categorize hydrology and soils onsite for the construction of created wetlands by VDOT. The site is located on a relatively flat landscape near two shallow created wetlands and one lake (Figures 5.7 and 5.8). Multiple 5 cm (2 in) diameter wells were installed initially to about -120 cm and then deepened to -240 cm, All wells were sampled manually twice per month. Some of the wells installed onsite had more interaction with the stream to the northwest and to some extent with the nearby borrow lakes. However, the wells we selected for this project were clearly on mineral flat portions of the local landscape and did not have a strong interactions with local surface water features. These wells are all located on

a Tomotley-Urban soil complex, a hydric soil series (Table 5.2; Figure 5.8). The well locations for this site are all mapped as PFO's by the NWI (Figure 5.9).

The hydroperiods clearly show a typical pattern of a winter high in February followed by a rapid drawdown during spring leaf-out and the associated increase of ET (Figure 5.10). This site shows a rapid water table drawdown during late spring early fall as is typical of mineral flats, with onsite the water levels recorded as deep at 150 cm or more. During 1993-1995, there were slight differences between the length of near-surface soil saturation, but not enough to change juristictional status. Shallow surface ponding occurred during the normal precipitation year, but did not appear in the subsequent dry year. Despres (2004) installed two pairs of nested peizometers near wells 201 and 213. At well location 201, the piezometers varied similarly throughout the year, indicating this was an area of throughflow for the wetland (Despres, 2004). However, near well 213 there was evidence of local groundwater recharge with the deep piezometer showing lower water levels that were well synchronized with the upper well readings. Both well locations demonstrated only endoaquic conditions, while similar nests installed in the adjacent wetland creation site indicated epiaquic conditions (Despres, 2004).

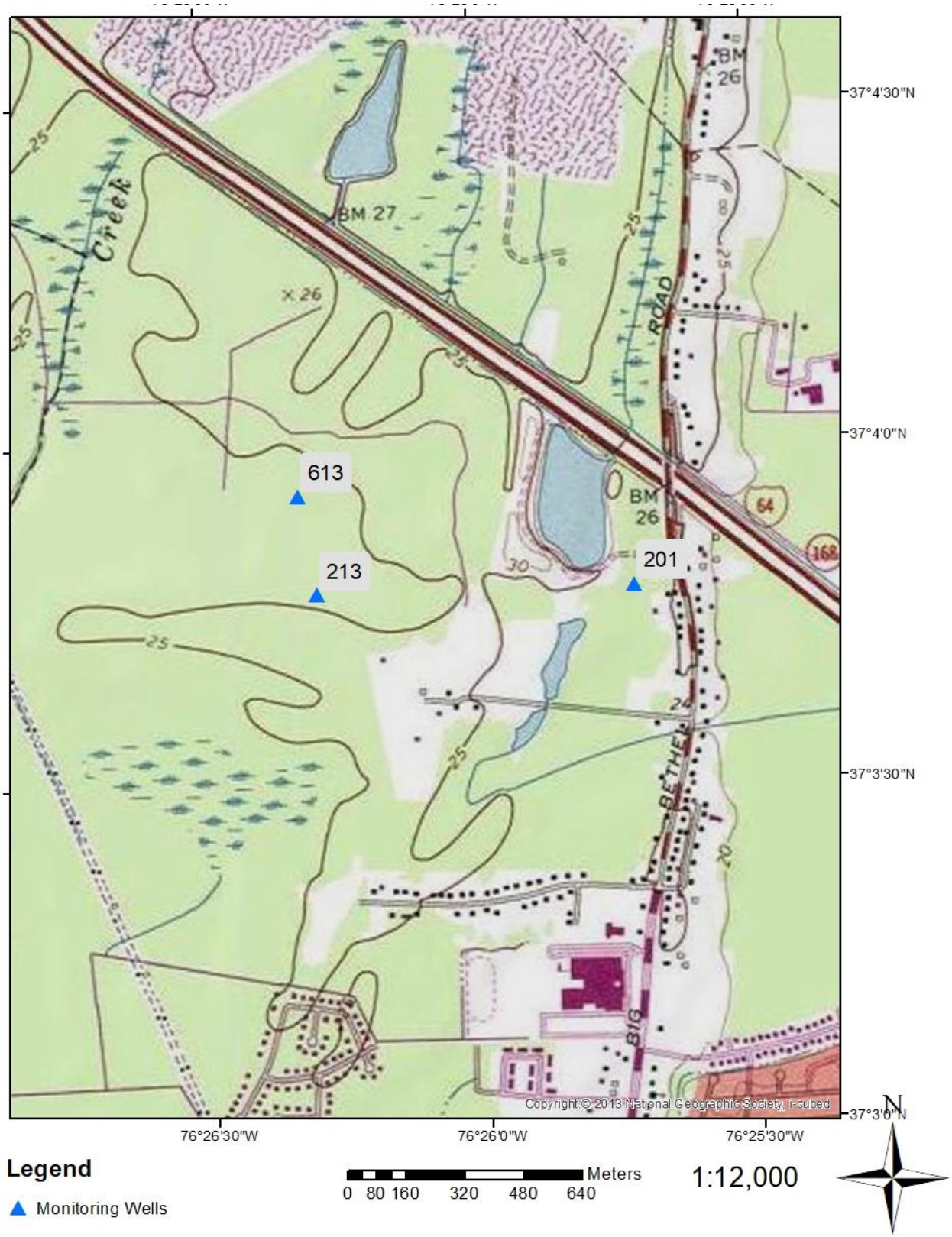


Figure 5.7. Topographic map for SBNP with monitoring well locations. Note that this map doesn't show all of the open water and wetland systems currently onsite.Three of original 19 wells shown.

Table 5.2. SBNP location, soil map unit symbols and names.

| Tidewater Cities Area, Virginia (VA715) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| 1 | Altavista-Urban land complex, 0 to 3 percent slopes |
| 7 | Bojac-Urban land complex, 0 to 3 percent slopes |
| 10 | Dragston-Urban land complex, 0 to 2 percent slopes |
| 12 | Johnston silt loam, 0 to 2 percent slopes, frequently flooded |
| 20 | Seabrook-Urban land complex, 0 to 2 percent slopes |
| 24 | Tomotley-Urban land complex, 0 to 2 percent slopes |
| 26 | Udorthents-Dumps complex |
| W | Water |


Figure 5.8. Soil and Imagery map for SBNP with monitoring well locations. Note the presence of the shallow created weland lakes to north of well 613, they were installed after the reported monitoring period. Dominant soil present was Tomotley.


Figure 5.9. NWI and Imagery map for SBNP with monitoring well locations. Note the presence of the shallow created weland lakes.

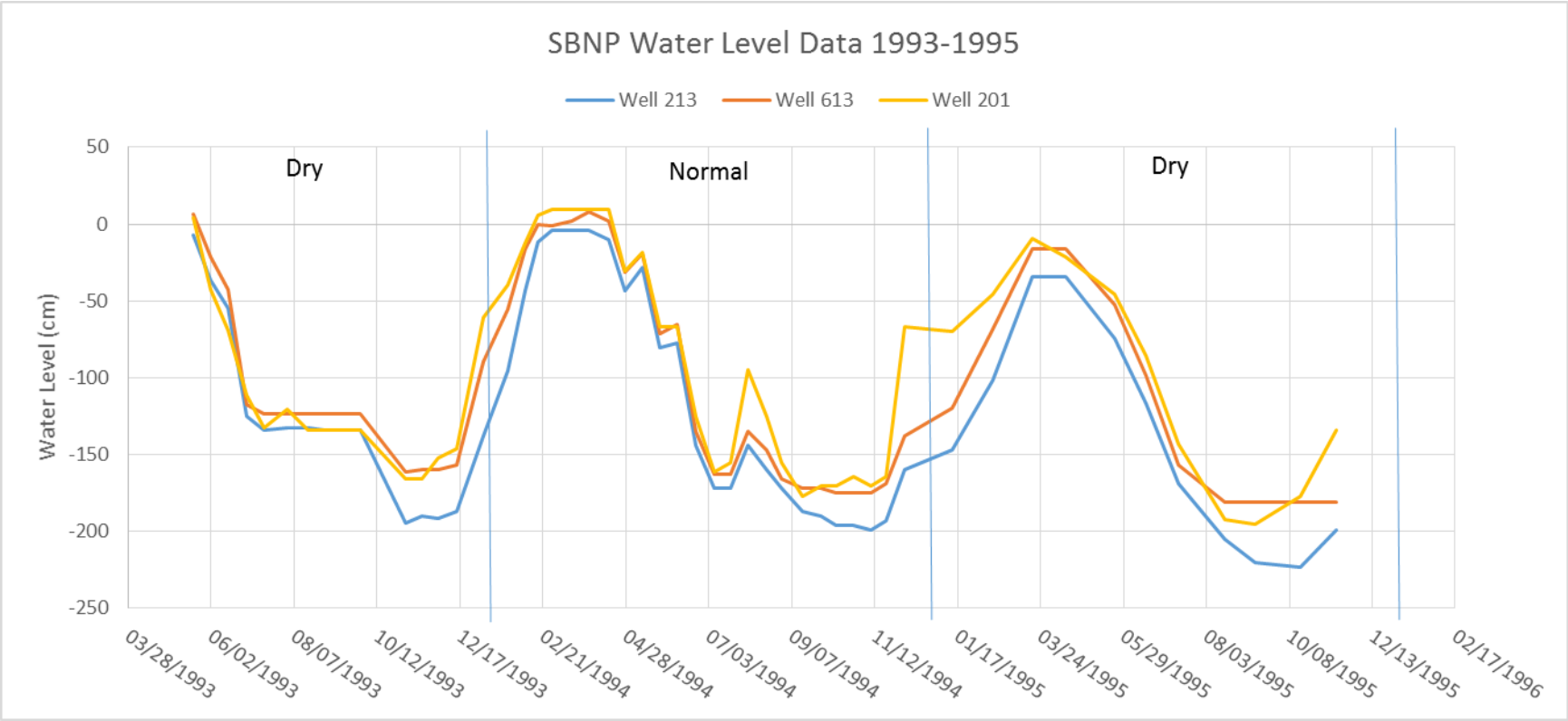


Figure 5.10. Water level monitoring data for wells 213, 613, and 201 located at SBNP from 1993 through 1995.

5.3.3. Roquist

This site is located east of Route 11 in Bertie County south of on Lewiston Woodsville NC, on the Yorktown Formation. Known for fossiliferous clay mixed with fine grained sand with lenses of shell material, and partially on the Dublin Formation, known for medium to coarse grained sand mixed with sandy marl and limestone. This site was previously logged, during which time elevated roads were constructed and ditches were installed. Logging was completed in 2003, at which point the land was left to regenerate naturally until site restoration began in 2007. Restoration following logging included the plugging of logging ditches between 2007 and 2008 and the planting of greater than 15 different tree species onsite. Figure 5.11 shows this site is a large pocosin, much larger than the others considered for this study, and is broached by drainage on the southeastern edge. The flat serves as part of the headwaters for the Roquist Creek which links up with the Cashie River and eventually empties into Swan Bay and the Albemarle Sound NC. The soil on this site is mapped (Figure 5.12, Table 5.3) as the Leaf series, fine, mixed, active, thermic Typic Albaquults. Leaf soils have a depleted E horizon starting around 7.6 cm (3 in.). The NWI has this site mapped as a freshwater PFO (Figure 5.13) and is called the Roquist Pocosin. The mostly continuous well data for this site spans from 2009 - 2012. The wells are located between 1500 m - 2000 m from the wetlands outlet. Well sensor depths varied between -50 to -100 cm (Figure 5.14).

This data set has mostly continuous monitoring data which covers four years starting two years after ditch plugging (Figure 5.14). The data shows a consistent winter high water level and similar summer drawdown depth among the monitoring years. Drawdown usually brought the water table to between -40 cm to -100 cm, and occurred between April and June each year. As is typical of mineral flats, this system did not stay wet year-round and dried down during the late spring. The

2011 monitoring year was especially wet during the fall and the water table rebounded sooner than in previous years. While 2012 was considered a normal year for rainfall totals, heavy precipitation in the late summer and early fall caused a number of large spikes in water levels. This wetland is consistent with previously described mineral flats in its hydroperiod, with wells drying down to at least -100 cm in 2009-2011, and again at GW-4 and GW-6 in 2012 (wet year). This site undergoes significant ponding in the winter/spring wet season to a much greater depth than the other mineral flats described in this study.

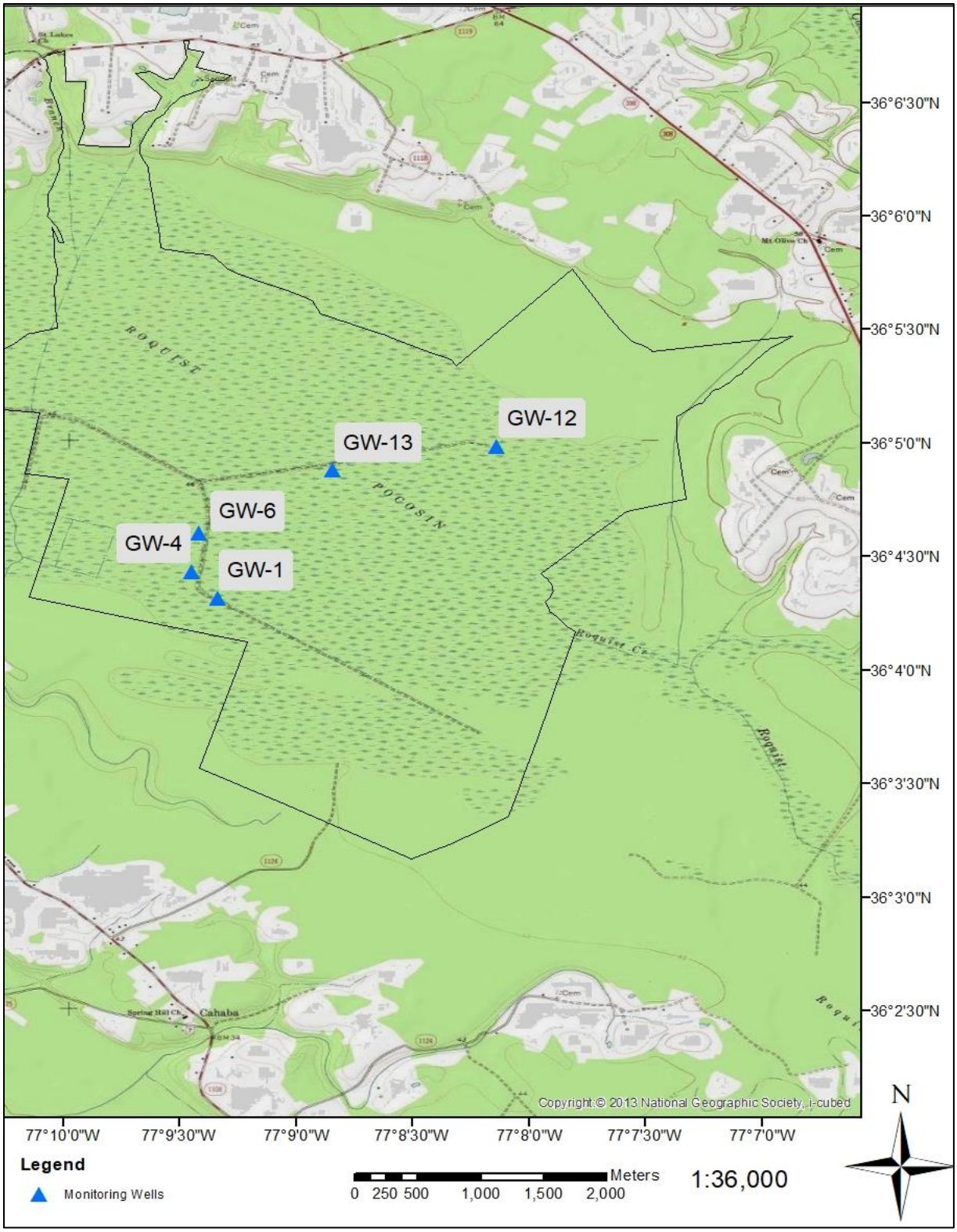


Figure 5.11. Topographic map for the Roquist site with well locations for reference groundwater monitoring wells GW-1, GW-4, GW-6, GW-12, and GW-13. Located east of Route 11 in Bertie County south of Lewiston Woodsville NC.

Table 5.3. Roquist location, soil map unit symbols and names.

| Bertie County, North Carolina (NC015) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| BB | Bibb and Johnston loams, frequently flooded |
| BoB | Bonneau loamy sand, 0 to 6 percent slopes |
| CrA | Craven fine sandy loam, 0 to 1 percent slopes |
| CrB | Craven fine sandy loam, 1 to 4 percent slopes |
| CrC | Craven fine sandy loam, 4 to 8 percent slopes |
| GoA | Goldsboro sandy loam, 0 to 3 percent slopes |
| Lf | Leaf loam |
| Ln | Lenoir fine sandy loam |
| Ly | Lynchburg sandy loam |
| NoA | Norfolk sandy loam, 0 to 2 percent slopes |
| NoB | Norfolk sandy loam, 2 to 6 percent slopes |
| Pa | Pantego loam |
| Ra | Rains sandy loam |
| Ro | Roanoke fine sandy loam, frequently flooded |
| Ud | Udorthents, loamy |
| W | Water |

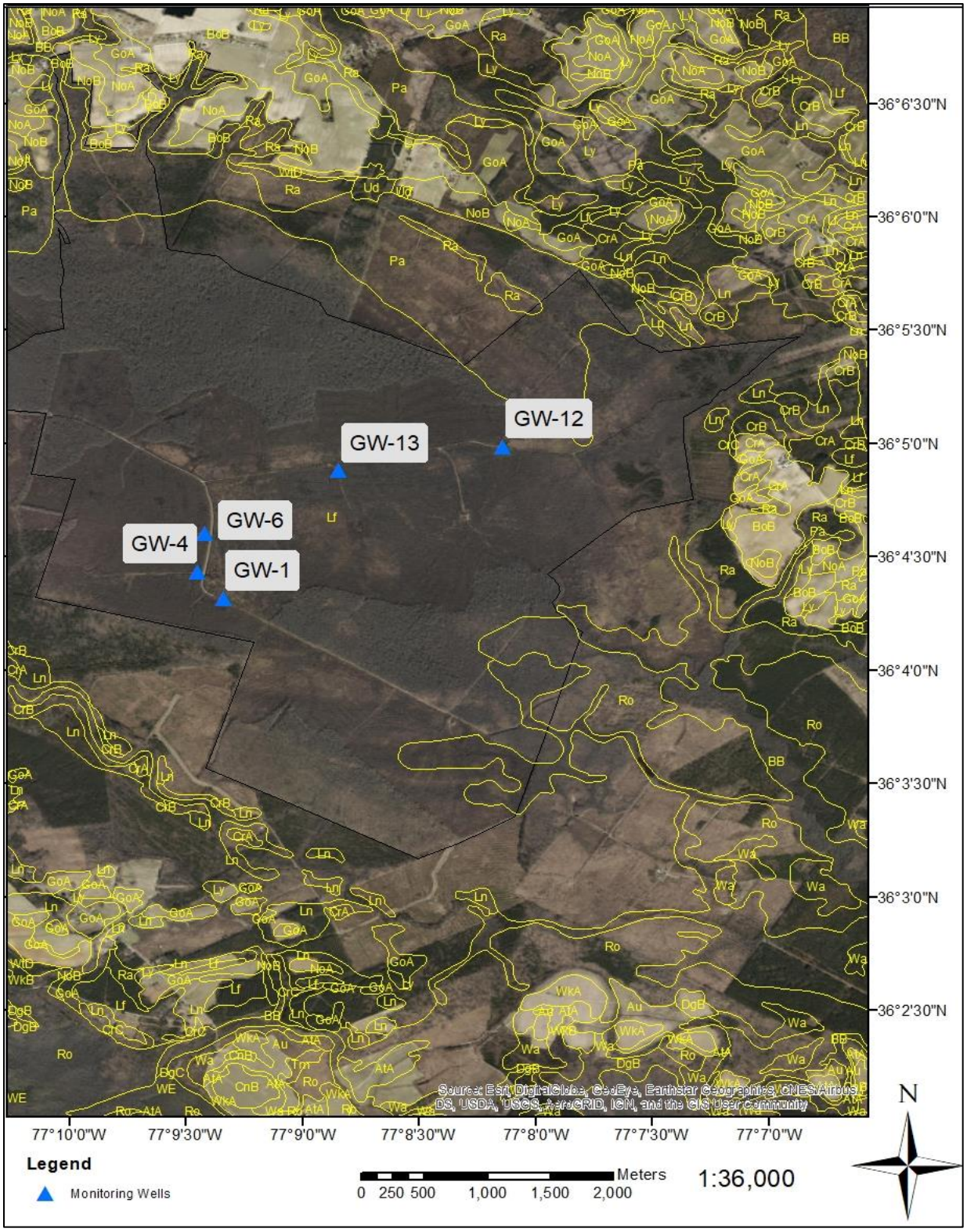


Figure 5.12. Soil map for the Roquist site with well locations for reference groundwater monitoring wells GW-1, GW-4, GW-6, GW-12, and GW-13 (Map unit "Lf"). Located east of Route 11 in Bertie County south of Lewiston Woodsville NC.

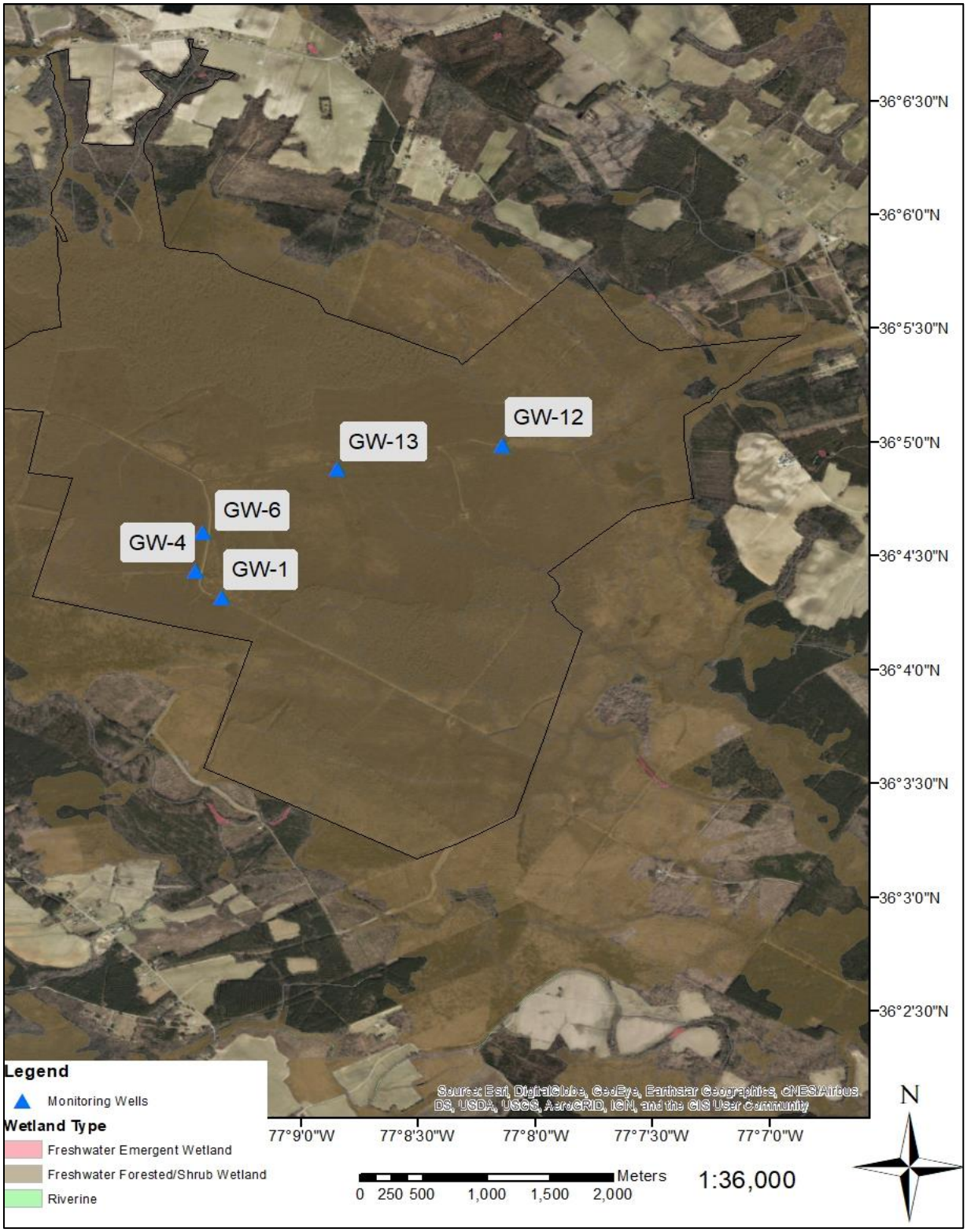


Figure 5.13. NWI map for the Roquist site with well locations for reference groundwater monitoring wells GW-1, GW-4, GW-6, GW-12, and GW-13. Located east of Route 11 in Bertie County south of Lewiston Woodsville NC.

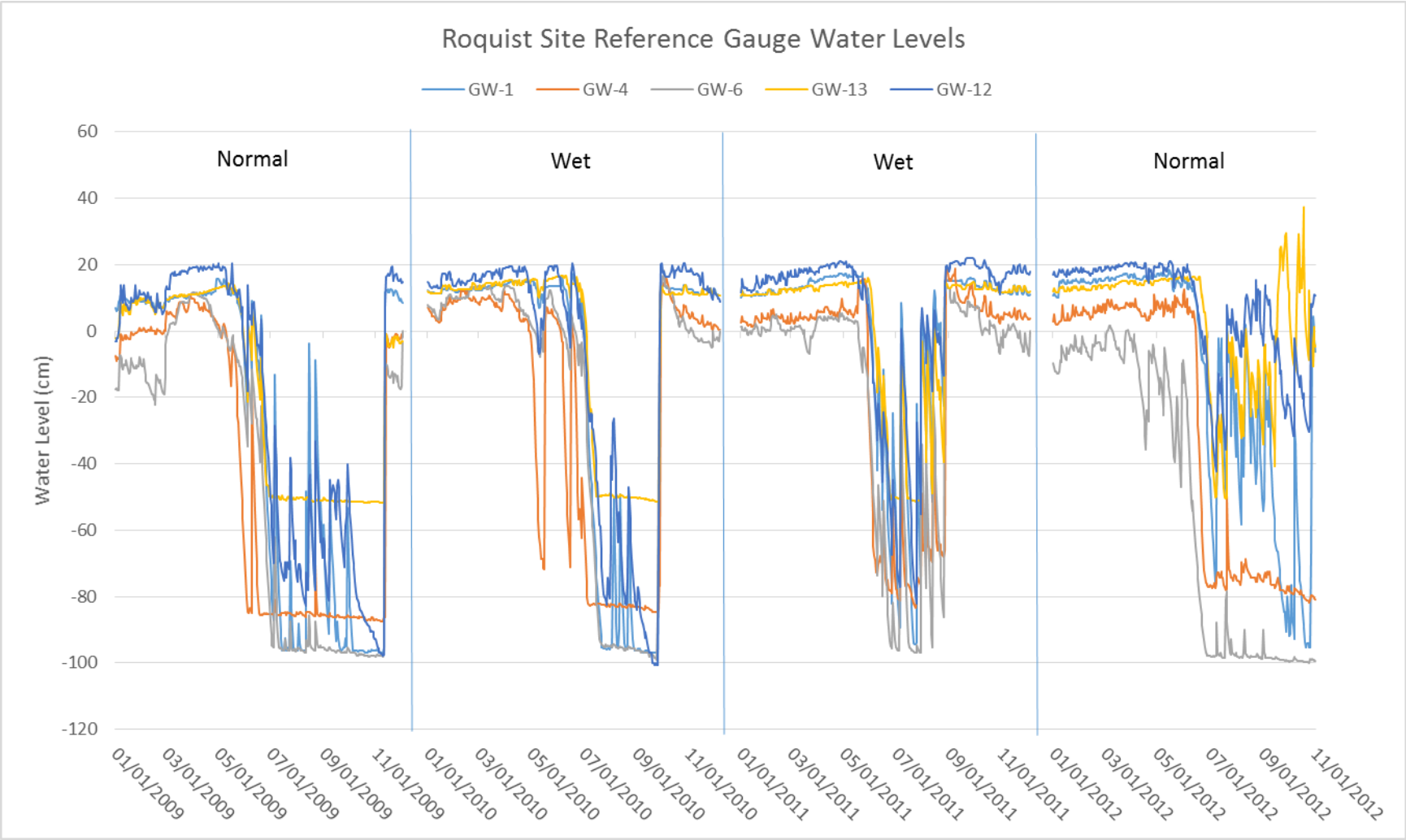


Figure 5.14. Water level monitoring data for wells GW-1, GW-4, GW-6, GW-12, and GW-13 located at the Roquist site for 2009-2012.

5.3.4. Level Ponds/deep creek

This site is located just north of Bayside in Accomack County, VA. The site occurs on the Kent Island formation, a thick bed of loose light-gray to reddish-brown coarse sand and pebble gravel with lenses of silty clay, clayey silt and interspersed with clay laminae (McDonald and Harbaugh, 1988). The wetland sits on a broad flat landscape with drainage into Doe creek which flows into Pocomoke Sound. This site is not tidally influenced and is about 100 m from an intermittent section of Doe Creek to the north of the well (Figure 5.15). The soils mapped on this site are Nimmo Series (Figure 5.16, Table 5.4). While mapped as a PFO by the NWI, the site is also located on the fringe of a palustrine emergent (PEM) wetland (Figure 5.17).

This data set has approximately five years of data spanning January 2011 through March 2016 (Figure 5.18). The well was installed at about -40 cm by The Nature Conservancy following standard USCOE technical guidelines. The winter high water levels varied year-to-year with 2013 and 2014 being higher than the other years monitored. Data from 2014 should be carefully considered given the apparent elevated well bottom depth. The well readings from 2014 likely represent either the movement of the water level sensor or an error during data correction producing a shift in the well bottom depth. This site had a late spring/early summer drawdown each year between March and June with brief high level spikes due to periodic rainfall events.

This hydroperiod is similar to the three other mineral flats in that there is ponding during the winter. However, the extent and depth varied greatly between years unlike the other sites which showed much more consistent depth and extent of ponding between years. While we can’t determine the full range of the hydroperiod, it is likely not as deep as the other flats we have presented due to the

increase rebound rate after spring drawdown and the limited elevation difference above the nearby open water system (< 1.5 m). Water level drawdown typically occurred between March and June followed by a late fall rebound in water level. It is unlikely that this site receives any surface water and the hydroperiod seems to be driven by a combination of ET, precipitation and limited groundwater movement.

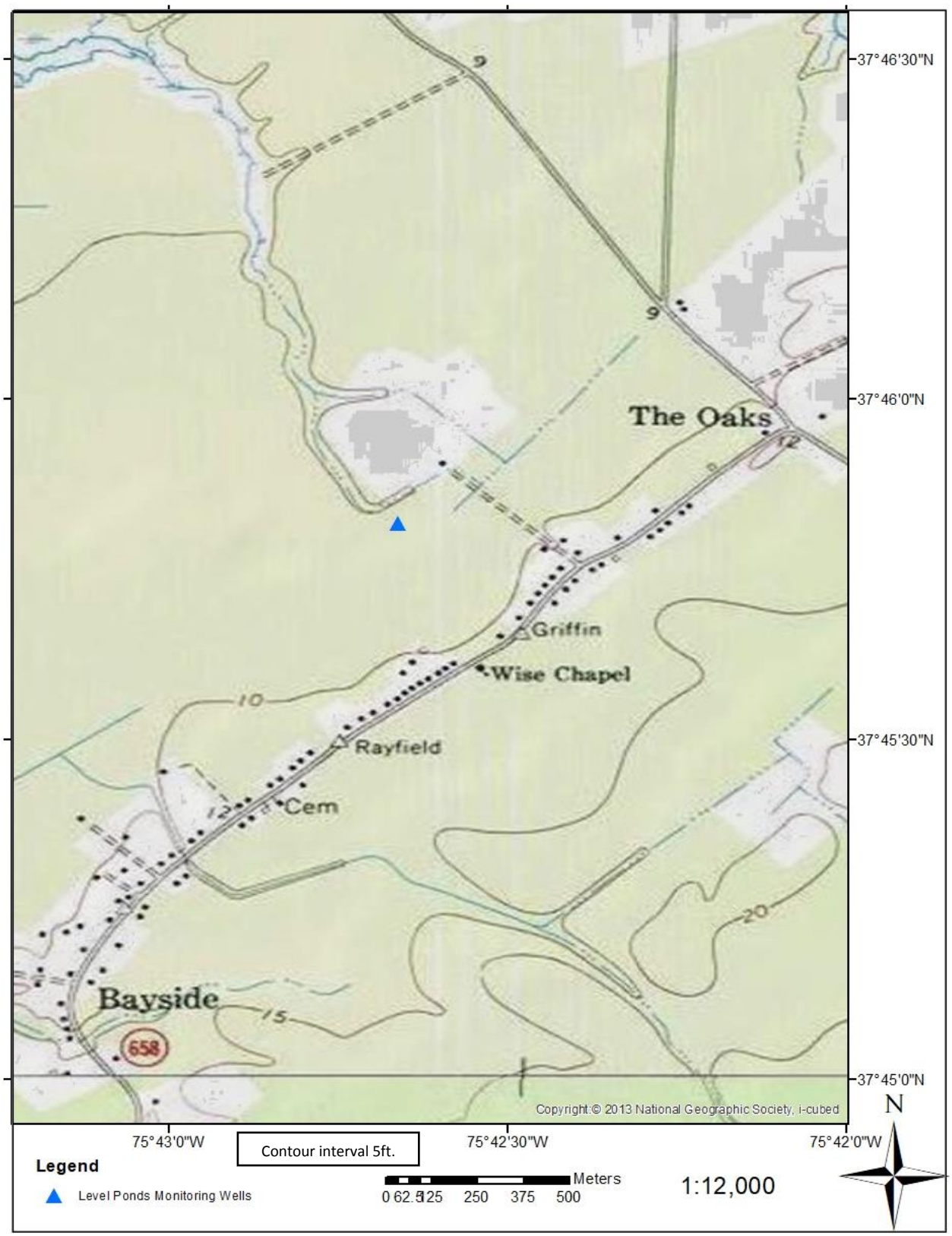


Figure 5.15. Topographic map for Level Ponds with monitoring well location. The site is located just north of Bayside, Accomack County, VA.

Table 5.4. Level Ponds county soil map unit symbols and names.

| Accomack County, Virginia (VA001) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| DrA | Dragston fine sandy loam, 0 to 2 percent slopes |
| McA | Melfa-Hobucken complex, 0 to 1 percent slopes, frequently flooded |
| NmA | Nimmo sandy loam, 0 to 2 percent slopes |

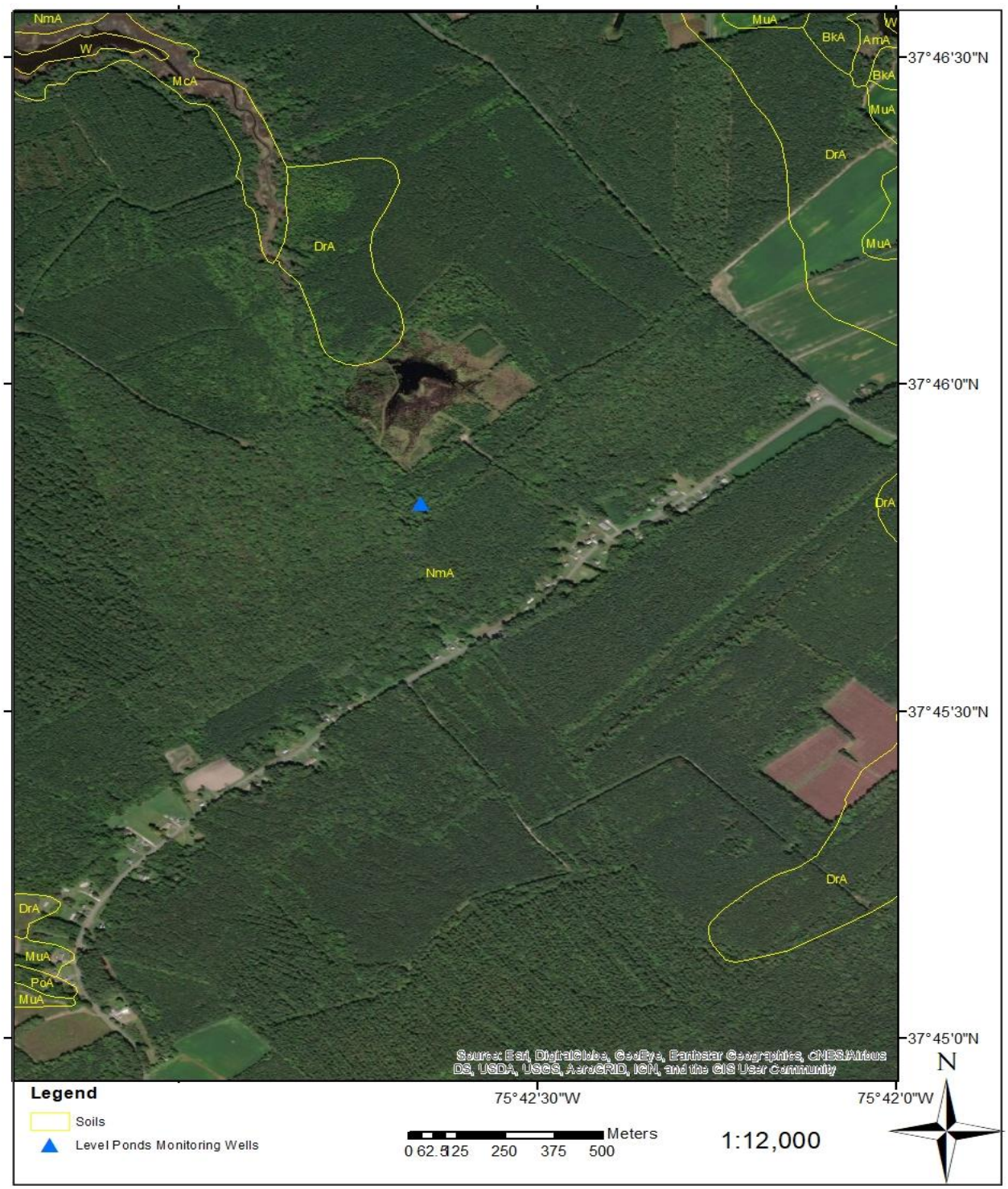


Figure 5.16. Soil and imagery map for Level Ponds with monitoring well location. The site is located just north of Bayside, Accomack County, VA.


Figure 5.17. NWI and imagery map for Level Ponds with monitoring well Location. The site is located just north of Bayside, Accomack County, VA.

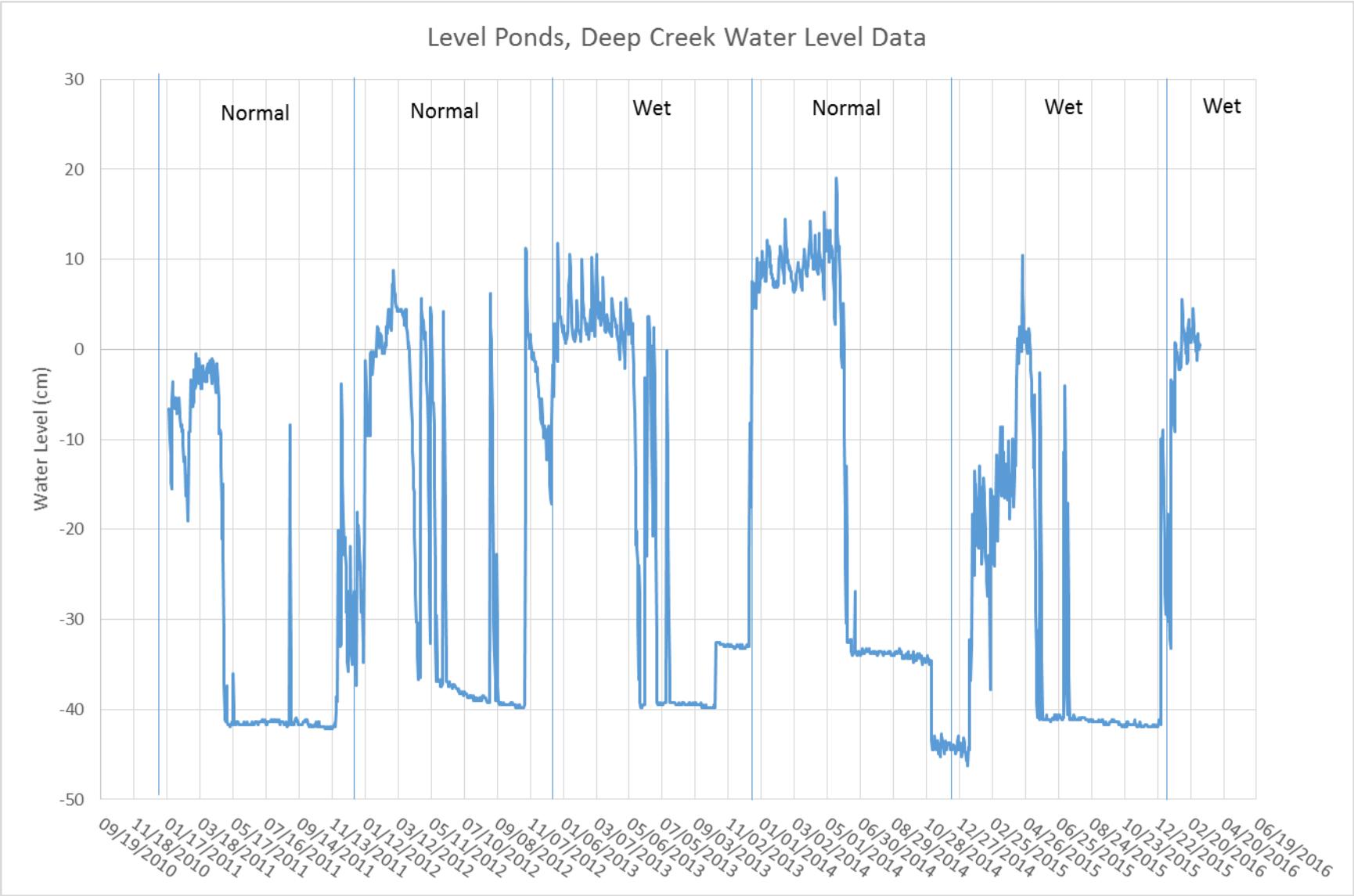


Figure 5.18. Water level monitoring data from level ponds from 2011 through 2015.

## 5.4. Riverine

These sites were geographically associated with a stream stream/river, while being far enough away that they were not exposed to frequent flooding or ponding. Thus, these sites were only subject to flooding on an occasional basis and none of these sites would be considered "bottomland swamps". Riverine systems are heavily influenced by their surrounding landscape and can be points of local groundwater recharge as well as regional discharge. Thus, through a combination of varying ET and precipitation, coupled with their location in the local watershed, a riverine system may alternately function as a groundwater recharge or discharge point at differing times. Riverine wetland system hydroperiods may also be dominated by water level fluctuations and flooding in the nearby river/stream system. Our intent here was to separate riverine wetlands from slope/seepage wetlands that are driven by direct discharge of upland groundwater and are often located along footslopes lateral to streams or in headwater concave positions. Thus, potential slope wetlands, two of which were in the final nine sites that I considered, were removed from the final selection set for riverine wetlands. As reviewed in Chapter 2, riverine wetlands are likely to support a blend of forested and scrub/shrub vegetation. During selection, it was also important to us that sites did not exhibit palustrine emergent wetland qualities.

### 5.4.1. Bull Run:

This site is a forested riverine system located in Prince William County VA south of Route 66 near Manassas. (Figure 5.19) and is associated with Cub Run. Bedrock in this area is mapped as the Newark Supergroup; Triassic sandstone, siltstone, and shale. This site had three wells located on the floodplain of Club Run which contributes to Bull Run (Figure 5.19). The soils onsite are a complex of the somewhat poorly drained Rowland series - Fine-loamy, mixed, superactive, mesic

Fluvaquentic Dystrudepts, and the poorly drained Bowmansville series - Fine-loamy, mixed, active, nonacid, mesic Fluventic Endoaquepts (Figure 5.20, Table 5.5). The three well location landforms had been capped with varied amounts of relatively recent local alluvium, and thus only one well location met NRCS Hydric Soil Indicator criteria. However, the other two sites contained appropriate hydric soil materials at depth below the cap of recent alluvium and all met the NRCS technical standard based on hydrology/saturation. However, the "anaerobic conditions" portion of that requirement was not rigorously evaluated. This area is mapped as a combination of PFO and PEM wetland types (Figure 5.21).

Figure 5.22 shows the well data from three USCOE standard -50 cm open screen wells, and Figure 5.23 shows the water levels in a nest of a well and two deeper piezometers at one location. The piezometers gave us insight into local groundwater interactions. It should be noted that all wells met the hydrology technical standard for saturation length during the growing season and we selected well BR-3 because of presence of NRCS Hydric Soil Indicators. We also selected well #3 as most representative of the site based on hydroperiod and detailed soil descriptions (Daniels et al., 2017).

The hydroperiod is primarily driven by ET, groundwater inflow, and precipitation during the late winter early spring. Subsequently, during the late spring to early winter, the hydrologic drivers stay the same, with the exception of groundwater being lost from the site instead of receiving it. It is clear from the hydroperiod that water levels in this system are quite variable over short periods of time, being quick to rise and fall with precipitation events. This soil remains saturated near the surface for large parts of the year and does experience occasional flooding, but not sustained

inundation. Figure 5.23 shows the head at -150 cm lower than shallow -50 cm open well during drier times of the year, indicative of “falling head with depth” and net local groundwater recharge (loss). Subsequently, as the shallow water table rose in the winter through early summer of 2013, the head pressures at -100 and -150 cm were higher than the -50 cm open well, indicating groundwater discharge, and then the relationship reversed again over the following summer. The full depth of the hydroperiod was at least 150 cm during 2012 and around 125 cm during 2013; this can be seen in the -150 cm piezometer data from Figure 5.23.

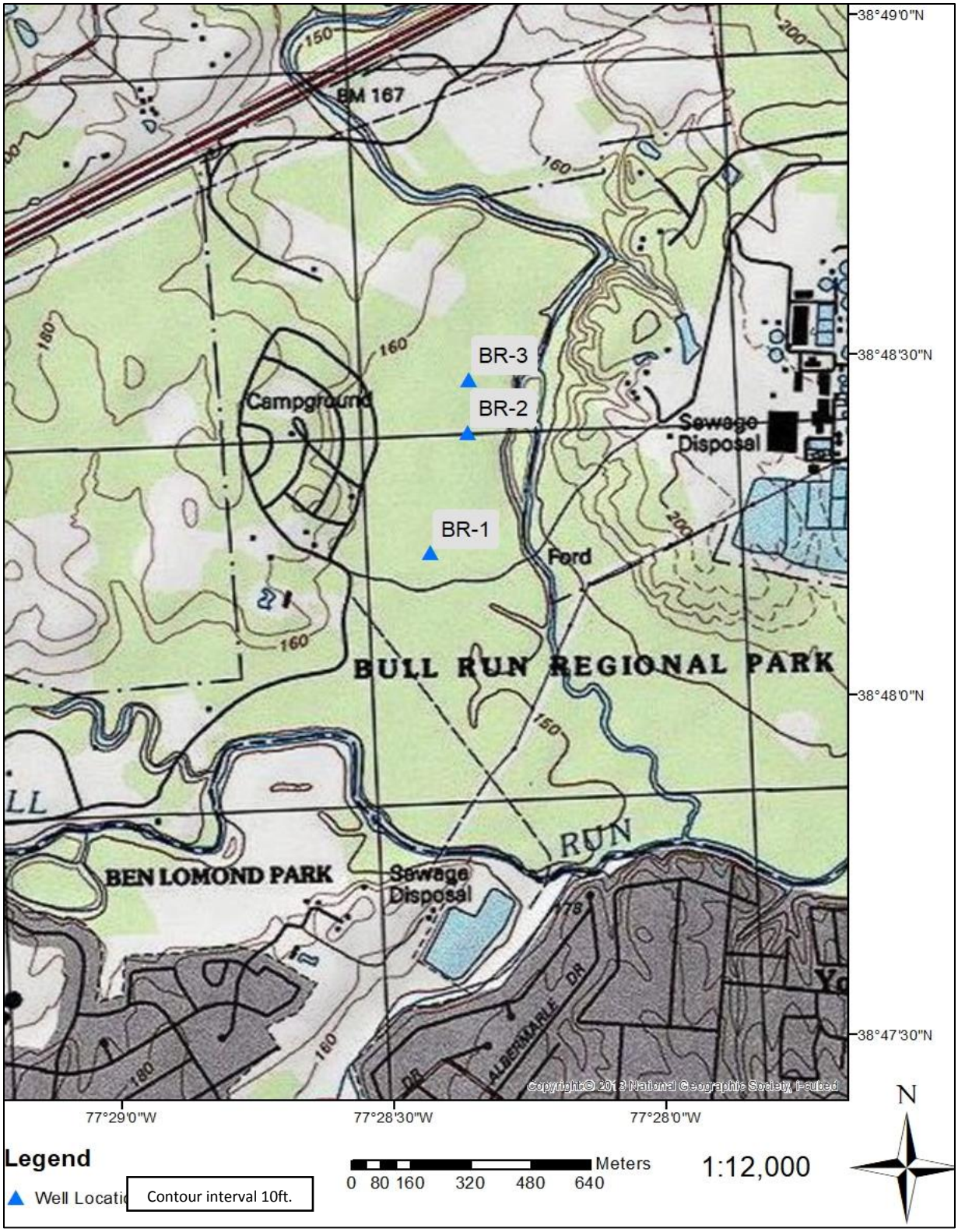


Figure 5.19. Topographic map for Bull Run with monitoring well locations. Prince William County, Virginia south of Route 66.

Table 5.5. Bull Run location soil map unit symbols and names.

| Prince William County, Virginia (VA153) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| 1A | Albano silt loam, 0 to 2 percent slopes |
| 2B | Ashburn silt loam, 0 to 7 percent slopes |
| 9B | Birdsboro loam, 2 to 7 percent slopes |
| 10A | Bowmansville silt loam, 0 to 2 percent slopes, occasionally flooded |
| 12 | Chantilly loam, 0 to 45 percent slopes |
| 16B | Chantilly-Birdsboro complex, 2 to 7 percent slopes |
| 32B | Delanco loam, 2 to 7 percent slopes |
| 34A | Dulles silt loam, 0 to 2 percent slopes |
| 75B | Manassas silt loam, 2 to 7 percent slopes |
| 80D | Nestoria channery silt loam, 15 to 25 percent slopes |
| 80E | Nestoria channery silt loam, 25 to 45 percent slopes |
| 85B | Penn silt loam, 2 to 7 percent slopes |
| 85C | Penn silt loam, 7 to 15 percent slopes |
| 89A | Rowland silt loam, 0 to 2 percent slopes, frequently flooded |
| 95 | Urban land |
| 97 | Urban land-Chantilly complex |
| W | Water |


Figure 5.20. Soil map of Bull Run (BR) with monitoring well locations. Prince William County, Virginia south of Route 66.


Figure 5.21. NWI map for Bull Run with monitoring well locations. Prince William County, Virginia south of Route 66.

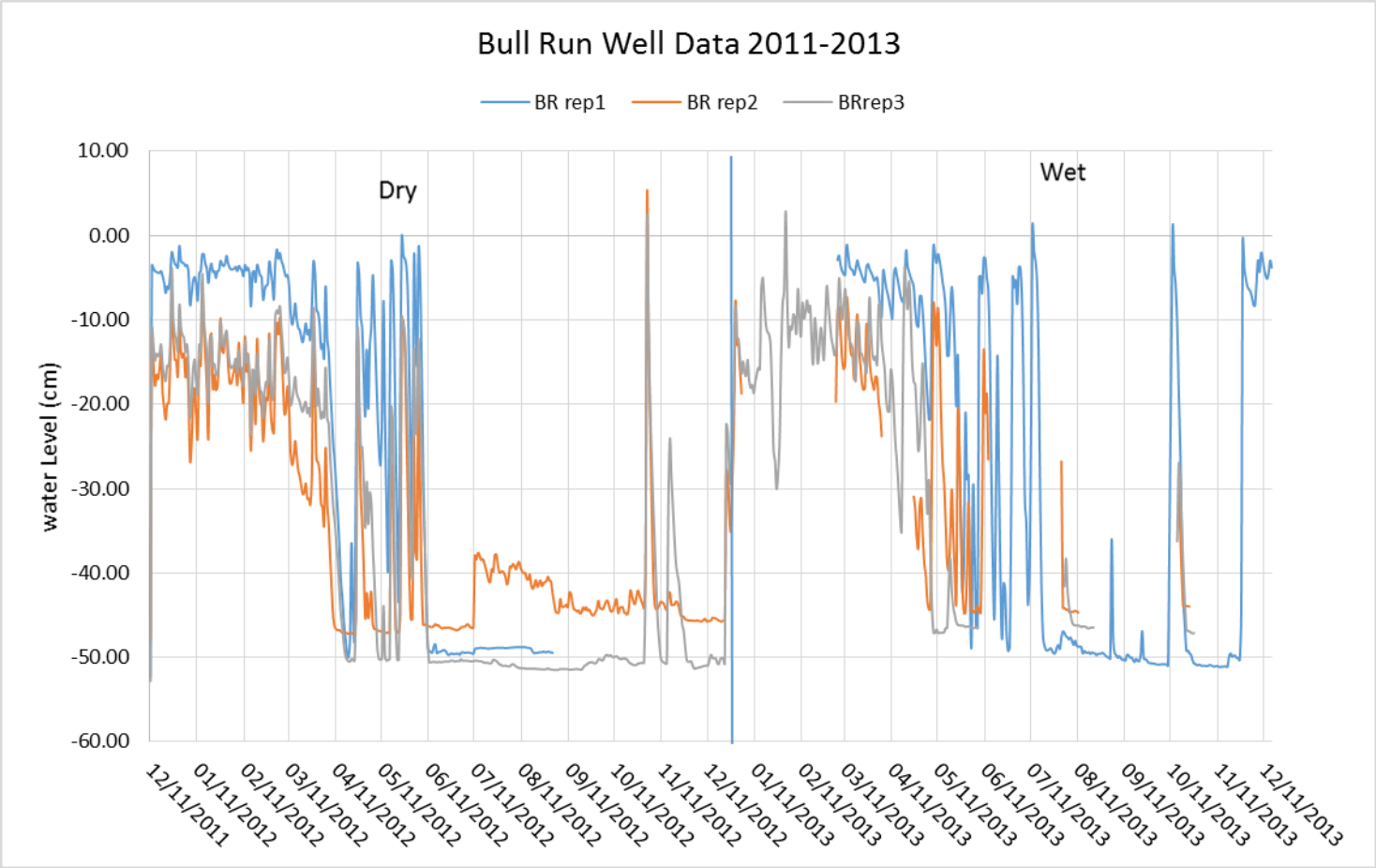


Figure 5.22. Three locations of -50 cm Well data for Bull Run for December 2011 through December 2013. Well location 1 was lost for the winter of 2012/2013 due to a flood event.

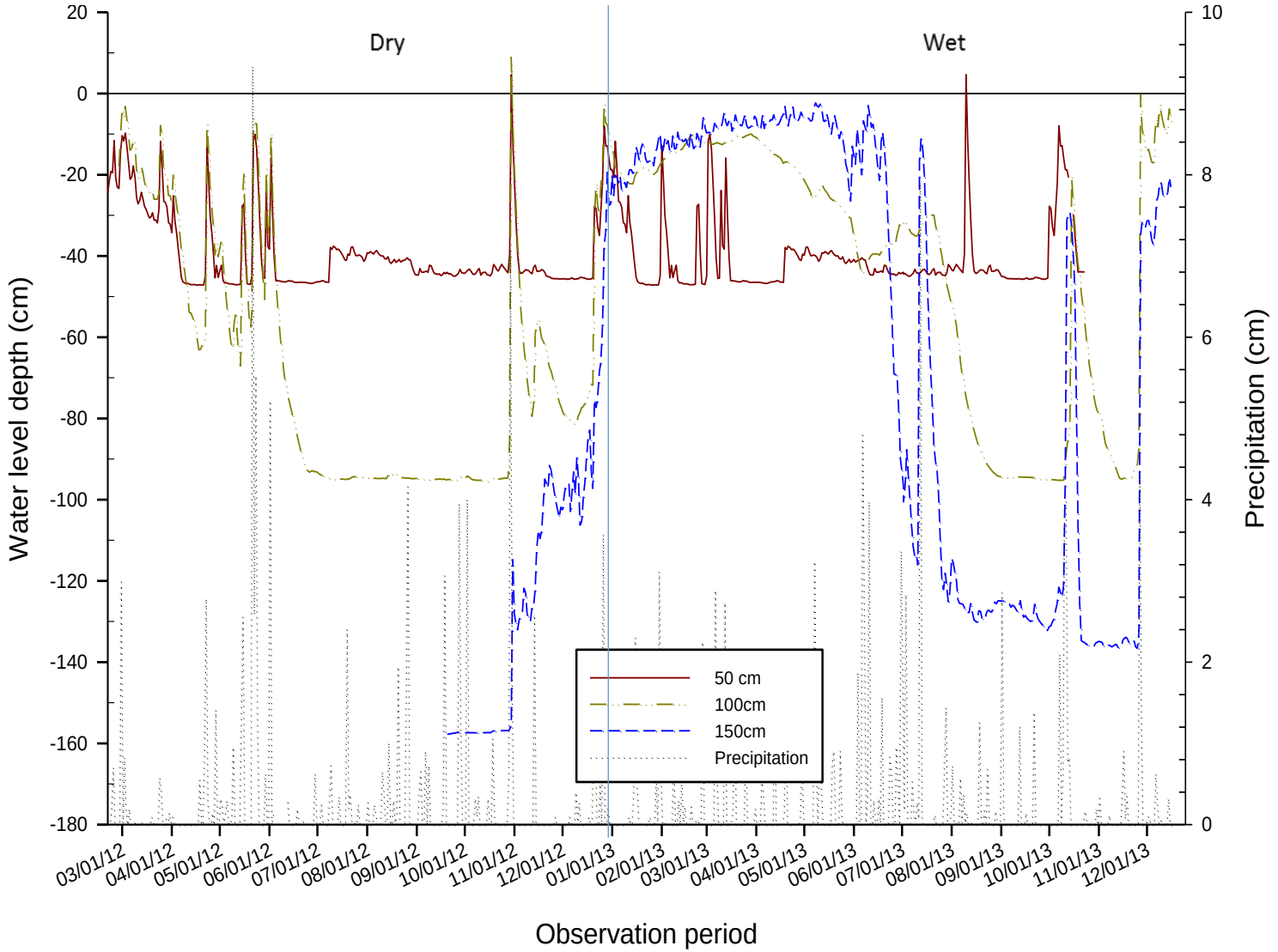


Figure 5.23. Well and piezometer monitoring data for Bull Run at -50, -100, and -150 cm graphed with precipitation for December 2011 through December 2013. The - 150 cm piezometer was not installed until September 2012.

5.4.2. Cedar Run 4:

This site is a forested riverine system located in Prince William County, Virginia, near Manassas and southwest of Merrimac Farm Wildlife Management Area and east of Fleetwood Drive. The site is located on the same northern Piedmont Triassic bedrock as the Bull Run site. This site is about 20 km (12 miles) south of Interstate 66 in the floodplain associated with Cedar Run (Figure 5.24). The soils found onsite are dominantly the poorly drained Bowmansville series (Figure 5.25, Table 5.6). This site is mapped as a PFO with fringes of PEM (Figure 5.26).

Figure 5.27 shows the well data from three USCOE standard -50 cm open screen wells, and Figure 5.28 shows the water levels in a nest of one well and two deeper piezometers at one location. These sites had also been capped with varied amounts of recent alluvium, and only well CR4-1 met Hydric Soil Field Indicator F3. However, the other two well location soils did contain redox features within the upper 20 cm. Well location 1 was selected for this particular riverine target hydroperiod. Data for the other two wells onsite are also depicted to provide further information on hydroperiod spatial variability. Water levels rose in early winter and the sites remained saturated above -30 cm until mid-June in 2012 and 2013. Short-term variations in water levels were common, however, and occurred in all seasons due to rainfall and flooding events. Figure 5.28 Indicates that with few exceptions, the site is not receiving significant regional groundwater discharge. The hydroperiod for this site was consistent among the three wells during 2012. Unfortunately, well 2 was lost during a flood in January 2013. During 2013, the two remaining wells were saturated near the surface long enough to meet jurisdictional hydrology criteria, however, they were not as consistent as in 2012. There was seasonal drawdown to at least -100 cm, as shown by the -150 cm piezometer (Figure 5.28).

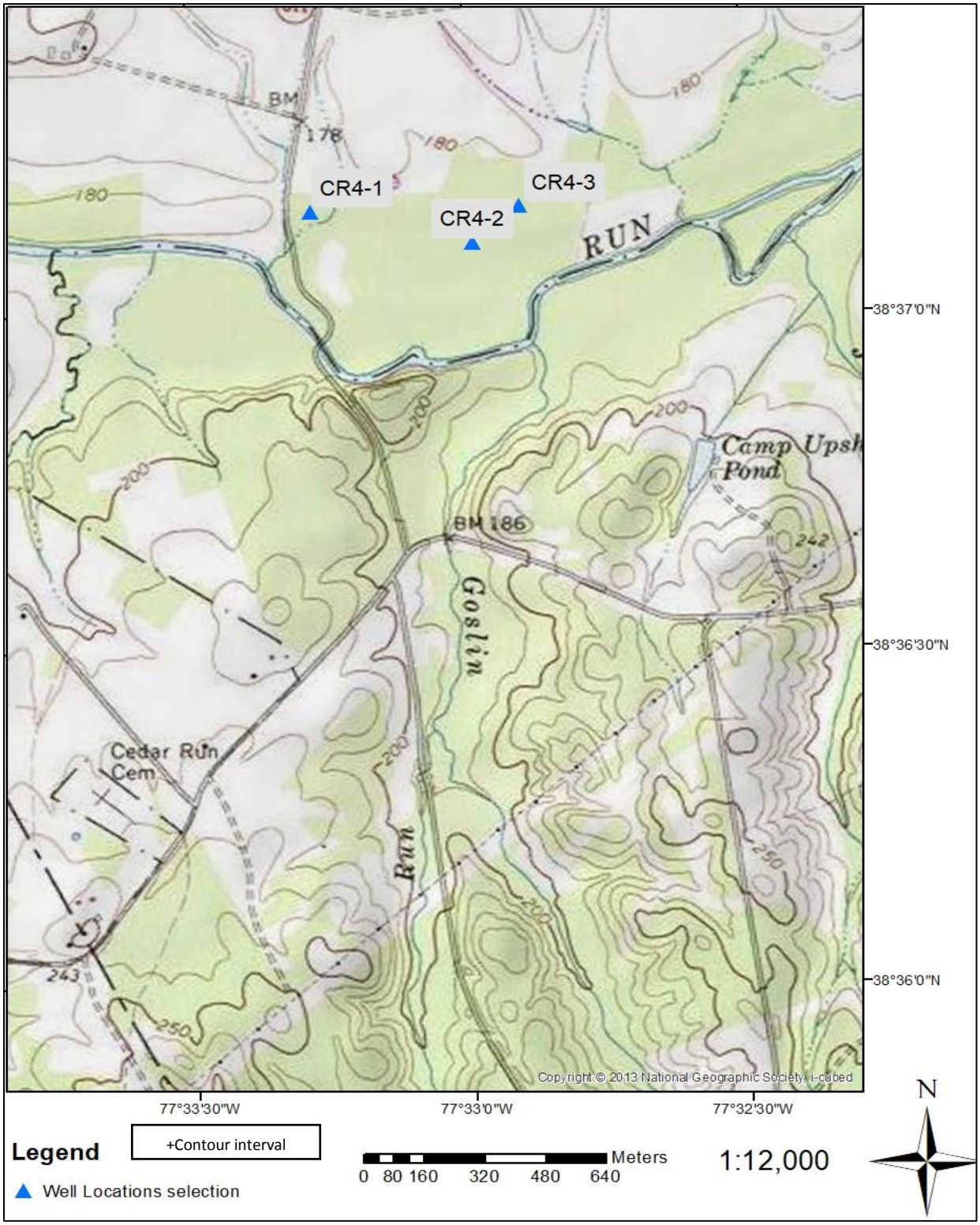


Figure 5.24. Topographic map for Cedar run 4 with monitoring wells. Located in Prince William county VA near Manassas, southwest of Merrimac Farm Wildlife Management Area and east of Fleetwood Drive.

Table 5.6. Cedar Run location soil map unit symbols and names.

| Prince William County, Virginia (VA153) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| 1A | Aden silt loam, 0 to 2 percent slopes |
| 3A | Albano silt loam, 0 to 4 percent slopes |
| 4B | Arcola silt loam, 2 to 7 percent slopes |
| 5C | Arcola-Nestoria complex, 7 to 15 percent slopes |
| 5D | Arcola-Nestoria complex, 15 to 25 percent slopes |
| 7A | Bermudian silt loam, 0 to 2 percent slopes |
| 11B | Calverton silt loam, 0 to 7 percent slopes |
| 15A | Comus loam, 0 to 2 percent slopes |
| 16A | Delanco fine sandy loam, 0 to 4 percent slopes |
| 17A | Dulles silt loam, 0 to 2 percent slopes |
| 20B | Elsinboro sandy loam, 2 to 7 percent slopes |
| 49A | Rowland silt loam, 0 to 2 percent slopes |
| W | Water |
| Wh | Wehadkee very fine sandy loam, 0 to 2 percent slopes |

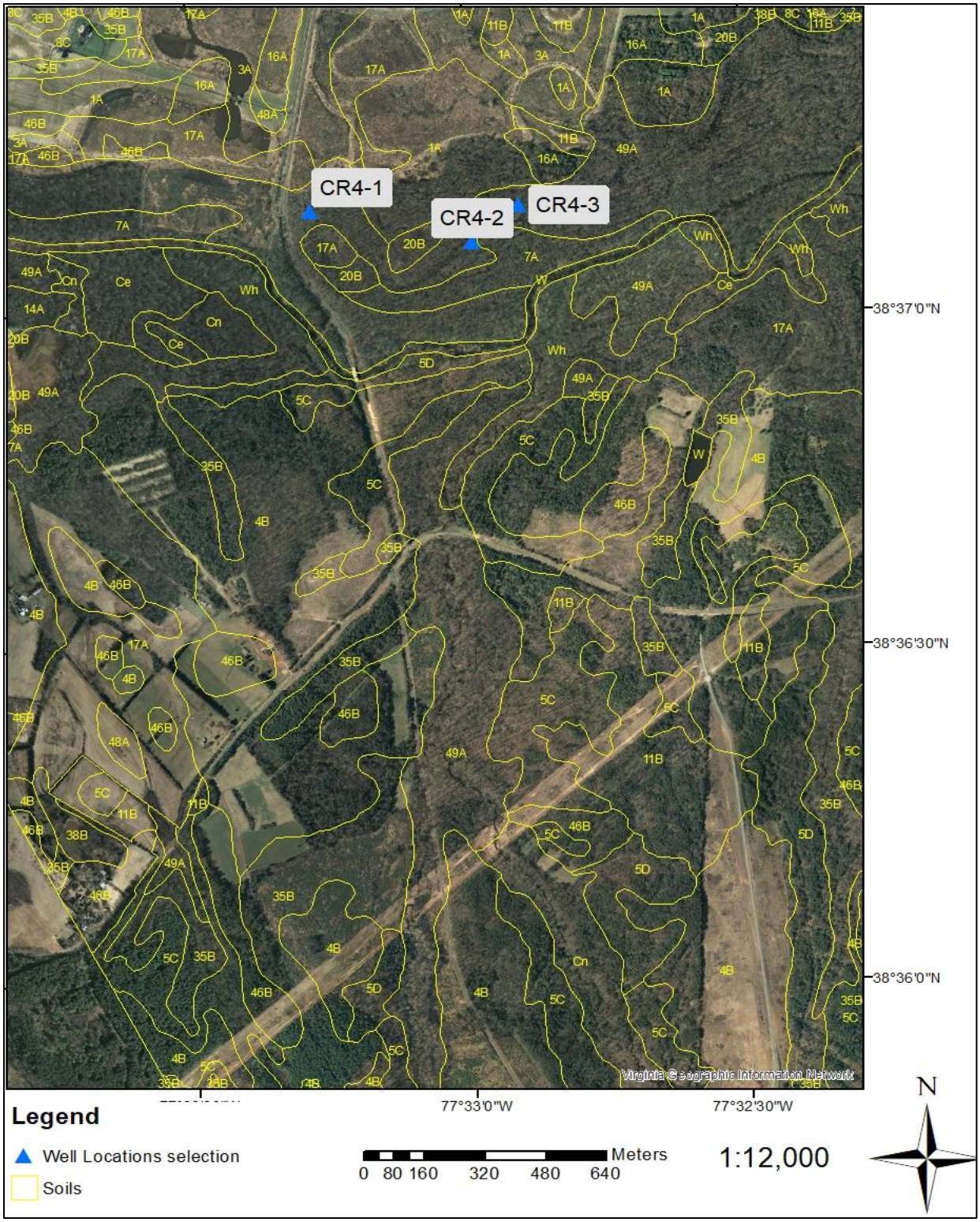


Figure 5.25. Soil map of Cedar Run 3 (CR) and Cedar Run 4 (CR4) with monitoring well locations. Located in Prince William county VA near Manassas southwest of Merrimac Farm Wildlife Management Area and east of Fleetwood Drive.

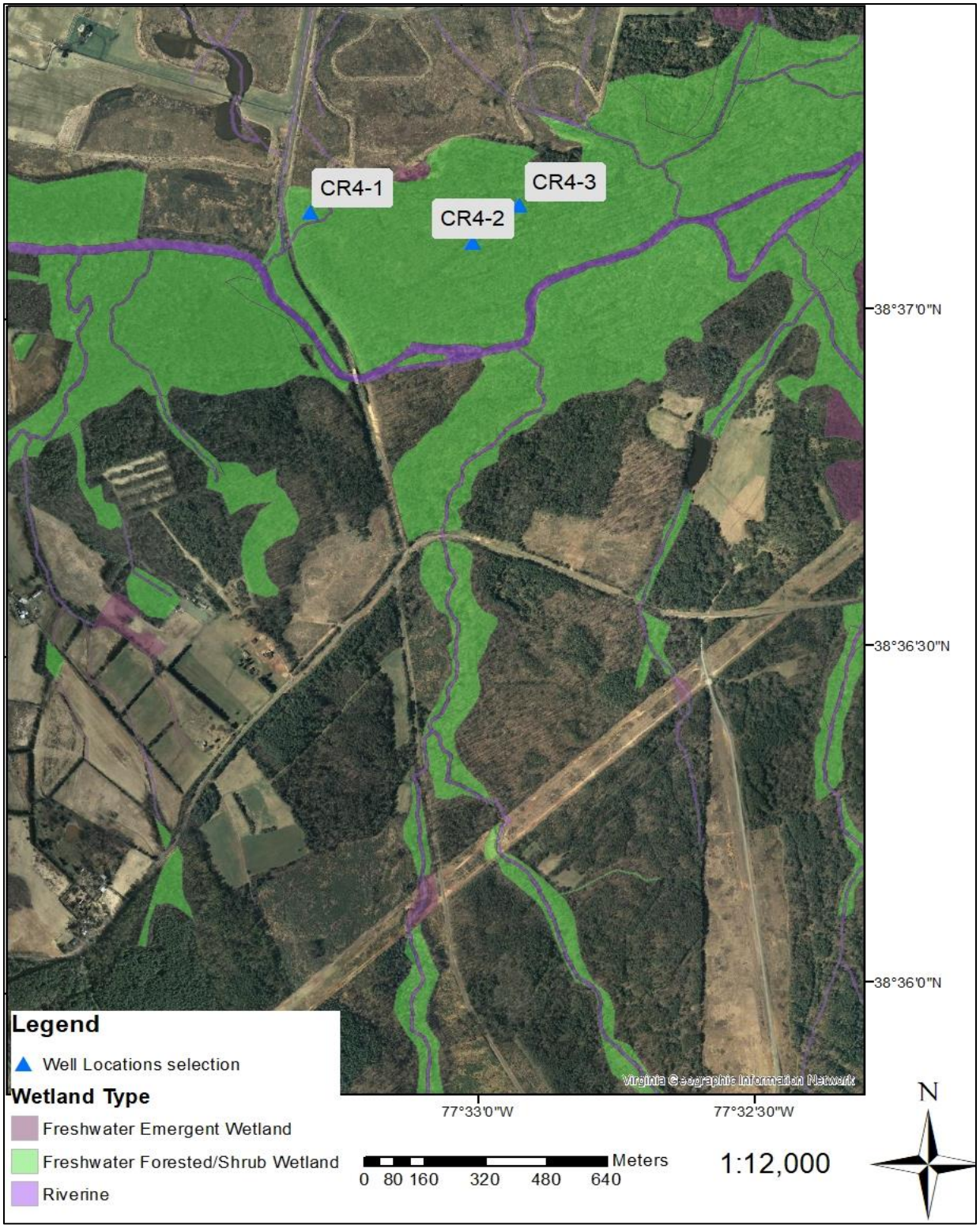


Figure 5.26. NWI map for Cedar Run 4 with monitoring well locations. Located in Prince William county VA near Manassas southwest of Merrimac Farm Wildlife Management Area east of Fleetwood Drive.

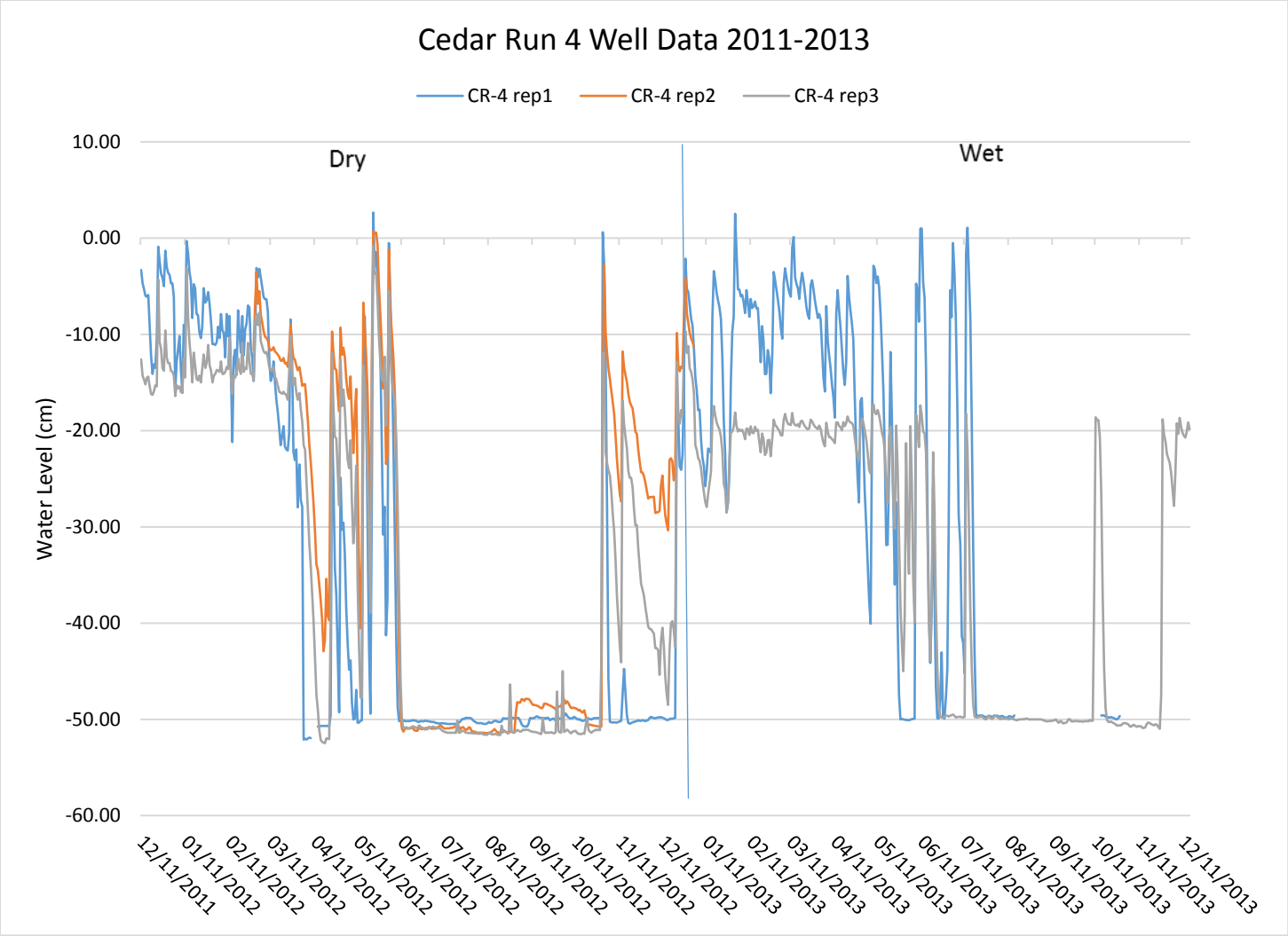


Figure 5.27. Three replications of -50 cm well data for Cedar Run 4 for December 2011 through December 2013.

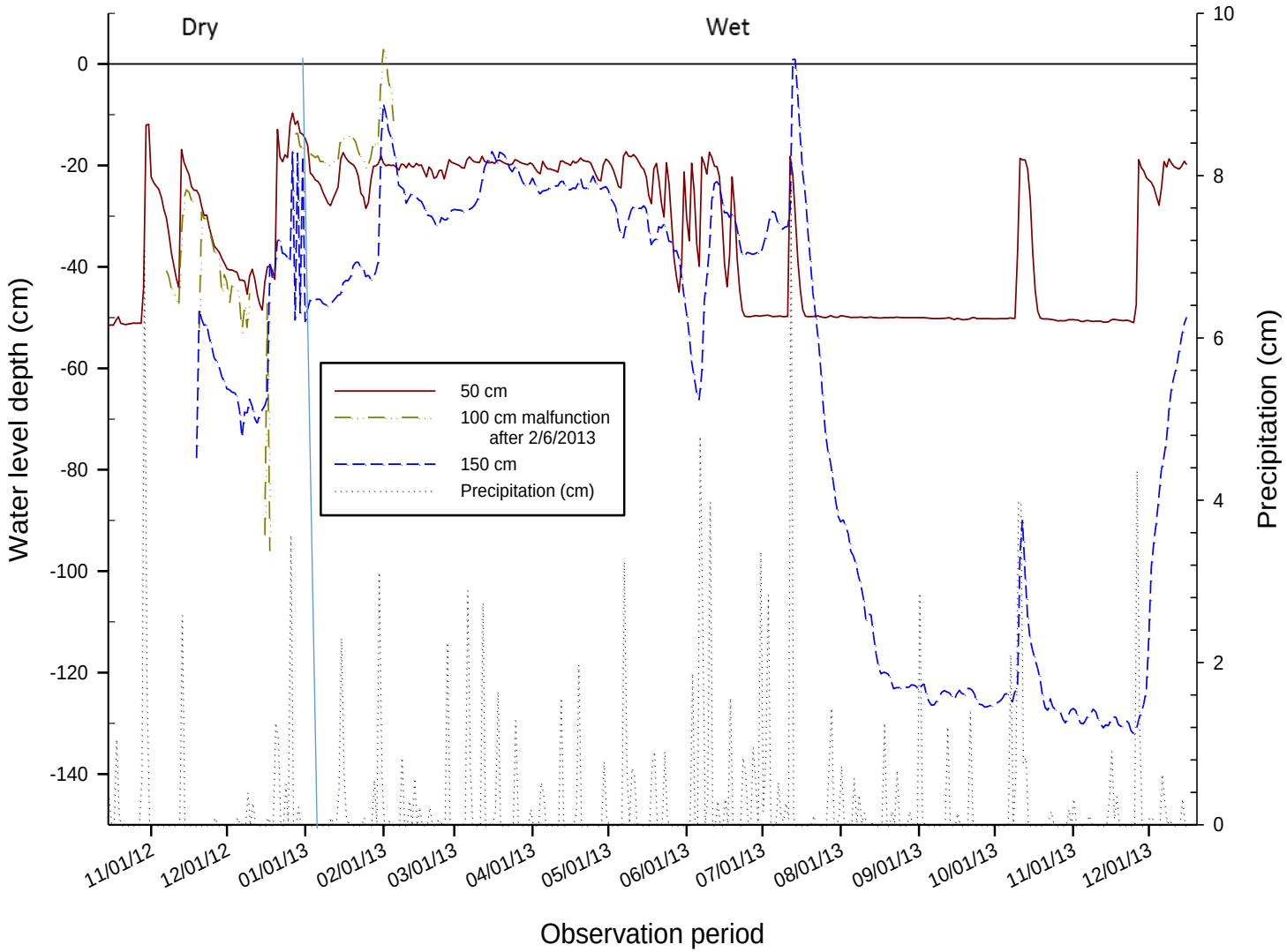


Figure 5.28. Piezometer monitoring data for Cedar Run 4 at -50, -100, and -150 cm graphed with precipitation for November 2012 through December 2013.

### 5.4.3. Whitelace Creek

This site is located in Lenoir County just west of Willie Measley Rd on Mosely Creek. This site overlies the Black Creek Formation, a Cretaceous aged coarse to fine unconsolidated detrital material. Gray to black clay with thin beds and laminae of micaceous sand are common and the upper part contains glauconitic clayey sand lenses (Rhodes and Conrad, 1985). Reference well 1 is located on a foot or toeslope position (Figure 5.29) on a Pamlico series soils - Sandy or sandy-skeletal, siliceous, dysic, thermic Terric Haplosaprists (NRSC, 2010) (Table 5.7 Figure 5.30). The NWI shows this well located just on the fringe of a PFO (Figure 5.31). This site may also be receiving groundwater from its adjacent upland in addition to its associated stream system. It is important to note that the well location coordinates provided by the North Carolina source do not appear to be correct with respect to the topographic and soil mapping layers shown below. The well is more likely in the much wetter soil unit just to the north of its location shown on these maps.

This set of data was recorded digitally and this well casing is a 5 cm PVC installed to -80 cm. The data set consisted of partial data from 2006, 2007, 2008 and 2011, as well as continuous data from 2009 to 2010 (Figure 5.32). The hydroperiod here is driven primarily by ET, precipitation, and groundwater interactions. This site shows rapid responses to precipitation, consistently fluctuates between -5 cm and -40 cm, and thus appears to be buffered by groundwater additions. Winter high water levels were not very consistent between years, with ponding in 2009 higher than any other year. During the summer months, the hydroperiod is as deep at -70 cm.

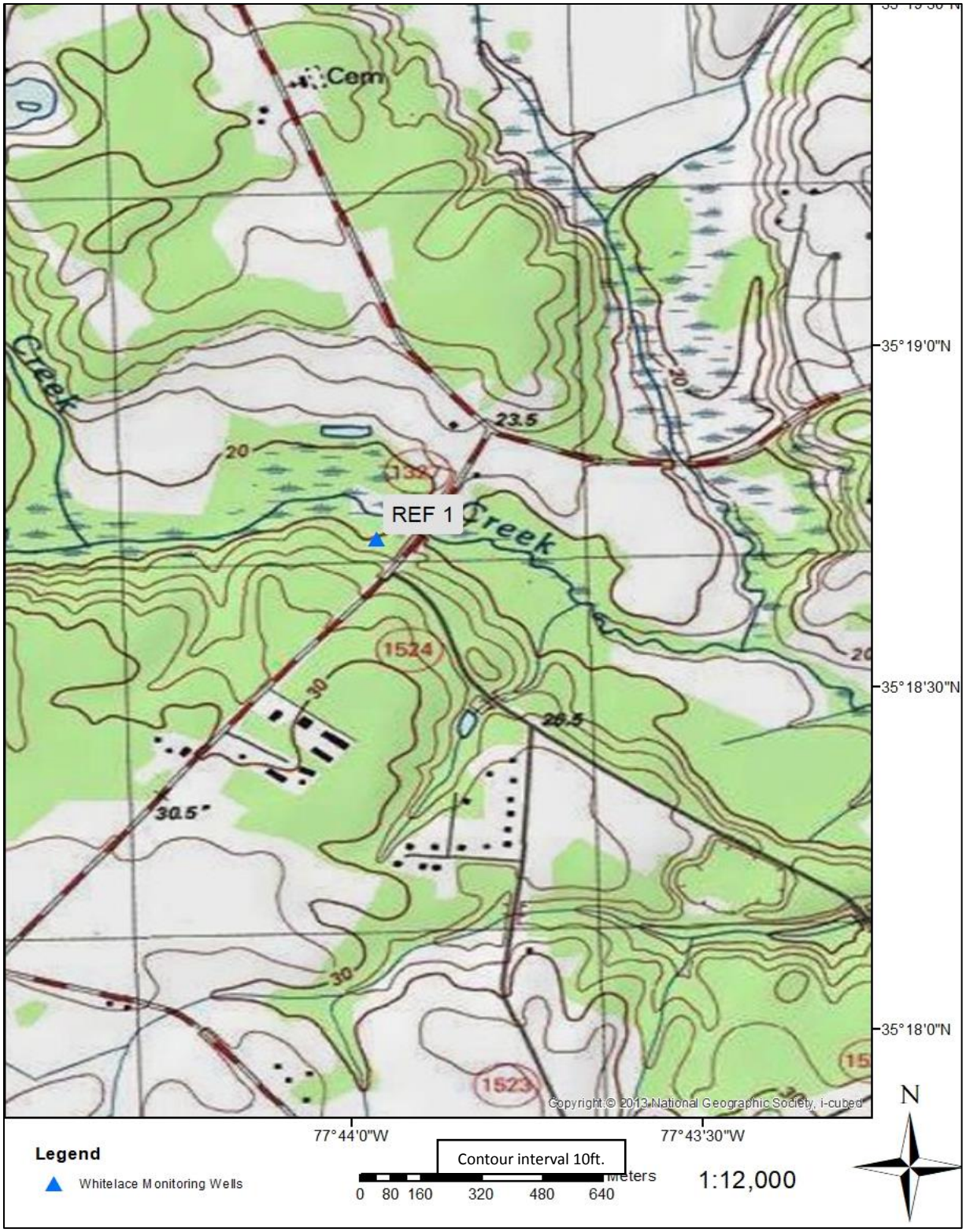


Figure 5.29. Topographic map for Whitelace Creek Reference Well 1. Located in Lenoir County just west of Willie Measley Rd. on Mosely Creek.

Table 5.7. Whitelace Creek soil map unit symbols and names.

| Lenoir County, North Carolina (NC107) | |
|---|---|
| **Map Unit Symbol** | **Map Unit Name** |
| Bn | Blanton sand, 0 to 6 percent slopes |
| GoA | Goldsboro loamy sand, 0 to 2 percent slopes, Southern Coastal Plain |
| Jo | Johns sandy loam |
| JS | Johnston soils |
| Pa | Pactolus loamy sand |
| Pc | Pamlico muck |
| Po | Pocalla loamy sand, 0 to 6 percent slopes |
| Pr | Portsmouth loam |
| Ra | Rains sandy loam, 0 to 2 percent slopes |
| St | Stallings loamy sand |
| W | Water |
| Wb | Wagram loamy sand, 0 to 6 percent slopes |
| Wc | Wagram loamy sand, 6 to 10 percent slopes |


Figure 5.30. Soil map for Whitelace Creek Reference Well 1. Located in Lenoir County just west of Willie Measley Rd. on Mosely Creek.

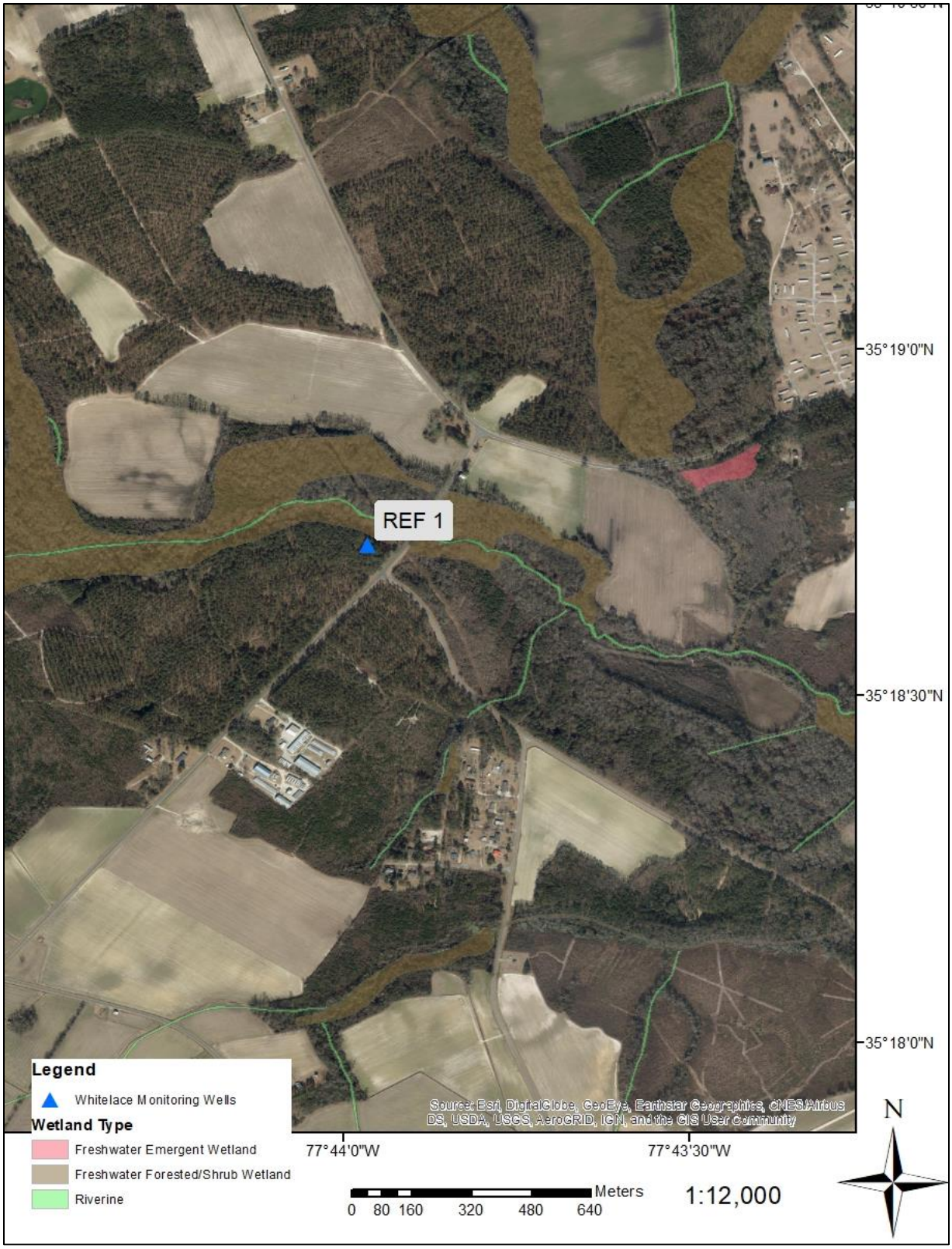


Figure 5.31. NWI map for Whitelace Creek Reference Well 1. Located in Lenoir County just west of Willie Measley Rd on Mosely Creek.

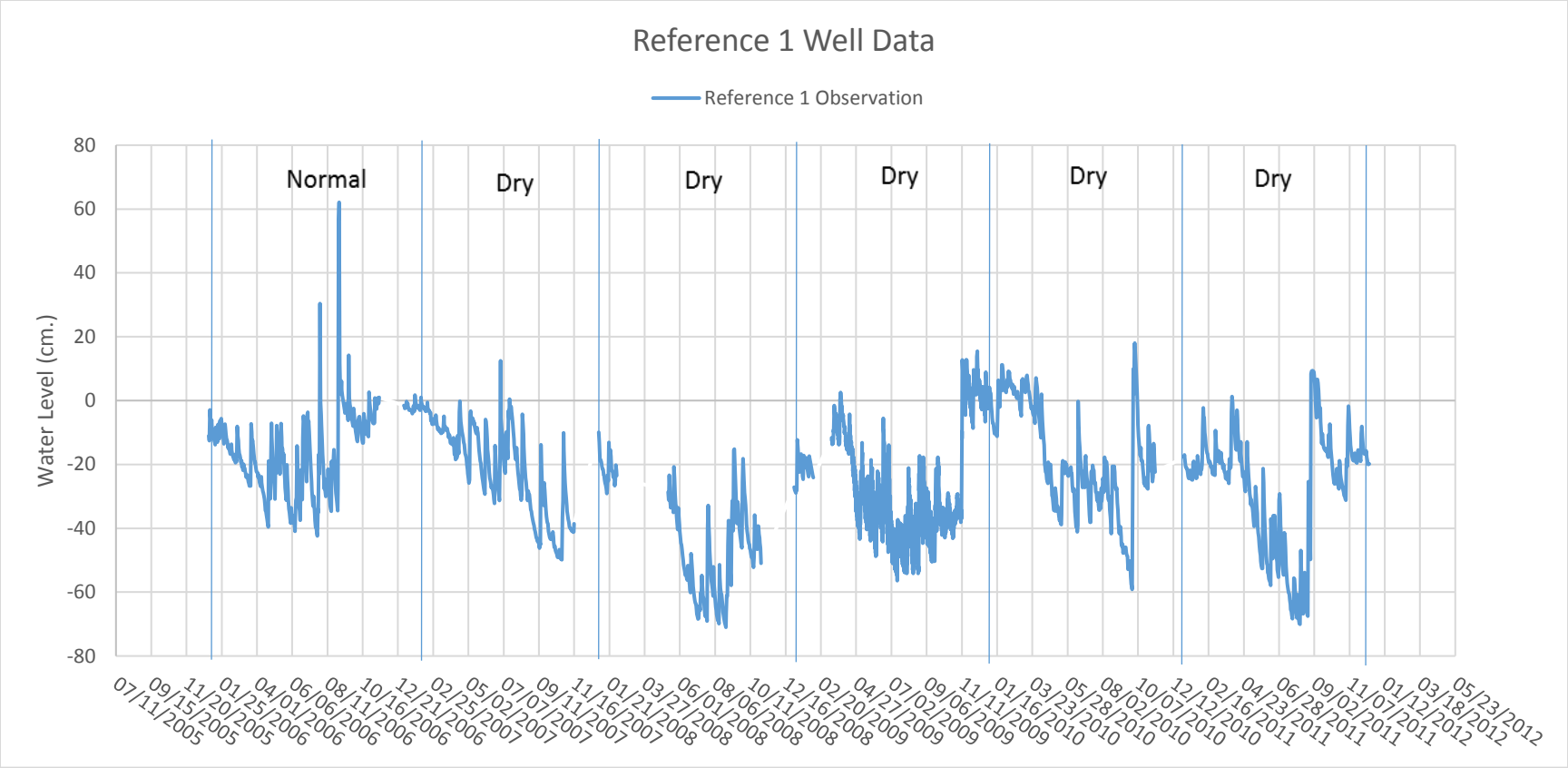


Figure 5.32. Water level monitoring data for Reference Well 1 located at Whitelace Creek from 2005 through 2011.

## 5.5. Depressional

This site is located in Dinwiddie County, just north of Route 40. This selection of site data contains monitoring data sourced from Virginia Tech, with this being the only depressional site that met our selection criteria. Our search resulted in three sites which were potentially suitable, but only one of these had a combination of clearly correct HGM configuration and continuous data which showed seasonal water level drawdown and rebound for this wetland type.

### 5.5.1. Iluka

This wetland site was monitored by Virginia Tech as part of a sponsored research program for Iluka Resources Inc. to establish target hydroperiods for wetland restoration following minerals sands mining impacts (Genthner et al., 1998). This forested site was never disturbed by mining and remains surrounded by relatively undisturbed agricultural lands. The underlying geologic unit for the site is unconsolidated Pleistocene/Pliocene sands and gravels. While not obviously expressed on the topographic map due to its relatively small size (Figure 5.33), the wetland has a low sandy rim to the southeast that is clearly notable in the field, but is broached by a small human enhanced ephemeral drainageway to the southwest. The soils here were mapped and classified as Roanoke series, and detailed soil evaluations were reported for wells onsite (Genthner et al., 1998). Roanoke soils are fine, mixed, semiactive, thermic Typic Endoaquults with a depleted matrix starting within -18 cm (~7 in), common redox concentrations in the E and Btg, and are poorly drained (Table 5.8, Figure 5.34). This site is somewhat higher than much of the local landscape which also contains numerous Carolina bays, the majority of which have been drained and converted to agricultural production. Figure 5.35 Shows the NWI map for this area.

This site was monitored continuously bimonthly between March 1991- September 1994 (Figure 5.36). This system is a depressional wetland which doesn't receive groundwater from any nearby uplands. It is unlikely that it receives any overland flow from the nearby farms due to the flat sandy soils surrounding it and its low elevated rim to the southeast that also wraps around most of the bay. Thus, shifts in water levels are primarily driven by ET and precipitation. The data for this site (Figure 5.36) show the site ponding at a consistently high winter level from year-to-year followed by a drastic drawdown of the water table once ET increases during the late spring/early summer. In all four recorded years, the summer drawdown pulled the water table to a depth lower than -125 cm and occurred during May to June.

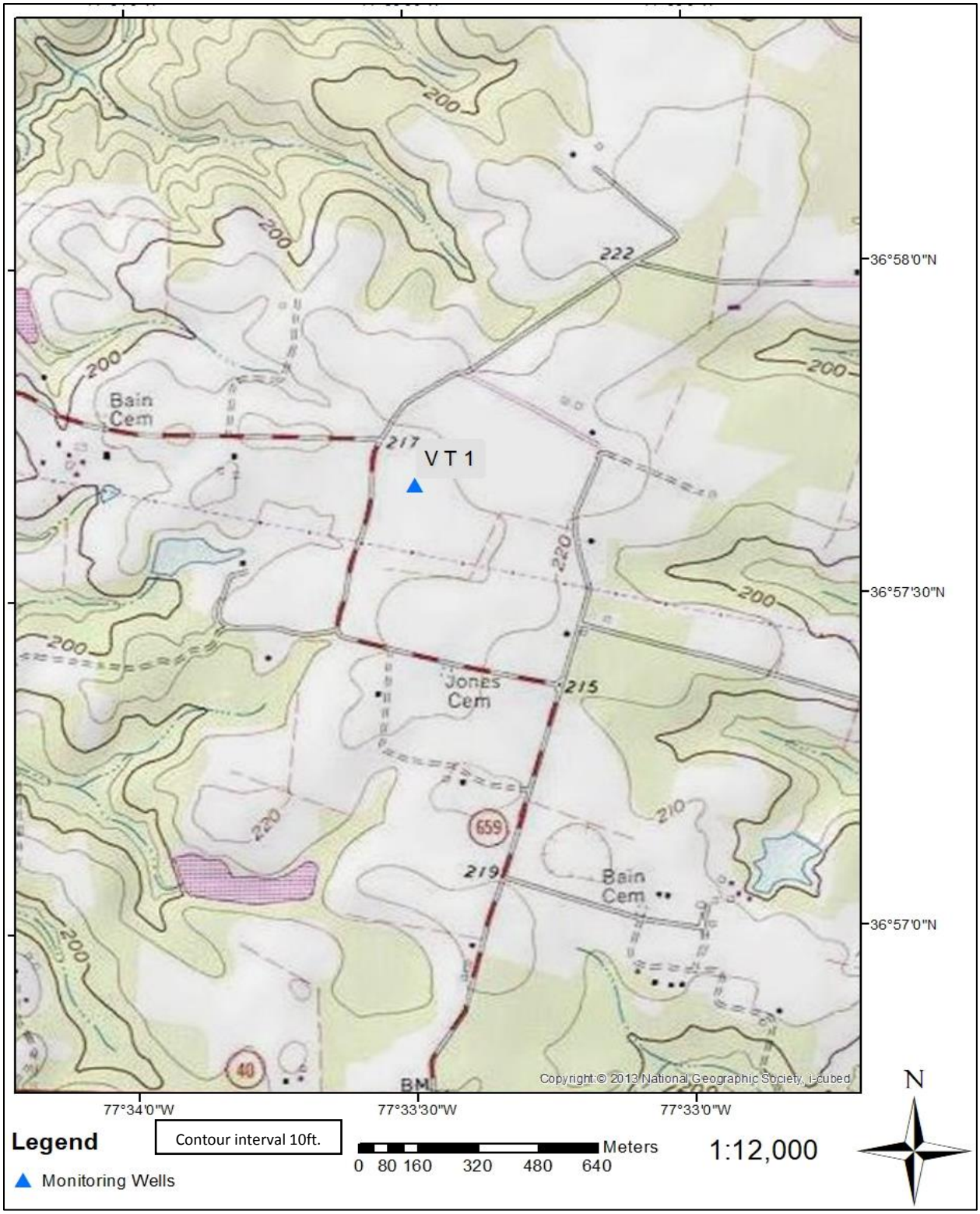


Figure 5.33. Topographic map showing approximate location of monitoring well 9C located at Iluka site VT1. To the southeast near the Bain Cemetery is a clearly expressed Carolina bay which has been drained and converted into cropland.

Table 5.8. Iluka location soil map unit symbols and names and slope.

| Dinwiddie County Area, Virginia (VA653) | | |
|---|---|---|
| Mucode | Map unit name | Slopes |
| 92A | Bibb loam | 0 to 2 percent slopes |
| 246A | Dothan loamy fine sand | 0 to 2 percent slopes |
| 246B1 | Dothan loamy fine sand | 2 to 6 percent slopes |
| 246B2 | Dothan sandy clay loam | 2 to 6 percent slopes |
| 246C1 | Dothan loamy fine sand | 6 to 10 percent slopes |
| 246C2 | Dothan sandy clay loam | 6 to 10 percent slopes |
| 74A | Dragston loamy sand | 0 to 3 percent slopes |
| 7B1 | Emporia loamy fine sand | 2 to 6 percent slopes |
| 346A | Faceville loamy sand | 0 to 2 percent slopes |
| 346B1 | Faceville loamy sand | 2 to 6 percent slopes |
| 346B2 | Faceville sandy clay loam | 2 to 6 percent slopes |
| 60B | FuquayVarina complex | 2 to 6 percent slopes |
| 60C | FuquayVarina complex | 6 to 10 percent slopes |
| 112B | Fuquay sand | 2 to 6 percent slopes |
| 20B2 | Georgeville sandy clay loam | 2 to 7 percent slopes |
| 17B1 | Helena fine sandy loam | 2 to 7 percent slopes |
| 16D | Herndon fine sandy loam | 15 to 25 percent slopes |
| L | Hog lagoon | |
| 8B1 | Masada gravelly fine sandy loam | 2 to 6 percent slopes |
| 26 | Myatt loam | 0 to 2 percent slopes |
| 69B | Nansemond fine sand | 0 to 4 percent slopes |
| 63A | Norfolk loamy sand | 0 to 2 percent slopes |
| 63B | Norfolk loamy sand | 2 to 6 percent slopes |
| 52B | Ocilla loamy sand | 0 to 4 percent slopes |
| 45A | Orangeburg loamy sand | 0 to 2 percent slopes |
| 45B1 | Orangeburg loamy sand | 2 to 6 percent slopes |
| 45B2 | Orangeburg loam | 2 to 6 percent slopes |
| 90 | Pickney loamy sand | 0 to 2 percent slopes |
| 29A | Roanoke loam | 0 to 2 percent slopes |
| 10A | Slagle fine sandy loam | 0 to 2 percent slopes |
| 10B | Slagle fine sandy loam | 2 to 6 percent slopes |
| 11B | Suffolk loamy sand | 2 to 6 percent slopes |
| 46A | Turbeville loamy sand | 0 to 2 percent slopes |
| 46B | Turbeville loamy sand | 2 to 6 percent slopes |
| 46B2 | Turbeville sandy clay loam | 2 to 6 percent slopes |
| 12B | Uchee loamy sand | 2 to 6 percent slopes |
| 14C | Vance fine sandy loam | 7 to 15 percent slopes |
| 146A | Varina fine sandy loam | 0 to 2 percent slopes |
| 146B | Varina fine sandy loam | 2 to 6 percent slopes |

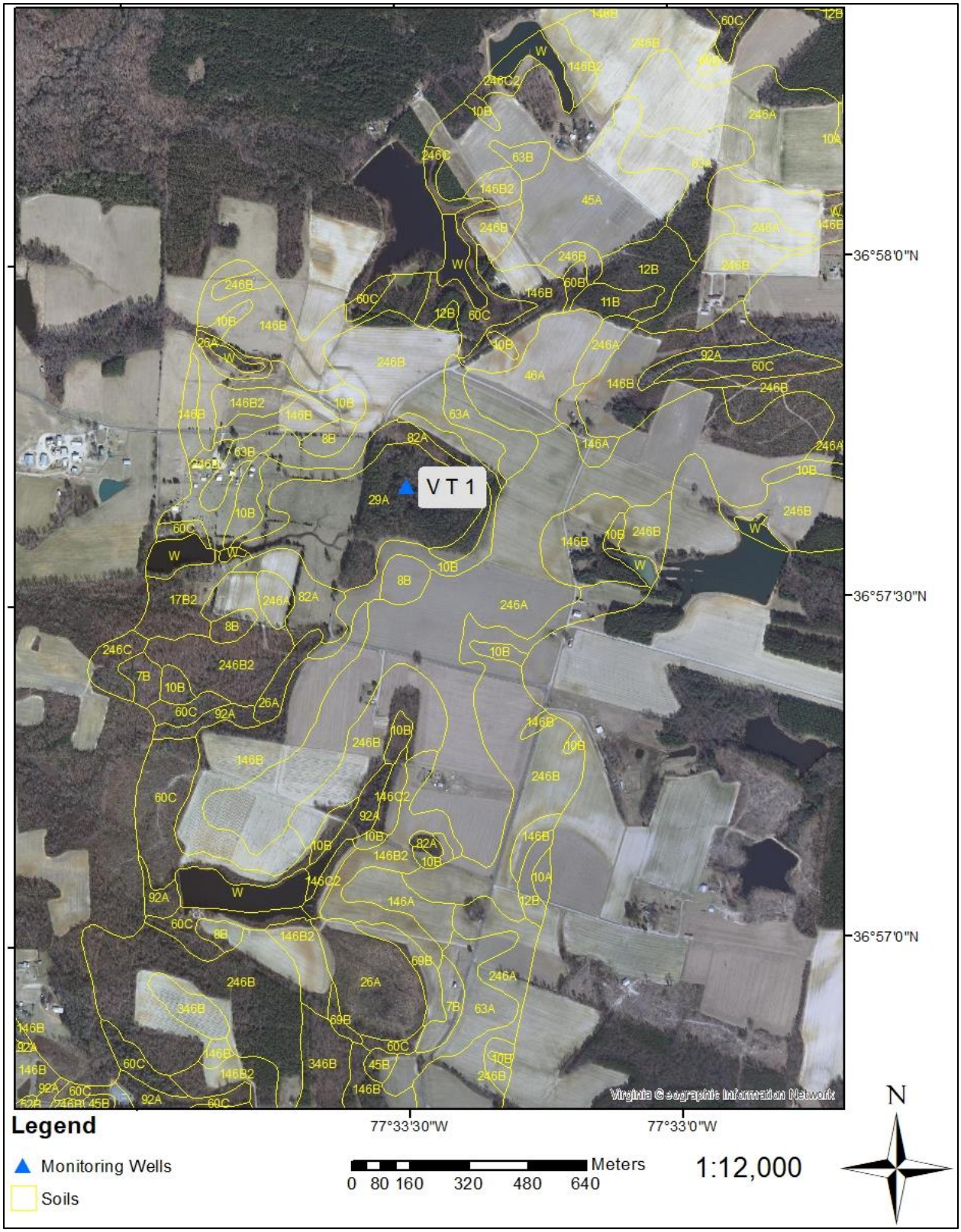


Figure 5.34. Soil map of Site VT1 with approximate location for well 9C.

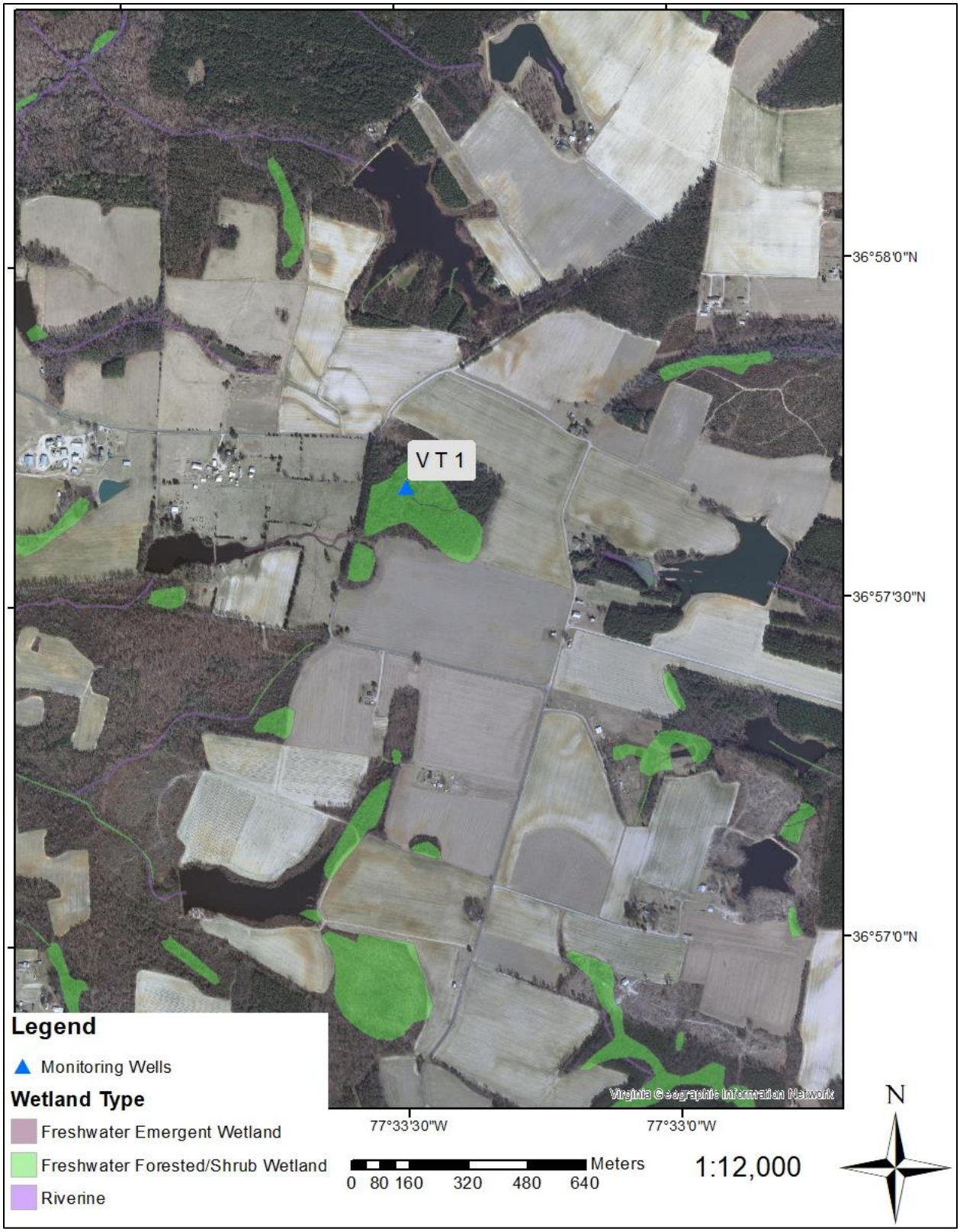


Figure 5.35. NWI map for Site VT1 with approximate location for well 9C.

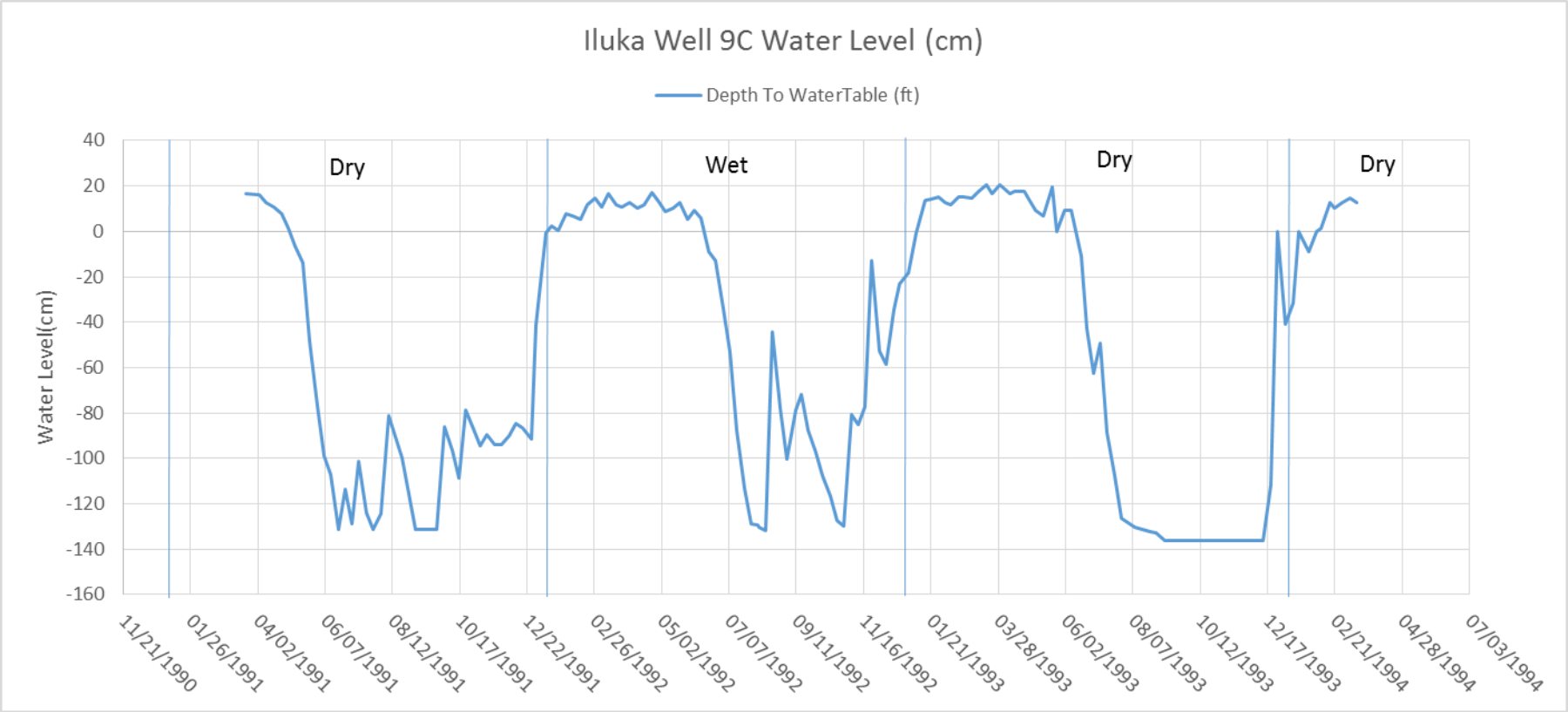


Figure 5.36. Water Level data for site VT1 Monitoring well 9C from 1991 through 1994.

## 5.6. Discussion

The secondary objective of this research effort was to develop a group or "library" of non-tidal forested wetland hydroperiods that could be used as "design targets" for wetland professionals during the permitting development process for created wetlands. Across the array of wetland hydroperiods reviewed and analyzed here it is important to note the limitations of this selected group. For example, within a given HGM class, it is essential to consider the similarities and differences among the sites, and then use that variability to inform their use in water budget design. While every effort was made to find representative hydroperiods for each class, the final number of suitable hydroperiods was directly affected by the overall availability of appropriate data sets.

The mineral flats selected were sourced from the largest stock of hydroperiods available and they provided the greatest number of alternative with respect to both length and continuity of the water level data. Within this class, hydroperiods varied in their range, and timing of seasonal drawdown and recovery. While all sites experienced ponding, the depth and extent varied between and within sites. Level Ponds presented the least consistent depth and extent of ponding between years, with some not ponding and others staying ponded for 10 months at a time. Roquist and Su stayed wetter and ponded for longer periods than the other two sites, and Roquist showed the deepest ponding (~+20cm) at well GW-12. SNBP wetted up briefly in the winter and dried down sooner into the growing season. While microtopographical differences in sites can produce difference in the observed hydroperiod, this doesn't explain the differences observed among these sites. The multiple seasons of hydroperiods available for Su Tract, SBNP, and Roquist showed variation across each site, and made it clear that well placement affected the highest and lowest observed water levels, but not the general pattern and total extent of drawdown. Among wells at SBNP, the

data show a consistent 3-5 month period of wetness from early winter just into the beginning of the growing season, with saturation between ground level and -30 cm for well 213 and between -20 cm up to +5 cm of ponding at well 201. All three SBNP wells indicated drawdown to between -150 cm and -220 cm each summer. Roquist also showed a range of winter high levels with between +5 cm to +20 cm of ponding among wells, and < -80 cm of drawdown at all wells. However, this site had shallower wells than SBNP, so the full extent of drawdown was difficult to ascertain. It is more likely that the differences between these two wetlands were caused by the interactions with their surrounding regional landscapes and underlying aquifers.

The riverine hydroperiods presented here were hydrologically distinct from the other two groups. These sites were characterized by a shorter precipitation response time and all of the riverine sites showed the effects of flooding events. The sites varied in their proximity to the stream: the Whitelace Creek site well is located about 80 m from the stream and may be closer based on previous notes about coordinate accuracy; Cedar Run 4 wells are about 120 – to 300 m from their stream; Bull Run well were approximately 160 – 200 m from the stream. The Whitelace Creek site showed a faster precipitation response than the other two sites selected and this is most likely due to it being much closer to the stream edge. Groundwater influences observed at Bull Run and Cedar Run 4 both showed seasonal variation. The riverine grouping is the only HGM class which experienced overbank flow, clearly presented in periodic flooding events in all three sites, most obviously in Whitelace. Among these three sites, the maximum depth of drawdown ranged from -60 cm to > -150 cm (Figures 5.22, 5.27, and 5.32), with Whitelace Creek experiencing the least drawdown. Thus, Whitelace Creek is more likely to be directly influenced by the shallow groundwater table associated with the adjacent stream versus Bull Run and Cedar Run which have

wells further away. Without additional wells and nested piezometer data, it is difficult to tell whether the stream was losing or gaining relative to the surrounding wetland. However, it appears that groundwater interactions between the stream and wetland was buffering drawdown in Whitelace Creek well REF 1.

With only one suitable depressional wetland hydroperiod available for analysis, it is questionable whether or not it can or should be used as a "target hydroperiod". That being said, this wetland still provided valuable multi-year data for use as a reference for depressional hydrology in an upper Coastal Plain landscape. With seasonally ponded water levels and complete drawdown during the late growing season, this site follows the typical patterns expected for a precipitation and ET driven system (Mitsch and Gosselink, 2000). However, for determining the "typical hydrology" of Carolina bay hydroperiods, a larger review of multiple sites and data sets would be required. Caldwell et al. (2007) showed three Carolina bay hydroperiods that were consistent in their timing and (to some degree) extent of drawdown. These bays were ponded much of the year followed by a complete drawdown of the water table for multiple months in similar fashion to the Iluka wetland reported here. Caldwell et al. (2007) proposed that the slight differences in the bay hydroperiods were likely related to the landscape surrounding each bay and so hydroperiods which would be adequate "design targets" would likely follow this pattern with slight variations. There are clear similarities between the Iluka depression's hydroperiod and the mineral flat sites. With both of these wetland types driven primarily by vertical flow (i.e. precipitation, infiltration, and ET), they tend to follow the same seasonal variation, being wetter during the late fall to early spring and drying out quickly as ET increases into the late spring. Rheinhardt et al. (2002) commented that mineral flats will often have depressional areas within them. Thus, the differences between

mineral flats and depressions are primarily based on local adjacent landforms and associated soil differences.

The selection of a ”target hydroperiod” for a priori development of a created wetland water budget should be take into account a number of important factors such as underlying geologic conditions, existing and post-disturbance soil conditions, human impacts such as ditching and surrounding urbanization, and estimates of major water inputs (precipitation, groundwater, overbank flow, watershed surface runoff). Foremost, designers should carefully target and manipulate their predicted hydroperiod based on their intended wetland type functional replacement goals. By doing so, the wetland design team can hopefully insure that creation site soils, hydroperiod and resultant vegetation type are as similar as possible to the intended target system.

This work now provides a limited set of “design hydroperiods” for wetland creation in the Mid-Atlantic USA, but it is important that we continue to build and research new tools and approaches to improve wetland creation success. Development of a deeper and wider set of reference hydroperiods for depressional wetlands and wetter systems (e.g. emergent/shrub-scrub) would be helpful in continuing to establish and validate suitable hydrologic targets for constructed wetlands.

## 6. Conclusions

My primary objective in this thesis research was to improve upon selected components of the Wetbud Basic model for application to created wetland design. Via a further detailed evaluation of the Basic model, I have demonstrated the overall capability of the program for use in wetland design along with identifying certain limitations. Since post-construction hydrology is one of the most difficult wetland parameters to accurately create, it is crucial that we have validated tools such as Wetbud for a priori design by professionals and for use in regulatory review. My second objective was to assemble a group of typical hydroperiods for common regional forested wetland types that could be used as "design targets" for mineral flats, riverine and depressional wetlands.

Evaluation of Wetbud's Basic model was performed with two years of water level monitoring data from two constructed wetlands in Prince William County, Virginia. The model was evaluated with both monthly and daily timesteps. The NSE and RMSE statistics were used to sequentially calibrate and then evaluate the accuracy of calibrated models using the recorded well data. Calibration was accomplished with the first year of recorded data and the second year was used to validate the fully parameterized models. Values for NSE ranged from -0.67 to 0.41 in calibration and from -4.82 to -0.26 during validation for NSE. Values for RMSE ranged from 5.92 cm to 12.71 cm during calibration, and from 8.26 cm to 18.54 cm during validation. During calibration NSE was used as our primary goodness of fit measure as recommended by the ASCE (2001). However, preference was given to RMSE, instead of NSE, as our final measure of accuracy for validation due to the effect that a limited absolute range of values (< 1.0 m) has on the NSE method (Gupta et al., 2009; Arnold et al., 2012).

Qualitatively, Wetbud performed well at modeling the overall range and timing of saturation and ponding at both sites given proper parameterization (calibration) along with the inclusion of a limiting layer. Users should take special care in model design when considering their wetland bottom depth as well as their contributing watershed as these were among the most influential parameters with regards to accuracy. Wetbud was able to model the seasonal water level rise very well; however, with regards to drawdown, the modeled sites often stayed wetter a longer into the growing season than actual measured water levels. With the limiting layer specified, Wetbud was able to produce excellent to good RMSE values during calibration and excellent to acceptable values during validation. Perhaps more importantly, even in the simple form tested here, the Basic model was able to produce an overall hydroperiod that was similar in both seasonal response and overall water levels to actual validation site conditions once I made the appropriate adjustments.

The primary objective for this study was the evaluation of the Wetbud Basic model, this has been accomplished here through these calibrated Basic models compared to actual onsite measurements through various qualitative and quantitative approaches. Given full parameterization, the model had the ability to match the onsite recorded days saturated very well during both calibration and validation (Figures 4.11, 4.12, 4.18, and 4.19). The addition of the limiting layer showed clear improvement in the case of the vernal pool models; all models with no limiting layer failed to predict even one point correctly.

While Wetbud is one of many available approaches and packages available (Skaggs, 1982; Voldseth 2007) for producing wetland water budgets, its unique strengths lay in the functionality and flexibility of the program. For users in Virginia (where our preloaded weather stations are

located), Wetbud provides end-users with a unique ability to easily produce wetland water budgets and to quickly evaluate relative effects of changing input parameters such as surface water inputs or outlet height. As shown by my evaluation along with other previous related studies (Dobbs, 2010; Gloe, 2011; Neuhaus, 2013; and Stone, 2017), Wetbud does an acceptable job of modeling the hydroperiod for a wide range of wetland designs and alterations. My work on this thesis project demonstrated that given a fully calibrated Basic model, it is possible to generate reasonably accurate hydroperiod predictions on both a monthly and daily scale. However, it is still not recommended that Wetbud be used on a daily basis since there are issues with program functionality at this scale, mainly a lack of accounting for surface water flow and elevation effects due vegetative resistance within a given wetland cell and residence time within the wetland simulation.

Created wetland hydroperiods often do not reflect those of comparable natural systems that they are designed to replace (Cole et al., 2016; Daniels et al., 1999). Therefore, our research group and sponsor presumes that wetland designers should use appropriate comparative hydroperiods from undisturbed wetlands of similar type as a "design target" for a priori water budget development. With the use of design models like Wetbud, we attempt to understand design factors that will directly affect post-construction wetland hydrologic response, but it is important that we have real world examples of these wetland hydroperiods to inform their design.

The sites that I have proposed here (5 mineral flats, 3 riverine, and 1 depression) for use as design targets are the result of an extensive research effort involving data obtained from The Nature Conservancy, The Army Corps of Engineers, The North Carolina Department of Environmental

Quality, and from scientists at Old Dominion University and Virginia Tech. While this search was not exhaustive, it represented my best effort to produce a library of design target hydroperiods that are representative of these common wetland systems. Unfortunately, data sets for depressional wetlands were rare relative to other HGM classes and/or had obvious abnormalities that eliminated them from final consideration.

Within the grouping of mineral flats, there was a wide variety of wetland sizes ranging from approximately 22 to 2200 ha. Only one of these wetlands had less than daily well measurements (SNBP) and all sites provided at least two years of data. The overall drawdown of these hydroperiods was the deepest among the three HGM types analyzed, with the deepest observed at SBNP (>200 cm). With regards to extent of saturation, these wetlands could be saturated near or at the soil surface, at some point, for periods ranging from three to nine months, depending on the year. All three riverine wetlands had daily water level measurements and contained at least two years of data with multiple well locations at two of the three sites. The riverine sites ranged in size from approximately 24 - 52 ha. The overall range of hydroperiods in the riverine sites was also very deep, ranging from 60 cm to >150 cm with the deepest drawdown observed at Cedar Run 4, which was located the farthest from its associated stream. These wetlands were saturated, at some point, during periods of six to twelve months depending on the year, with Whitelace Creek staying saturated year round in wetter years. The one depressional wetland selected for use was characterized by four continuous years of twice monthly manual water level readings and was around 5 ha in size. The hydroperiod at Iluka had an overall drawdown depth of -140 cm or greater depending on the year, and was saturated at some point for a period between five to seven months,

depending on rainfall. It is our hope that during wetland design these hydroperiods will be useful for professionals as design targets.

The hydroperiods within the mineral flat sites closely resembled that of the Iluka Carolina bay wetland, but were distinct from the riverine sites. One consistent factor which most of the hydroperiods show is the deep extent of annual drawdown (excluding Whitelace Creek); much lower than the North Fork sites discussed in Chapter 3. All of the mineral flat and depressional sites reported appear to show endoaquic groundwater interactions. This emphasizes the fact that our current "go-to" model for wetland creation, the simplified Pierce Method, is unlikely to reproduce similar hydroperiods. This is because of recommended subsoil compaction, intended to create epiaquic (perched) conditions, to maximize probability of meeting the technical standard of saturation during the growing season. These created wetlands lose their vertical interaction with the surrounding groundwater table making drawdown and infiltration like these sites, by design, impossible. This is exacerbated by the installation of berms intended to keep water within the constructed cells, making them different from the upland/wetland gradient present in most natural wetlands.

Chapter 5 illustrates my best effort to achieve the secondary objective laid out here, the creation of a design target hydroperiod library for the Mid-Atlantic Coastal Plain region. While not all HGM classes were equally represented there has been success with identifying sites and collecting good hydroperiod data for both mineral flats and Riverine systems. This portion of my study demonstrates the importance of understanding wetland hydroperiods and their similarities and differences among HGM classes and sites. Monitoring data which is collected, corrected properly,

and well-maintained is hard to come by and expensive to generate. These data sets, however, are critical to our understanding of wetland systems and to our ability to create new wetlands going forward. With wetland design modeling capabilities like those found in Wetbud being developed and improved, the importance of good reference data sets will also be critical to their successful application. Models like Wetbud which automate calculations and freely provide publicly available data to the user could help standardize the process of wetland design, and hopefully produce better design results.

In terms of how these hydroperiods could be used for improving wetland design, the approach will vary depending on what the starting landscape and target wetland type are. These hydroperiods should be used in tandem with information on intended vegetative communities and HGM class to establish approximate targets for saturation/ponding periods. Additionally, they can inform the planned physical components of the created wetland that control the maximum depth of ponded water, hydrologic inputs, and outputs which regulate the hydroperiod for a given design. These components will help determine the suitability of a given site for wetland replacement depending on the target wetland assuming a typical type-for-type replacement mandate.

In the future, it would be a benefit to all groups involved in wetland creation to produce and maintain a database of natural wetland hydroperiods for wetlands across the country. This project was plagued by the fact that data was collected by many different groups, including government sources, in a wide range of formats. Furthermore, continuous year-round data sets are rare since most consultants only monitor the winter/spring drawdown period. Given the expense of recording this data, it seem only fitting that there should be a public repository available that would also

archive site metadata (methods, site history, jurisdictional determination forms, errors etc…). That way, common resources could be used for future projects including development of wetland design targets, future model development and evaluation efforts, along with a number of other applications. Given larger data sets to leverage, water budgeting models could have a far better level of accuracy, and created wetlands could more easily achieve functional replacement goals.

Additional work related directly to the improvement of Wetbud should involve the exploration of water residence times in relation to site vegetation. This could improve the effectiveness of daily water level estimates through more accurate flow routing within the wetland. Next steps for this project could include the use of remote sensing software to identify possible reference wetland sites. This would be followed up with the instrumentation and field vetting of wetland sites identified as potential reference wetland targets. Wetlands selected for this purpose should be wetland types which are most commonly created and restored. If possible, government agencies involved in wetland monitoring, or similar activities, should be included in an effort to aid in regulatory transparency and help foster an air of cooperation in the name of wetland protection.

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## 8. Appendix A

Listed here are all sites considered for addition to the standardized hydroperiod library. This includes: site name, County location, agency source, mitigation status if applicable and/or wetland classification and additional notes regarding the site or data.

| *Site Name* | *Agency* | *County* | *Wetland classification* | *Dominant Soils* | *Notes on data availability* |
|---|---|---|---|---|---|
| *Scamp Snyder* | WSSI, VT | Prince William | PFO - Riverine | Alluvium capped Waxpool | Two years of continuous data |
| *Bull Run* | WSSI, VT | Prince William | PFO - Riverine | Recent alluvium overtop Bowmansville | Two years of continuous data |
| *Cedar run* | WSSI, VT | Prince William | PFO - Riverine | Recent alluvium overtop Rowland and Bowmansville | Two years of continuous data |
| *Bishop Road* | NC DEQ | Hyde | Forest Organic Flat | Unpublished | Multiple years of continuous data |
| *Jumping Run* | NC DEQ | Harnett | Stream Restoration, Reference well supposedly in a preserved riverine wetland | undetermined, Site was removed before soils were evaluated | |
| *Little River* | NC DEQ | Randolph | Forested Riverine | undetermined, Site was removed before soils were evaluated | Multi-year continuous data |
| *Meadowbranch* | NC DEQ | Robeson | Frosted riverine | undetermined, Site was removed before soils were evaluated | Multi-year continuous data |
| *Perry Property* | NC DEQ | Chowan | Depressional -Carolina Bay | Unpublished | Two years of discontinuous data |

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|---|---|---|---|---|---|
| *Roquist* | NC DEQ | Bertie | Formerly ditched Carolina Bay | Unpublished | About five years of data, four of which are continuous from 2009-2013 |
| *Sandy Creek* | NC DEQ | Durham | Riverine forested | undetermined, Site was removed before soils were evaluated | two years of data, Doesn't show drawdown/recharge |
| *Whitelace Ck* | NC DEQ | Lenoir | Forested Riverine/slope wetland | Pamlico | six years of data for three reference wells |
| *Su Tract* | TNC | Chesapeake | Mineral Flat, PFO4Bd, PFO1Bd | Dragston, Tomotley, Nimmo, and Betire | Restored Cropland - good well data |
| *Level Ponds* | TNC | Chesapeake | Mineral Flat, mixed PFO | | Near some sort of landscape disturbance |
| *Stumpy Lake* | VACOE | VA Beach | mineral flat PFO1Bd, PFO4/1B, | undetermined, Site was removed before soils were evaluated | Unsure of well locations but full year data looks good |
| *Woodard mills* | VACOE | Unpublished | Forested, possible mineral flat | undetermined, Site was removed before soils were evaluated | Multiyear semi-continuous data |
| ***Iluka*** | VT | Multiple Sites: | | | |
| ***VT1*** | VT | Sussex | PFO | Myatt, Roanoke, Yemassee | Carolina-Bay-like, open at one end, one small stream which flows in late winter/early spring |
| ***VT2*** | VT | Sussex | PFO | Dragston, Yemassee, Bibb, Nimmo, Mattan | Large strand wetland associated with a perennial stream |
| ***VT3*** | VT | Sussex | PFO | Pickney | Seep wetland at the head of a drainageway |
| ***VT4*** | VT | Sussex | PFO | Pickney | Small sized strand wetland associated with a perennial stream |

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| ***VT5*** | VT | Sussex | PFO | Augusta, Yemassee, Bibb, Kinston | Intermediate sized strand wetland associated with a perennial stream |
| ***VT6*** | VT | Sussex | PFO | Kinston | Intermediate sized strand wetland associated with a perennial stream |
| ***VT7*** | VT | Sussex | PFO | Yemassee, Bibb | Intermediate sized strand wetland associated with a perennial stream |
| *Sandy bottom Nature Preserve* | VT and ODU | Hampton | PFO1/4E | Primarily Tomotley series with sections of Alavist, Augusta, Bibb, Dragston, and Nimmo. | Multiple well data sets |
| ***Huntley meadows*** | VT and ODU | Fairfax | PFO and PFE | Hatboro, Elkton silt loam, Gunston, and Mattapex | Multiple Well data sets |
| *Newtown* | NC DEQ | Union | Forested Riverine | undetermined, Site was removed before soils were evaluated | 1.5 years of data |
| *Silver Moon non-riparian Wetland mitigation site* | NC DEQ | Craven | Torhunta, Patego | undetermined, Site was removed before soils were evaluated | data measured from march to November |
| *St Clair Creek Restoration* | NC DEQ | Beaufort | Riverine Forested restoration | undetermined, Site was removed before soils were evaluated | One year of data, Doesn't show drawdown |
| *BSNA Preserve* | VACOE | Lot W | PFO | Roanoke, Kinston | Multiple years of discontinuous data |
| *BP Amoco* | VACOE | Unpublished | PFO | Tomotley | Passes FAC neutral |
| *Jacobson* | VACOE | Chesapeake | Seasonally saturated mineral flat | Arapahoe, Tomotley | Discontinuous data |

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|---|---|---|---|---|---|
| *Oak Grove* | VACOE | Chesapeake | PFO1E, PFO1B, PFO1C | Tomotley-nimmo Complex, Bertie | Restored cropland |
| *Su Tract* | VACOE | Chesapeake | Mineral Flat, PFO4Bd, PFO1Bd | Tomotley-nimmo Complex | Two sets of multiyear data, TNC data is mostly continuous and the USCOE data has wells removed yearly. |
| *Armstrong Property* | NC DEQ | Hyde | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Brown Farm* | NC DEQ | Durham | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Brown's Summit* | NC DEQ | Guilford | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Clayhill Farm* | NC DEQ | Jones | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Columbus Swamp* | NC DEQ | Robeson | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Conoconnara Swamp* | NC DEQ | Halifax | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Cox Site* | NC DEQ | Johnston | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Croatan Mitigation Bank Phase I* | NC DEQ | Craven | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Daniels Farm #2* | NC DEQ | Franklin | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Farrar Dairy* | NC DEQ | Harnett | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Five Mile Branch* | NC DEQ | Iredell | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Foust Creek Mitigation Site* | NC DEQ | Alamance | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Glade Creek II* | NC DEQ | Alleghany | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |

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| *Gregory Site* | NC DEQ | Halifax | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Haw Branch* | NC DEQ | Onslow | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Henry Fork Stream and Wetland Mitigation Project* | NC DEQ | Catawba | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Herman Dairy Farm Stream and Wetland* | NC DEQ | Alexander | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Hoppers Creek - Melton Farm* | NC DEQ | McDowell | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Howell Woods* | NC DEQ | Johnston | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Jarmans Oak* | NC DEQ | Onslow | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Martins Creek II* | NC DEQ | Cherokee | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Mill Branch* | NC DEQ | Columbus | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Plum Creek* | NC DEQ | Brunswick | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Rich Fork FDP (Bodenheimer-Parker)* | NC DEQ | Davidson | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *SALT (Sandhill Area Land Trust)* | NC DEQ | Moore | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |
| *Summit Seep Wetland Mitigation* | NC DEQ | Davidson | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated |

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| *Suther (Dutch Buffalo)* | NC DEQ | Cabarrus | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Three Mile Creek* | NC DEQ | Avery | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Underwood Mitigation site* | NC DEQ | Chatham | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Upper Silver Creek Stream and Wetland* | NC DEQ | Burke | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *UT to Crab Creek* | NC DEQ | Alleghany | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *UT to Jumping Run Creek* | NC DEQ | Cumberland | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *UT to Lilliput Creek (Hog Branch Ponds)* | NC DEQ | Brunswick | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *UT to Mill Swamp Restoration Project* | NC DEQ | Onslow | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *UT to Town Creek* | NC DEQ | Stanly | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Vile Creek Mitigation Site* | NC DEQ | Alleghany | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Watts Property(UT Little River)* | NC DEQ | Perquimans | Mitigation/restoration site | undetermined, Site was removed before soils or well data were evaluated | |
| *Upper Silver Creek* | NC DEC | Burke | Forested/scrub shrub restoration | undetermined, Site was removed before soils were evaluated | About one year of data |
| *Devils Racetrack* | NC DEQ | Johnston County | Mitigation/restoration site | undetermined, Site was removed before soils were evaluated | Possibly limited data |

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|---|---|---|---|---|---|
| *Haw's Run* | NC DEQ | Pender | Ranges from wet savannah to forested swamp | undetermined, Site was removed before soils were evaluated | |
| *Hofler Property* | NC DEQ | Gates | Mitigation/restoration site | undetermined, Site was removed before soils were evaluated | Limited Data |
| *Lilliput* | NC DEQ | Brunswick | Riverine | undetermined, Site was removed before soils were evaluated | Limited Data |
| *Lyle Creek Mitigation site* | NC DEQ | Catawba | Riverine Mitigation Site | undetermined, Site was removed before soils were evaluated | Limited Data |
| *Moore Property* | NC DEQ | Johnston | Riverine Floodplain | undetermined, Site was removed before soils were evaluated | Limited Data |
| *North Fork Mountain Creek Site* | NC DEQ | Catawba | Mitigation/restoration site | undetermined, Site was removed before soils were evaluated | less than one year of data, doesn't show drawdown or recharge |
| *Powell* | NC DEQ | Bertie | Mitigation/restoration site | undetermined, Site was removed before soils were evaluated | No Data |
| *Stanley's Slough Stream and Wetland Mitigation Site* | NC DEQ | Northampton | Riverine Forested Wetland | undetermined, Site was removed before soils were evaluated | Stream Restoration - less than one year data |
| *Twin Bays* | NC DEQ | Duplin | Forested depressional/mineral flat? | undetermined, Site was removed before soils were evaluated | Restored cropland - reference well just off site - less than one year of data |
| *Underwood* | NC DEQ | Chatham | Forest riverine Restoration | undetermined, Site was removed before soils were evaluated | Under one year of data |

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|---|---|---|---|---|---|
| *Sandhill Natural Area* | NC DEQ | Moore | Mitigation/restoration site | undetermined, Site was removed before soils were evaluated | Limited data |
| *Buck Horn* | VACOE | Unpublished | Mitigation/restoration site | undetermined, Site was removed before soils were evaluated | Limited data |
| *Hampton Golf course* | VACOE | Unpublished | Mitigation/restoration site | Tomotley | Discontinuous data |
| *West Neck* | VACOE | Unpublished | Mineral Flat | Tomotley series | Less than one year of data |
| *Woodville Park* | VACOE | Unpublished | PFO(1C, 1B, 1A, 4B, 4A, 4C) | Maggett, Tomotley, Bertie | Jan-May, not full year data |
| *Wellington park* | VACOE | Isle of Wight | Unpublished | Chickahominy | Limited Data |