Evaluation of a Water Budget Model for Use in Wetland Design

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

in

Biological Systems Engineering

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August 2, 2013
Blacksburg, Virginia

Keywords: wetland hydrology, modeling, Modflow, mitigation, evapotranspiration

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Abstract

Wetland ecological function greatly depends on the wetland hydrology. As a result, correctly estimating the wetland water budget, is essential to the success of created wetlands. A wetland water budget model, Wetbud, was developed by collaborators from Virginia Tech, Old Dominion University, and the Technical University of Crete for estimating wetland water budgets to assist wetland design in the Virginia Piedmont. The Wetbud model has basic and advanced modules. The basic module uses level pool routing to compute average monthly water levels. Based on the groundwater model MODFLOW, the advanced module estimates groundwater interactions and vegetative resistance to surface flows on a daily timestep. The overall goal of this research was to assess Wetbud as an uncalibrated design model for mitigation wetland water budget estimation in the Virginia Piedmont. Specific objectives were to compare predictions using the basic and advanced modules and to compare the Thornthwaite and the FAO-56 Penman-Monteith potential evapotranspiration estimation methods for the design of created wetlands. The Wetbud model was tested using data from two existing mitigation wetlands. Both modules produced reasonable results; however, the basic module did not accurately predict drawdown occurring during dry periods. Results showed that the Wetbud advanced module produced more accurate and detailed results when compared to the basic module: Nash-Sutcliffe model efficiency ratings for the advanced module ranged from to 0.44 to 0.63. Potential evapotranspiration estimates by the FAO-56 Penman Monteith method were more accurate than those from the Thornthwaite method in nearly every model scenario.

Table of Contents

List of Figures

Introduction

The term wetland is often used loosely to describe many different environments with different functions and characteristics. From a regulatory standpoint, the United States (U.S.) Army Corps of Engineers defines the term "wetland" in Section 404 of the 1977 Clean Water Act Amendments as follows:

> *"Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions."(EPA, 1992)*

This definition has become the U.S. regulatory standard. Before the ecological value of wetlands was understood, wetland destruction was common practice and was even encouraged by some governmental policies (Mitsch and Gosselink, 2000). It is estimated that approximately 283,000 ha of intertidal wetlands; 7.7 million ha of forested wetlands; and 2.8 million ha of emergent wetlands have been drained or lost since the 1950s (Dahl and U.S. Fish and Wildlife Service., 2011). However, through the late 1970s and 1980s the importance of wetland functions was recognized and the beginnings of protective regulations were put into motion.

Recognized wetland functions include water-quality improvement, groundwater recharge, shoreline stabilization, and water retention, which moderates fluctuations in stream flow. Wetlands also maintain a unique environment for both aquatic and terrestrial species of plants and animals, some of which are included on the U.S. rare and endangered species lists (U.S. National Research Council Committee on Mitigating Wetland Losses., 2001). As the importance of wetland ecosystems gained recognition, regulatory initiatives were implemented. In 1987, a National Wetlands Policy Forum was convened by the Conservation Foundation at the request of the U.S. Environmental Protection Agency (EPA) to investigate the issue of wetland management in the U.S. (Mitsch and Gosselink, 2000). The overall result of the forum was a recommendation that the U. S. mandate no further overall net loss of the remaining wetlands base.

Compensatory mitigation developed out of this no net loss legislation. The primary goal of compensatory mitigation is to increase or maintain the quantity and quality of the overall wetland base in the United States (Bingham and U.S., 1990). A compensatory mitigation project involves the creation, restoration, enhancement, or preservation of a wetland to offset permitted losses of wetland functions. Compensatory mitigations projects are often referred to as mitigation wetlands, created wetlands, and/or wetland restorations. Individual projects have a desired set of hydrological, water quality, habitat functions depending on the conditions of the project watershed and the permitted loss site (National Research Council Committee on Mitigating Wetland Losses., 2001). In 2002, the United States National Research Council (NRC) set a goal of restoring 40,500 km^2 of wetlands including 643,738 km of river-riparian ecosystem. (Mitsch et al., 2002). Compensatory mitigation plays a critical role in meeting the national goal of no net loss of wetlands as well as the NRC goal of area restored (USACE, 2008). However, it is important that compensatory mitigation projects incorporate quality of wetland function into design as well as overall gain of wetland acreage. Trends in restored or mitigated wetland location and type have implications for the Unites States national policy goals, wetland biodiversity, and geospatial distribution (Dahl and U.S. Fish and Wildlife Service., 2011). While compensatory mitigation has been successful at increasing the area of wetlands on a national level, the diversity and spatial distribution has not been maintained. For example, freshwater emergent marshes and/or open water ponds have been preferentially reestablished compared to forested wetlands which are rarely reestablished successfully (Dahl and U.S. Fish and Wildlife Service., 2011).

According to the regulation set forth by the United States Army Corps of Engineers (ACOE), created or restored wetlands should have the same form and function as the ecosystems they are replacing. While this concept seems basic and straightforward, wetland ecosystems vary based on a number of local and regional factors. These factors need to be considered when designing compensatory mitigation wetlands to ensure the successful replacement of wetland functions. Factors influencing design include site selection, hydrologic analysis, water source and quality, plant material selection, soil and geologic conditions, buffer zone placement, and maintenance procedures. All of these factors play a role in design, but hydrology is one of the primary factors controlling wetland functions (Arnold et al., 2001; Koreny et al., 1999; Zhang and Mitsch, 2005). Many of the complex interactions that occur in a wetland are dictated by the hydrology, or water budget (Hammer and Kadlec, 1989). Even slight changes or differences in wetland hydrology can have a major effect on plant and animal species composition as well as ecosystem productivity (Mitsch and Gosselink, 2000). Consequently, hydrology is often the primary initial focus of regulators when defining compensatory mitigation project success but is difficult for designers and engineers to accurately predict.

To eliminate some of the complexity in estimating wetland hydrology, it has become an "industry standard" to underlie mitigation wetlands with a compacted clay to minimize groundwater interactions. This method, referred to as the "Pierce methodology" after its original developer and promoter, utilizes subsoil compaction to minimize permeability and limit groundwater interactions. The "Pierce methodology" can create a wetland system that is above as well as disconnected from the groundwater table in the area, creating what is referred to as a perched wetland system (Mitsch and Gosselink, 2000). In a perched wetland system, soils are considered epiaquic because wetness and reductions occur in the surface horizons down to 50 cm. Epiaquic soils contrast traditional wetland soils which are considered endoaquic soils where true groundwater wetness exists in the lower horizons (Richardson and Vepraskas, 2001).

Limiting groundwater interactions reduces the number of parameters in the water budget, allowing the designer to base the water budget primarily on precipitation data and to use outlet structures to regulate water levels (Koreny et al., 1999; Owen, 1995; Pierce, 1993). However, limiting groundwater flows limits wetland functions and does not mimic the hydrologic interactions that occur in natural wetlands. As an alternative, the MODFLOW groundwater simulation model has been used to consider groundwater flow in wetland design (Bradley, 2002; Gloe, 2011). Through the use of a groundwater model such as MODFLOW there is potential for designers to more accurately predict wetland hydrology and to improve mitigation wetland design.

Goals and Objectives

The overall goal of this research was to assess a newly developed model, Wetbud, as an uncalibrated design model for mitigation wetland water budget estimation in the Virginia Piedmont. Specific objectives include the following:

1. To compare the Pierce methodology with the Wetbud advanced (MODFLOW-NWT) groundwater simulation method for the design of mitigation wetlands; and
2. To compare the Thornthwaite and the FAO-56 Penman-Monteith potential evapotranspiration estimation methods for the design of perched and groundwater driven mitigation wetlands.

To complete the objectives listed above, Bender Farm Mitigation Site (latitude: 38°37'52" N, longitude: 77°35'07" W) in Fauquier County, Virginia and Cedar Run Mitigation Bank (latitude: 38°37'34" N, longitude: 77°32'54" W) in Prince William County, Virginia were modeled using

Wetbud. The Bender Farm Mitigation Site is a groundwater-driven mitigation wetland, as opposed to Cedar Run Mitigation Bank which is a perched wetland. Both wetland sites were constructed in the basic module and the Cedar Run Wetland Mitigation bank was constructed within the advanced module. Model output was compared to observed groundwater monitoring data for each site. Additionally, evapotranspiration values were estimated using two different methods and model effectiveness as well as seasonal trends in the estimations were investigated.

Literature Review

A review of existing literature on wetland hydrology, current design standards for water budget prediction, and previous models used for water budget estimation is presented below. The fundamental aspects of wetland hydrology, its components, and their influence on the system are also presented. Different estimation and prediction techniques for each component and associated errors were also considered with the intent of understanding the advantages and disadvantages of the different prediction methods. Current design models used for created and restored wetlands were also examined. Required input data such as weather, precipitation, and soil information were investigated. The precision and accuracy of the different design models as well as the evaluation and assessment techniques for past and present models were reviewed. This information was used to understand which models are used for wetland creation and restoration design, both currently and previously; how these models are assessed and evaluated for design in specific geographic locations, and what considerations need to be emphasized during the assessment process.

Wetland Hydrology and Water Budgets

Due to the regulatory requirements and ecological importance placed on wetland hydrology, it is important to adequately understand the components affecting wetland hydrology. Quantification of the wetland water balance can aide in distinguishing wetland type and function (Bradley, 2002). The basic mass balance equation, change in storage = inputs – outputs, is used to express the hydrologic processes in a wetland and is often referred to as a water budget (Owen, 1995). The general water mass balance can be broken down to inputs and outputs as illustrated graphically in
Figure 1 and mathematically in Equation (1):

$$\frac{\Delta S}{t} = P + R + GW_i - ET - S_o - GW_o \tag{1}$$

where, P = Precipitation;
R = Runoff;
GW_i = Groundwater In;
ET = Evapotranspiration;
S_o = Surface Outflows; and,
GW_o = Groundwater Out

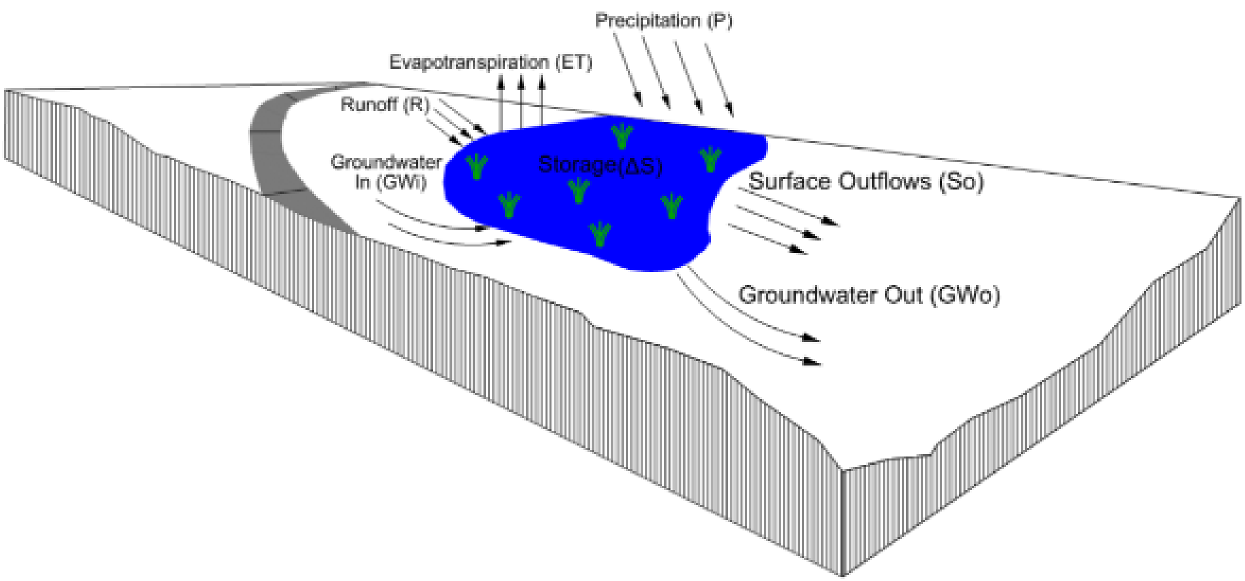

Figure 1: Inputs and outputs of the wetland water budget based on the mass balance equation.

Considering

Figure 1, and Equation 1, and assuming the dimensions of a constructed wetland are known, the wetland water level can be calculated using the parameters listed. While the process seems simple, water-budget calculations are affected by difficulties in measuring water inflows and outflows, and by the relatively large errors associated with many of the budget components (Favero et al., 2007). Some components of the wetland water budget are easily measured and can be directly applied to the mass balance equation, such as precipitation and surface outflows. Others such as evapotranspiration and groundwater inflows and outflows are difficult to measure and/or estimate; several studies have investigated techniques to quantify reasonable values (Favero et al., 2007; Mansell et al., 2000; Meselhe et al., 2010; Pyzoha et al., 2008). Components of the wetland water budget and typical methods of estimation and prediction are discussed below.

Precipitation

In the water budget calculation, precipitation is one of the major inputs considered. Precipitation is defined in the water budget as the direct net rainfall or snowfall that inundates the wetland minus the interception losses that occur due to wetland vegetation (Chaubey and Ward, 2006). Precipitation data can be obtained from sources such as the National Oceanic and Atmospheric Administration (NOAA) or National Climatic Data Center (NCDC); however, precipitation can vary based on geographic location and season, and interception values are difficult to calculate. For example, in a study conducted in Taylor Slough in the southern Everglades, with a neotropical wet season, the study area received 80% of its precipitation from June to November (Michot et al., 2011). In comparison, in two semi-permanent marshes at Cottonwood Lake in a Stutsman County, North Dakota, snowmelt was a major influence on spring precipitation and overall water level in the wetland (Poiani and Johnson, 1993). These two extreme cases illustrate how precipitation timing can vary across different physiographic provinces and climates. In the Virginia Piedmont, seasonal thunderstorms can result in localized heavy precipitation events. This variation in precipitation has a direct effect on the overall water budget and should be investigated in preliminary wetland design investigations.

Surface Inflows and Outflows

Surface inflows and outflows are based on factors including wetland topography, drainage area, relative distance to the nearest surface water, wetland storage capacity, and outlet structure design. Two main sources of surface inflows are surface runoff from adjacent upland slopes and water input from adjacent tributaries or streams. Rainfall along with runoff can be the major water input to the wetland system (Chaubey and Ward, 2006). The most commonly used method for converting rainfall values to runoff values for surface inflows into wetlands is the National Resource Conservation Service (NRCS) rainfall excess estimation technique (Favero et al., 2007; Owen, 1995). This method is shown below in Equations (2) and (3). It utilizes watershed land use and soil type to determine an empirical curve number which relates excess runoff volume on a daily time step to precipitation and volume of total soil storage based on initial abstraction and infiltration values where initial abstraction includes all losses before runoff begins (Novotny, 2003). This method is widely used for constructed wetland design as well as wetland hydrology studies. It is important to acknowledge that determining the storage value (S) in these equations is unit-dependent and the equation will change based on the desired units.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2}$$

where, Q = Depth of Runoff
P = Precipitation
S = Storage in Soil

$$S = \frac{25{,}400}{CN - 254} \tag{3}$$

where, S = Storage in Soil (mm)
CN = Empirical Curve Number

Separate from runoff values, stream inflows add another layer of complexity to water budget estimation. Stream inflows can have a major influence on the water budget of constructed wetlands and can be the major source of water input into the wetland system (Sanderson et al., 2008). Stream inflows directly into wetlands are most simply calculated using the stream cross-sectional area and average velocity. Estimating inflows using this technique can be difficult when flow rates in streams vary drastically with seasonal precipitation events (Mitsch and Gosselink, 2000). In addition, many small streams are ungaged and seasonal stream stages are difficult to estimate.

An even more difficult prediction of surface inflow and outflow is when wetlands are adjacent to streams. It is common for streams to occur adjacent to wetlands when surface water begins to develop a preferential flow path through the saturated area (Restrepo et al., 1998; Zhang and Mitsch, 2005). During flood events, surface water flows into and out of wetlands, from and to adjacent streams and rivers. This shallow overland sheet flow is difficult to measure and is often roughly estimated as a percentage of the total stream flow, introducing error into the water budget (Owen, 1995). In addition, adjacent floodplains are often covered in vegetation which resists flows into and out of wetlands. Vegetation size and type can greatly affect the rates of surface flow and can lead to errors in water budget estimation if not accounted for. The large fluctuation of stream water levels, the location of the wetlands on the floodplains, and the presence of varying types of vegetation create a dynamic hydrologic system that is difficult to model.

A common assumption is that failure of constructed wetlands to develop the designed ecosystem is due to a lack of water. However, many failed mitigation sites are too wet to support the target ecosystem. For example, a study conducted on Virginia Department of Transportation mitigation wetland sites in eastern Virginia found that, due to conservative water budgeting and a lack of understanding of local water sources, 21% of sites were too wet (Whittecar and Daniels, 1999). To give designers the ability to control hydrology, outflow structures are frequently included in constructed wetland designs (Koreny et al., 1999; Meselhe et al., 2010). Outflow structures simplify designs by providing the designer an easy way to regulate stage and surface outflow rate within the wetland; however, concentrated outflows are not typically observed in natural wetlands, indicating a lack of understanding of wetland hydrologic processes on the part of the designer. Outflow rates are also affected by the resistance from vegetation within the wetland. Vegetative resistance can reduce designed outflow rates, resulting in deeper ponding and longer inundation periods. Wetland mitigation sites with underestimated design outflows as a result of vegetation resistance end up too wet. Mitigation wetlands that are designed to be too wet lack summer and fall dry down periods and struggle to support forested vegetation (Whittecar and Daniels, 1999).

Evapotranspiration

Evapotranspiration is one of the more difficult parameters in the water budget to estimate. Evapotranspiration refers to the evaporation that occurs from the water and the soil in a wetland coupled with the moisture that is removed through vascular plants to the atmosphere. Evapotranspiration is largely a product of meteorological factors such as solar radiation, temperature, humidity, and wind speed (Hammer and Kadlec, 1989; Mitsch and Gosselink, 2000). Multiple studies have shown that evapotranspiration is a major component of the water budget: reported values for evapotranspiration range anywhere from 20-40% and as high as 69% of water losses (Arnold et al., 2001; Bradley, 2002; Sanderson et al., 2008; Sun et al., 2011). The wide range of estimated evapotranspiration losses can be attributed to the variety of ways it can be calculated, the difference in measurement techniques, and differences due to varying vegetation.

Two common methods for predicting evapotranspiration are the Thornthwaite and FAO-56 Penman-Monteith combination method. The Thornthwaite method uses mean monthly temperature and latitude to predict monthly evapotranspiration, as illustrated in Equations (4) and (5) (Ward and Trimble, 2004).

$$E_{tp} = 16\left[\frac{10T}{I}\right]^{a} \tag{4}$$

$$I = \sum_{j=1}^{12}\left[\frac{T_j}{5}\right]^{1.514} \tag{5}$$

where: E_{tp} = monthly predicted evapotranspiration (mm)
T = mean monthly temperature (°C)
T_j = mean monthly temperature during month j (°C)
a = $6.75\text{x}10^{-7}I^3 - 7.71\text{x}10^{-5}I^2 + 1.792\text{x}10^{-2}I + 0.49239$

The FAO-56 Penman-Monteith equation, shown in Equation 6, is based on the Penman equation (Penman, 1948). It was initially designed to use with agricultural crops; however, by setting the parameters to mimic spatially consistent vegetation across a study site, such as short grass, with no shortage of water, the equation can be used to model the wetland conditions (Mao et al., 2002).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \tag{6}$$

where, ET_o = evapotranspiration (mm/day)
U_2 = wind speed measured at 2 meter height (m/s)
R_n = net radiation flux at surface (MJ/m^{2}s)
G = soil heat flux (often estimated) (MJ/m^{2}s)
γ = psychometric constant (kPa °C^{-1})
e_a = Saturation vapor pressure (kPa)
e_d = Actual Vapor Pressure (kPa)
T = Temperature (°C)
Δ = Slope of saturation vapor pressure curve

While the FAO-56 Penman-Monteith equation provides more accurate estimates for evapotranspiration (Kumar et al., 1987), the required solar data supplied by the National Solar Radiation Database (NSRDB) is not readily available for all areas and dates. Typically, wetland designers use the Thornthwaite equation to estimate evapotranspiration for created wetland design due to the fact that the needed climatic data are readily available through NOAA and/or NCDC (Pyzoha et al., 2008).

Groundwater Inflows and Outflows

It is important that the interactions between groundwater and other hydrologic water budget components in constructed wetlands be accurately simulated (Restrepo et al., 1998), as groundwater provides a major portion of the water supply to natural wetlands which are not perched systems (Whittecar and Daniels, 1999). In natural wetlands, net groundwater flows can either be into or out of the wetland, based on the relative location of the local groundwater and wetland water levels. Groundwater inflows occur when the wetland water surface is hydrologically lower than the surrounding water table. Springs and seeps often have groundwater inflows due to their location at the base of slopes where groundwater commonly intercepts the land surface. When water levels in a natural wetland are higher than the surrounding groundwater, water will flow out of the wetland. If the wetland water level is much higher and hydrologically disconnected from the water table in the area the wetland is referred to as perched (Mitsch and Gosselink, 2000). Depending on the type of wetland and its surroundings, groundwater can have a large or small effect on wetland hydrology. Varying groundwater influence results in different ecological processes as the amount of groundwater flow impacts the intensity and rate of soil chemical and physical processes and plant community response (Richardson and Vepraskas, 2001). In created wetlands, it is important to identify and reproduce the groundwater interactions that are present in the system that is being replaced so that the ecological processes and benefits are consistent.

Groundwater inputs are difficult to quantify because they cannot be measured directly (Favero et al., 2007). To estimate groundwater inputs at a wetland site, subsurface flow patterns must be understood and monitored using a series of observation wells and piezometers. However, heterogeneity within the wetland substrate can greatly affect flow patterns. In addition, seasonal variations in the hydraulic gradient require that monitoring be conducted over a long period to understand groundwater patterns. This lengthy study period increases the costs of created wetland projects (Favero et al., 2007; Zhang and Mitsch, 2005). In addition, soil properties such as porosity and permeability can significantly affect groundwater hydrologic processes. A highly porous wetland soil will hold large amounts of water, while highly permeable soils, such as sands, allow rapid groundwater flow rates (Mitsch et al., 1988). Varying soil parameters and surface water interactions significantly affect groundwater dynamics.

Due to the difficulty in predicting groundwater flow, the “industry standard” for design has been the Pierce methodology. The Pierce methodology involves on-site subsoil compaction to create a clay liner to minimize vertical permeability. The Pierce methodology reduces the number of parameters in the water budget, and allows the designer to base the water budget primarily on precipitation, evapotranspiration, and outflow data (Koreny et al., 1999; Owen, 1995; Pierce, 1993). However, limiting groundwater flows limits wetland functions. As an alternative, the MODFLOW groundwater simulation model can aide in calculating groundwater flow in wetland design (Bradley, 2002). By utilizing the MODFLOW groundwater simulation model, designers can account for groundwater inputs and outputs in the wetland water budget and ultimately improve constructed wetland designs by eliminating the need for compacted clay liners.

Constructed Wetland Water Budget Modeling

The application of the Pierce methodology along with pressure to increase wetland acreage gains, financial considerations, and engineering constraints have unintentionally shifted wetland mitigation projects from forested wetlands and marshes, to open water depressions (Dahl and U.S. Fish and Wildlife Service., 2011). Open water depressions are typically designed with an impermeable clay-lined bottom installed to eliminate groundwater/surface water interaction and to ensure ponding (Pierce, 1993). The Pierce methodology creates a wetland system that is easier to design, but it does not effectively replicate the form and function of forested wetlands and marshes (Dahl and U.S. Fish and Wildlife Service., 2011).

If an impermeable clay liner is not installed, it is typical for projects to use Darcy’s law to calculate groundwater flow rates, where a proportional relationship of the hydraulic conductivity and hydraulic gradient are used to estimate the discharge through porous soil. Alternatively, an assumption about a constant infiltration rate (net loss) is made about the wetland soil and used for design. These design assumptions simplify the wetland water budget, making it easier for designers to predict water levels. However, ecological functions are often not correctly replicated when this approach is applied. In addition, by limiting the water budget components, evapotranspiration is often found to be the most influential component in the water budget (Sanderson et al., 2008). The emphasis on evapotranspiration rates causes a major design concern as these rates are difficult to estimate accurately. In more recent years, studies have investigated using groundwater modeling programs to incorporate groundwater flux into the wetland water budget. By incorporating groundwater flow, less emphasis is placed on evapotranspiration and fewer assumptions are made about wetland hydrology.

Chaubey and Ward (2006) analyzed the hydrologic budget of a 15.1-ha wetland located within the Talladega Wetland Ecosystem (TWE) in Hale County, Alabama. Each component of the wetland water budget was measured over a two year period including net precipitation, surface inflows, stream overbank flows, groundwater inflows, surface outflows, groundwater outflows, and evapotranspiration. Evapotranspiration was also estimated using the Penman-Monteith (PM) method on a daily basis. Study results showed that precipitation was the largest inflow and evapotranspiration was the largest outflow in the water budget which is consistent with results of previous studies (Mansell et al., 2000). The results also showed that groundwater flow accounted for approximately 20% of the total outflow. While Chaubey and Ward did not construct a model to estimate wetland parameters, their in-depth investigation of the water budget showed how influential groundwater dynamics can be in a natural wetland system and the importance of incorporating groundwater in created wetland design.

In a study by Arnold et al. (2001) a long-term wetland water budget model was developed for a proposed 15.4 ha wetland site within the Trinity River Mitigation Bank in Fort Worth, Texas. In the design, water would be diverted from the adjacent Walker Creek to create and maintain function in a floodplain wetland system. The Soil and Water Assessment Tool (SWAT) model was used to simulate stream flows, and was calibrated using a base flow filter system to ensure that the stream flows could support the wetland hydrology. In the base flow filter system, surface runoff and base flow, or flow derived from groundwater flow or flow out of soils, are separated and calibrated individually. A wetland sub-model was used to simulate the interaction between the soil and groundwater system within the wetland. The required submodel inputs included weather data, topography, soils, growing season, vegetation type, initial water storage, maximum surface area, and drain flow rate. Water balance equations for inflows, evapotranspiration, and seepage were only utilized in the case where the wetland submodel indicated a ponded condition. Potential evapotranspiration values were calculated using the Penman-Monteith equation. While seepage was considered in the model if groundwater saturated the soil profile seepage was set to zero. Groundwater inflow to the wetland was assumed zero, using justification that the soils were clayey and had low permeability.

The SWAT model for Trinity River Mitigation Bank revealed simulated wetland flows can be calibrated to gauged watershed data to develop long-term hydrologic budgets. This study supported extended modeling periods rather than the typical wet, dry and average years (Mansell et al., 2000; Pierce, 1993) based on the concept that a model that accurately simulates the water budget over a decade increases confidence that the system hydrology is understood. The study supported *in situ* monitoring for gaining knowledge about constructed wetland sites, but addressed that modeling provides a more efficient method of gathering hydrologic knowledge for a proposed site for extended periods.

Mansell et al. (2000) modeled the local hydrology of a cypress pond/flatwood forest system in Florida using a multidimensional water flow and solute transport numerical model that linked surface water, groundwater, and unsaturated soil zones. The modeled output was compared to observed water level data. Precipitation and evapotranspiration were the primary inputs and outputs, respectively, for the water budget. A form of Richards equation for describing two-dimensional variably saturated flow for isotropic subsurface conditions was used to estimate groundwater flow. The Priestley-Taylor equation was used to estimate total potential evapotranspiration rates and was calibrated using groundwater and surface water measurements from an adjacent experimental cypress pond. Differences between measured and simulated data were summarized using the Average Absolute Deviation (AAD) method; overall results found that AAD values were 13 cm and 16 cm for the pond and uplands, respectively. AAD errors were greatest in the dry year and lowest in the wet year. This study verified that while precipitation and evapotranspiration are typically the primary inputs and outputs, to achieve the best prediction results for the water budget some form of groundwater flow estimation needs to be incorporated. In addition, the AAD results demonstrated how estimating the wetter portion of wetland hydrology is typically easier than creating the needed hydroperiod including seasonal dry-down.

Bradley (2002) simulated the annual water table dynamics of the 9.5 ha Narborough Bog floodplain wetland in Central England. The simulation was an extension of an advanced monitoring program that was carried out from 1991 to 1992. The hydrological data obtained from the monitoring study were used in the development of a MODFLOW model of the wetland. A field survey was done to determine the subsurface flow properties of the soil on the site to use in the MODFLOW model. Three layers were used within the MODFLOW model - an alluvial aquifer, a compressed layer of wood peat, and an overlying deposit of herbaceous peat. Hydraulic conductivities and specific yields were estimated using the information from the monitoring study as well as lab experiments with samples of the wetland substrate.

The MODFLOW finite difference grid had 36 rows and 15 columns with 10 m by 10 m cells. The model was run on a daily time step with daily means for evapotranspiration and precipitation based on data from an adjacent weather station. Independent MODFLOW packages including recharge and evapotranspiration were used for model inputs and outputs. In addition, the River package was loaded into MODFLOW for subsurface exchanges between the site and an adjacent river. Calibration was done for selected 10-day periods of the monitoring study that were characterized by negligible evapotranspiration due to temperature and/or negligible precipitation due to drought. For the calibration period with no precipitation or evapotranspiration, the predicted water surfaces were identical to the field observed data. For the calibration periods where there was precipitation but no evapotranspiration, the model results differed from the water surface by no more than 0.01 m. Similarly, for the calibration periods with evapotranspiration but no precipitation, the model results differed from the water surface by no more than 0.01 m. The results of the calibration period illustrated how the variation in wetland water storage can be predicted using a transient numerical model simulation. Model comparison to measured data was conducted using the Root Mean Squared (RMS) statistic (Bradley, 2002).

Bradley (2002) cited the accuracy of the evapotranspiration estimates as one of the largest limitations of model function, recommending more attention be paid to improving evapotranspiration estimation. Results showed that at the grid scale used, variability in hydraulic conductivity and/or specific yield does not affect model accuracy. Even though the stratigraphy of the site had more variation than could be compensated for by the 10 m by 10 m grid, the model was still able to predict wetland hydrology with some accuracy. The ability of the model to produce accurate results with a 10 m by 10 m grid supports usability of MODFLOW for wetland modeling. While users have to understand the basic stratigraphy of a site, they do not have to have detailed information to accurately estimate the water budget. Furthermore, the model results showed the importance of estimating surface water and groundwater interaction from an adjacent river or stream into a floodplain wetland. MODFLOW's flexibility to load separate packages such as the River package used in this study and correctly model interaction between an adjacent stream and a floodplain wetland supports its application for wetland water budget monitoring.

Model Assessment

Model assessment is an important step in the process of model development. As shown by the studies outlined above, accurate water budget models can contribute to ecosystem management decisions. Model assessment provides a way of comparing the predictive ability of different hydrologic models. While the model components, input parameters, and level of detail can vary, model results typically consist of a hydrograph indicating water table levels in a wetland over a corresponding season and time period. Comparing model results to measured water level data provides a good measure of model accuracy. In addition, statistical methods can be used to make data comparisons and aid in model assessment.

Nash and Sutcliffe (1970) proposed an efficiency rating (NSE) which is commonly used for evaluating model performance (eqn. 7). NSE value ranges from -∞ to 1 with 1 indicating a perfect a fit. Negative NSE values show the mean of the observed time series provides a better predictor than the model (ASCE, 1993; Krause, 2005).

$$NSE = 1 - \frac{\sum (O - P)^2}{\sum (O - O_{mean})^2} \quad (7)$$

where, O = observed values
P = model predicted values
O_{mean} = mean of the observed values

An advantage to the NSE rating is that it can be applied to a variety of model types and can provide a goodness-of-fit indicator for most if not all surface water and other continuous moisture models (McCuen et al., 2006). The flexibility of the NSE rating, along with an endorsement by the American Society of Civil Engineers (ASCE, 1993), has made it a commonly used assessment method throughout hydraulic and hydrologic modeling.

Research Methods

Collaborators from Virginia Tech, Old Dominion University, and the Technical University of Crete have developed a wetland water budget model, Wetbud. Wetbud is designed to estimate water budgets for wetland mitigation design in the Virginia Piedmont. In this study, basic and advanced modules within the Wetbud model were evaluated based on existing mitigation wetland water level data. Two existing mitigation sites were simulated using the basic module and one wetland mitigation site simulated with the advanced module of Wetbud. Estimated water elevations for both models were compared to existing monitoring well data for the sites to assess model accuracy. The basic module of Wetbud was developed based on the traditional mass balance method operating on a monthly basis and treating the wetland as level

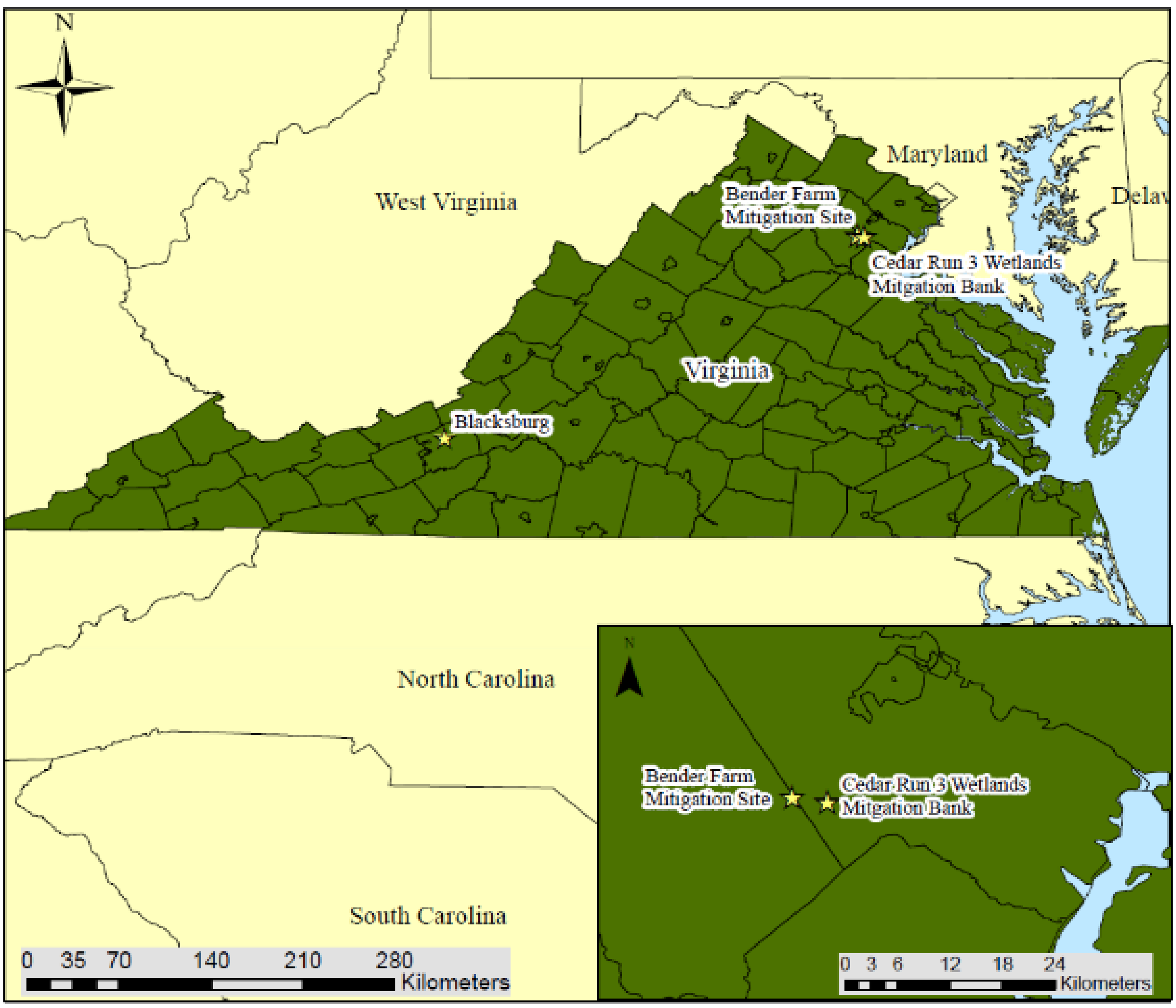

Figure 2: Study Site Locations

pool. The advanced module is a generated user interface designed to develop and run a simplified MODFLOW-NWT model. The advanced module incorporates advanced groundwater dynamics, sloping wetland topography, and surface water flow resistance due to vegetation. In addition, the advanced module provides a higher level of spatial precision compared to the average values used in the basic module. The FAO-56 Penman-Monteith (Penman) and Thornthwaite methods of potential evapotranspiration (PET) methods were incorporated in both the basic and advanced modules. Model performance was statistically analyzed using the Nash-Sutcliffe model efficiency rating for both the basic and advanced modules, as well as the two different evapotranspiration methods (ASCE, 1993).

Study Sites

Data from two existing wetland mitigation sites were used to test Wetbud and to compare the Penman and the Thornthwaite PET models. The design of the two sites is different and, as a result, the hydrology differs. The sites were chosen to test the breadth of the Wetbud model design competences and to investigate model capability in designing both traditional Pierce mitigation wetlands (Pierce, 1993) and groundwater-driven mitigation wetlands within the Virginia Piedmont. Both sites are located in the Potomac drainage basin of the Piedmont Physiographic Province of Virginia where the climate is humid temperate.

Bender Farm Mitigation Site (latitude: 38°37’52” N, longitude: 77°35’07” W) is located in Fauquier County, Virginia on the west bank of the third order stream Cedar Run within the HUC 0207010 watershed (Figure 2;Figure 3). Before the wetland creation and restoration was completed in November 2006, the 9.90 ha area was actively used for agriculture, primarily hay and pasture. Drainage ditches were present to quickly convey runoff from the adjacent agricultural fields and dairy operation to Cedar Run. The overall project goal was to re-establish seasonally saturated, forested wetlands in the Cedar Run floodplains to provide wetland and hydrologic functions similar to those of a natural forested floodplain wetland. By conveying agricultural runoff into a series of shallow, braided channels, Marsh Resources, Inc. increased the surface flow path length by a factor of 10. Minor excavation (less than 0.3 meters) was also done to reduce high points within the wetland and to establish ephemeral pools. To increase detention time and promote ponding within the wetland, a constructed outlet of soil and riprap was constructed with an invert elevation of 55.75 m in the middle of the outlet berm (Figure 3)

(Acorn Environmental, 2005). The maximum elevation on the site occurred in the most northwestern corner at an elevation of 56.10 m.

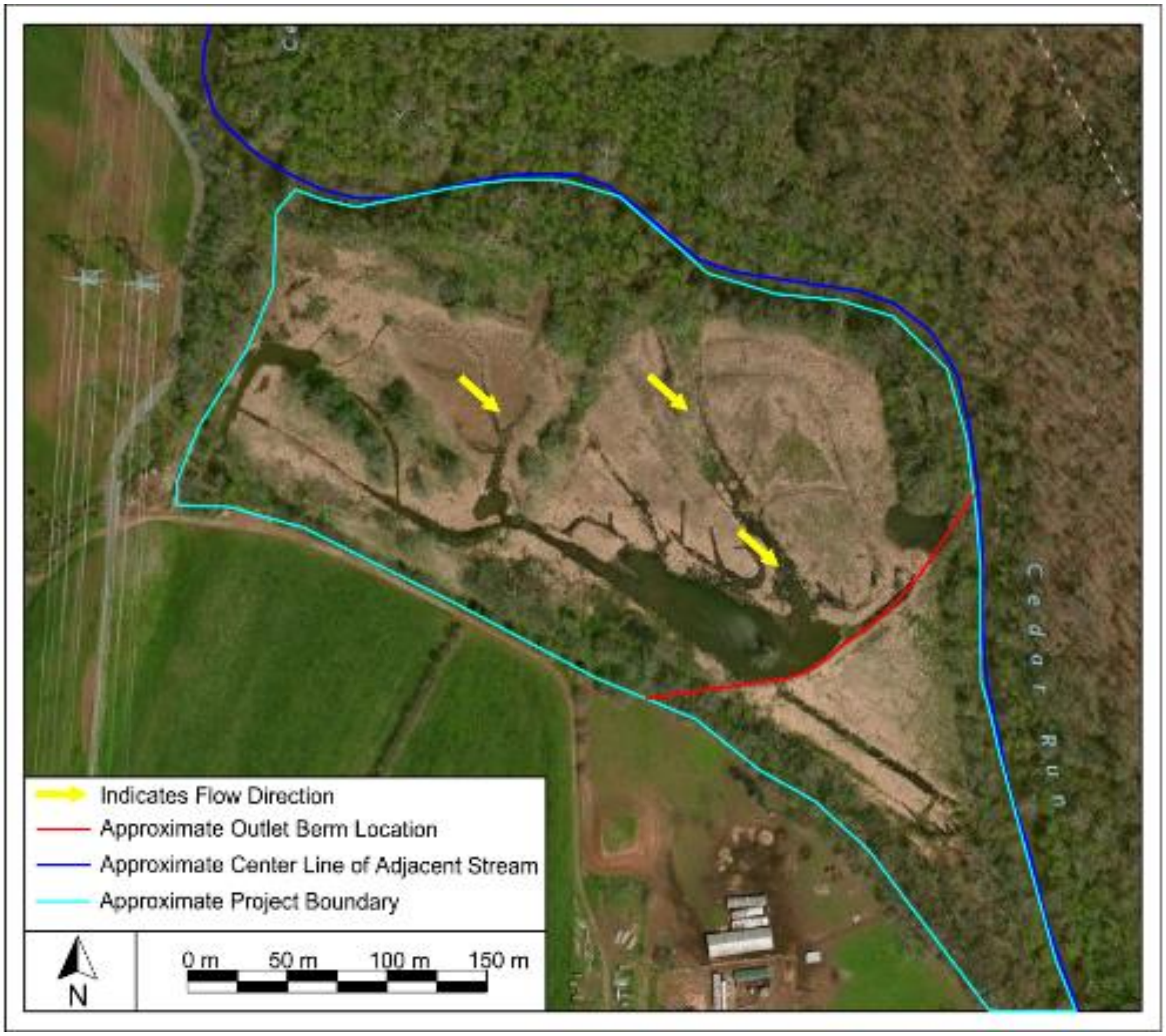

Figure 3: Bender Farm Mitigation Site (latitude: 38°37’52” N, longitude: 77°35’07” W) layout and details.

The original *in situ* soils at Bender Farms Mitigation Bank consist predominately of Rowland silt loam (map unit 5A) with 0% to 2% slopes. Rowland soils are formed in fine alluvial sediments, are moderately well drained, and belong to Hydrologic Group C. Rowland soils are not considered hydric but they are frequently flooded for brief periods. Other minor soils included in the USDA Soil Survey information were Sowego loam (14B) with 2% to 7% slopes, Penn loam (73C) with 7% to 15% slopes, Ashburn silt loam (74B) with 2% to 7% slopes, and Albano silt loam (79A) with 0% to 2% slopes(Acorn Environmental, 2005; USDA, 2012).

The majority of the soils were left undisturbed on the site with minimal excavation done to develop microtopography based on the design.

Cedar Run Wetland Mitigation Bank (latitude: 38°37’34” N, longitude: 77°32’54” W) is located in southern Prince William County, Virginia in the headwaters of Cedar Run, a tributary of the Occoquan River. Cedar Run Wetland Mitigation Bank lies within the HUC 02070010 watershed. Wetland Studies and Solutions, Inc. (WSSI) in Gainesville, Virginia designed and constructed Cedar Run. An in-depth site study was done prior to design and construction, including a soil survey and investigation, groundwater monitoring, and stratigraphic cross sections. The preconstruction soil survey identified the in-situ soils types as Aden silt loam (1A), Albano silt loam (3A), Calverton silt loam (11B), Delanco fine sandy loam (16A), Dulles silt loam (17A), and Panorama silt loam (46B). Albano silt loam, Dulles silt loam, and Delanco fine sandy loam dominated most of the site. Albano series are poorly drained soils with slow infiltration and are identified as hydric. Dulles series soils are moderately and somewhat poorly drained, and are not considered hydric. Delanco series soils are moderately well and somewhat poorly drained and are not considered hydric (USDA, 2012; WSSI, 2001).

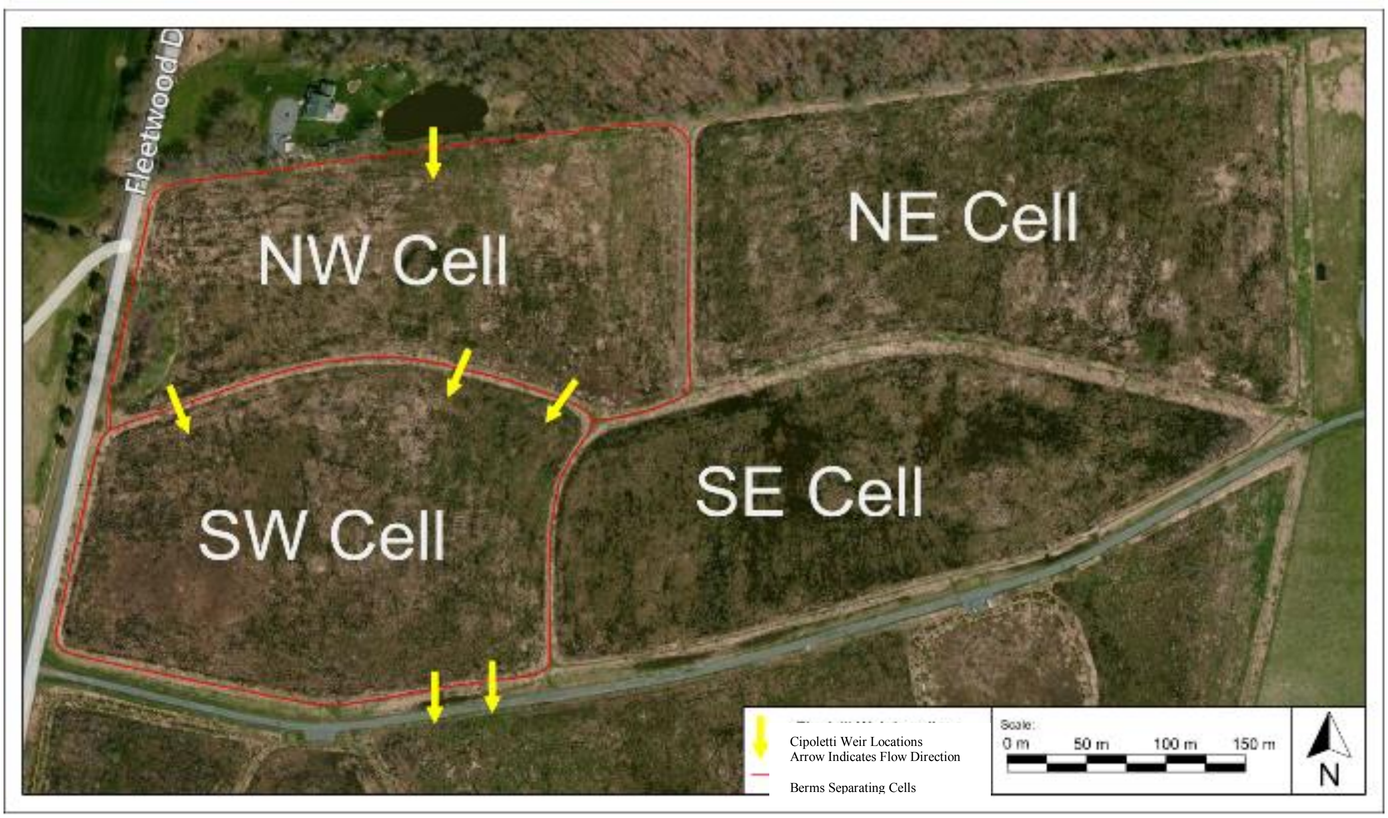

Figure 4: Cedar Run 3 Wetland Mitigation Site layout (latitude: 38°37’34” N, longitude: 77°32’54” W).

The overall goal at the Cedar Run Wetland Mitigation site was to produce an area that was predominately a forested wetland with some shrub/scrub and emergent areas caused by microtopography from grading and disking. To achieve this goal, a traditional Integrated Pierce design was implemented where the site was cut and the underlying soils were compacted to create a perched system (Pierce, 1993). The constructed site strata consist of a 23-cm layer of returned topsoil, underlain by a 31-cm thick layer of compacted impermeable subsoil. The bedrock on site was weathered shale and sandstone and the existing soils consisted of abundant fine grained soils and sediments. The design required the impermeable soil layer be compacted so that the hydraulic conductivity was approximately 2.3×10^{-7} cm/sec based on field-testing. By compacting the existing subsoil layer, a perched system was created where groundwater could be assumed negligible within the wetland water budget.

The site is separated into four cells using berms. Only two of the wetland cells, the northwest (NW) and the southwest (SW), were used for the study. The NW and SW cells are 5.5 ha and 5.9 ha respectively and are hydrologically connected by a series of Cipoletti-style weirs (Figure 4). The original design only included two weirs to connect and drain the NW and SW cells, but after the site was completed three additional weirs were added to reduce ponding and encourage forested vegetation (WSSI, 2001). To calculate water inputs into the SW cell from the NW cell, a water budget for the NW cell was calculated in the basic and advanced modules. Water overtopping the weirs within the water budget was added to SW cell as surface inflow.

The major difference between the wetland water budgets at the two sites is the groundwater component and the stream inputs. At the Bender Farm Mitigation Site, the adjacent stream flow and potential groundwater input from the hillslope at the south end of the site appear to have a major effect on the overall wetland hydrology of the site. While, at the Cedar Run Wetland Mitigation site, surface water drives the hydrology and groundwater inputs and outputs are minimized by the use of an impermeable subsoil layer. The contrasting design of the sites was ideal for testing the Wetbud software and achieving the overall project goals.

Water Level Data

Water level data for the Cedar Run Wetland Mitigation site was acquired as part of a separate study conducted by Dr. W Lee Daniels and Nicole Troyer (Troyer, 2013). Water levels within the SW cell (Figure 5) of the wetland were monitored from September 1, 2009 to May 22, 2012. The three monitoring wells were installed per the U.S. Army Corps of Engineers standard observation well guidelines (USACE, 2005). Water level data loggers (Remote Data Systems WL40, Navassa, NC) were installed in the three observation wells and were set to record water levels every ten minutes. The water level data for each day was averaged to obtain daily water levels within the SW cell of the Cedar Run Wetland Mitigation Site.

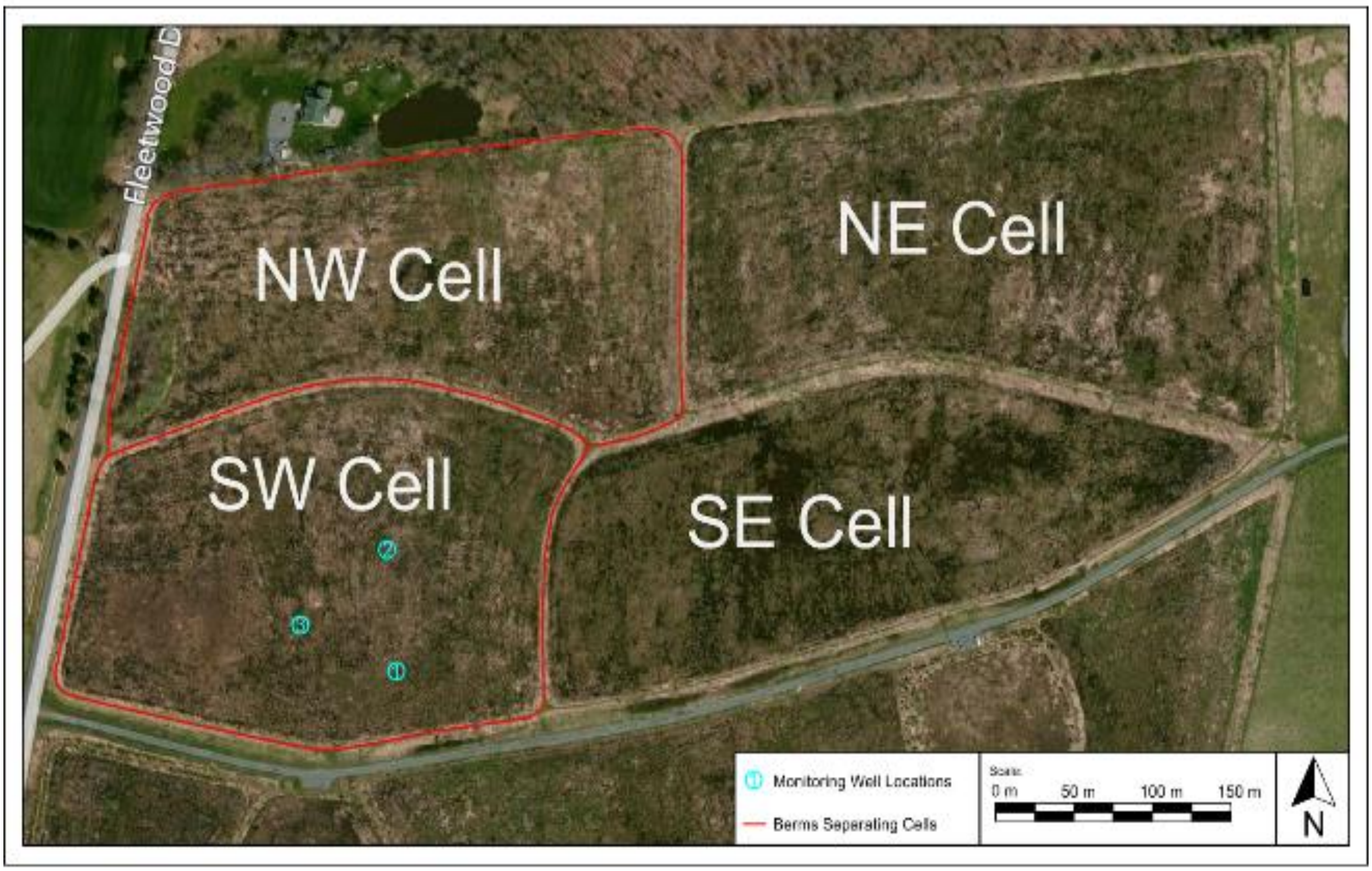

Figure 5: Monitoring well locations at Cedar Run 3 Wetland Mitigation Site.

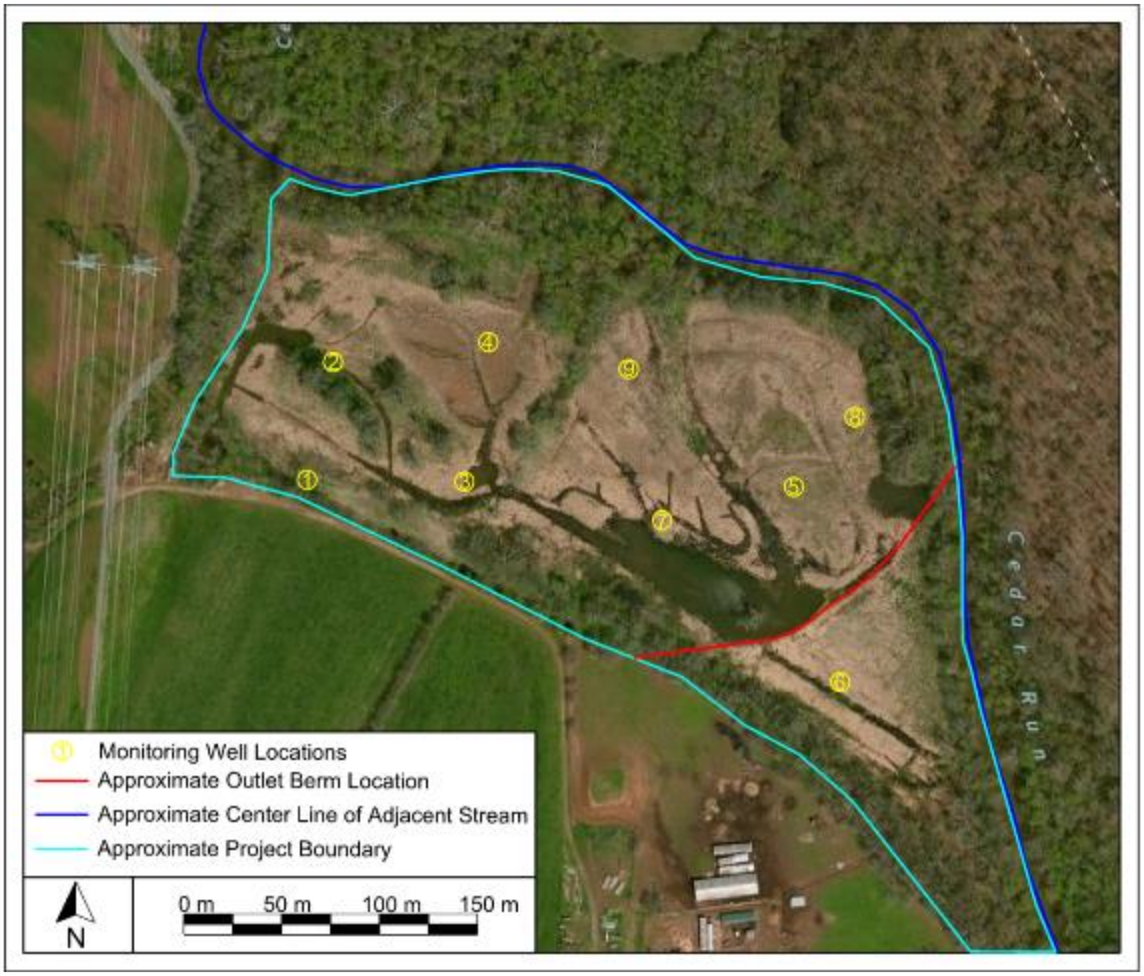

Figure 6: Monitoring well locations at Bender Farms Mitigation Site.

Water level data for the Bender Farms Mitigation Site was obtained from Marsh Resources Inc. Marsh Resources Inc. downloaded data from eight monitoring wells as part of their pre-construction and post-construction monitoring plan. Daily water levels were collected with automated loggers within the Bender Farm Mitigation Site. Daily water levers were supplied from March 26, 2010 to November 3, 2010 and from March 10, 2011 to August 30, 2011. Monitoring well locations are shown in Figure 6. While Figure 6 shows nine monitoring wells, data from monitoring well six was not supplied for the monitored period. Daily data supplied by Marsh Resources Inc. was averaged to obtain an average daily water level across the entire site to be used for Wetbud basic module comparison.

Basic Model Description

As stated previously, the Wetbud model contains a basic and an advanced module. The basic module computes average monthly water levels within a wetland using a mass balance equation (eqn. 1), for the user specified time period of the model run. The user can model the default wet, dry, and average years calculated by the Wetbud model using corresponding WETS station information, specify custom wet, dry, and average years, or specify a custom range of time for the modeled period (McLeod, 2013). Meteorological data including precipitation and minimum and maximum temperatures are required for estimating the components of the water budget when using the Thornthwaite PET method. Additional data including wind speed, solar radiation, and dew point are needed when using the FAO Penman-Monteith PET method. Creating a user-friendly data retrieval and storage system within the Wetbud basic module interface was an emphasis during model development. Wetbud output for the basic model is expressed as an average depth of water relative to ground surface within the study site. Calculations within the basic module are performed in units of depth.

Precipitation

Within the Wetbud basic module, daily precipitation data from NOAA, NCDC, and NRCS WETS stations can be imported and used for water budget calculations. In addition, users can import their own daily precipitation data. A mapping interface shown in Figure 7 is implemented in the model so that users can determine the closest possible available weather station to their site. Once the closest station is identified, the data can be imported into and stored in Wetbud for the wetland water budget calculation.

Weather Data

Weather data are needed in the Wetbud basic module for the PET calculations. Similar to the precipitation data, available weather data can be identified on the mapping interface (Figure 7), downloaded, and stored within the Wetbud basic module. Weather data from the NOAA Global Historical Climatology Network (GHCN) and the NOAA Global Summary of the Day (GSOD) are available for download. Stored weather data include average daily temperature, maximum and minimum daily temperature, dewpoint, and wind speed. Users also have the option to manually import weather data.

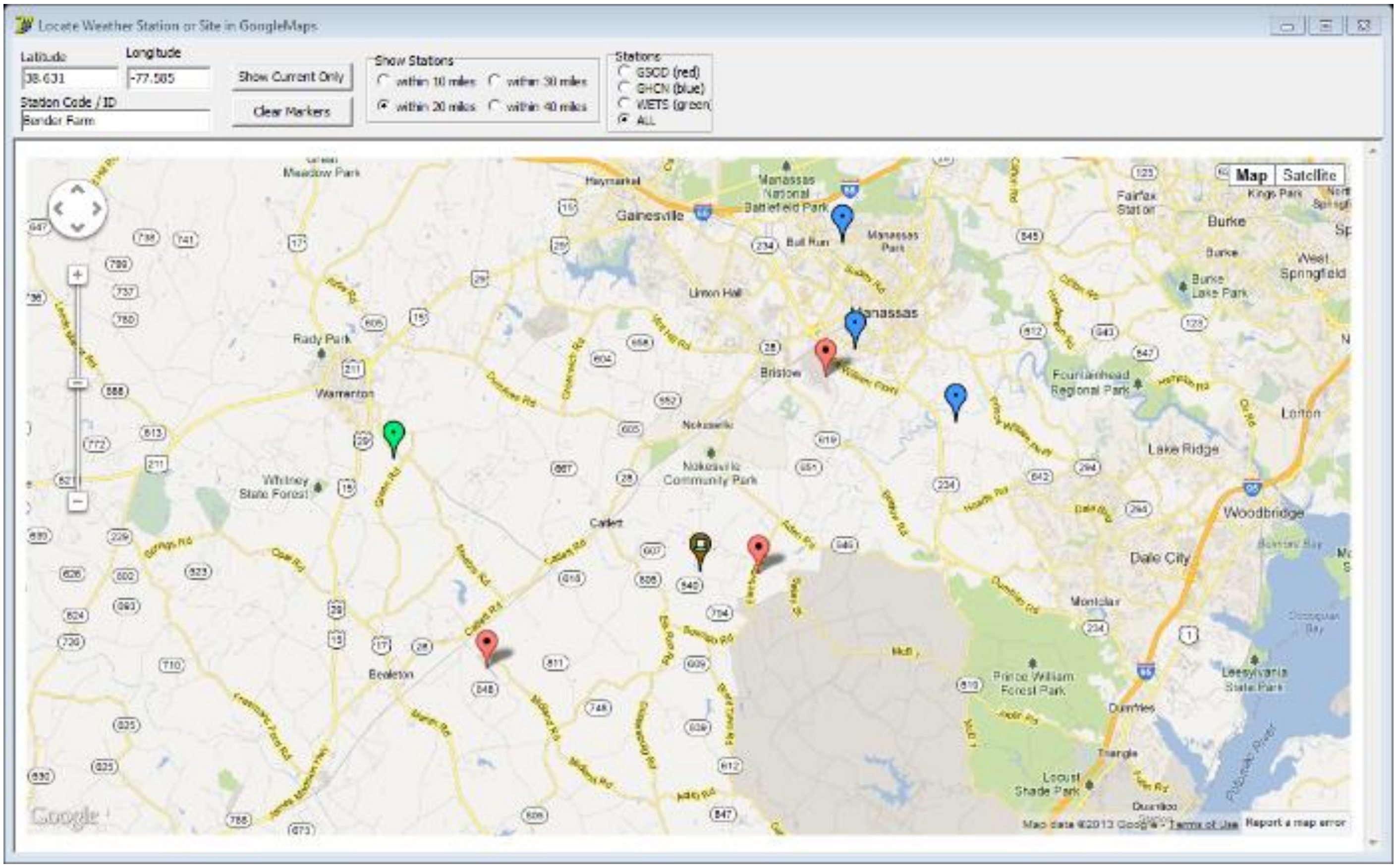

Figure 7: Example of the Wetbud mapping interface for data retrieval showing all available weather and precipitation data within 32.2 km (20 miles) of the Bender Farm Mitigation Site

Surface Inflows

The Wetbud basic model calculates surface runoff into the wetland from the adjacent drainage area using the NRCS rainfall excess estimation technique (2). The user supplies the drainage area, the curve number, the area of the constructed wetland, and any existing wetland area. Wetbud calculates daily runoff values based on the precipitation data supplied from the selected weather station. A default initial abstraction value is set to 0.2 to compensate for soil storage. The rainfall excess estimation technique calculates the depth of water over the drainage area (Q_R). To convert the drainage area runoff depth to the water depth into the constructed wetland site (D_W), a runoff inflow volume (R_V) is calculated by multiplying the drainage area runoff depth (Q_R) by the drainage area (A_{DR}) (eqn. 8). The water depth into the constructed wetland site (D_W) is calculated by dividing the runoff inflow volume (R_V) by the constructed wetland area (W_A) (eqn. 9).

$$R_V = Q_R * A_{DR} \tag{8}$$

$$D_w = R_V / W_A \tag{9}$$

where, Q_R = Drainage Area Runoff Depth (m)
A_{DR} = Drainage Area (ha)
R_V = Runoff Inflow Volume (m^3)
W_A = Constructed Wetland Area (ha)
D_W = Depth Contributed to Wetland Water Budget (ha)

Runoff is calculated on a daily time step within the basic module. To calculate monthly values for the wetland water budget calculation, the values are summed.

The Wetbud basic module can also incorporate other surface inflows that occur on the site. A 'user water in' option and a 'stream overbank flow' option are both available in the basic module. Users can input depth of water per month into the wetland based on an external calculation. This feature allows the user to incorporate any surface water input into their sites that may not be accounted for with SCS/NRCS rainfall excess estimation submodel.

Evapotranspiration

The Wetbud basic module can calculate PET using the FAO Penman-Monteith PET equation (4) or the Thornthwaite PET equation (4). As an alternative, the user can also import values calculated externally into the basic module.

For the Thornthwaite calculation, mean monthly temperature values can be downloaded from any NOAA weather station or imported manually by the user. Site latitude is supplied by the user within the project data.

Most of the variables in the FAO Penman-Monteith equation (4) can be obtained by NOAA weather stations. However, average relative humidity (RH_{avg}) (eqn. 10) slope of the saturation vapor pressure curve (Δ)(eqn. 12), saturation vapor pressure at the maximum temperature (e_{max}) (eqn. 11) and saturation vapor pressure at the minimum temperature (e_{min}) (eqn. 11) are calculated (Maidment, 1993; NRMED, 1998). Actual vapor pressure (e_d) is calculated (eqn. 13) using values of average relative humidity (RH_{avg}), saturation vapor pressure at the maximum temperature (e_{max}), and saturation vapor pressure at the minimum temperature (e_{min}).

$$RH_{avg} = 100 * \frac{\exp\left(\frac{17.271T_D}{237.7+T_D}\right)}{\exp\left(\frac{17.271T}{237.7+T}\right)} \tag{10}$$

$$e_s = 0.6108 * \exp\left(\frac{17.27T}{237.3+T}\right) \tag{11}$$

$$\Delta = \frac{4098e_s}{(237.3+T)^2} \qquad \text{kPa °C}^{-1} \tag{12}$$

$$e_d = \frac{\frac{RH_{AVG}}{100} * (e_{max}+e_{min})}{2} \qquad \text{kPa} \tag{13}$$

where, RH_{avg} = Average relative humidity (%)
e_s = saturation vapor pressure at corresponding temperature (kPa)
Δ = Slope of saturation vapor pressure curve (kPa $°C^{-1}$)
e_d = Actual vapor pressure (kPa)
T = Average daily temperature (ºC)
T_D = Dewpoint (ºC)

Net longwave radiation, solar radiation, and extraterrestrial radiation are needed to calculate net radiation flux at the surface. In addition, an albedo value and a clear sky radiation fraction need to be assumed. Solar radiation data provided by the NSRDB can be accessed within the Wetbud basic module interface. However, if needed data are not available from NSRDB, solar radiation data can be collected from the Western Regional Climate Center (WRCC) RAWS USA climate archive and imported manually. Extraterrestrial solar radiation data is not provided by the WRCC RAWS USA climate archive. Extraterrestrial solar radiation (S_0) can be calculated using equations 15 – 19 (Maidment, 1993).

$$\omega_s = \arccos(-\tan\phi\tan\delta) \tag{15}$$

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.405\right) \tag{16}$$

$$N = \frac{24}{\pi}\omega_s \tag{17}$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad (18)$$

$$S_0 = 15.392 d_r(\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \quad (19)$$

where, ω_s = Sunset hour angle (radians)
δ = Solar declination (radians)
ϕ = Site latitude (positive for the Northern Hemisphere, negative for Southern Hemisphere)
N = Maximum possible daylight hours
d_r = Relative distance between the earth and the sun
J = Julian day number
S_0 = Extraterrestrial solar radiation (mm/day)

Albedo values (α) depend on the land cover. Since vegetation will vary based on the site, users have the ability to define the albedo value for their particular site. Measured solar radiation (R_m) is adjusted to factored solar radiation (R_f) based on the user specified albedo factor using Equation 20 (Maidment, 1993).

$$R_f = (1 - \alpha) * R_m \quad (20)$$

Actual clear sky radiation (R_{so}) is determined within the basic module using Equation 21 with the 22-year National Aeronautics and Space Administration (NASA) average clear sky radiation fraction (f_r) value of 0.7 (NRMED, 1998). The default clear sky radiation fraction in the basic module is 0.7 and it cannot be changed by the user.

$$R_{so} = S_0 * f_r \quad (21)$$

Net longwave radiation (R_{nl}) is proportional to the absolute temperature of the surface raised to the forth power. The relation is expressed by the Stefan-Boltzmann law. Equation 22 shows the calculation of net longwave radiation (R_{nl}) used in the Wetbud basic module (NRMED, 1998).

$$R_{nl} = \sigma\left[\frac{T_{max}+T_{min}}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_f}{R_{so}} - 0.35\right) \quad (22)$$

where, R_{nl} = net longwave radiation (MJ m^{-2} day^{-1})

σ = Stefan-Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1})
T_{max} = maximum absolute temperature during the 24-hour period (K)
T_{min} = minimum absolute temperature during the 24-hour period (K)
e_a = actual vapor pressure (kPa)
R_f/R_{so} = relative shortwave radiation
R_f = measured and factored solar radiation (MJ m^{-2} day^{-1})
R_{so} = clear-sky radiation fraction (MJ m^{-2} day^{-1})

Once net longwave radiation is calculated *(R_{nl})*, net radiation flux *(R_n)* at the surface can be calculated using Equation 23 (NRMED, 1998).

$$R_n = R_f - R_{nl} \quad (23)$$

The psychometric constant (γ) for the Penman equation in the basic module is calculated with Equation 24 (NRMED, 1998). A value of 101.3 kPa is used as the default atmospheric pressure.

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P \quad (24)$$

where, γ = psychrometric constant (kPa °C^{-1})
P = atmospheric pressure, 101.3 (kPa)
λ = latent heat of vaporization , 2.45 (MJ kg^{-1})
c_p = specific heat at constant pressure, 1.013 10^{-3} (MJ kg^{-1} °C^{-1})
ε = ratio molecular weight of water vapor/dry air = 0.622

Soil heat flux (G) for the Penman evapotranspiration calculation is assumed zero in the basic module. It is assumed that vegetation, along with the wetland water surface would interfere and little radiation would reach the ground so heat storage can be neglected (Maidment, 1993). The Penman equation is very extensive, but the calculation is done internally for the user in the basic module. Only basic solar radiation, temperature, and wind speed data are needed for the basic module to perform the calculations outlined above.

Groundwater Inflows and Outflows

The simplest version of the basic module of Wetbud does not include any internal groundwater calculations automatically. However, several Wetbud options exist to permit the user to estimate groundwater inflows and outflows. Users can estimate groundwater flow rates externally and import them as a negative or positive depths in the wetland each month.

Groundwater entering the wetland as well as groundwater leaving the wetland can be imported into the basic module or can be estimated using the wetland effective monthly recharge (WEM) calculation package. The user can input constant groundwater rates over the modeled period or can vary groundwater rates by month for the modeled period. If a constructed wetland is designed using the Pierce methodology and groundwater is assumed negligible, the user can disable the groundwater option within the basic module. If the user wants to use Wetbud for groundwater calculations, the advanced module and the wetland effective monthly recharge (WEM) package are available within the model. More information on the advanced module is provided in the Advanced Model Description section. For more information on the WEM package see McLeod (2013) and (Dobbs, 2013).

Initial Fill and Depth to Weir

The basic module requires the user to define an initial fill value and an average wetland depth to weir. The depth to weir value is the depth of storage within the wetland below the invert of the outlet weir. The depth to weir value defined by the user limits the maximum water depth in the wetland. Any water depth that exceeds the depth to weir value will be converted to outflow each month. For example, if an average depth to weir value in a basic module run is set to 5 cm, the maximum depth in the wetland becomes 5 cm and any depth in the wetland that exceeds 5 cm is assumed to leave through the outflow weir.

The initial fill value input by the user is the depth in the wetland relative to the ground surface for the first month of the modeled period. Initial fill values for subsequent months of the modeled period are based on the wetland water budget for the preceding month. If standard wet, dry, and average analysis years are run, the initial fill value will be used at the beginning of each model year. If a custom time range is used, the initial fill will be used at the beginning of user defined modeled period. Initial fill should not exceed the depth to weir value in the model. If the user wants the wetland to be started full of water with no water storage available, the initial fill should equal the depth to weir. If the user wants to start the modeled period with the wetland empty, the initial fill value should be zero. When determining the initial fill value, the starting season of the modeled period should be used to determine a reasonable water surface elevation to begin the model.

Soil Storage and Surface Storage Factors

The basic module uses a surface storage factor to account for plant volume above the ground surface and a soil storage factor to account for the fillable porosity within the wetland substrate. The surface storage factor and soil storage factor are determined by the user based on soil and site conditions. The surface storage factor and the soil storage factor convert the change in water volume determined by the water budget equation (expressed as a depth) to a head of water (e.g. water surface elevation) within the wetland. The soil storage and surface storage factor concept is displayed graphically in Figure 8**Error! Reference source not found.**

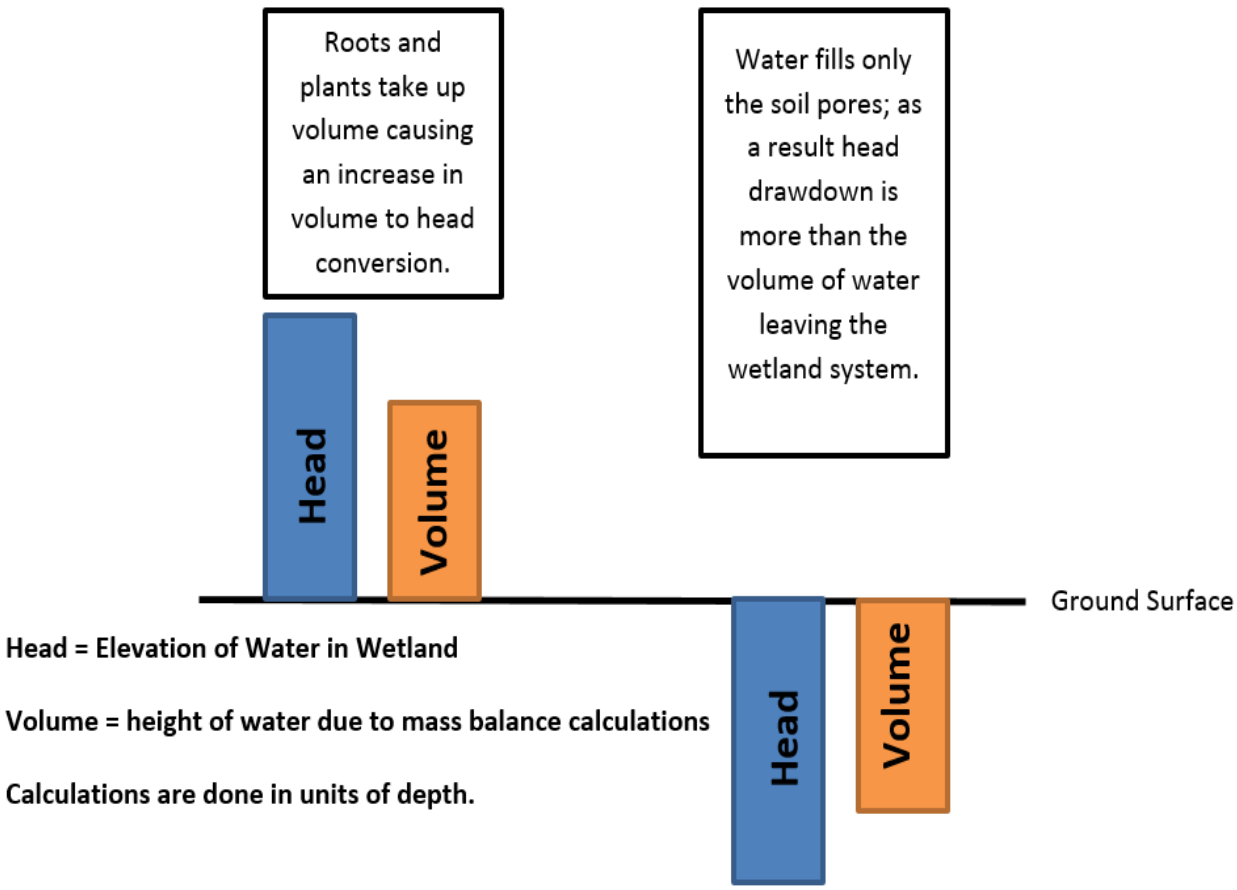

Figure 8: A conceptual representation of the effects of the soil storage and surface storage factor within the Wetbud basic module.

To calculate the water surface elevation for each month in the modeled period, the Wetbud basic module first converts the initial fill elevation from the previous month (factored initial fill in Figure 9), or the user-input initial fill value for the first month, to a volume based on the appropriate factor. Volume of initial fill is calculated using a surface storage factor if the initial fill is positive. If the initial fill value is negative (i.e. water surface below ground surface), the soil storage factor is used to convert the initial water volume to a water table elevation. Using the volumetric initial fill value and the other water budget inputs and outputs within the model, the Wetbud basic module calculates a change in water volume for the month. The result from the water balance equation is then converted back to an elevation within the wetland based on the surface storage factor and/or the soil storage factor. If the water volume balance equation result

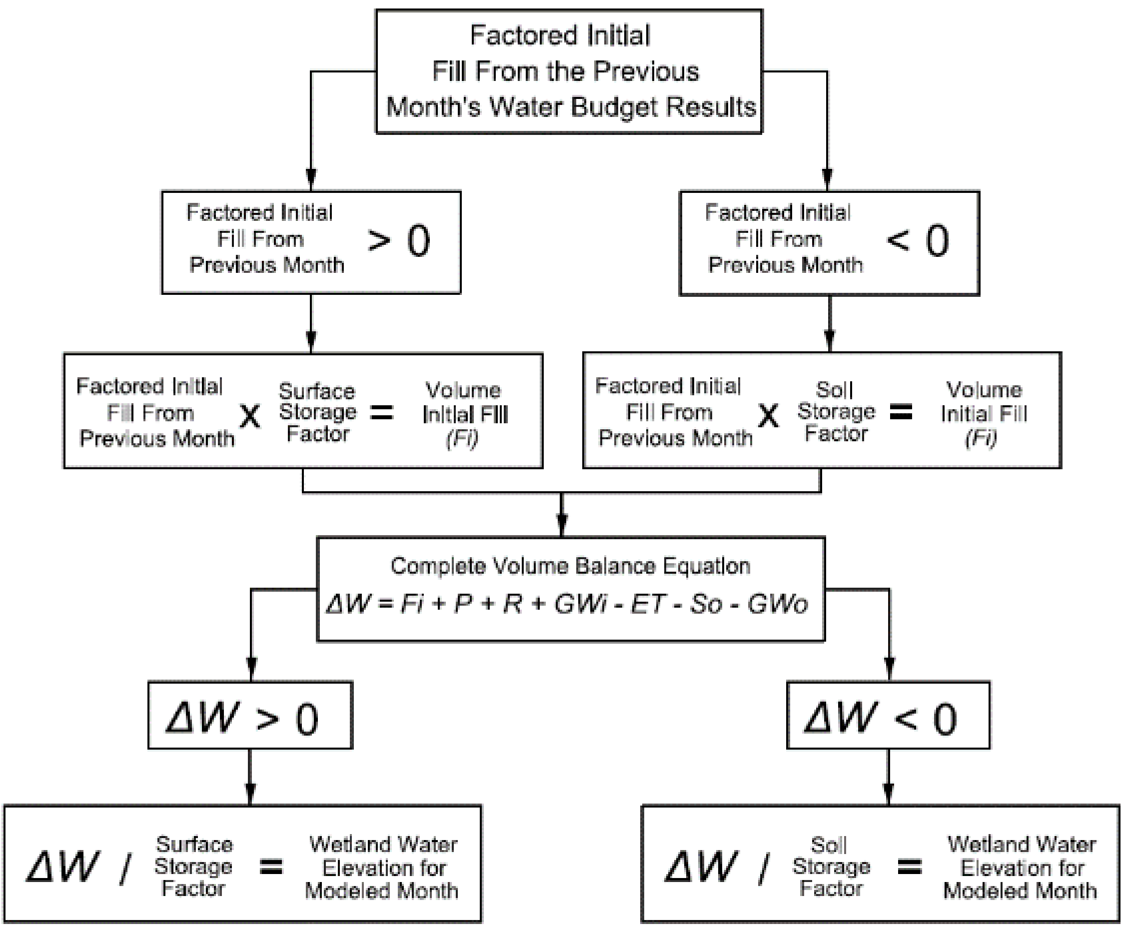

Figure 9: Flow chart showing the calculation process for incorporating the surface storage factor and soil storage factor the Wetbud basic module. Factored initial fill refers to the previous month initial fill which is already factored by a surface/soil factor because it is a water table elevation.

is positive, it is converted to an elevation using the surface storage factor. If the water balance equation result is negative, the water volume is converted to an elevation using the soil storage factor. The calculation process for incorporating the surface storage factor and the soil storage factor is shown in Figure 9.

Basic Model Output Format

The Wetbud basic model outputs the average monthly water level in inches and centimeters for the modeled wetland and period. In addition, the Wetbud basic model also supplies the user with each component of the water budget for the modeled period including monthly values of precipitation, stream inflow, runoff, groundwater in/out, initial fill, evapotranspiration, and outflow. The numerical results for the basic model can be exported to an Excel file. In addition to the numerical results, the results are shown graphically in the results interface of the Wetbud basic model. The Wetbud basic model results interface was designed to allow users to investigate the water budget and all the inputs and outputs within the wetland site and not just the overall water level within the wetland.

Basic Model Setup

The Bender Farms Mitigation site and the Cedar Run Wetland Mitigation bank were each modeled using the Wetbud basic module. The models were set up based on site conditions during the monitored period.

Bender Farms Wetland Mitigation Site

For the Bender Farm Wetland Mitigation Site model, daily precipitation data from the Manassas Regional Airport NOAA station approximately 20 km from the site were used (Figure 10). Missing precipitation values were replaced with data from the Dulles International Airport NOAA station which is approximately 50 km from the site (Figure 10). From the daily precipitation values, daily runoff was calculated using Equation 2 with a curve number of 91and a drainage area of 11.98 ha, based on the design documents (Acorn Environmental, 2005). A runoff volume was calculated for the site using Eqn. 8. The runoff volume was converted to a water volume, expressed as a depth in the wetland, by dividing by the wetland area (9.90 ha) (5).

The Bender Farm Wetland Mitigation Site was run in the Wetbud basic module using both PET calculation methods. For the Thornthwaite calculation, mean monthly temperature recorded at the NOAA weather station at Manassas Regional Airport were used (Figure 10). Missing values were replaced with mean monthly temperatures from the NOAA weather station at Dulles International Airport (Figure 10). For the Penman PET calculation, maximum daily temperature, minimum daily temperature, average daily temperature, dew point, and average wind speed values were measured at the Manassas Regional Airport NOAA weather station (Figure 10).

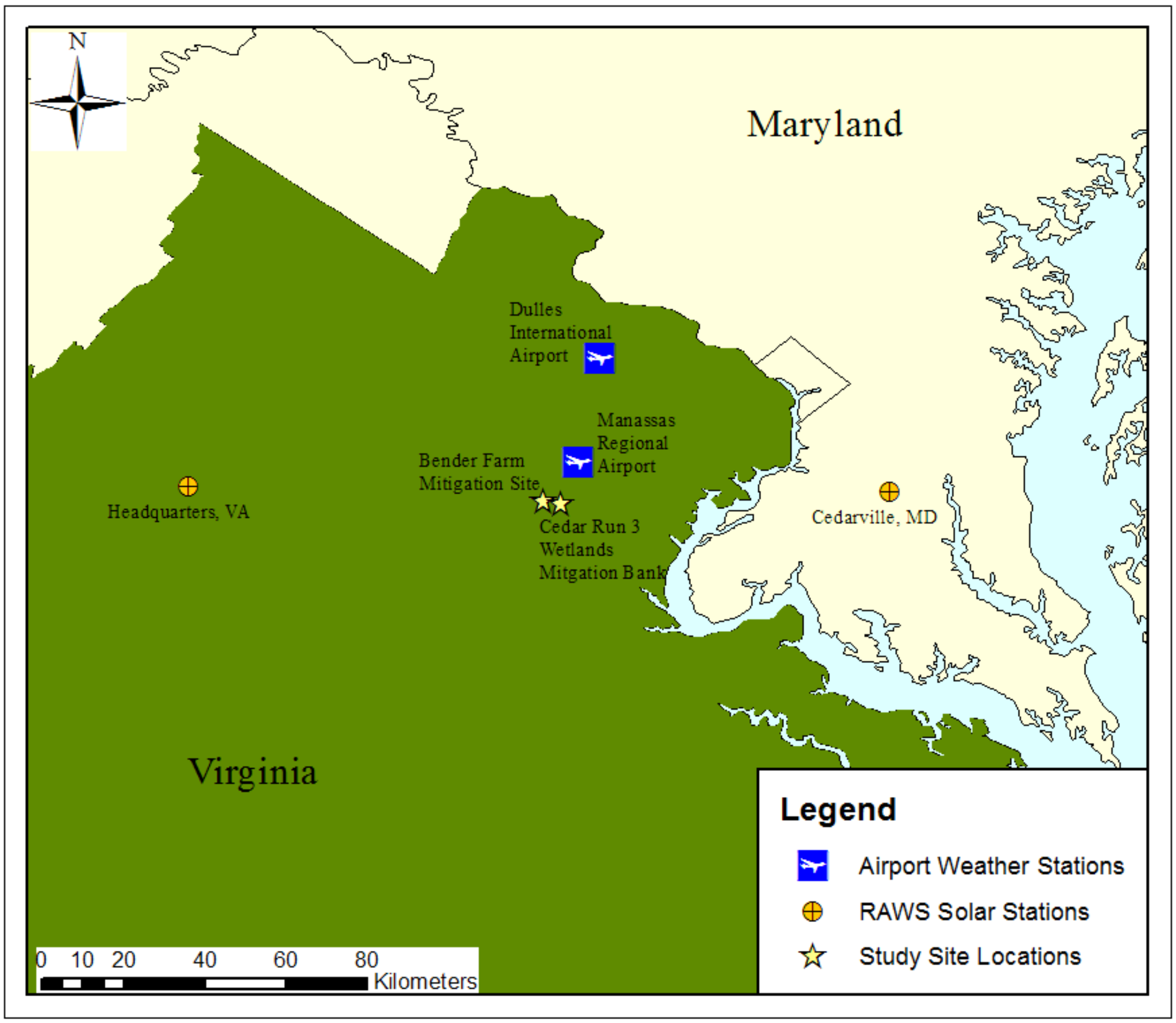

Figure 10: Stations where weather, solar, and precipitation data were collected for the two study sites.

Solar radiation values from the Cedarville, Maryland WRCC weather station and the Headquarters, Virginia WRCC weather station were averaged to estimate solar radiation at the wetland site (Figure 10). Extraterrestrial solar radiation data were not provided by the WRCC RAWS USA climate archive. Instead, Extraterrestrial solar radiation (S_0) was calculated using equations 15 – 18 for the Cedarville, Maryland and the Headquarters Virginia WRCC weather stations (Maidment, 1993). Extraterrestrial solar radiation values were than averaged for the two sites. An albedo value of 0.14 was determined by averaging albedo values traditionally used for open water (0.08) and consistent short grass (0.20) (Maidment, 1993).

The depth to weir value for the Bender Farms Mitigation site was constant for the modeled period. The initial design of the site utilized a storage depth of 2.54 cm over the entire site. To confirm this design parameter, the site grading plan was obtained and the available storage volume when the wetland was fully ponded was calculated. The calculated storage volume was then divided by the entire wetland area to calculate an average depth of available storage in the wetland. The calculation resulted in a depth to weir of 2.46 cm, very close to the design depth to weir value originally used.

The Bender Farm Mitigation Site basic model was run for the time period from January 2010 to August 2011 using the custom analysis range feature. Measured water level data were only supplied from March 26, 2010 to November 3, 2010 and from March 10, 2011 to August 30, 2011; however the model was run for the entire period. January of 2010 was chosen as the first month of the modeled period so that the model run would begin during the wet season and the wetland site could be assumed full with the initial fill value set at 2.46 cm (Mitsch and Gosselink, 2000).

Groundwater flows for the Bender Farms Mitigation Site were calculated externally from the model and imported as monthly variables. Based on the topography in and around the site, the location of the third order stream, and the interbedded shale and sandstone geology with abundant weathered Triassic basin fine grained soils and sediments, it was assumed that groundwater was flowing from the toe of the adjacent up-gradient slope towards Cedar Run. Groundwater in was calculated as the flow passing laterally into the uphill end of the constructed wetland, divided by the surface area of the constructed wetland:

$$GW_{in/out} = \frac{Q_{lat}}{A_w} \tag{25}$$

where, $GW_{in/out}$ = groundwater inflow or outflow (cm/month)
A_w = surface area of constructed wetland (cm^2)
Q_{lat} = lateral flow into uphill end or out of downhill end of constructed wetland (cm^3/month)

Lateral flow into the uphill and downhill end of the constructed wetland was calculated using Darcy's Law, assuming the flow area was a vertical rectangle (Mitsch and Gosselink, 2000) :

$$Q_{lat} = kiA_x \tag{26}$$

where, Q_{lat} = lateral flow into uphill end of constructed wetland (cm^3/month)
i = hydraulic gradient
A_x = cross sectional area of flow (cm^2)
k = hydraulic conductivity (cm/s)

To calculate the cross sectional area of flow for groundwater in, a seepage face length of 167.6 m was taken from the project plans. Using Web Soil Survey estimations of saturated later hydraulic conductivity, the pre-construction soil investigation, and knowledge of the geology in the Virginia Piedmont, a 1 m layer of colluvium on top of a 1 m layer of moderately cemented Triassic sandstone was estimated as the wetland substrate. For Darcy's Law, an estimated hydraulic conductivity of 10 x 10^{-5} cm/s and 10 x 10^{-8} cm/s was used for the colluvium layer and the cemented sandstone layer respectively. It was estimated that the hydraulic gradient ranged from 0.01 to 0.001. A median value of 0.055 was used from the estimated range to calculated groundwater flow at the site.

Groundwater out was calculated in a similar manner as groundwater in. The lateral flow volume out of the down gradient side of the constructed wetland was divided by surface area of the constructed wetland to express the volume as a depth over the wetland (Eqn. 25). To calculate the cross sectional area of flow for groundwater out, a seepage face length along the adjacent stream of 289.6 m was measured on the project plans. From Web Soil Survey information it was estimated that the substrate consisted of a 0.45 m layer of silty loam, a 0.78 m layer of silty clay, and a 0.87 m layer of sandy material. Estimate saturated hydraulic conductivity values were taken from web soil survey and were 9.28 x10^{-6} m/s for silty loam, 1.00 x 10^{-5} m/s for silty clay, and 1.00 x 10^{-7} m/s for the sandy material layer (USDA, 2012).

Hydraulic gradient values for Darcy's Law were calculated as the difference between the water surface elevation calculated for the wetland in the preceding month and the elevation of the adjacent stream baseflow water surface, divided by the width between the wetland edge and the adjacent stream. The adjacent stream head was estimated based on stage data collected at the United States Geological Survey's (USGS) 01656000 Cedar Run stream gage. Since head values were used in the calculation of the hydraulic gradient, different groundwater out values were calculated for the two separate methods of PET.

Based on the Web Soil Survey and the preconstruction soils investigation, a soil storage factor of 0.25 was used. For the surface storage factor, a value of 0.98 was assumed to compensate for volume occupied by the vegetation (Gloe, 2011). For further information on how these soil storage and surface storage factors were applied, see the Soil Storage and Surface Storage Factors section under the Basic Model Description section.

Cedar Run Wetland Mitigation Bank

As previously stated, both the NW and SW cells of the Cedar Run Mitigation Bank were modeled. The NW cell was modeled to get surface outflow from the NW cell into the SW cell. For both cells, on-site precipitation data collected by WSSI were used. Data was downloaded monthly and included daily values of precipitation. Data were imported into Wetbud as daily precipitation and used as an input into the wetland water budget. Any missing data were replaced with data from the Manassas Regional Airport NOAA station (Figure 10).

The runoff volume for the Cedar Run 3 NW cell was calculated using a curve number of 81 and a drainage area of 21.3 ha. The runoff volume was converted to a depth in the constructed wetland by dividing by the NW cell area (5.5 ha). Outflow from the NW cell model was input into the SW cell to represent water flowing through the weir connecting the two cells. The runoff volume for the Cedar Run 3 SW cell was calculated using a curve number of 81 and a drainage area of 26.86 ha. The runoff volume was converted to a depth in the constructed wetland by dividing by the SW cell area (5.90 ha).

The Cedar Run 3 SW cell and the Cedar Run 3 NW cell were run in the Wetbud basic module using both available calculation methods of PET. For the Thornthwaite calculation at the sites, mean monthly temperature values were taken from the NOAA weather station at Manassas Regional Airport (Figure 10). Missing values were replaced with mean monthly temperatures from the NOAA weather station at Dulles International Airport (Figure 10). For the two modeled cells, maximum daily temperature, minimum daily temperature, average daily temperature, dew point, and average wind speed values were obtained from the Manassas Regional Airport NOAA weather station (Figure 10).

To calculate daily solar radiation values for the two cells, solar radiation values from the Cedarville, Maryland WRCC weather station and the Headquarters, Virginia WRCC weather station were averaged (Figure 10). Extraterrestrial solar radiation data were not provided by the WRCC RAWS USA climate archive. Extraterrestrial solar radiation (S_0) was calculated using equations 15 – 18 for the Cedarville, Maryland and the Headquarters Virginia WRCC weather stations and then averaged for the two sites (Maidment, 1993).

The depth to weir value in both cells was held constant for the modeled period. The original estimated depth to weir value used in the design for both cells was 7.62 cm. To confirm the depth to weir value, as-built survey points for the two cells were obtained from WSSI and AutoCAD three dimensional surfaces were created. A fully ponded water surface elevation was estimated based on the surveyed weir inverts. Fully ponded water surface elevations were used to create AutoCAD three dimensional surfaces for each cell. A volumetric difference between the as-built ground surface and the water surface elevation was calculated within the AutoCAD Civil 3D software package for both cells. Volumetric storage values for each cell were divided by the surface area of each cell to obtain an average depth to weir value. Calculated depth to weir values of less than 1.00 cm were substantially less than the design values of 7.62 cm. The reason for the difference in the calculated values and the design values was that the fully ponded water surface elevation within the two cells was assumed flat in the calculation. In reality, the water surface elevation is sloped towards the weir due to vegetation resistance. Since the Wetbud model is being evaluated for uncalibrated design, it was decided that the original design value of 7.62 cm would be better to use for the purposes of model evaluation.

Groundwater inflow into the NW and SW cell was assumed zero based on the compaction of the existing clayey soils on site creating an impermeable layer and isolating the system from any potential groundwater entering the system. The groundwater outflow rate was assumed constant for all wetland water elevations in both cells for every month within the modeled period. The constant groundwater outflow rate was calculated from the designed hydraulic conductivity of the 2.3×10^{-7} cm/s. The hydraulic conductivity was converted to a groundwater outflow rate per month. For both the NW and the SW cell a groundwater outflow rate of 0.50 cm/month was estimated.

Based on the preconstruction soils investigation a soil storage factor of 0.25 was used. For the surface storage factor, a value of 0.98 was assumed to compensate for the volume occupied by the vegetation. For further information on how these soil storage and surface storage factors were applied, see the Soil Storage and Surface Storage Factors section under the Basic Model Description heading.

The NW and SW cells are connected by a series of weirs (Figure 4). To calculate the surface water inflow from the NW cell to the SW cell, the Wetbud basic module water budget was calculated for both methods of PET for the NW cell. From the water budget calculations, monthly surface outflow was determined. Monthly surface outflow was defined as any excess water depth above the depth to weir value in the NW cell. The monthly surface outflow depth was converted to a monthly surface outflow volume by multiplying by the surface area of the NW cell. The monthly surface outflow volume for the NW cell was converted to a monthly surface inflow depth into the SW cell by dividing by the surface area of the SW the cell. The monthly surface inflow depth into the SW cell from the NW cell was imported into the SW cell Wetbud basic module for the modeled period (i.e. the NW cell was modeled first to provide inputs into the SW cell model).

Advanced (MODFLOW-NWT) Model Description

The Wetbud advanced module is a generated user interface (GUI) for a simplified version of the USGS modular finite difference model, MODFLOW-2005. The Wetbud advanced module can also act as a GUI for the edited USGS modular finite difference model, MODFLOW-NWT. MODFLOW-NWT is a Newton formulation for MODFLOW-2005 and is used for solving problems that involve the drying and rewetting of cells (Niswonger et al., 2011). The Newtonian solver used in the MODFLOW-NWT model can compensate for the large fluctuations that occur throughout a wetland hydroperiod. The ability of MODFLOW-NWT to deal with the drying and rewetting of cells in the model makes it a valid application for wetland water budget modeling. This study used MODFLOW-NWT to construct the wetland water budget model. As a result, only information about the MODFLOW-NWT module in Wetbud is included in the model description below.

While Wetbud has a number of different options, the capabilities of MODFLOW-NWT have been limited so that users unfamiliar with the MODFLOW software can construct, edit, and run models. Model setup and analysis for the advanced module requires more detailed information about the proposed wetland site than for the basic module. The required meteorological information for the advanced module is the same as the basic module and Wetbud allows the user to access basic module meteorological data and apply it to the advanced module. Advanced module results are given as head values in each layer for each user specified time step within every cell of the finite difference grid.

Model Units

Establishing the units to be used in the advanced Wetbud projects is a simple but critical initial step for model development. The user must choose a time unit and a length unit that will be used for every input and output within the Wetbud advanced module. Once model units have been designated, all values input into the model need to correspond to the chosen units. For example, if the user chooses units of meters for length and seconds for time, cell size will need to be in meters and time steps will need to be in seconds. Any rates input into the model would need to be in meters per second. The initial units chosen are consistent throughout all values in the advanced model. If model units are changed during model development, new values corresponding to the new units will need to be developed and input.

Model Grid

Setting up the finite difference grid is the initial step for the advanced module. The user must specify the number of rows and columns for the finite difference grid as well as the column and row widths for the grid. The size of the grid is based on the size of the modeled site and the desired spatial accuracy of the model results. The user must also decide how many layers are needed in the finite difference grid to accurately represent the site strata. Column and row widths are identical for all layers within the advanced module. Many of the modular parameters associated with the model such as no flow cells, hydraulic conductivities, precipitation, evapotranspiration, specific yield, and specific storage are assigned to each cell in the advanced module grid.

Model Layers and Layer Parameters

Once the finite difference grid is set up and the number of model layers has been determined, the associated layer parameters must be specified by the user. Wetbud allows users to model wetland layers as flat or sloping. For flat layers, the user supplies elevations for only the top and bottom of the associated layers. For sloping layers, the user can import topographic data at each cell for the top and bottom of each layer and the model interpolates the elevations between each cell. In addition to elevation information, each layer must have a defined horizontal anisotropy condition for the hydraulic conductivities. Horizontal anisotropy conditions for the layers can be set to isotropic, specified per cell of the model grid by the user, or set to a uniform value for the site.

Many of the layer property options are dependent on the flow package and solver package chosen by the user. Wetbud has the option to use either the Layer Property Flow (LPF) package or the Upstream-weighting (UPW) package depending on which MODFLOW model is being used. For the MODFLOW-NWT model, the UPW package must be used. With the UPW package, layer type and interblock transmissivity do not need to be specified by the user. In addition, when using the MODFLOW-NWT model the Newtonian Solver (NWT) package must be used (Niswonger et al., 2011). Wetbud intentionally limits the number of available flow packages and solvers within the program so that users unfamiliar with MODFLOW can still construct and run water budget models and achieve successful convergence. More detailed information on the different available MODFLOW solvers and packages can be found through the USGS software package website (http://water.usgs.gov/nrp/gwsoftware/modflow.html). In addition, both the MODFLOW-NWT and MODFLOW-2005 models have online guides available through USGS.

An additional parameter that the user must decide on for each layer in the Wetbud advanced model is the initial head value. The initial head is the wetland water elevation where the model simulation will begin the iteration solving process for head values within the wetland. Convergent head values will ultimately end up within the same range regardless of the initial head; however computation times will increase greatly if the initial head values are outside a range that is reasonable for the wetland site (Niswonger et al., 2011). It is recommended that wetland water budget models in the advanced module of Wetbud are started in the winter months when it can be reasonably assumed that water will be ponded in the wetland. Under this assumption, the initial head for each layer can be set at a local maximum head for the designed wetland site. For further information on setting up layers in Wetbud, a User's Manual and help file can be accessed within the software.

Time Step Array

Another fundamental parameter in model development is setting up the model time step array. The time step array controls the number of time steps the model will run for, and also dictates the amount of time the model will run for each time step. Consequently, the time step array determines the length of the entire modeled period. The time step length needs to correspond to the model units chosen at the beginning of model development.

In addition to controlling the number of time steps and the length of each time step, the time step array is where the user will designate the model time steps as steady state or transient. In transient simulations, a set of finite-difference equations is reformulated at each time step and a new system of simultaneous equations is solved (Harbaugh, 2005). This study focuses on running transient simulations in the Wetbud advanced model. Within each allotted transient time step, there is a sub step and a time step multiplier assigned. The number of iterations allotted within each time step for the model to converge is assigned by the sub step. The time step multiplier is the ratio of the length of each time step to that of the preceding time step (Harbaugh, 2005). The default value for the sub step and time step multiplier in the Wetbud advanced model is 3 and 1.2 respectively. The default values are recommended for all models and should not be changed by the user unless he/she has previous experience with MODFLOW transient models. More information about the iteration calculation process can be found in the MODFLOW-2005 manual (Harbaugh, 2005).

The time step array is also where time step volumetric rates for modular packages such as recharge, evapotranspiration, and wells are input. More information about the modular packages and the required inputs are outlined in the ensuing sections. Values such as precipitation, surface runoff, and evapotranspiration calculated in the Wetbud basic module can be imported in the time step array for modular packages.

Advanced Model Grid Setup

Once the grid size, layer properties, and time step array are setup in the Wetbud advanced model, the user can begin populating the grid zones and cells zones within the MODFLOW grid.

Grid zones must be populated with hydraulic conductivities and specific yield and storage values for all active packages and cells within an advanced model. Recharge rate rates as well as evapotranspiration rates are also grid zone parameters that need to be specified if the corresponding modular packages are utilized by the model. Cell zones are dependent on site boundary conditions and are only specified as needed by the user. Cell zones can include drains, general head boundaries, monitoring points, no flow cells, wells, and drain returns.

Hydraulic Conductivity

Hydraulic conductivities in the x, y, and z directions in the Wetbud advanced module are set as part of the grid zone parameters. Within the grid zone parameters the user can set up as many conductivity zones as needed to represent the proposed wetland site. Conductivity values are in units of length per time with the exact units corresponding to the units chosen during initial model setup. Once a user sets up conductivity zones, the zones are given a number and color. Within the grid editor the user populates the cells of each layer with the hydraulic conductivity zone of his/her choice. Figure 11 shows a Wetbud advanced model grid, with the top layer populated with a consistent hydraulic conductivity. All of the grid zone and cell zone parameters are designated spatially using a similar interface.

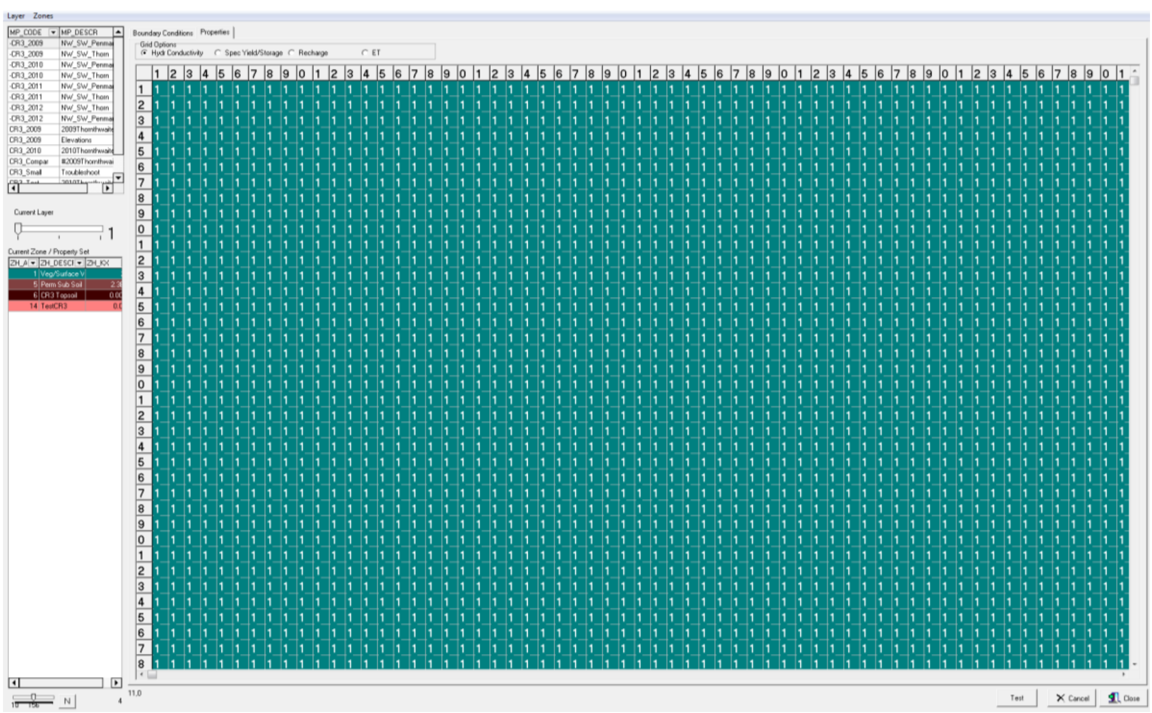

Figure 11: Wetbud advanced model grid populated with hydraulic conductivity values

Specific Yield and Storage

Specific yield and specific storage define the amount of groundwater that can be stored in and released from the cells in the model. Specific yield and specific storage are only used in transient model simulations. For confined layers, specific storage values for each cell are multiplied by the cell volume to calculate the storage capacity of the confined layer (Harbaugh, 2005). For unconfined layers, the specific yield values for each cell are multiplied by the cell area to calculate an unconfined storage capacity (Harbaugh, 2005). Both values are unitless and should be between 0 and 1 depending on the site geologic conditions. For surface water and vegetation layers, it is recommended that the specific storage value is set to a value close to 1.0 because there is very little storage capacity within vegetated areas and no storage capacity in open water areas.

In the Wetbud advanced model, the specific storage and specific yield values are grid zone parameters and must be defined in all cells for every layer of the modeled site. Storage

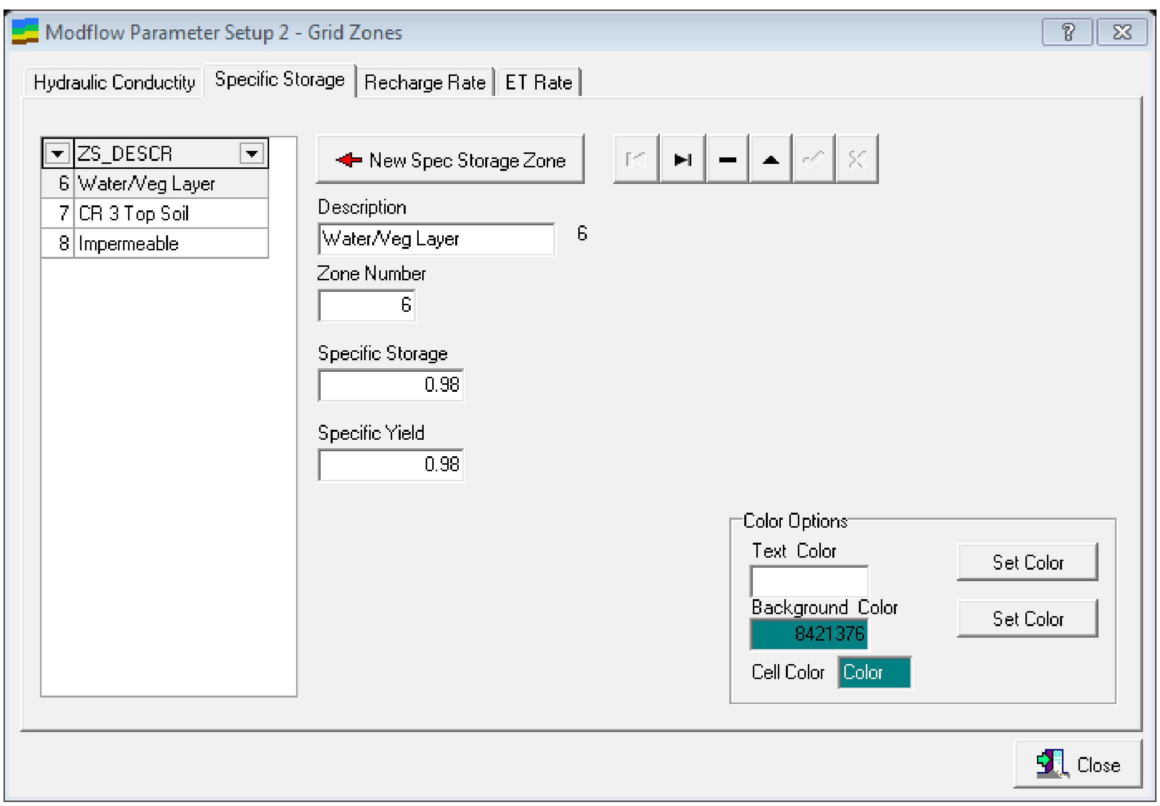

Figure 12: Storage zone setup in the Wetbud advanced model.

zones are set up by the user. Within each storage zone a specific storage, specific yield, zone description, zone number, cell color, and text color are defined (Figure 12).

Once a user has created storage zones, they are spatially defined in the advanced model grid for each layer and cell. It is important that the user defines a storage zone for each cell and layer in a model. Users can create as many storage zones as needed to model a wetland site. Storage zones can be very easily edited and developed to allow the properties of specific materials/substrates to be defined. The flexibility of the storage zones reduces the amount of time and effort required during model setup.

Recharge Modular Package

Modular packages for the MODFLOW finite difference model are used to add options to the standard model. The Wetbud advanced module has preloaded modular packages to ensure users can simulate all inputs and outputs into the designed wetland systems. The recharge modular package simulates areal precipitation into the wetland system (Harbaugh, 2005).

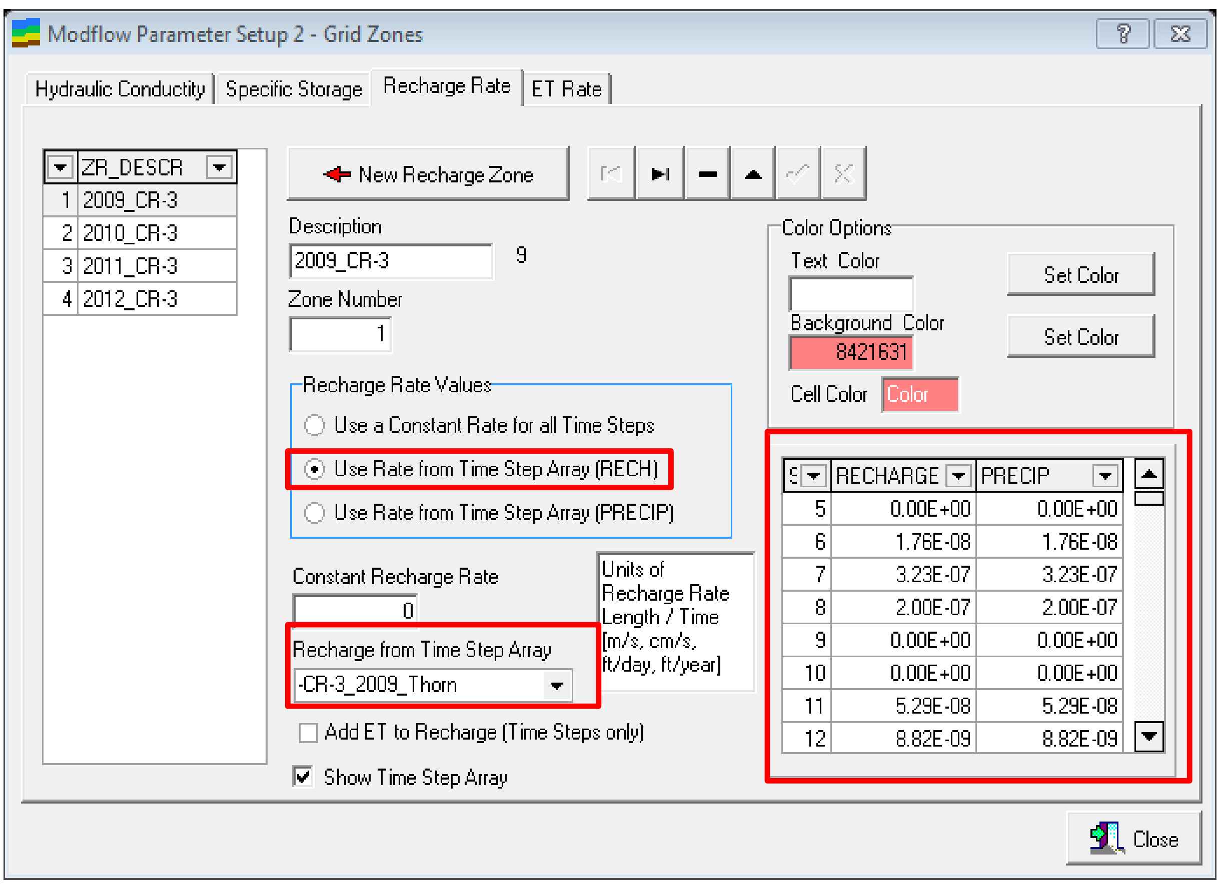

Figure 13: Recharge zone setup in the Wetbud advanced module.

Recharge is defined as any water input into the modeled system, primarily recharge refers to precipitation. Recharge zones are designated by the user and assigned recharge rates in units of length per time. Recharge rates are input into the time step array that is constructed and assigned to the advanced scenario within the model. An individual recharge rate can be assigned to each time step. Recharge rates can be imported into the time step from a Microsoft Excel file, or these values can be imported from precipitation data stored within the Wetbud model. Precipitation values are converted from depths to rates by dividing the precipitation depth by the individual time step duration. Figure 13 shows the interface for recharge grid zone setup in the advanced model. Recharge zones are given a number, description, text color, and background color. Figure 14 shows the interface for importing downloaded precipitation data stored in the Wetbud interface into the advanced model time step.

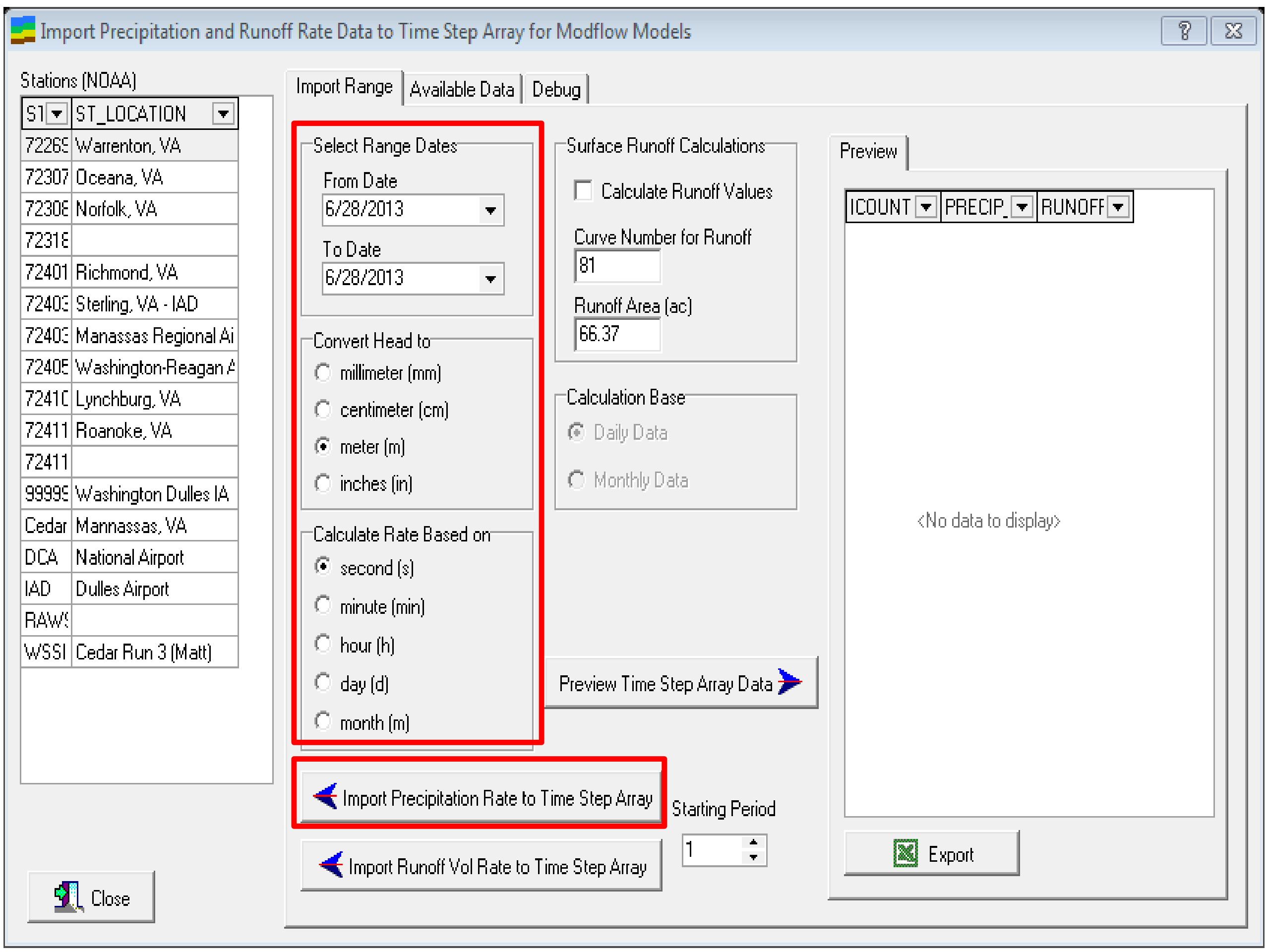

Figure 14: Interface for importing precipitation data into the time step array to be used for the recharge modular package.

Once recharge zones are designated and the corresponding rates are assigned in a time step array, the recharge zones can be spatially assigned in the advanced model grid using the same process as other grid zone parameters discussed previously. Unlike other grid zone parameters, Wetbud only allows recharge zones to be placed in the uppermost layer of the grid. However, in the advanced model setup tab under recharge options, the user can change the layer to which recharge is added. Recharge can enter the top layer; or can enter the uppermost variable-head cell in each vertical column (Harbaugh, 2005). If recharge is only permitted to enter into the top layer, when the head value in the model falls below the bottom elevation of the top layer (i.e. the cell becomes dry), the recharge will be ignored. To avoid errors due to negated recharge values, it is recommended that recharge be set to enter the uppermost variable-head cell in each vertical column.

Evapotranspiration Modular Package

The evapotranspiration (ET) modular package simulates evaporation and plant transpiration by removing water from the modeled wetland system (Harbaugh, 2005). Similar to the recharge grid zone setup, ET zones are created and given a description, zone number, and text and background colors. Maximum ET rates in units of length per time are defined in the time step array that is referenced to the advanced model scenario. Maximum ET rates can be imported into the time step array from a Microsoft Excel spreadsheet. Values of ET can be calculated in the basic module of Wetbud using either the Penman equation (eqn. 6) or the Thornthwaite equation (eqn. 5). ET values from the basic module can be exported and converted into rates for the advanced module by dividing by the individual time step duration. ET zones are spatially assigned to the model using the advanced model grid interface. Similar to the recharge grid interface, evapotranspiration zones can only be added to the first layer of the advanced model grid editor.

For head variable cells the user must define an ET surface and an ET extinction or cutoff depth below the ET surface. At the ET surface elevation, the maximum ET rate defined in the time step array is applied to the model. When the depth of the water table in the model is beneath the extinction depth, ET ceases. In between the ET surface and the extinction depth, ET values vary linearly between maximum ET rate at the ET surface and zero at the extinction depth (Harbaugh, 2005).

The user has three options for defining the ET surface elevations. Under the first option, the ET is always drawn from the uppermost layer of the model. For the second option, the user defines the elevation in each active cell where maximum ET will begin by importing an ET surface. For the third option, the ET surface is defined as the highest variable head cell in each vertical column (Harbaugh, 2005). The highest variable head cell will vary based on the water table elevation throughout the modeled period.

It is up to the user to determine which method of defining the ET surface and what extinction depth is best for their site depending on site conditions. The ET surface definition method is chosen by the user in the advanced scenario setup tab. If the second option is chosen, the user will need to import the ET surface in the advanced module layers tab using either a spatially distributed Microsoft Excel file or a Microsoft Excel file containing coordinates and elevations corresponding to the grid. The grid spacing for the ET surface elevations must be the same as the grid defined in the initial project setup. Extinction depth for the ET surface is defined for each ET zone in the grid zone parameters options. Having options for the ET modular package gives the Wetbud advanced module the flexibility to model a variety of site conditions.

No Flow Cells

For no flow cells, equations in the model are not formulated, and no influence on adjacent cells is calculated (Harbaugh, 2005). As a result, no modular package parameters or other grid zone parameters will have an effect on no flow cells. No flow cells are used to create an accurate shape of the modeled wetland site from the approximate grid shape in the initial setup by removing cell activity outside the wetland boundary.

No flow cell zones are defined as cell zone parameters within the advanced module. Cell zone parameters and grid zone parameters are similar in setup and spatial designation; however, the major difference between the two parameters is that unlike grid zone parameters, cell zone parameters do not have to be defined for every cell in a model. No flow zones are given a number, description, text, and color options, and a head value. They are then spatially placed in the model using the advanced model grid interface. No flow cell patterns can be copied from layer to layer in the advanced model grid interface to decrease model setup time. The head value for no flow cells is defined in the general tab of the advanced module scenarios. The head for no flow cells has no effect on the head in the active model area; it is simply a placeholder so the user can identify the no flow cells in the model results.

Drains

The modular drain package is designed to simulate the removal of water from the wetland at a rate proportional to the difference between the head in the wetland and the invert elevation of a weir (Harbaugh, 2005). Drains are set up as cell zone parameters in the Wetbud advanced model. Multiple drains with varying parameters can be created and placed spatially in the advanced model grid. Drains can be placed in any active cell of any layer. In addition to the drain locations, drains must also be assigned an elevation corresponding to the invert and a conductance.

Conductance (eqn. 27) has units of length squared per time and is a function of hydraulic conductivity (k), cell length (L), cell width (W), and cell thickness (M) (Gloe, 2011; Harbaugh, 2005).

$$C = \frac{kLW}{M} \tag{27}$$

To estimate a range of conductance values for a drain, a range of hydraulic conductivity (k) values is needed. A range of hydraulic conductivity values for a drain can be calculated by using Darcy's Law (eqn. 28) and a range of discharge rates, with an assumed hydraulic gradient (i) and a cross sectional area of a weir (A) (Gloe, 2011).

$$k = \frac{Q}{iA} \tag{28}$$

From the range of calculated conductivity values determined, a range of conductances can be determined using the model cell dimensions. If a reasonable range of discharge rates within the modeled wetland can be estimated, a mean and median conductance value calculated from that range provide a good starting point for iteration in the model. The selection of a final conductance value is based on whether the model will converge and whether the calculated discharge values are reasonable for the designed outlet structure.

Wells

The well modular package is designed to add water to the wetland system at a constant rate over a stress period. The input rate is independent of the cell area and the head in the cell (Harbaugh, 2005). In the Wetbud advanced module, wells can be used to model input water into a wetland system from adjacent drainage areas as runoff. Wells are spatially input into the advanced model grid editor as cell zone parameters. Wells reference the time step array which contains rates of water input into the system per stress period.

Runoff rates can be calculated within the Wetbud model using the SCS/NRCS rainfall excess estimation technique and the precipitation data stored within the model. Wetbud will also convert the calculated runoff values to rates and import them into the time step array. Figure 15 shows the interface used to import runoff rates into the time step array for the well modular package. The user must define a curve number, runoff area, length unit, and time unit. Once these values have been determined, the user must choose the range of dates to calculate runoff

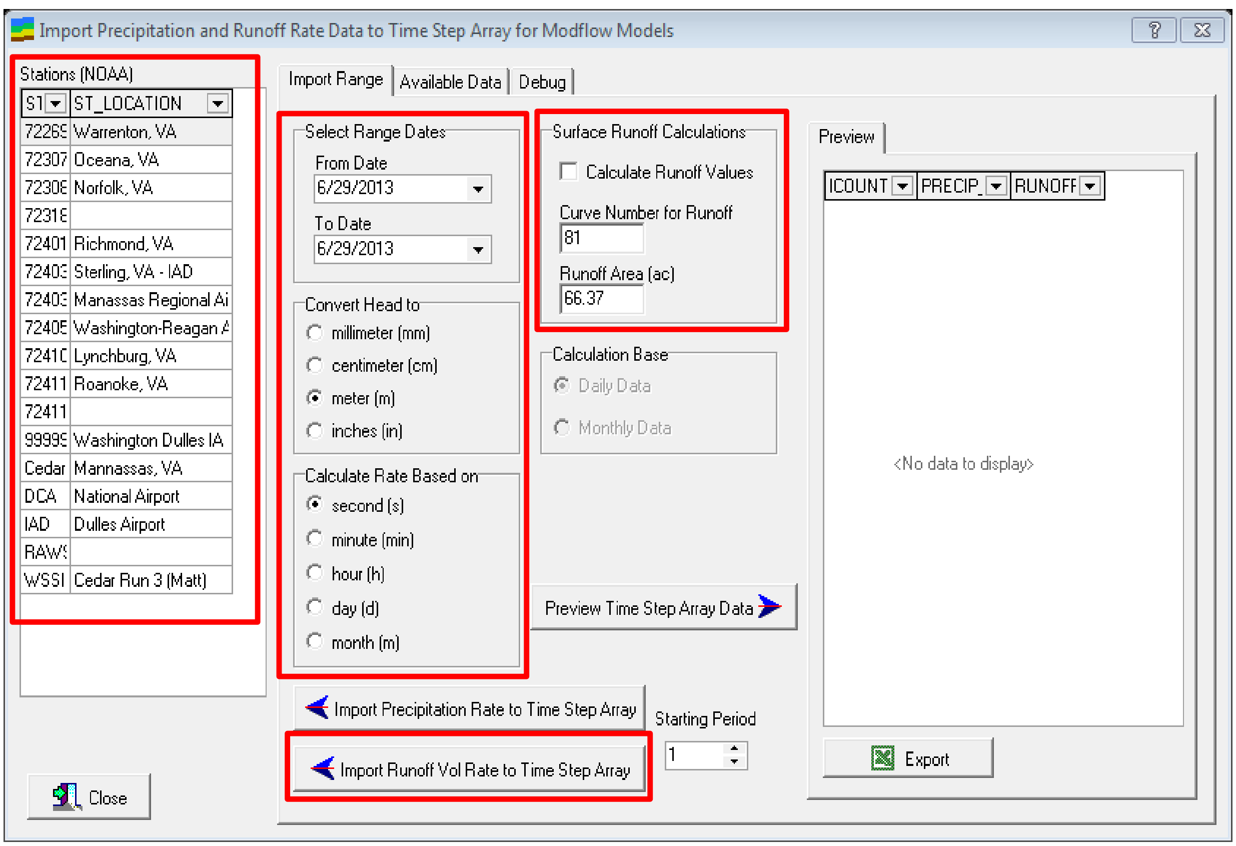

Figure 15: Interface to import runoff rates into the time step array which will be input into the modeled system using the well modular package.

and the weather station from which the precipation data will be obtained. After the runoff rates are imported into the time step array, they can associated with a well zone and placed in the Wetbud advanced model grid at appropriate locations.

Drain Returns

The drain return modular package is simlar to the drain modular package. The drains remove water from the modeled wetland system as long as the head in the wetland is above the invert elevation set for the drains. This water is removed from the wetland; however, a percentage of this water can be input back into the wetland at a specified grid in the drain return package. The drain returns are set up as cell zone parameters, and similar to the drain package, are given an invert and a conductance. The drain return cell zones are also given a return cell location (layer, row, and column) and a flow proportion. The flow proportion calculates the fraction of water leaving through the drain that will be reintroduced at the return cell location. Drain returns are placed in the advanced model grid in the same format as the drains. Using the drain return package, Wetbud can model stepped wetland systems with multiple cells where berms are placed between wetland cells and surface water is transferred between cells by a series of weirs or culverts.

General Head

The general head boundary module package simulates flow into or out of a wetland from a boundary cell, based on the head assigned to the boundary cell and the wetland head calculated in the model (Harbaugh, 2005). General head boundary zones are cell zone parameters and are given a number, description, and conductance value. Boundary cell head values for each time step are located in the time step array designated for the model. General head boundary zones are assigned spatially in the advanced model grid interface. While general head boundary zones are an option in the Wetbud advance module, they were not used in this study. As a result, detailed information about how the model calculates inputs and outputs between cells based on the general head boundaries is not included. For more information about the general head boundary zone calculation see the MODFLOW-2005 Modular Ground-Water model manual (Harbaugh, 2005).

Advanced Model Output and Monitoring Points

The Wetbud advanced module output consists of head values within every active cell for each modeled layer at every time step. Water surface elevation along the rows and columns can be seen at each time step and model results for each cell can be viewed as a hydrograph with the water table elevation on the y-axis and the time step on the x-axis. The Wetbud advanced model results can also be displayed as a color-coded water surface elevation plan view map for each time step. Figure 16 shows an example of the Wetbud advanced model results display interface. In the plan view grid of the modeled site, colors represent water surface elevation changes in the model results. In Figure 16, the highest water surface elevations are represented by the light green color, and the lowest water surface elevations are represent by the light blue color. This display allows the user to see if the model is correctly predicting overall trends of water movement in the wetland. The hydrograph on the right of Figure 16 shows water surface elevation at a chosen cell over the modeled period of one year. Results such as the ones shown in Figure 16 can be viewed for every active cell in a model grid.

Model results can also be exported to a Microsoft Excel file for manipulation and display. To allow straightforward comparison of model results to monitoring well data, monitoring points can be spatially assigned in the advanced model grid editor. Once monitoring points have been assigned in the grid editor, they can be selected in the results display interface and the advanced model results will be displayed for the assigned cell location. By assigning grid cells as monitoring points, users can pinpoint areas where measured well data may be available and make comparisons between modeled and measured data more easily.

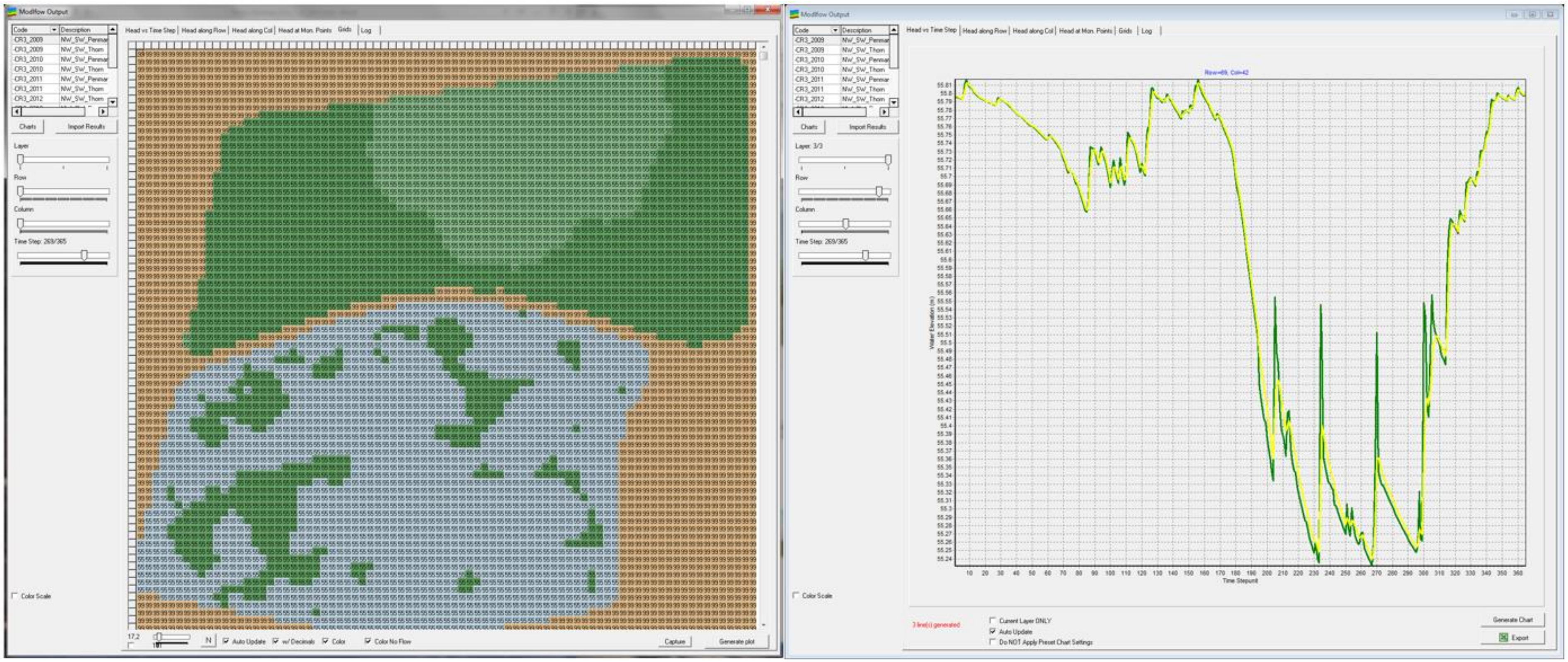

Figure 16: Example of the results display interface from the Wetbud advanced model with a plan view color contour map of water surface elevation on the left, and a hydrograph of water surface elevation versus time step on the right.

Advanced (MODFLOW-NWT) Model Setup

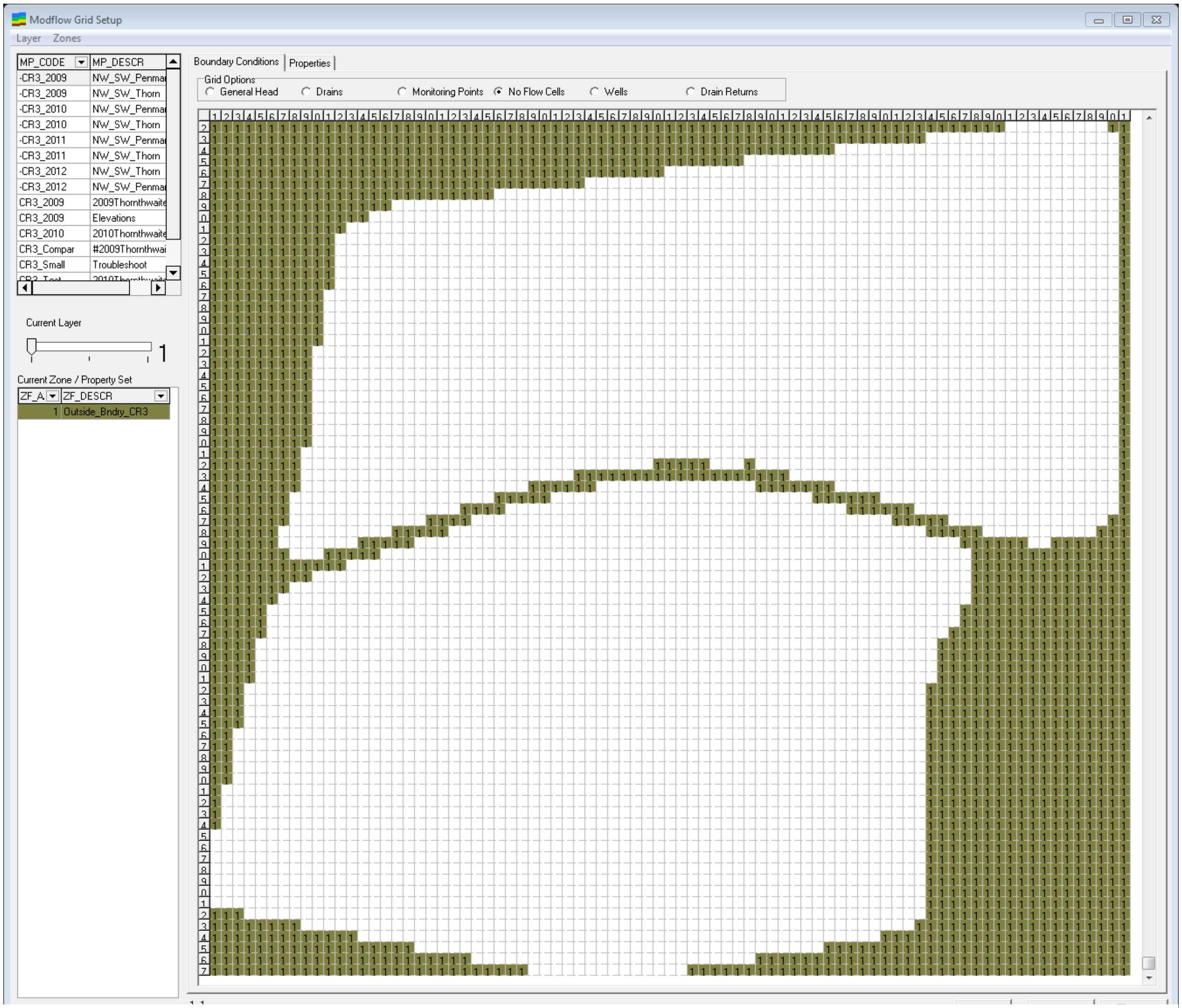

Figure 17: No flow cells isolating the wetland area in the Wetbud advanced model grid editor.

Cedar Run Wetland Mitigation Bank Model Construction

A model of the NW and SW cells of the Cedar Run Wetland Mitigation Bank was constructed to evaluate the Wetbud advanced (MODFLOW-NWT) model. The site was simulated with 5 m by 5m cells in 77 rows and 81 columns. No flow cells were used to remove cells outside the site boundary and transform the model grid into the corresponding wetland shape (Figure 17).

The model units chosen were meters for length and seconds for time. The wetland was modeled as an unconfined three-layer system. The first layer of the model represented the surface water and vegetation. The bottom of the first layer represented the ground surface and elevations were imported from a topographic surface created from an as-built survey provided by WSSI.

Based on the design information provided by WSSI, the geologic site strata consisted of a 23 cm (9 in.) layer of returned top soil placed over a 31 cm (12 in.) cut and compacted impermeable clay liner. Thicknesses of the bottom two layers were added to surface elevation points to calculate elevations points for the top and bottom of each layer. The model was run on a daily time step for 2009, 2010, 2011, and 2012. All model years were run with the Thornthwaite and Penman PET methods. Each year was run as an individual model starting on January 1 of the modeled year. Since model runs began during the winter months, the wetland was assumed to be inundated at initial conditions. Initial head values were set to the invert elevation of the drains in the wetland. Model results for the Cedar Run 3 SW cell were compared with measured well data collected in the SW cell from August 2009 to March 2012.

Precipitation – Recharge Package

The same on-site precipitation data collected by WSSI that was used in the basic module was used also for the advanced module. The recharge modular package was used to simulate the precipitation. Precipitation events were converted to rates for each time step and imported into the time step array for the model. Recharge was applied to the highest active cell in each vertical column within the wetland model.

Evapotranspiration

Model years were run using both the Penman and Thornthwaite estimation methods of PET. Monthly PET values were calculated in the basic module of Wetbud using the solar and weather data described in the Basic Model Description section. PET values from the basic module were exported and externally converted to average daily rates and imported into the time step array of the model for use in the ET package. The ET surface was set as the highest active layer in each vertical column with an extinction depth of 0.30 m.

Hydraulic Conductivities and Specific Storage

Hydraulic conductivities were set in each model layer and were assumed isotropic. For the top layer representing the surface water and vegetation, data from a previous modeling study conducted by Gloe et al (2011) were used. In this study, field observations of existing plant communities within the Cedar Run Mitigation Bank SW cell were collected on May 24, 2010 and February 11, 2011. Utilizing a procedure similar to that of Piercy (2010), a stem density for the collected plants was determined. Frontal areas for depth ranges from 0-10 cm, 10-20 cm and 20 - 30 cm were determined from the collected stems and an average stem diameter for each height class was formulated.

From these data a momentum absorbing area was determined per plant height interval and a friction factor was calculated assuming laminar flow. The friction factor was converted to a hydraulic conductivity for MODFLOW utilizing the Reynolds number equation and a transformed version of the Darcy-Weisbach equation. Hydraulic conductivities were determined by rearranging both equations to isolate the hydraulic gradient, equating the two expressions, and solving the equation for hydraulic conductivity (eqn. 29).

$$K = \frac{8gR}{fv} \qquad (29)$$

where, K = hydraulic conductivity (m/s)
g = gravitational acceleration (m/s^2)
v = cross sectional averaged velocity (m/s)
R = assumed to be water depth (m)

Conductivity values for each height class in three plant community zones was determined for the spring/summer and fall/winter seasonal periods. Calculated values of hydraulic conductivity ranged from 1.42 cm/s to 2.96 cm/s (Gloe, 2011). Because the surface water and vegetation was represented by one layer and a model was run for an entire year, the hydraulic conductivity range was averaged and the surface and vegetation layer was assigned a hydraulic conductivity of 2.30 m/s for the Wetbud advanced model. A specific storage value of 0.98 was given to the surface water and vegetation layer. While almost the entire layer is available for storage, a small portion of the layer was removed using the specific storage factor to compensate for the volume occupied by the plant stems.

Based on the mitigation design, the soil top layer was constructed from material originally stripped from the wetland site prior to construction. A soils analysis for the site prior to construction was performed by WSSI. In addition, an online web soil survey review was performed for the modeled site. From these references it was estimated that the top soil layer consisted primarily of Aden, Albano, and Roland soil series. Based on this information, the hydraulic conductivity of the soil top layer was estimated to be 1.00×10^{-4} m/s with a specific storage and specific yield value of 0.25.

For the mitigation design, the impermeable soil layer was compacted to achieve a hydraulic conductivity of approximately 2.3×10^{-7} m/s. Since the Wetbud advanced model was evaluated for design purposes, it was assumed that the design criterion was met throughout the impermeable layer constructed in the wetland. As a result, the hydraulic conductivity of the lowest model layer was set to 2.3×10^{-7} m/s and the layer specific storage and specific yield value were set to 0.25.

Drains and Drain Returns

The drain and drain return modular packages were utilized to model surface flows in the top layer of the wetland model. Drains were placed in the two locations where constructed trapezoidal weirs discharge water from the SW cell (Figure 18). Drain returns and their inlets were placed where constructed trapezoidal weirs connect the NW and SW cells (Figure 18). Drain return inlets were set to input 100% of the water draining from the NW cell into the top layer of the SW cell. Drain and drain return inverts were located within the wetland model based on an as-built survey of the constructed trapezoidal weirs at the Cedar Run Wetland Mitigation Bank site.

To calculate a range of discharge rates for the weirs, a rating curve was created using the Cipoletti weir equation (eqn. 30) for a range of reasonable head values in the wetland (0.00 m to 0.33 m).

$$Q = 1.84LH^{3/2} \qquad (30)$$

where, Q = discharge rate (m^3/day)
L = bottom length of trapezoidal weir (m)
H = head above the bottom of the weir (m)

From the range of discharge rates calculated, a range of conductance values was determined for the head above the weir (0.15 m^2/sec to 4.80 m^2/sec). From the range of conductance values developed, an average value of 1.33 m^2/sec was calculated. The average conductance value was used for all drain and drain return values in the model.

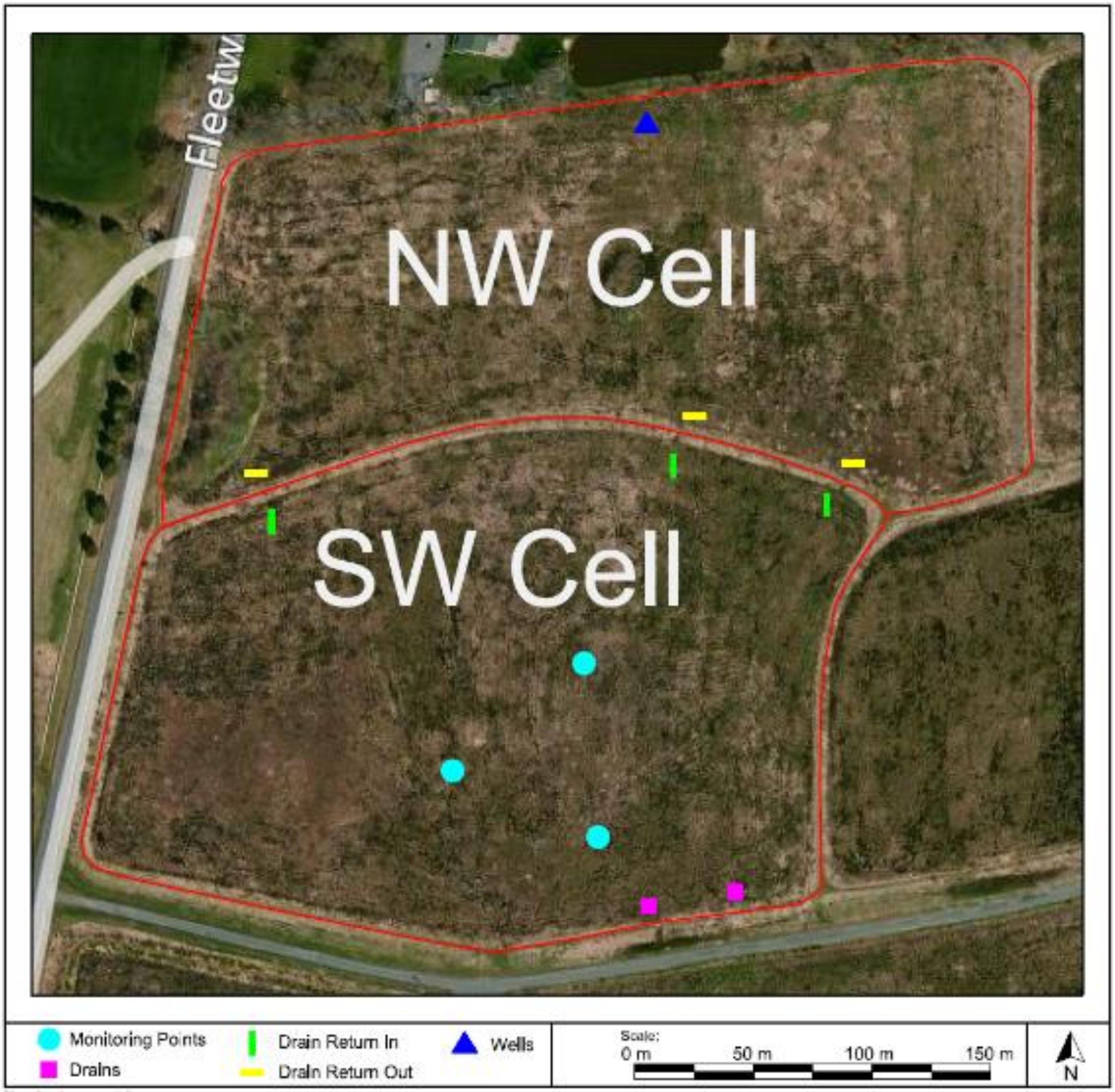

Figure 18: Placement of modular package elements in the Wetbud advanced model.

Wells

The well modular package was used to input surface water runoff from the wetland watershed into the wetland site. Runoff depths were calculated from the on-site precipitation data using the SCS/NRCS rainfall excess estimation technique with a curve number of 81 and drainage area of 26.86 ha. Runoff depths were converted to rates by dividing by the time step duration (one day). The runoff rates were imported into the time step array at dates corresponding to the runoff events. The well was placed at the point on the grid corresponding to the location where a culvert from the wetland watershed discharges water into the wetland system (Figure 18). The invert of the well was set to the ground surface at that location, based on an as-built site survey provided by WSSI.

Solver and Solver Parameters

As stated previously, the Newtonian (NWT) solver and Upstream-weighting (UPW) flow package were used for this model. For the NWT, solver a head tolerance of 1.5×10^{-3} m was used. A flux tolerance of 5.78×10^{-3} m^3/s and a cell thickness adjustment of 1.5×10^{-3} m were assigned for the solver. These values were based on the USGS Online User's Guide to MODFLOW-2005 recommended default values for the NWT solver. To encourage model convergence, maximum iteration values were increased from the recommended value of 500 to a value of 700 per time step. In addition, sub-steps within the time step array were set to a value of 3 with a time step multiplier of 1.2. For the Wetbud advanced model, it is recommended that these solver and flow package defaults are not changed unless a user is experienced with the MODFLOW modular finite difference model software.

Results and Discussion

Overview

Using observed water level data from two existing mitigation wetlands, this study evaluated the basic and advanced modules of a newly developed wetland water budget model, Wetbud. Wetbud was developed as a mitigation wetland design model/tool for application in the Virginia Piedmont. If applied as intended, Wetbud does not require calibration. The objectives of this study were 1) to compare the traditional Pierce water budget wetland design methodology using Wetbud in a basic mode (which limits groundwater influences with respect to the wetland water budget simulated), with the Wetbud advanced (MODFLOW-NWT) module methodology, (which accommodates groundwater interaction with the wetland), and 2) to compare the model results when using two alternative PET estimation methods (Thornthwaite and the Penman Monteith FAO). Model performance was evaluated using three metrics, the Nash-Sutcliffe model efficiency rating (NSE) (eqn. 7), the root mean square error (RMSE), and regression analysis.

Observed water elevations at the Bender Farms Mitigation site showed drawdown periods in early-to-mid-spring, likely due to increased evapotranspiration from wetland plants. The greatest drawdown periods were seen during summer months, when water levels varied from -25.5 cm to -65.8 cm (Figure 19 and Table 1). Cedar Run 3 measured water levels followed a similar trend of drawdown during spring and summer months, supporting the importance of ET in wetland water budgets (Chaubey and Ward, 2006; Owen, 1995). Observed water levels in the Cedar Run 3 wetland changed rapidly when seasons changed from summer to fall and winter (Figure 20 and Table 2). For example, from September 2010 to October 2010, water levels in the wetland rose 42.3 cm over a period of 30 days. Response to precipitation events was more evident in the observed site data from Cedar Run 3 (Figure 20 and Table 2). The faster response to precipitation events is attributed to the compacted impermeable layer installed at Cedar Run 3 which creates a more precipitation-driven system. In addition, the compacted layer can have a tendency to crack if it dries out during the summer/fall and allow water to rapidly penetrate the soil until swelling from the clay would seal the flow paths. Bender Farm Mitigation Site seasonal water level fluctuations were harder to evaluate due to the lack of measured well data during winter months.

Basic Model Results

Wetbud basic module results for the Bender Farms Wetland Mitigation Site are shown in Table 1 and Figure 19. The Wetbud basic module results for the SW cell at the Cedar Run Wetland Mitigation Bank are shown in Table 2 and Figure 20.

Table 1: Observed monthly water levels and Wetbud basic model predicted water levels for the Bender Farms Wetland Mitigation Site.

Month	*Year*	*Observed Average Monthly Water Level (cm)*	*Wetbud Basic Model (Thornthwaite) (cm)*	*Wetbud Basic Model (Penman) (cm)*
March	2010	-0.3	2.5	2.5
April	2010	-20.0	0.0	-27.4
May	2010	-31.7	2.5	0.2
June	2010	-25.5	-34.7	-51.4
July	2010	-41.5	-50.4	-72.2
August	2010	-34.3	-38.4	-58.2
September	2010	-56.6	-5.2	-35.8
October	2010	-8.7	2.5	2.2
November	2010	-5.0	2.5	2.5
March	2011	1.4	2.5	2.5
April	2011	0.0	2.5	2.5
May	2011	-10.1	1.7	-3.1
June	2011	-44.7	-31.8	-46.2
July	2011	-58.8	-66.4	-84.4
August	2011	-65.8	-80.4	-98.0

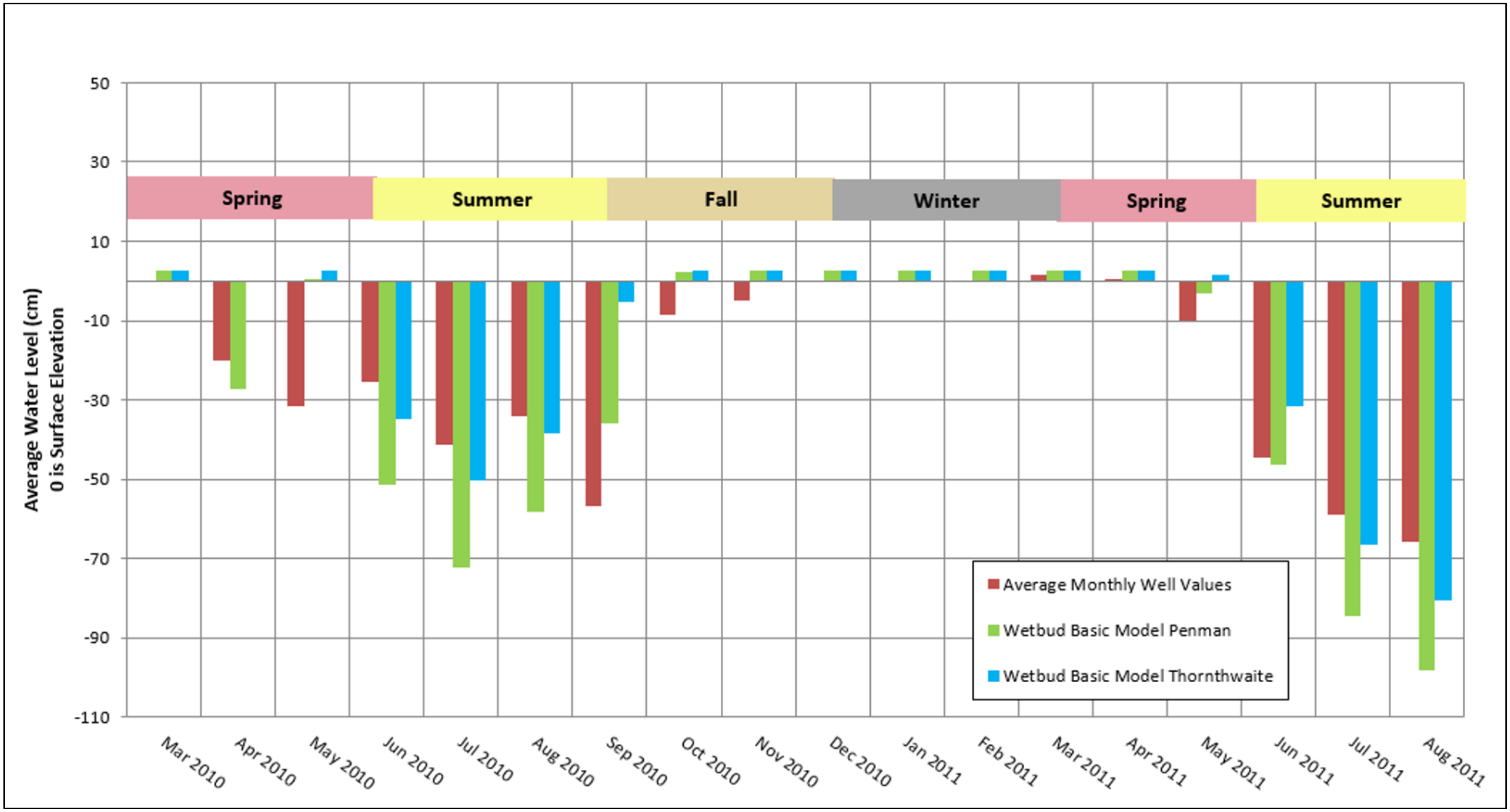

Figure 19: Wetbud basic module results for the Bender Farms Wetland Mitigation Site for the Thornthwaite and FAO-56 Penman Monteith PET methods. No measured water level data were available during the winter period.

Table 2: Observed monthly water levels and Wetbud basic model predicted water levels for the Southwest cell of Cedar Run Wetland Mitigation Bank.

Month	*Year*	*Observed Average Monthly Water Level (cm)*	*Wetbud Basic Model (Thornthwaite) (cm)*	*Wetbud Basic Model (Penman) (cm)*
August	2009	-48.3	-3.4	-14.5
September	2009	-48.6	-11.9	-27.3
October	2009	-40.5	3.2	-11.5
November	2009	7.4	7.6	7.6
December	2009	9.8	7.6	7.6
January	2010	6.8	7.6	7.6
February	2010	10.3	7.6	7.6
March	2010	8.5	7.6	7.6
April	2010	-2.0	7.4	0.4
May	2010	-20.0	7.6	-0.6
June	2010	-13.6	4.5	-20.7
July	2010	-33.8	7.6	5.3
August	2010	-38.0	7.6	6.3
September	2010	-41.3	7.6	7.6
October	2010	0.9	7.6	7.6
November	2010	7.2	7.6	7.6
December	2010	5.4	7.6	7.2
January	2011	2.5	7.6	7.6
February	2011	7.3	7.6	7.6
March	2011	8.5	7.6	7.6
April	2011	10.1	7.6	7.6
May	2011	7.4	7.6	6.9
June	2011	-35.4	0.9	-4.1
July	2011	-37.2	-22.9	-34.4
August	2011	-38.4	-26.4	-37.7
September	2011	-2.1	7.6	7.6
October	2011	8.2	7.6	7.6
November	2011	7.8	7.6	7.6
December	2011	8.6	7.6	7.6
January	2012	7.8	7.6	7.5
February	2012	8.2	7.6	7.6
March	2012	4.2	2.8	-1.0
April	2012	-28.3	2.7	-20.5
May	2012	-18.6	6.3	-9.6

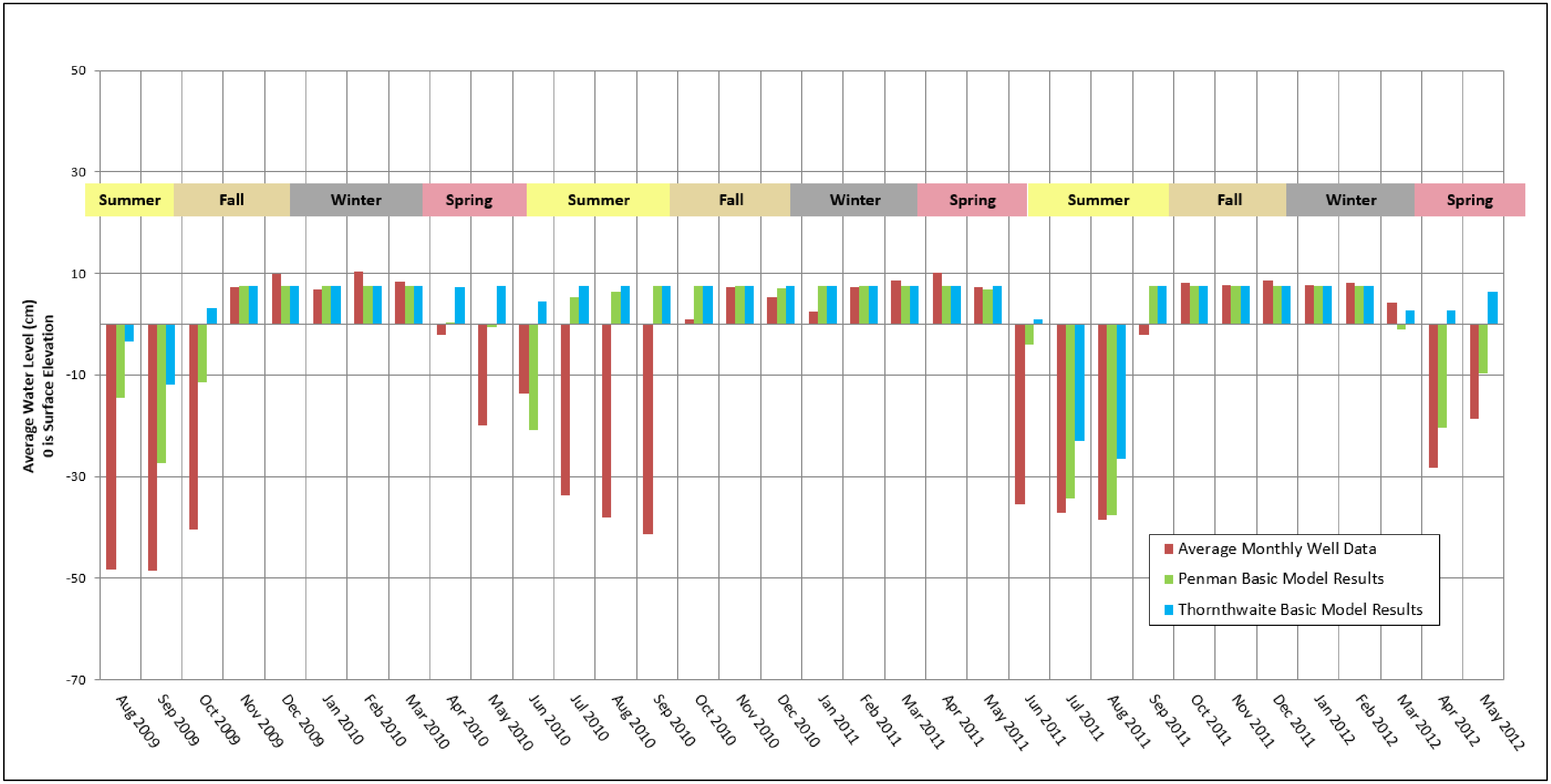

Figure 20: Cedar Run Wetland Mitigation Bank Southwest cell basic model results for both FAO-56 Penman-Monteith and Thornthwaite evapotranspiration methods.

Bender Farms Wetland Mitigation Site

For the Bender Farms Wetland Mitigation site, well data recorded daily with automated loggers were available for the period of March 2010 to October 2010 and March 2011 to October 2011; measured water levels were not available in the winter months. In the summer, the predicted water levels were lower than measured water levels. For the June, July, and August summer period, the Wetbud basic module using the Thornthwaite PET method under estimated water levels in the wetland by an average of 7.4 cm in 2010 and 3.1 cm in 2011. The Wetbud basic module using the Penman PET method underestimated water levels in the wetland for June, July, and August by an average of 26.9 cm in 2010 and 19.8 cm in 2011. If wetland designers based a wetland water budget on the predicted summer periods predicted, the wetland would be too wet for woody species to germinated to create a forested wetland (Kellogg et al., 2003).

Conversely, during the short fall and spring periods where measured water level data were available, the Wetbud basic module generally overestimated water levels. For September, October, and November of 2010, the Wetbud basic module using the Thornthwaite PET method overestimated water levels by an average value of 23.3 cm. During this same period, the Wetbud basic module using the Penman PET method over estimated water levels by an average value of 13.1 cm. Similarly, in the spring months of March, April, and May the Wetbud basic module overestimated water levels by an average value of 5.1 cm using the Thornthwaite PET method and 3.5 cm using the Penman PET method. If a mitigation wetland was designed with these trends of over prediction in the spring and fall, the designed wetland would lack the water needed during the growing season, resulting in poor vegetation growth and too few days of inundation to meet ACOE regulation.

Predicted water levels lower than measured values could be the result of multiple model errors including underestimated groundwater input, overestimated groundwater output, over predicted PET, errors in precipitation data, etc. However, looking at the results, the periods of overestimated water levels for the Bender Farm Wetland Mitigation site occurred when the predicted and observed water levels in the wetland were very close to the ground surface or above the ground surface. The periods of underestimation occurred during the summer months, when observed water levels were below the ground surface. Based on these trends, the underestimation during these periods could possibly be attributed to an underestimation of the soil storage factor. If the soil storage factor was increased from 0.25 to 0.40 or 0.45, model results during summer months would have improved. However, a soil storage factor that high is unrealistic for the Bender Farms Mitigation Site because the soil field capacity would be greater than the PET.

In addition, since no up-gradient well data were available for the groundwater calculation, the assumptions made about groundwater flow through the site could have induced error and are likely a major reason for the low statistical ratings shown below. For the model run, groundwater in and groundwater out were estimated based on an assumed flow area and water table gradient. Groundwater-out also included the modeled water surface elevation for the prior month in the gradient calculation which could have propagated model error from previous months. Also, groundwater-in was held constant for the entire modeled period and not varied based on water levels in the wetland. Groundwater-in could have varied seasonally and was likely too low during the growing season. The difference in groundwater-in and groundwater-out calculated for the site was small in magnitude (less than 1 cm per month), and, as a result, groundwater flows had little effect on the basic module water levels. The assumptions required and the small effect of calculated groundwater flow on the system show the limitations of the basic module to accurately represent groundwater flows in the water budget if no quality uphill groundwater data is available.

Dobbs et. al (2013) performed a similar modeling study using quality up gradient water level data. Model results and statistical ratings were improved over the results from this study, the improved results are primarily attributed to collection of up gradient well data and collected stratigraphy information. The consideration of groundwater in and out as the source of model error supports that the Bender Farm Mitigation Site is a groundwater dominated site and detailed groundwater information would have improved model results.

Cedar Run Wetland Mitigation Bank Results

The basic module predicted measured water levels within an average of 69% of measured water levels in the SW cell of the Cedar Run Wetland Mitigation Bank during the wetter periods when the observed water levels were above the soil surface. During some of the wetter periods, such as March and April of 2011, the model under-predicted the water levels. The inaccuracy during these months is a result of the limitations of the basic module, which uses level pool routing to calculate water depths. Level pool routing assumes that any water in excess of the weir invert elevation is removed from the wetland; thus, the depth to weir value set in the model creates a maximum water level that cannot be exceeded. Even though the original wetland design has a maximum depth to weir set at 7.62 cm, resistance from vegetation and topographic variation within the wetland controls the outflow rate, creating a sloping water surface which increases the water depth with distance from the outlet and limits outflow over the weir.

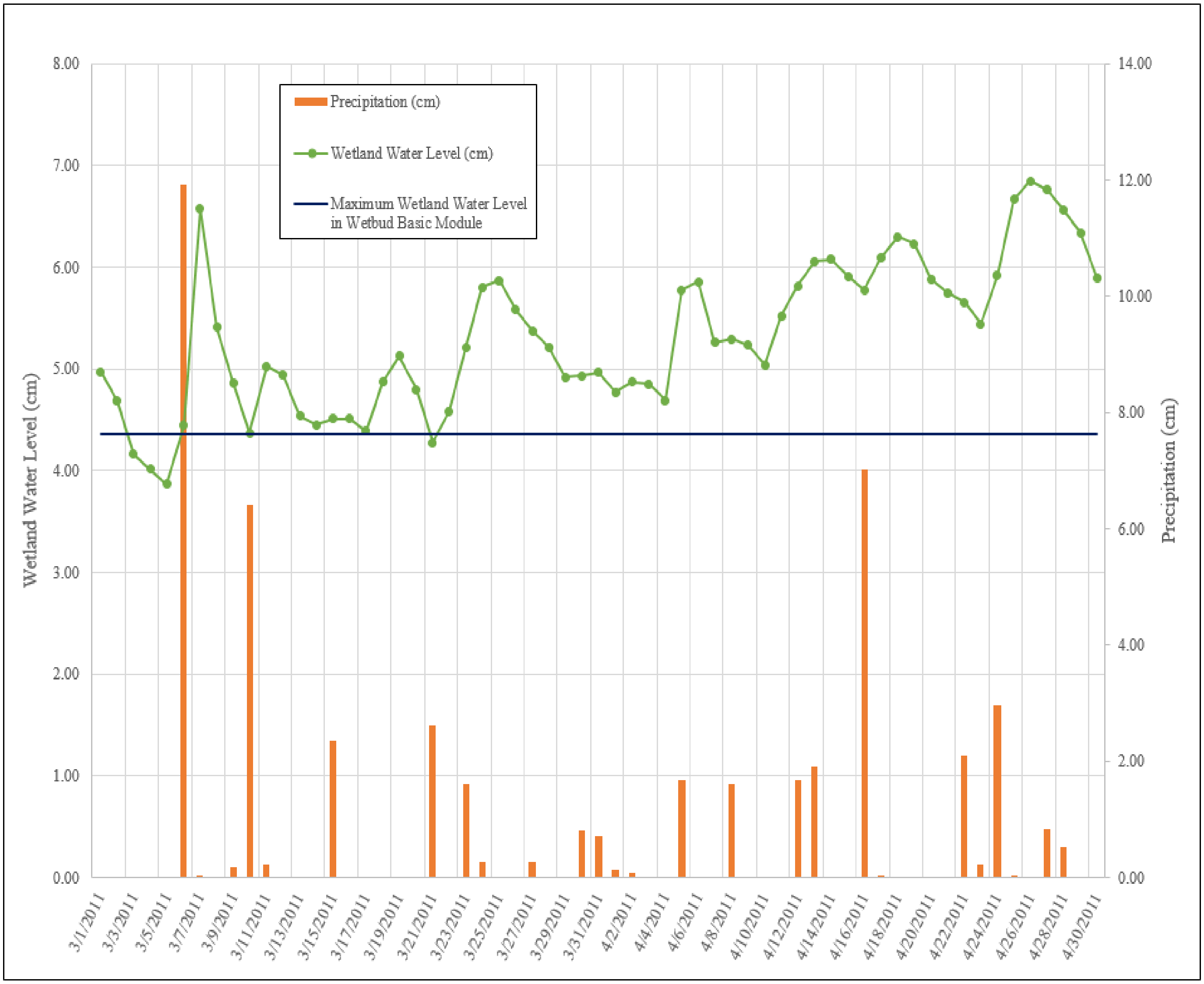

Figure 21: Measured water levels in the Cedar Run Southwest Cell, measured precipitation data, and the local maxima set within the basic module.

Figure 21 shows the average measured water levels in the SW cell, the measured precipitation in the SW cell, and the maximum wetland water depth set within the basic module. On March 8, 2011 the water level in the wetland reached 11 cm (0.11 m) overall (4.5 cm above the weir invert) due to a large precipitation event. The wetland did not drain back to the weir invert elevation for 3 days, during which there were no precipitation events. According to the stage-discharge curve calculated for the Cipoletti weirs, it should take approximately 50 hours to drain the 4.5 cm of head through the two outlet weirs in the wetland. The delay in drainage rates supports the supposition that the increased vegetation resistance controlled the wetland outflow and caused ponding within the wetland in excess of the weir elevation.

The excess ponding due to vegetation resistance is likely why the average daily wetland water depth for almost the entire period from March to April in 2011 is above the designed maximum. For the entire modeled period of 34 months, a total of 10 months had average measured wetland water levels above the maximum value set within the basic module. The maximum measured average monthly water level within the wetland was 10.1 cm in April of 2011, which was 2.5 cm higher than the weir invert elevations.

All three wells in the wetland were centrally located (Figure 5) with an average distance to the outlet weirs of 67 m. The average difference between the measured monthly water level during the inundated periods and the weir invert elevation set was 1.2 cm. Based on the above numbers and assuming a linear slope, the average water surface slope is approximately 0.017%. According to this slope the farthest distance from the weir in the SW cell could be ponded nearly 3.4 cm above the weir invert. Increased water levels and decreased drawdown times could result in mitigated wetlands that are continuously ponded even during dry periods. The continuous inundation could inhibit the establishment of abundant vegetation during the growing season and alter ecosystem properties (Mazer et al., 2001).

The basic module under predicted the drawdown that occurred within the wetland during the drier periods when the monthly average measured water levels were below the soil surface. During a large portion of the growing season in 2010 (March – September), the basic module dramatically under predicted the drawdown that would occur. The Thornthwaite basic model predicted standing water would remain in the wetland throughout 2010. The Penman basic model did show drawdown occurring in May and June of 2010, but showed ponding occurring in the wetland in July, August, and September. In reality, measured water levels showed that drawdown occurred beginning in April and that the water levels actually remained beneath the ground surface until October. The maximum drawdown occurred in September with a value of -41.3 cm.

During the other dry seasons within the modeled period both basic models (utilizing the Thornthwaite and Penman PET methods) under predicted model drawdown, resulting in over predicted water levels. The trend of over predicted water levels during summer periods at Cedar Run 3 was opposite from what was seen in the Bender Farms Mitigation Site basic models. For 2010, the Cedar Run 3 Thornthwaite basic model over predicted water levels by an average value of 31.9 cm, with a maximum over prediction of 48.9 cm in September of 2010. For the other dry months in the modeled period, the Thornthwaite basic model over predicted water levels in the wetland by an average value of 28.2 cm, with a maximum over prediction of 44.8 cm in August of 2009. For 2010, the Penman basic model over predicted water levels in the wetland by an average value of 30.8 cm, with a maximum over prediction of 48.9 cm occurring in September of 2010.

For the other dry months in the modeled period, the Penman basic model over predicted water levels in the wetland by an average value of 16.2 cm, with a maximum over prediction of 33.8 cm in August of 2009. Based on the precipitation data collected on-site and the NRCS WETS tables for the site, 2009 and 2010 are average precipitation years, 2011 is a wet precipitation year. If the wetland site was designed to meet regulatory hydrology standards in what is considered a dry year by the NRCS WETS tables, over inundation could be occurring at that site and could attribute to model over prediction. Precipitation data is very influential on wetland design as well as the Wetbud model results. Considering the wet, dry, and average precipitation years during design is important to wetland and model success. Collecting the best possible precipitation data should be a high priority and it is recommended that on-site precipitation data should be collected for the best model results.

If a wetland mitigation design was done based on these either the Penman or the Thornthwaite basic model results, the site could potentially end up drying out for a longer period than predicted due to the over prediction of the water levels in the dry periods. This model error could result in a failure to comply with the hydrology requirements set forth by the Army Corps of Engineers (ACOE) and could also limit water supply for hydrophyitic vegetation resulting in little to no wetland vegetation growth.

Basic Model Statistical Analysis

The root mean square error (RMSE) for the entire modeled period and both PET methods was calculated for the Bender Farm Wetland Mitigation Site and the Cedar Run 3 Wetland Mitigation Bank. The RMSE is commonly used to evaluate simulation models (Willmott et al., 1985). The RMSE is calculated by taking the square root of the average sum of the squared residuals and represents average absolute error.

For the Wetbud basic module, the monthly water level outputs from the model in cm and the average monthly water level of the monitoring well data in cm were converted to water table elevations in meters based on an average ground surface elevation for the site. The RMSE statistic was calculated for the water table elevations with the model output corresponding to the predicted values and the monitoring data corresponding to the observed.

The Bender Farms Wetland Mitigation Site basic module results had RMSE values of 0.19 m for both the Thornthwaite and the Penman evapotranspiration methods. For the Cedar Run 3 Wetland Mitigation Bank, the basic module utilizing the Penman evapotranspiration method had a better RMSE value (0.17 m) than the Thornthwaite basic model (0.22 m). The RMSE values for the basic model were similar to RMSE values (0.30 m for Thornthwaite method and 0.19 m for the Penman method) found in a study by Gloe, et al. where an Integrated Pierce model was used to estimate wetland water budgets (Gloe, 2011). Considering measured wetland water elevations ranged from an average monthly maximum of 10.1 cm to a minimum of -48.6 cm, model error was nearly 30% of the range of observed water levels. These RMSE values indicate that even the best basic module results have a limited ability to estimated actual wetland water budgets.

Nash-Sutcliffe model efficiency (NSE) shown in Equation 7 indicates the fit of observed and predicted values to an equal value line. It provides a goodness of fit indicator for many surface water models and is endorsed by the ASCE (ASCE, 1993; McCuen et al., 2006). Moriasi et. al (2007) stated that calibrated watershed models with NSE ratings less than 0.5 are considered to perform unsatisfactorily to poor, values of 0.5 to 0.65 are considered satisfactory, and values ranging from 0.65 to 1.00 are considered good or very good. Skaggs et al., (2012) cited that for calibrated daily water table depth prediction models, an NSE rating greater than 0.4 was considered acceptable, values greater than 0.6 are considered good, and values greater than 0.75 are considered excellent. For this study the Moriais et.al (2007) categories were chosen because they are a more stringent overall evaluation criteria. A negative NSE rating indicates that taking the mean of the observed values is a better predictor than the model simulation. While these values cannot be directly applied to Wetbud because Wetbud is a design model and not a calibrated model, they provide a good basis for model evaluation and assessment.

For the Wetbud basic module, NSE ratings were calculated with the predicted and observed monthly water level elevations in meters. For both the Bender Farms Wetland Mitigation site and the Cedar Run 3 Wetland Mitigation Bank, the basic module NSE values scored in the unsatisfactory to poor category with values ranging from -0.05 to 0.30. The highest NSE rating for the basic module was for the Bender Farms Mitigation Site model using the Thornthwaite method for PET. The Bender Farms Mitigation Site was the only model out of all the basic and advanced models where the Thornthwaite PET method provided the best NSE rating. This anomaly is more than likely due to an underestimated value of soil storage or poor groundwater flow estimates due to limited data. NSE ratings and RMSE ratings for the basic module support that it is very difficult to predict wetland water levels using only a mass balance equation, level pool routing, assuming or eliminating groundwater flows, and in large monthly intervals.

Advanced Model Results

The Wetbud advanced (MODFLOW-NWT) module provides wetland water elevations for each day of the modeled period at each cell location in the model. Figure 22 shows the Wetbud advanced model results for well 2 in the SW cell (Figure 5) of the Cedar Run Wetland Mitigation Bank for both Thornthwaite and Penman PET estimation techniques.

Each year is plotted separately because each year was run as an individual model with inputs corresponding to that year. Well 2 was chosen for display because it is centrally located in the SW cell and provides representative results for the site. Along with the model results, the ground surface at the well and 30.5 cm below the ground surface is plotted in Figure 22. The 30.5 cm depth corresponds to the ACOE hydrology requirement for inundation in wetland mitigation design. Also plotted on Figure 5 is the maximum depth limit of the installed ACOE wells in the Cedar Run 3 SW cell. The wells were installed to a depth of 47.5 cm, which equals a minimum well reading of 55.3 m. Because of the daily time step and the spatial definition, the advanced model results have a much greater temporal and spatial resolution than the basic module results. The higher resolution results provide mitigation wetland designers with a more comprehensive water budget on which to base designs. Problem areas and time periods in a potential wetland site can be identified and remedied during the design process rather than post construction.

Advanced model results follow the overall hydroperiod of the wetland site accurately. However, model results do not reflect the rapid increases and decreases of the observed water levels at the site. In addition, local maxima in the hydroperiod are not reached by the model; however, local minima are often exceeded by the model results (lowest well elevation recorded was 55.3 m). These errors could be a result of errors in the estimated specific storage value and could potentially be corrected with some calibration. Another consideration is that MODFLOW has difficulty reproducing rapid water level changes because of issues with model stability; thus it is questionable whether the model could ever completely reproduce the rapid water level changes observed in the Cedar Run 3 wetland.

An important parameter for mitigation wetland design is meeting the ACOE hydrology criterion, which requires continuous saturation within the top 30 cm of the soil surface during a fraction of the growing season. The specific growing season for an area is determined by soil temperature, air temperature, and a soil survey that identifies the optimum growing season for the o-site wetland vegetation.

For this study, the growing season was assumed to be from March to October of each modeled year. From the measured well data it was calculated that over the modeled period, the three wells were inundated in the top 30 cm of the soil an average of 54% of the growing season. The advanced model utilizing Thornthwaite for PET estimation calculated that the three wells were inundated in the top 30 cm of the soil an average of 64% of the growing season. These results support that the advanced model utilizing the Thornthwaite PET method under predicts PET during the growing season, which leads to an over prediction in water levels. The model utilizing the Penman PET method calculated that the three wells were inundated in the top 30 cm of the soil an average of 59% of the growing season. These values are much closer to the measured percentages of inundation during the growing season and would provide the designer with a better estimate of inundation period during the growing season.

From visual inspection of the results, it can be seen that the model has the most difficulty predicting periods where the water table draws down quickly and remains below the soil surface for extended periods. In the 2010 and 2011 model years, this is very evident because the entire years are modeled and the summer drawdown period and fall upsurge stands out as the most difficult period for the model to predict. Conversely, when the wetland has standing water in it and is nearly full, the model predicts head values more accurately. The increased difficulty in predicting the subsurface patterns is attributed to the difficulty in predicting site geologic strata and the associated model parameters such as hydraulic conductivity, specific yield and storage, and spatial geologic distribution of materials. It is much easier to determine, estimate, and even assume parameters for the surface water and vegetation layer because of the accessibility to observe and measure the site surface characteristics.

Other wetland modeling studies have produced results for water budget prediction that match measured hydrographs more closely (Bradley, 2002; Mansell et al., 2000). However, the models in these studies are calibrated. It is important to emphasize that Wetbud is being evaluated without calibration and models in this study were constructed based on design parameters to evaluate the ability of the model to aid in mitigation wetland design.

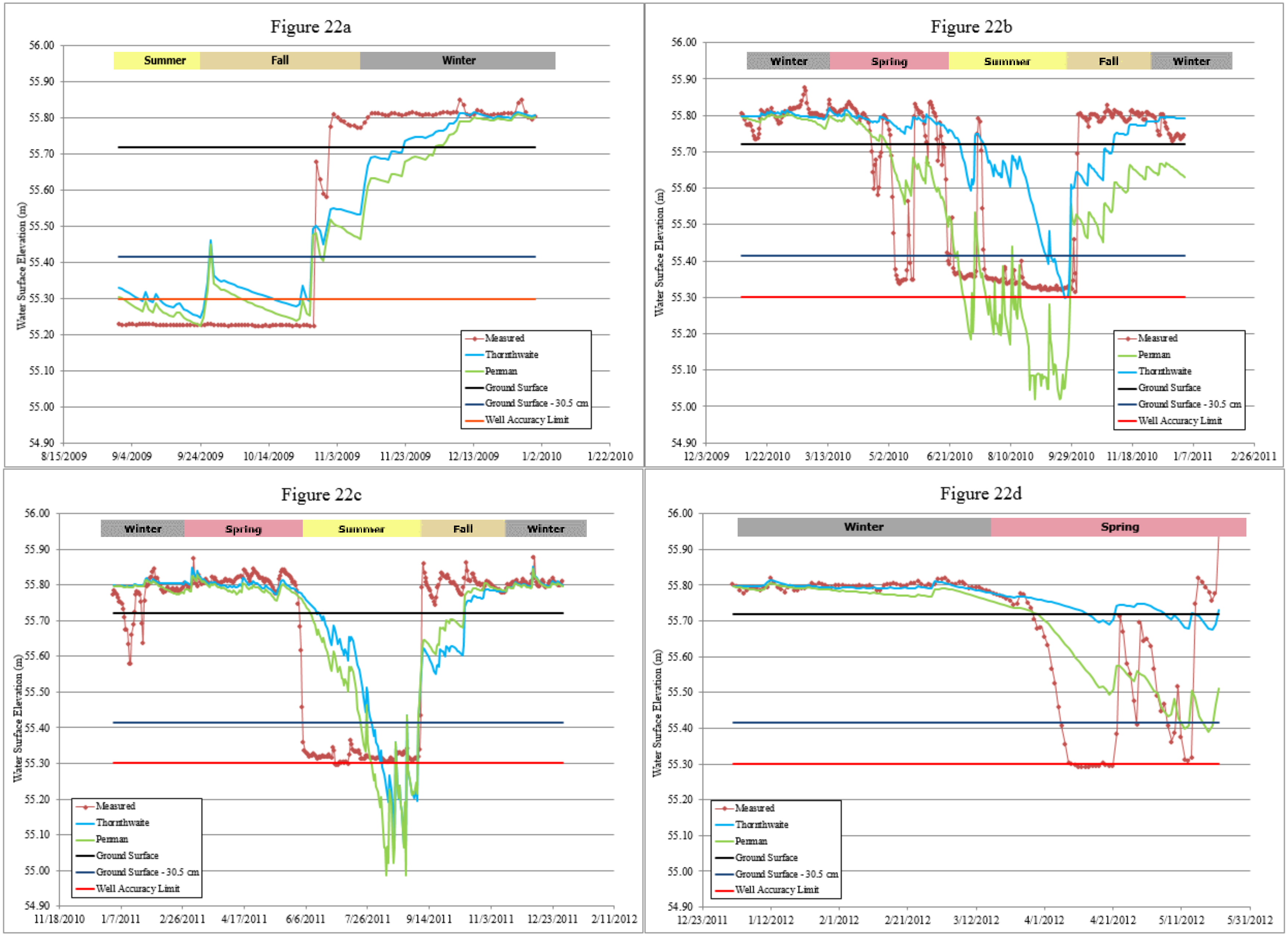

Figure 22: Wetbud advanced (MODFLOW-NWT) model result for well 2 at Cedar Run Wetland Mitigation Bank. Figure 22a: August to December 2009, Figure 22b: January to December 2010, Figure 22c: January to December 2011, Figure 22d: January to May 2012.

Advanced Model Statistical Analysis

Similar to the basic module statistical analysis, RMSE and NSE values were calculated to evaluate model performance. NSE values were calculated for the modeled period for each well on a daily and monthly basis. For easy comparison to the basic module performance, NSE values were also calculated for average monthly water levels of the three wells. In addition to the entire modeled periods, RMSE analysis was conducted on the seasonal performance of the advanced model. As previously stated, the ACOE wells were installed to a depth of 47.5 cm, translating into a maximum well depth reading of 55.30 m of water surface elevation. As a result, for statistical analysis when observed well readings were less than 55.3 m, observed and modeled results were excluded from the statistical calculation because no exact water surface elevation is known for the deeper water levels.

For the entire modeled period, average RMSE values for all three wells aggregated monthly were 0.11 m for the advanced model utilizing the Penman PET method and 0.14 m for the advanced model utilizing the Thornthwaite PET method. Based on these values, the model utilizing the Penman PET technique is more accurate than the model utilizing the Thornthwaite PET technique. The RMSE value for the advanced model utilizing the Penman PET method was 22% lower than the RMSE for the basic model utilizing the same PET method. Similarly, the RMSE value for the advanced model utilizing the Thornthwaite PET method was 18% lower the RMSE for the basic model utilizing the Thornthwaite PET method. Based on the RMSE statistic, the advanced model results reduce model error by an average value of 17% or 7 cm.

Similarly, average NSE model ratings for the entire modeled period with well data and results aggregated monthly were 0.61 for the model utilizing the Penman PET method and 0.44 for the model utilizing the Thornthwaite PET Method. The NSE results indicate the advanced model utilizing the Penman PET method produces an excellent rating (>0.65) while the model utilizing the Thornthwaite PET method provides a borderline poor rating (<0.5) (Moriasi et al., 2007). These statistics support that the Penman model provides better predictions of wetland PET than the Thornthwaite model. On a daily basis, as well as for each individual well, the evaluation results supported this trend. The calculated NSE values for each well on both a daily and monthly basis can be seen in Table 3.

Seasonal model performance was also investigated using the RMSE statistic. NSE values were considered for seasonal evaluation; however, because the NSE rating is normalized by the observed mean, and little water level fluctuation occurs during some seasons, such as winter, the NSE ratings were low and not representative of the model performance. The RMSE value, is not normalized by the observed mean, and is thus more representative of model performance in seasonal periods.

Table 3: NSE results for the Wetbud advanced module for the entire modeled period and each well.

	Penman NSE	*Thornthwaite NSE*
Adv. Model Monthly Well 1	0.62	0.49
Adv. Model Monthly Well 2	0.55	0.41
Adv. Model Monthly Well 3	0.63	0.44
Adv. Model Daily Well 1	0.53	0.42
Adv. Model Daily Well 2	0.49	0.38
Adv. Model Daily Well 3	0.55	0.36

Seasonal model results were evaluated for monthly averages of all three wells for the spring, summer, fall, and winter seasons. In addition, a RMSE value for the growing season which spans May through October was calculated to evaluate model performance during this sensitive period for hydrophytic vegetation. Results from the RMSE analysis for models utilizing both the Penman and Thornthwaite evapotranspiration methods are shown in Table 4. The RMSE ratings support what visual analysis of the modeled results showed: model estimates of water tables during the summer (RMSE values of 0.16 m and 0.24 m) are least accurate due to the rapid water level fluctuations (characteristic of the precipitation-driven Cedar Run 3 SW site) and minimum data amounts due to low water levels beyond the depth of the installed wells.

Conversely, as indicated by the RMSE values, the model produces the best results during the winter season (0.06 m and 0.03 m); during the winter the wetland is generally full to the outlet structure and water surface fluctuations are small.

Table 4: RMSE seasonal evaluation values for the Wetbud advanced model.

	Penman RMSE (m)	*Thornthwaite RMSE (m)*
Spring	0.07	0.13
Summer	0.16	0.24
Fall	0.16	0.11
Winter	0.06	0.03
Growing Season	0.13	0.17

*Spring (Mar, Apr, May); Summer (Jun, Jul, Aug); Fall (Sept, Oct, Nov); Winter (Dec, Jan, Feb); Growing Season (Mar-Oct)

The growing season RMSE value supports what was shown previously; the Penman model produces better predictions than the Thornthwaite model (0.13 m compared to 0.17 m, respectively). Accurate water level predictions are particularly important during the growing season where approximately 12.5% or 2-3 weeks of the growing season must be inundated in the top 30 cm of the soil surface for a consecutive period.

Wetbud Advanced Versus Basic Module Performance

An objective of this study was to compare the results of the basic module which utilizes the traditional Pierce methodology for the design of mitigation wetlands with the groundwater simulation technique applied in the Wetbud advanced (MODFLOW-NWT) module. To achieve this goal, both NSE and RMSE ratings were calculated for the Wetbud basic module using the entire modeled period and average monthly well water levels.

As is shown in Figure 23, the advanced module outperformed the basic module using both evapotranspiration techniques. The NSE values for the uncalibrated Wetbud advanced model ranged from a rating of excellent at the highest to a rating of borderline poor at the lowest. The uncalibrated Wetbud basic module results utilizing both methods of evapotranspiration

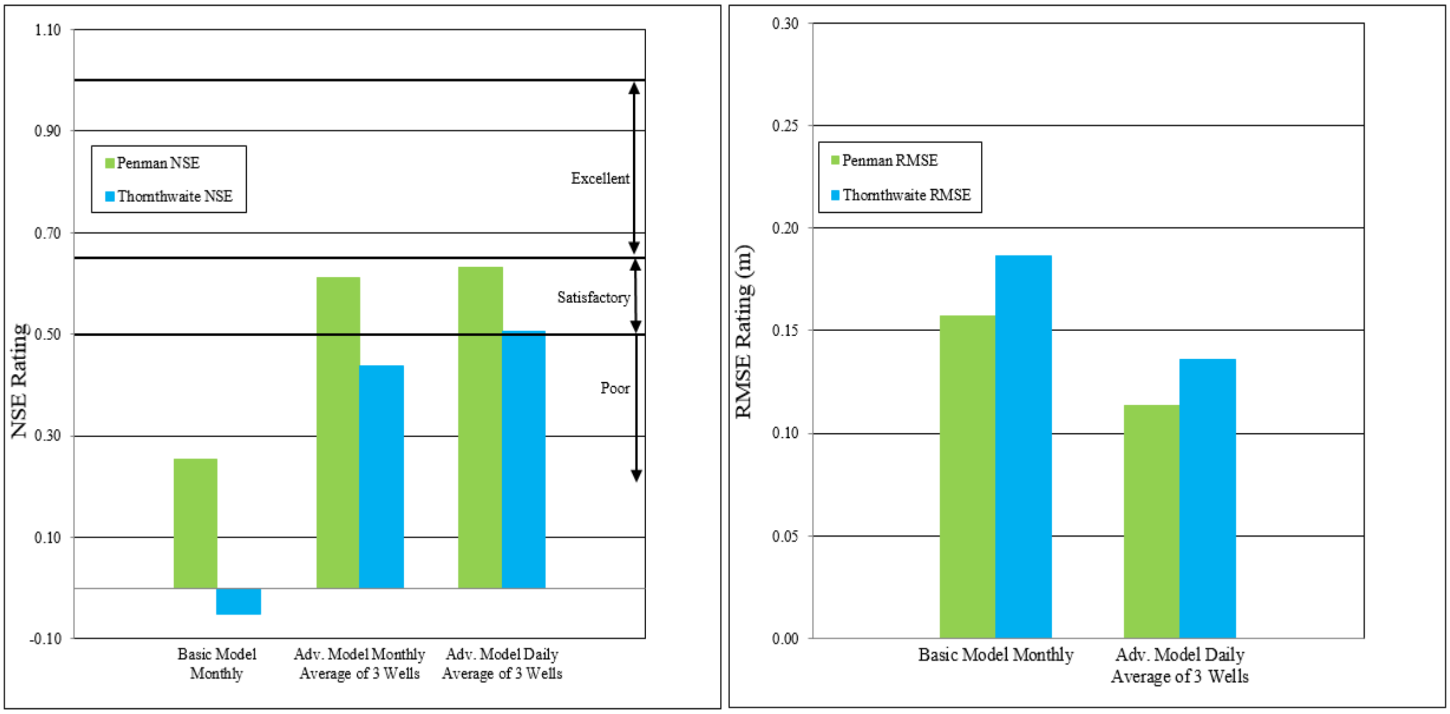

Figure 23: NSE and RMSE ratings comparing Wetbud advanced module performance with Wetbud basic module performance.

estimation rated poor. In addition, the uncalibrated Wetbud basic model using Thornthwaite PET produced a negative NSE result, indicating that taking the mean of the observed data is a better predictor than the model.

RMSE values also supported that the advanced module produced better results than the basic model, with RMSE values of 0.11 m using the Penman PET method and 0.14 m using the Thornthwaite PET method. RMSE values for the basic module results were 0.17 m using the Penman PET method and 0.22 m using the Thornthwaite method.

Overall, while the advanced module takes more effort and knowledge of site characteristics, it produces better predictions of wetland water levels. It also provides the designer with a much more spatially and temporally detailed result. The more spatially and temporally detailed results give the designer the ability to make specific changes to the site as needed and to recognize potential problem areas within the wetland, as well as potential seasonal issues (i.e. being too wet or too dry during a modeled period). The advanced module compensates for vegetative resistance and sloping surfaces, which are lacking in the basic module. The basic module is a good starting point for design, but the advanced module is a much better option if a detailed wetland water budget is required for a mitigation site.

Thornthwaite versus FAO-56 Penman Monteith Evapotranspiration Estimate

In addition to the NSE and RMSE ratings, a linear regression of model results was plotted for the individual years of the basic and advanced modules to compare the two methods of estimating PET. Weekly advanced model linear regressions of predicted water levels versus observed water levels were created in the R statistical software package and are shown in Figure 24.

A one-to-one line is shown to represent perfect model prediction. Figure 24 shows differences in water level predictions due to ET model. Consistent trends can be observed in Figure 24. Typically, when water table values are lower, the Thornthwaite method under predicts PET resulting in over predicted water levels. While the Penman equation also under predicts PET during low water tables, the overall water level predictions are closer to the observed.

In higher water table situations during wetland saturation, it appears that based on the overall water level trends in the model results both methods have a tendency to over predict evapotranspiration. However, again the Penman equation outperforms the Thornthwaite equation in this aspect of prediction in two out of the four years and performs equally as well in one out of the four years. These same trends were observed on a monthly time scale with the basic module predictions. The water levels produced by the advanced module utilizing the Penman PET method are better in 2010 than in 2011. The weather data shows that in 2010 there was approximately 27 cm less rainfall than in 2011. Since the Penman PET method consistently predicts larger values of PET (Owen, 1995), the lower water levels due to dry conditions contributed to improved model results.

Results of the linear regression analysis supports the finding that the Penman equation provides better PET predictions than the Thornthwaite equation for wetland vegetation, leading to significantly better water budget predictions. The NSE ratings were higher for every model scenario (basic and advanced) at Cedar Run 3. For the Bender Farms Mitigation Site, the NSE ratings for the basic model were poor for both methods of PET (0.24 for Penman and 0.30 for Thornthwaite).

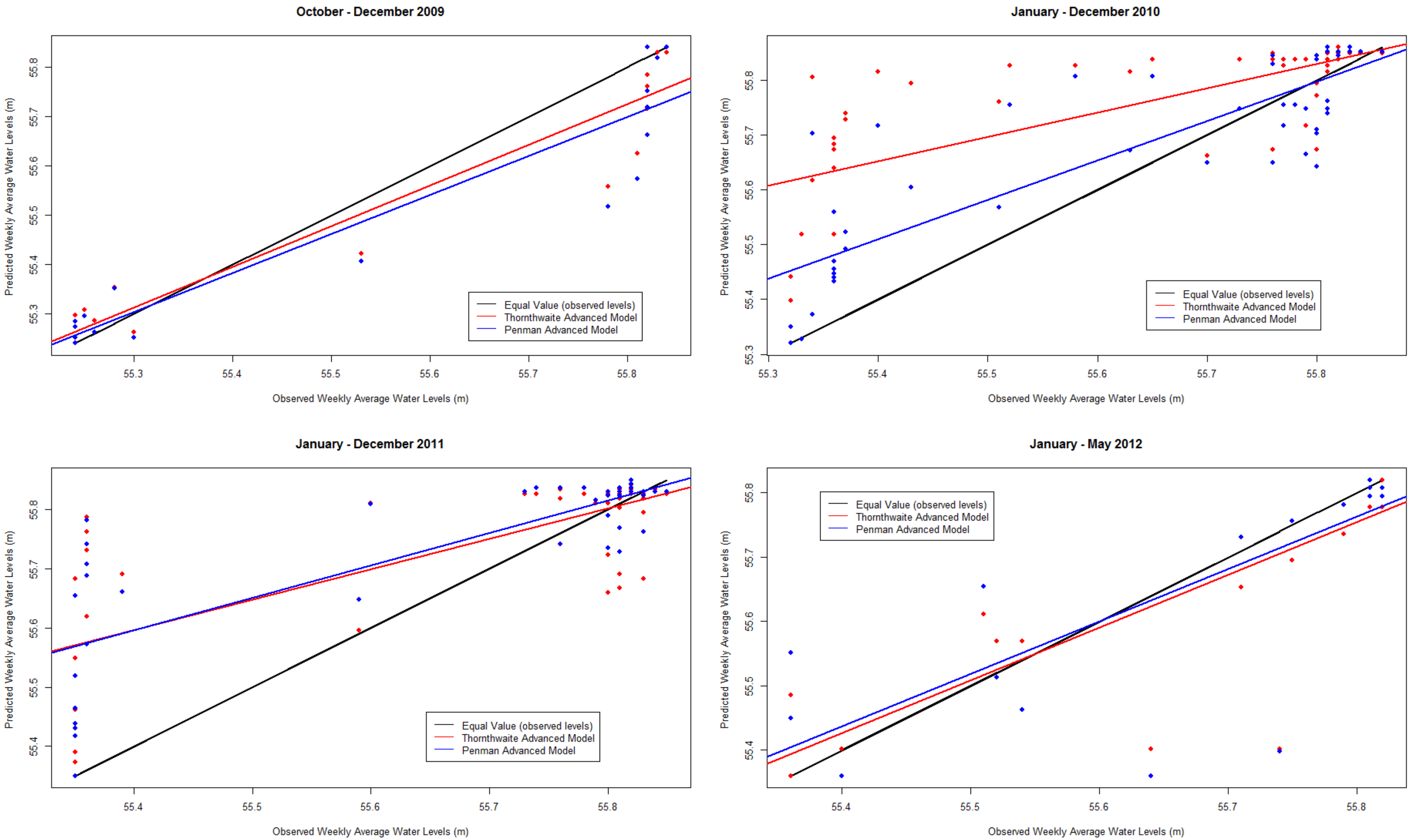

Figure 24: Linear regression of weekly Wetbud advanced module results.

Additionally, the RMSE values for the models which utilized the Penman equation were consistently lower than the RMSE values for the models utilizing the Thornthwaite equation. Based on statistical evaluation of the model, visual inspection of the results, and consistent trends over both modules of Wetbud, it is recommended that the Penman equation be used for evapotranspiration estimation when adequate data are available.

Conclusions

The goal of this study was to evaluate the uncalibrated Wetbud basic and advanced modules as design tools for mitigation wetland water budgets in the Virginia Piedmont. This study aimed to compare the Pierce methodology with the MODFLOW groundwater simulation method for the design of mitigation wetlands and to compare the Thornthwaite and the Penman PET estimation methods for the design of mitigation wetlands.

The basic module is easy to set up, import needed weather and precipitation data, and produce model results. However, these results are limited to monthly average water levels in the wetland and provide a temporally and spatially coarse water budget for mitigation designers. While groundwater inflows and outflows can be included in the basic module, a separate tool such as WEM must be used to calculate groundwater flows within the wetland which requires quality observed well data both on the site and in an up gradient location.

The basic module is also very sensitive to the soil storage factors input by the user. Incorrectly estimating this value can dramatically affect the model results by directly magnifying or reducing the effects of water input into the system. The basic module is limited by using an average wetland depth by setting a depth to weir input and can underestimate the influence of vegetation resistance to surface water flows on wetland water depths. For the entire modeled period of 34 months for the Cedar Run 3 SW cell, a total of 10 months had average measured wetland water levels above the depth to weir value set within the basic module. Measured water levels being higher than predicted for nearly 30% of the monitoring period indicates flow resistance within the wetland, rather than the outlet structures, is controlling wetland water depths. Thus, it is important to consider flow resistance from vegetation in wetland water budgets as it has a significant effect on controlling water depths. The depth to weir limitation and under estimation of ponded water in the wetland results in an under estimation of the storage capacity in the wetland. An average depth to weir in the wetland removes any ability of the wetland to store water in local maxima that exist in the topography.

The basic module over predicted water levels at the Cedar Run 3 Wetland Mitigation Bank during summer periods by 52% (31 cm) using the Thornthwaite PET method and by 35% (21 cm) using the Penman PET method during summer. For the Bender Farms Wetland Mitigation Site, basic module results had RMSE values of 0.19 m for both the Thornthwaite and the Penman evapotranspiration methods. For the Cedar Run 3 Wetland Mitigation Bank, the basic module utilizing the Penman evapotranspiration method had a better RMSE value (0.17 m) than the Thornthwaite basic model (0.22 m). The best RMSE value for the basic module was 0.17 m and was achieved by the Cedar Run 3 Wetland Mitigation Bank basic module utilizing Penman equations for PET estimation. Measured wetland water elevations at CR-3 ranged from an average monthly maximum of 10.1 cm to a minimum of -48.6 cm; RMSE results showed that the lowest simple model error was 17 cm. The variation displayed by the RMSE values shows that even the best basic module results have a limited ability to accurately estimate wetland water budgets.

The advanced module provides temporally and spatially detailed model results and performs well based on the NSE rating (0.63 for the model utilizing the Penman PET method and 0.50 for the model utilizing the Thornthwaite PET method), especially considering the design model is not calibrated. Setting up the model parameters in the advanced module is labor-intensive and time-consuming. Detailed information about the wetland substrate is needed to accurately model a proposed mitigation design. However, the advanced module predicts groundwater flow and vegetation resistance to surface water flows in flat and sloped wetlands. It is best utilized in systems where groundwater is a major influence on the wetland water budget. The advanced module is sensitive to solver parameters and specific storage values: convergence of the advanced module can be difficult if these values are not within a reasonable range. PET is influential in wetland water budget calculations (Owen, 1995). This study determined that regardless of whether the basic or advanced module was utilized, when the Penman equation was used for PET estimation, model results were more accurate than when the Thornthwaite equation was used for PET estimation. If detailed solar data are available, the Penman equation should be used for wetland water budget modeling to obtain the best results.

In both modules of Wetbud, the effects of precipitation and weather data proximity to the site on the water budget were observed. Precipitation and weather data should be chosen carefully and users should ensure that values are being obtained from the closest available station to their site. If possible, on-site weather and precipitation data ultimately will provide the best model results.

Advanced model results from Wetbud were compared to a previous modeling study by Gloe et.al, which utilized Groundwater Modeling System (GMS ver, 8.0, Aquaveo, Provo, UT) to model the Cedar Run 3 SW cell. On an annual basis, the Wetbud advanced model was more accurate when predicting water levels according to NSE ratings (0.63-0.50 for Wetbud advanced model and 0.42 for GMS model). For the growing season, the Wetbud advanced model produced better RMSE values than the GMS model produced (18.7 cm for GMS and 13.0 cm for Wetbud advanced model). Seasonally, the Wetbud advanced model produced better RMSE results for every season of the modeled period (Gloe, 2011). The NSE and RMSE results from the two models, supports that the Wetbud advanced model is capable of producing results that are consistent with other modeling packages available for wetland water budget modeling such as the Groundwater Modeling System.

Recommendations for Future Work

This study evaluated the first Wetbud version. Further investigations would improve the user interface and usability of the model. In addition, many options in the model were not utilized or tested in this study because they were not needed to represent the modeled sites. Modeling more sites within the Virginia Piedmont could expose needed features for the advanced module package and provide an opportunity to test any packages that were not utilized in this study. In practice, many designers have access to monitoring data for a short period prior to the design. Model calibration using a short period of monitoring data would likely improve model predictions.

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Appendix A

Model Data Documentation

Table 5

Data Type	Source	Location
Precipitation Data	Wetland Studies and Solution Inc.	See below
Supplemental Precipitation and Weather Data	Dulles International Airport NOAA GSOD Station Code 724030 WBAN 93738	http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html
Supplemental Precipitation and Weather Data	Manassas Regional Airport NOAA GSOD Station Code 724036 WBAN 03710	http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html
Solar Radiation Data	Western Regional Climate Center (WRCC) RAWS USA Climate Archive Cedarville, MD Station	http://www.raws.dri.edu/index.html
Solar Radiation Data	Western Regional Climate Center (WRCC) RAWS USA Climate Archive Headquarters, VA Station	http://www.raws.dri.edu/index.html

WSSI Precipitation Data

Table 6

2009 WSSI Precipitation (cm) (Missing Data Supplemented with NOAA Station Data)								
Day	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.051	0.000	0.000	0.000	0.000	0.000	2.565	0.000
2	0.229	1.194	0.025	0.000	0.000	0.000	0.000	1.219
3	2.845	3.658	0.000	0.000	0.000	0.000	0.000	0.203
4	1.626	0.940	0.000	0.000	0.000	0.000	0.000	0.000
5	0.635	2.337	0.000	0.000	0.000	0.000	0.000	0.762
6	5.918	0.000	0.000	0.000	0.000	0.000	0.000	1.499
7	1.092	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.025	0.000	0.000	0.000	0.000	0.000	0.000	1.194
9	0.000	0.076	0.000	0.000	0.000	0.000	0.000	3.099
10	0.000	0.025	0.000	0.000	0.000	0.000	0.000	0.000
11	0.711	0.051	0.000	0.000	0.000	0.000	3.175	0.000
12	0.000	0.025	0.000	0.000	0.000	0.000	1.905	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.838	1.676
14	0.889	0.000	0.000	0.000	0.000	0.000	0.102	0.025
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	1.854	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.152	1.372	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.203	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	1.041	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.067
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.102	1.727	0.000
24	0.000	0.000	0.000	0.000	0.000	0.711	0.254	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.305	1.803
26	1.524	0.000	0.000	0.000	0.000	0.000	0.203	1.118
27	0.127	0.000	0.000	0.000	0.000	4.039	0.051	0.025
28	0.737	0.000	0.000	0.000	0.000	1.448	0.000	0.000
29	0.432	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000	0.711	0.000
31	1.499	-	0.000	0.000	-	0.762	-	0.914

Table 7

2010 WSSI Precipitation (cm) (Missing Data Supplemented with NOAA Station Data)												
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.000	0.025	0.000	0.000	0.000	0.711	0.000	0.051	0.000	0.051	0.000	1.473
2	0.000	0.000	0.229	0.000	0.000	0.000	0.000	0.737	0.000	0.000	0.000	0.000
3	0.000	1.092	0.076	0.000	0.305	3.454	0.000	0.000	0.000	0.965	0.432	0.000
4	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.559	0.000	0.940	2.997	0.000
5	0.000	0.330	0.000	0.000	0.000	0.000	0.000	2.261	0.000	0.025	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.406	0.000	0.000	0.000	0.076	0.000	0.000
7	0.000	1.651	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.025	0.000	0.000
8	0.051	0.000	0.000	1.626	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.102	0.000	0.152	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.457	0.000	0.000	0.000	0.203	1.651	0.000	0.000	0.000	0.000	0.000
11	0.000	0.356	0.229	0.000	0.356	0.000	0.000	0.000	0.000	0.000	0.000	0.152
12	0.000	0.000	1.321	0.000	0.076	1.041	1.016	3.912	1.549	0.000	0.000	1.219
13	0.000	0.000	2.362	0.254	0.000	0.406	7.417	0.076	0.000	0.000	0.000	0.051
14	0.000	0.000	1.473	0.000	0.000	0.127	0.051	0.000	0.000	2.413	0.000	0.000
15	0.000	0.152	0.051	0.000	0.000	0.102	0.000	0.584	0.000	0.025	0.406	0.000
16	0.000	0.000	0.000	0.000	0.025	0.737	0.000	0.000	0.203	0.000	2.311	0.000
17	1.346	0.000	0.000	0.000	2.845	0.025	0.000	0.000	0.178	0.000	0.483	0.584
18	0.000	0.000	0.000	0.000	0.102	0.000	0.000	1.880	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.051	0.000	0.356	0.000	0.000	0.000	0.000	0.000
20	0.051	0.000	0.000	0.000	0.025	0.000	0.152	0.000	0.000	0.076	0.000	0.000
21	0.787	0.000	0.000	0.584	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000
22	0.965	0.381	0.914	0.025	2.083	1.524	0.000	0.076	0.000	0.000	0.000	0.000
23	0.000	0.000	0.051	0.000	2.870	0.025	0.000	0.000	0.000	0.000	0.000	0.000
24	0.305	0.000	0.025	0.559	0.025	0.000	0.000	0.025	0.000	0.000	0.000	0.000
25	1.245	0.000	0.025	0.152	0.000	0.000	0.813	0.000	0.000	0.000	0.025	0.000
26	0.000	0.000	0.889	2.134	0.000	0.000	0.000	0.000	0.178	0.000	0.025	0.000
27	0.000	0.000	0.000	0.000	1.041	0.000	0.000	0.000	0.279	3.658	0.000	0.000
28	0.000	0.000	2.540	0.000	0.076	0.432	0.000	0.000	0.635	0.025	0.000	0.000
29	0.000	-	0.559	0.000	0.000	0.000	1.854	0.000	1.524	0.000	0.000	0.000
30	0.000	-	0.254	0.000	0.000	0.000	0.025	0.000	8.839	0.000	0.152	0.000
31	0.584	-	0.000	-	0.000	-	0.279	0.000	-	0.000	-	0.000

Table 8

2011 WSSI Precipitation (cm) (Missing Data Supplemented with NOAA Station Data)												
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.000	0.432	0.000	0.076	0.000	0.279	0.000	0.381	0.000	0.660	0.000	0.000
2	0.127	1.600	0.000	0.051	0.025	0.000	0.000	0.025	0.051	0.127	0.000	0.000
3	0.000	0.000	0.000	0.000	0.203	0.000	1.143	0.102	0.457	0.152	0.000	0.000
4	0.000	0.000	0.000	0.000	1.448	0.000	0.051	0.000	0.000	0.025	0.000	0.000
5	0.000	0.305	0.000	0.965	0.000	0.076	0.051	0.025	2.718	0.000	0.000	0.000
6	0.000	0.051	6.807	0.000	0.000	0.000	0.483	0.533	2.667	0.000	0.000	0.610
7	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.025	3.404	0.000	0.000	7.137
8	0.178	0.000	0.000	0.914	0.025	0.000	1.270	0.000	5.334	0.000	0.000	0.000
9	0.000	0.000	0.102	0.000	0.000	0.178	0.025	0.000	0.381	0.000	0.000	0.000
10	0.000	0.152	3.658	0.000	0.000	0.152	0.000	0.000	0.025	0.000	0.254	0.000
11	0.000	0.000	0.127	0.000	0.000	0.356	3.124	0.000	0.076	0.025	0.000	0.000
12	0.178	0.000	0.000	0.965	0.000	0.025	0.025	0.000	0.000	1.245	0.000	0.000
13	0.000	0.000	0.000	1.092	0.102	0.025	1.092	1.041	0.000	5.512	0.000	0.000
14	0.000	0.000	0.000	0.000	1.930	0.000	0.025	0.381	0.000	0.533	0.000	0.000
15	0.000	0.000	1.346	0.000	0.737	0.000	0.000	0.025	0.152	0.000	0.051	0.000
16	0.000	0.000	0.000	4.013	1.753	1.067	0.000	0.000	0.025	0.000	1.702	0.000
17	0.000	0.000	0.000	0.025	2.235	0.051	0.000	0.000	0.000	0.000	0.051	0.000
18	1.016	0.000	0.000	0.000	0.864	0.000	0.000	2.515	0.000	0.000	0.000	0.000
19	0.025	0.000	0.000	0.000	0.279	0.152	0.000	0.229	0.000	1.956	0.000	0.000
20	0.000	0.000	0.000	0.000	0.025	0.991	0.000	0.051	1.168	0.000	0.000	0.000
21	0.000	0.102	1.499	0.000	0.000	0.025	0.000	0.660	0.356	0.000	0.127	0.152
22	0.000	0.457	0.000	1.194	0.051	0.000	0.000	0.000	0.051	0.000	1.880	1.626
23	0.000	0.000	0.914	0.127	0.152	0.000	0.000	0.025	2.210	0.000	0.965	0.864
24	0.000	0.406	0.152	1.702	0.254	0.000	0.000	0.000	0.025	0.000	0.000	0.000
25	0.000	0.457	0.000	0.025	0.025	0.000	1.854	0.635	0.254	0.025	0.000	0.000
26	1.524	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.025	0.025	0.000	0.000
27	1.829	0.000	0.152	0.483	0.457	0.152	0.000	3.988	0.051	0.051	0.000	1.346
28	0.635	1.829	0.000	0.305	0.051	2.667	0.000	0.229	1.397	0.457	0.000	0.000
29	0.000	-	0.000	0.000	0.000	0.025	0.000	0.000	0.025	2.946	1.168	0.000
30	0.000	-	0.457	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000
31	0.000	-	0.406	-	0.000	-	0.000	0.000	-	0.000	-	0.025

Table 9

2011 WSSI Precipitation (cm)
(Missing Data Supplemented with NOAA Station Data)

Day	Jan	Feb	Mar	Apr
1	0.025	0.000	0.025	0.102
2	0.000	0.483	0.838	0.025
3	0.000	0.000	0.178	0.000
4	0.000	0.152	0.000	0.000
5	0.000	0.203	0.203	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.330	0.000	0.000
9	0.102	0.000	0.051	0.000
10	0.381	0.025	0.000	0.000
11	1.930	0.381	0.000	0.000
12	0.940	0.000	0.000	0.000
13	0.127	0.000	0.025	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.051	0.508	0.000	0.000
17	0.076	0.025	0.000	0.000
18	0.000	0.000	0.000	0.559
19	0.000	0.102	0.102	0.025
20	0.000	0.381	0.025	0.000
21	0.305	0.000	0.000	0.914
22	0.127	0.000	0.000	2.794
23	0.483	0.203	0.000	0.279
24	0.000	0.711	0.584	0.000
25	0.000	0.000	0.406	0.000
26	0.025	0.000	0.000	0.152
27	0.203	0.000	0.000	0.000
28	0.000	0.000	0.076	1.422
29	0.000	2.997	0.000	0.076
30	0.000	-	0.152	-
31	0.000	-	0.025	-

Wetbud Advanced (MODFLOW-NWT) Results

Table 10

2009 Wetbud Advanced (MODFLOW-NWT) Results - Thornthwaite PET (m) Average of Well 1, Well 2, and Well 3

Day	Sep	Oct	Nov	Dec
1	55.34	55.36	55.56	55.75
2	55.34	55.36	55.56	55.76
3	55.33	55.35	55.56	55.76
4	55.32	55.35	55.56	55.77
5	55.32	55.35	55.56	55.77
6	55.31	55.34	55.55	55.78
7	55.31	55.34	55.55	55.78
8	55.30	55.33	55.55	55.79
9	55.33	55.33	55.54	55.81
10	55.31	55.33	55.54	55.81
11	55.30	55.32	55.63	55.81
12	55.32	55.32	55.68	55.81
13	55.31	55.32	55.70	55.81
14	55.30	55.32	55.70	55.81
15	55.29	55.31	55.70	55.81
16	55.29	55.31	55.70	55.81
17	55.29	55.31	55.69	55.80
18	55.29	55.30	55.69	55.80
19	55.30	55.30	55.71	55.80
20	55.28	55.30	55.71	55.80
21	55.28	55.29	55.71	55.80
22	55.27	55.29	55.71	55.80
23	55.27	55.30	55.74	55.80
24	55.26	55.35	55.74	55.80
25	55.26	55.31	55.75	55.81
26	55.28	55.31	55.75	55.81
27	55.36	55.51	55.75	55.81
28	55.47	55.51	55.75	55.81
29	55.37	55.50	55.74	55.81
30	55.37	55.46	55.75	55.80
31	55.358	55.50	-	55.81

Table 11

2010 Wetbud Advanced (MODFLOW-NWT) Results - Thornthwaite PET (m)
Average of Well 1, Well 2, and Well 3

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	55.80	55.80	55.79	55.80	55.79	55.78	55.69	55.63	55.50	55.60	55.70	55.78
2	55.80	55.80	55.79	55.80	55.78	55.80	55.67	55.62	55.48	55.62	55.71	55.78
3	55.80	55.81	55.79	55.80	55.78	55.80	55.66	55.63	55.47	55.64	55.75	55.78
4	55.80	55.81	55.79	55.79	55.78	55.79	55.64	55.67	55.45	55.64	55.75	55.78
5	55.80	55.81	55.79	55.79	55.78	55.79	55.63	55.66	55.44	55.64	55.75	55.78
6	55.80	55.80	55.79	55.79	55.77	55.79	55.62	55.65	55.43	55.64	55.75	55.78
7	55.80	55.81	55.79	55.80	55.77	55.79	55.60	55.64	55.42	55.63	55.75	55.78
8	55.80	55.81	55.79	55.80	55.77	55.78	55.59	55.63	55.41	55.63	55.75	55.78
9	55.80	55.81	55.79	55.80	55.76	55.78	55.61	55.61	55.40	55.62	55.75	55.78
10	55.80	55.81	55.79	55.79	55.76	55.78	55.60	55.60	55.39	55.62	55.75	55.79
11	55.80	55.81	55.79	55.79	55.76	55.78	55.61	55.69	55.49	55.61	55.75	55.79
12	55.80	55.81	55.80	55.79	55.76	55.78	55.74	55.68	55.42	55.61	55.75	55.79
13	55.80	55.80	55.81	55.79	55.76	55.78	55.75	55.67	55.41	55.67	55.75	55.79
14	55.80	55.80	55.82	55.79	55.75	55.77	55.75	55.67	55.40	55.67	55.75	55.79
15	55.80	55.80	55.81	55.79	55.75	55.77	55.74	55.66	55.40	55.66	55.77	55.79
16	55.80	55.80	55.81	55.79	55.77	55.77	55.73	55.65	55.40	55.66	55.77	55.80
17	55.80	55.80	55.81	55.78	55.77	55.77	55.73	55.69	55.37	55.65	55.77	55.80
18	55.80	55.80	55.80	55.78	55.77	55.76	55.72	55.68	55.36	55.65	55.77	55.79
19	55.80	55.80	55.80	55.78	55.77	55.76	55.71	55.67	55.35	55.65	55.77	55.79
20	55.80	55.80	55.80	55.78	55.76	55.75	55.70	55.65	55.34	55.64	55.77	55.79
21	55.80	55.80	55.80	55.78	55.78	55.76	55.69	55.64	55.33	55.64	55.77	55.79
22	55.81	55.80	55.80	55.78	55.80	55.76	55.67	55.63	55.32	55.63	55.77	55.79
23	55.81	55.80	55.80	55.78	55.79	55.75	55.66	55.62	55.30	55.63	55.77	55.79
24	55.81	55.80	55.80	55.78	55.79	55.75	55.67	55.60	55.29	55.63	55.77	55.79
25	55.81	55.80	55.80	55.80	55.79	55.74	55.65	55.59	55.30	55.62	55.77	55.79
26	55.81	55.80	55.80	55.80	55.79	55.73	55.64	55.58	55.30	55.71	55.77	55.79
27	55.81	55.79	55.81	55.79	55.79	55.73	55.62	55.57	55.33	55.71	55.77	55.79
28	55.80	55.79	55.81	55.79	55.79	55.72	55.66	55.55	55.42	55.71	55.77	55.79
29	55.80	-	55.81	55.79	55.79	55.71	55.65	55.54	55.62	55.70	55.77	55.79
30	55.80	-	55.81	55.79	55.78	55.70	55.64	55.52	55.60	55.70	55.78	55.79
31	55.81	-	55.80	-	55.79	-	55.63	55.51	-	55.70	-	55.79

Table 12

2011 Wetbud Advanced (MODFLOW-NWT) Results Thornthwaite PET (m)
Average of Well 1, Well 2, and Well 3

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	55.80	55.81	55.81	55.80	55.79	55.78	55.65	55.39	55.23	55.63	55.79	55.80
2	55.80	55.82	55.81	55.80	55.79	55.77	55.63	55.35	55.22	55.63	55.79	55.80
3	55.80	55.81	55.80	55.79	55.79	55.77	55.64	55.34	55.24	55.63	55.79	55.80
4	55.80	55.81	55.80	55.79	55.80	55.77	55.63	55.32	55.21	55.63	55.78	55.80
5	55.80	55.81	55.80	55.80	55.80	55.76	55.62	55.30	55.44	55.63	55.78	55.79
6	55.80	55.81	55.84	55.79	55.79	55.76	55.61	55.33	55.47	55.62	55.78	55.80
7	55.80	55.81	55.83	55.79	55.79	55.75	55.60	55.29	55.53	55.62	55.78	55.85
8	55.80	55.80	55.82	55.80	55.79	55.75	55.62	55.27	55.62	55.62	55.78	55.83
9	55.80	55.80	55.82	55.80	55.78	55.75	55.60	55.25	55.64	55.61	55.78	55.82
10	55.80	55.80	55.84	55.79	55.78	55.74	55.59	55.23	55.63	55.61	55.78	55.82
11	55.80	55.80	55.83	55.79	55.78	55.74	55.65	55.21	55.63	55.61	55.78	55.81
12	55.80	55.80	55.82	55.80	55.78	55.73	55.64	55.15	55.62	55.64	55.78	55.81
13	55.80	55.80	55.82	55.80	55.77	55.73	55.65	55.26	55.61	55.74	55.78	55.81
14	55.80	55.80	55.81	55.80	55.79	55.72	55.64	55.22	55.60	55.75	55.78	55.80
15	55.80	55.80	55.82	55.80	55.79	55.71	55.62	55.17	55.60	55.76	55.78	55.80
16	55.80	55.80	55.81	55.82	55.80	55.72	55.61	55.13	55.59	55.76	55.79	55.80
17	55.80	55.80	55.81	55.82	55.81	55.71	55.59	55.08	55.58	55.75	55.79	55.80
18	55.80	55.80	55.81	55.81	55.81	55.70	55.58	55.37	55.57	55.75	55.79	55.80
19	55.80	55.80	55.80	55.81	55.81	55.69	55.56	55.24	55.56	55.77	55.79	55.80
20	55.80	55.80	55.80	55.80	55.81	55.71	55.54	55.21	55.58	55.77	55.79	55.80
21	55.80	55.80	55.81	55.80	55.80	55.70	55.52	55.25	55.59	55.77	55.79	55.80
22	55.80	55.81	55.81	55.80	55.80	55.68	55.50	55.20	55.58	55.77	55.80	55.81
23	55.80	55.80	55.81	55.80	55.80	55.67	55.47	55.18	55.63	55.77	55.81	55.81
24	55.80	55.80	55.81	55.81	55.79	55.66	55.44	55.07	55.62	55.76	55.81	55.81
25	55.80	55.80	55.80	55.81	55.79	55.65	55.52	55.20	55.62	55.76	55.80	55.80
26	55.81	55.80	55.80	55.80	55.79	55.63	55.48	55.05	55.61	55.76	55.80	55.80
27	55.82	55.80	55.80	55.80	55.79	55.63	55.45	55.45	55.61	55.76	55.80	55.81
28	55.82	55.81	55.80	55.80	55.79	55.68	55.43	55.30	55.63	55.76	55.80	55.81
29	55.81	-	55.80	55.80	55.79	55.67	55.41	55.27	55.63	55.79	55.80	55.80
30	55.81	-	55.80	55.80	55.78	55.66	55.39	55.25	55.62	55.79	55.80	55.80
31	55.81	-	55.80	-	55.78	-	55.37	55.23	-	55.79	-	55.80

Table 13

2012 Wetbud Advanced (MODFLOW-NWT) Results
Thornthwaite PET (m)
Average of Well 1, Well 2, and Well 3

Day	Jan	Feb	Mar	Apr	May
1	55.80	55.79	55.81	55.76	55.74
2	55.80	55.79	55.81	55.75	55.74
3	55.80	55.79	55.81	55.75	55.73
4	55.80	55.79	55.80	55.75	55.73
5	55.80	55.79	55.80	55.75	55.72
6	55.80	55.79	55.80	55.74	55.71
7	55.80	55.79	55.79	55.74	55.70
8	55.80	55.79	55.79	55.74	55.69
9	55.80	55.79	55.79	55.73	55.71
10	55.80	55.79	55.79	55.73	55.70
11	55.81	55.79	55.79	55.72	55.69
12	55.81	55.79	55.79	55.72	55.67
13	55.81	55.79	55.78	55.71	55.67
14	55.81	55.79	55.78	55.71	55.72
15	55.80	55.79	55.78	55.70	55.72
16	55.80	55.79	55.78	55.69	55.71
17	55.80	55.79	55.78	55.69	55.70
18	55.80	55.79	55.77	55.70	55.68
19	55.80	55.79	55.77	55.69	55.67
20	55.80	55.79	55.77	55.68	55.67
21	55.80	55.79	55.77	55.70	55.69
22	55.80	55.79	55.77	55.74	55.73
23	55.80	55.79	55.76	55.75	-
24	55.80	55.80	55.77	55.74	-
25	55.80	55.79	55.77	55.74	-
26	55.79	55.79	55.77	55.74	-
27	55.80	55.79	55.77	55.74	-
28	55.79	55.79	55.76	55.75	-
29	55.79	55.81	55.76	55.75	-
30	55.79	-	55.76	55.75	-
31	55.79	-	55.76	-	-

Table 14

2009 Wetbud Advanced (MODFLOW-NWT) Results - Penman PET (m) Average of Well 1, Well 2, and Well 3

Day	Sep	Oct	Nov	Dec
1	55.31	55.34	55.53	55.70
2	55.31	55.33	55.52	55.73
3	55.30	55.33	55.51	55.73
4	55.29	55.32	55.51	55.73
5	55.29	55.32	55.51	55.74
6	55.28	55.31	55.50	55.75
7	55.28	55.31	55.49	55.75
8	55.30	55.30	55.49	55.76
9	55.28	55.30	55.48	55.79
10	55.27	55.30	55.48	55.79
11	55.30	55.29	55.57	55.79
12	55.29	55.29	55.62	55.79
13	55.27	55.28	55.64	55.80
14	55.27	55.28	55.65	55.80
15	55.26	55.28	55.64	55.80
16	55.26	55.27	55.64	55.80
17	55.27	55.27	55.64	55.79
18	55.27	55.27	55.63	55.79
19	55.26	55.26	55.65	55.79
20	55.25	55.26	55.65	55.80
21	55.25	55.26	55.65	55.80
22	55.25	55.25	55.65	55.80
23	55.24	55.26	55.69	55.79
24	55.24	55.31	55.69	55.79
25	55.26	55.27	55.70	55.80
26	55.34	55.27	55.70	55.81
27	55.46	55.49	55.70	55.81
28	55.35	55.49	55.69	55.80
29	55.34	55.43	55.69	55.80
30	55.34	55.42	55.70	55.80
31	-	55.47	-	55.80

Table 15

2010 Wetbud Advanced (MODFLOW-NWT) Results - Penman PET (m)
Average of Well 1, Well 2, and Well 3

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	55.80	55.79	55.78	55.79	55.70	55.61	55.33	55.25	55.10	55.51	55.54	55.66
2	55.80	55.79	55.78	55.79	55.70	55.69	55.31	55.19	55.10	55.52	55.55	55.66
3	55.79	55.80	55.78	55.79	55.69	55.68	55.29	55.23	55.09	55.54	55.63	55.66
4	55.79	55.80	55.78	55.78	55.68	55.66	55.27	55.39	55.08	55.54	55.63	55.65
5	55.79	55.80	55.78	55.78	55.66	55.66	55.24	55.25	55.10	55.53	55.62	55.65
6	55.79	55.80	55.77	55.77	55.65	55.64	55.22	55.23	55.09	55.53	55.62	55.65
7	55.79	55.80	55.77	55.78	55.64	55.63	55.20	55.22	55.09	55.52	55.62	55.64
8	55.79	55.80	55.77	55.78	55.63	55.61	55.15	55.20	55.09	55.51	55.61	55.64
9	55.79	55.80	55.77	55.78	55.61	55.60	55.31	55.16	55.07	55.50	55.61	55.64
10	55.79	55.80	55.76	55.77	55.61	55.59	55.20	55.14	55.07	55.49	55.60	55.64
11	55.79	55.80	55.76	55.77	55.60	55.60	55.27	55.45	55.30	55.48	55.60	55.67
12	55.79	55.80	55.77	55.77	55.59	55.60	55.54	55.29	55.20	55.48	55.60	55.67
13	55.78	55.80	55.79	55.76	55.58	55.58	55.50	55.27	55.18	55.55	55.59	55.67
14	55.78	55.79	55.80	55.76	55.56	55.57	55.42	55.31	55.07	55.55	55.60	55.66
15	55.78	55.79	55.80	55.76	55.55	55.58	55.39	55.26	55.13	55.54	55.66	55.66
16	55.78	55.79	55.79	55.75	55.61	55.56	55.37	55.25	55.13	55.53	55.67	55.67
17	55.79	55.79	55.79	55.75	55.61	55.54	55.35	55.40	55.10	55.53	55.67	55.67
18	55.79	55.79	55.79	55.74	55.60	55.53	55.37	55.28	55.06	55.52	55.66	55.67
19	55.79	55.79	55.79	55.74	55.59	55.50	55.34	55.27	55.05	55.52	55.66	55.66
20	55.79	55.79	55.79	55.74	55.57	55.47	55.31	55.25	55.03	55.51	55.66	55.66
21	55.79	55.79	55.78	55.73	55.62	55.52	55.29	55.24	55.08	55.50	55.65	55.66
22	55.80	55.79	55.79	55.73	55.68	55.50	55.27	55.22	55.10	55.48	55.65	55.66
23	55.80	55.79	55.79	55.73	55.67	55.46	55.25	55.21	55.06	55.48	55.64	55.65
24	55.80	55.79	55.78	55.72	55.66	55.44	55.30	55.19	55.08	55.47	55.64	55.65
25	55.80	55.79	55.79	55.75	55.65	55.42	55.24	55.14	55.13	55.46	55.64	55.65
26	55.80	55.79	55.79	55.74	55.67	55.41	55.22	55.07	55.15	55.57	55.64	55.64
27	55.80	55.79	55.80	55.74	55.66	55.42	55.20	55.10	55.21	55.57	55.63	55.64
28	55.80	55.79	55.80	55.73	55.64	55.38	55.34	55.09	55.30	55.57	55.63	55.64
29	55.80	-	55.80	55.72	55.63	55.36	55.23	55.09	55.57	55.56	55.63	55.64
30	55.79	-	55.80	55.71	55.62	55.35	55.23	55.07	55.53	55.55	55.66	55.63
31	55.80	-	55.80	-	55.63	-	55.20	55.08	-	55.55	-	55.63

Table 16

2011 Wetbud Advanced (MODFLOW-NWT) Results - Penman PET (m)
Average of Well 1, Well 2, and Well 3

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	55.80	55.80	55.79	55.79	55.78	55.76	55.57	55.26	55.23	55.71	55.80	55.80
2	55.80	55.81	55.79	55.79	55.78	55.76	55.55	55.22	55.23	55.71	55.80	55.79
3	55.80	55.81	55.78	55.78	55.78	55.76	55.57	55.21	55.26	55.71	55.79	55.79
4	55.80	55.80	55.78	55.78	55.79	55.75	55.55	55.16	55.23	55.71	55.79	55.79
5	55.80	55.80	55.78	55.79	55.78	55.74	55.53	55.15	55.45	55.70	55.79	55.79
6	55.80	55.80	55.82	55.78	55.78	55.74	55.53	55.20	55.48	55.70	55.79	55.79
7	55.80	55.80	55.82	55.78	55.78	55.73	55.50	55.10	55.54	55.69	55.79	55.84
8	55.80	55.79	55.81	55.78	55.77	55.72	55.53	55.04	55.64	55.69	55.79	55.83
9	55.79	55.79	55.81	55.78	55.77	55.71	55.50	55.08	55.66	55.69	55.79	55.82
10	55.79	55.79	55.83	55.78	55.77	55.71	55.48	55.00	55.66	55.68	55.79	55.82
11	55.79	55.79	55.82	55.77	55.76	55.70	55.57	55.08	55.66	55.68	55.79	55.81
12	55.79	55.79	55.82	55.78	55.76	55.69	55.55	55.03	55.65	55.71	55.79	55.81
13	55.79	55.79	55.81	55.78	55.76	55.68	55.57	55.24	55.64	55.77	55.78	55.80
14	55.79	55.79	55.81	55.78	55.77	55.66	55.55	55.20	55.64	55.78	55.78	55.80
15	55.79	55.78	55.81	55.78	55.77	55.65	55.53	55.09	55.64	55.78	55.78	55.80
16	55.79	55.78	55.81	55.80	55.78	55.67	55.50	55.05	55.63	55.78	55.79	55.80
17	55.79	55.78	55.80	55.80	55.80	55.65	55.48	55.07	55.62	55.78	55.79	55.80
18	55.80	55.78	55.80	55.80	55.80	55.64	55.45	55.37	55.62	55.78	55.79	55.79
19	55.80	55.78	55.80	55.79	55.80	55.63	55.43	55.24	55.61	55.79	55.79	55.79
20	55.80	55.77	55.79	55.79	55.80	55.64	55.41	55.22	55.64	55.79	55.79	55.79
21	55.79	55.77	55.80	55.79	55.79	55.63	55.39	55.25	55.64	55.79	55.79	55.79
22	55.79	55.78	55.80	55.79	55.79	55.62	55.37	55.20	55.64	55.79	55.80	55.80
23	55.79	55.77	55.80	55.79	55.79	55.60	55.35	55.18	55.69	55.79	55.81	55.81
24	55.79	55.78	55.80	55.80	55.79	55.59	55.33	55.07	55.69	55.79	55.80	55.80
25	55.79	55.78	55.80	55.80	55.78	55.58	55.46	55.20	55.69	55.79	55.80	55.80
26	55.80	55.78	55.80	55.79	55.78	55.56	55.35	55.02	55.68	55.78	55.80	55.80
27	55.81	55.78	55.79	55.79	55.78	55.55	55.33	55.45	55.68	55.78	55.80	55.80
28	55.81	55.79	55.79	55.79	55.78	55.61	55.31	55.30	55.71	55.79	55.79	55.80
29	55.81	-	55.79	55.79	55.77	55.60	55.29	55.26	55.70	55.80	55.80	55.80
30	55.81	-	55.79	55.79	55.77	55.59	55.27	55.24	55.70	55.80	55.80	55.80
31	55.80	-	55.79	-	55.77	-	55.24	55.23	-	55.80	-	55.80

Table 17

2012 Wetbud Advanced (MODFLOW-NWT) Results - Penman PET (m) Average of Well 1, Well 2, and Well 3

Day	Jan	Feb	Mar	Apr	May
1	55.80	55.78	55.79	55.69	55.53
2	55.79	55.78	55.79	55.68	55.51
3	55.79	55.78	55.79	55.67	55.49
4	55.79	55.78	55.79	55.66	55.48
5	55.79	55.78	55.79	55.65	55.46
6	55.79	55.78	55.78	55.64	55.44
7	55.79	55.78	55.78	55.63	55.43
8	55.79	55.78	55.78	55.62	55.43
9	55.79	55.78	55.78	55.60	55.48
10	55.79	55.78	55.77	55.59	55.42
11	55.80	55.78	55.77	55.58	55.41
12	55.80	55.78	55.77	55.57	55.39
13	55.80	55.78	55.77	55.56	55.40
14	55.80	55.77	55.76	55.54	55.51
15	55.80	55.77	55.76	55.53	55.47
16	55.80	55.77	55.76	55.51	55.43
17	55.79	55.77	55.75	55.50	55.41
18	55.79	55.77	55.75	55.51	55.40
19	55.79	55.77	55.75	55.49	55.38
20	55.79	55.77	55.74	55.47	55.40
21	55.79	55.77	55.74	55.51	55.46
22	55.79	55.77	55.74	55.57	55.52
23	55.79	55.77	55.73	55.57	-
24	55.79	55.77	55.73	55.56	-
25	55.79	55.77	55.74	55.55	-
26	55.79	55.77	55.73	55.54	-
27	55.79	55.77	55.73	55.52	-
28	55.79	55.77	55.72	55.55	-
29	55.79	55.79	55.71	55.55	-
30	55.79	-	55.71	55.54	-
31	55.78	-	55.70	-	-

Runoff Depths from Cedar Run Northwest to Southwest Cell for Wetbud Basic Module

Table 18

	NW - Thornthwaite	
Month	Wetbud Basic Model Thornthwaite Outfllow (cm)	Depth Contributed to SW Cell (cm)
Jan-09	7.86	7.05
Feb-09	0.00	0.00
Mar-09	5.05	4.53
Apr-09	7.03	6.30
May-09	20.89	18.74
Jun-09	0.24	0.21
Jul-09	0.00	0.00
Aug-09	0.00	0.00
Sep-09	0.00	0.00
Oct-09	0.00	0.00
Nov-09	7.22	6.48
Dec-09	16.26	14.59
Jan-10	4.84	4.34
Feb-10	4.07	3.65
Mar-10	9.82	8.81
Apr-10	0.00	0.00
May-10	2.35	2.11
Jun-10	0.00	0.00
Jul-10	6.66	5.97
Aug-10	0.01	0.01
Sep-10	20.15	18.08
Oct-10	6.50	5.83
Nov-10	7.18	6.44
Dec-10	3.02	2.71
Jan-11	5.32	4.77
Feb-11	5.15	4.62
Mar-11	27.14	24.34
Apr-11	9.51	8.53
May-11	1.54	1.38
Jun-11	0.00	0.00
Jul-11	0.00	0.00
Aug-11	0.00	0.00
Sep-11	8.12	7.28
Oct-11	18.23	16.36
Nov-11	4.15	3.72
Dec-11	22.53	20.21
Jan-12	2.97	2.66
Feb-12	5.14	4.61
Mar-12	0.00	0.00
Apr-12	0.00	0.00
May-12	0.00	0.00

Table 19

Month	Wetbud Basic Model Penman Outflow (cm)	Depth Contributed to SW Cell (cm)
	NW - Penman	
Jan-09	4.59	4.12
Feb-09	0.00	0.00
Mar-09	0.00	0.00
Apr-09	0.00	0.00
May-09	13.44	12.06
Jun-09	0.00	0.00
Jul-09	0.00	0.00
Aug-09	0.00	0.00
Sep-09	0.00	0.00
Oct-09	0.00	0.00
Nov-09	0.00	0.00
Dec-09	12.99	11.65
Jan-10	1.02	0.92
Feb-10	0.53	0.47
Mar-10	4.19	3.76
Apr-10	0.00	0.00
May-10	0.00	0.00
Jun-10	0.00	0.00
Jul-10	0.00	0.00
Aug-10	0.00	0.00
Sep-10	13.04	11.70
Oct-10	4.68	4.20
Nov-10	4.65	4.17
Dec-10	0.00	0.00
Jan-11	1.95	1.75
Feb-11	0.36	0.33
Mar-11	22.24	19.95
Apr-11	4.01	3.59
May-11	0.00	0.00
Jun-11	0.00	0.00
Jul-11	0.00	0.00
Aug-11	0.00	0.00
Sep-11	7.91	7.10
Oct-11	18.10	16.24
Nov-11	1.71	1.54
Dec-11	20.16	18.09
Jan-12	0.00	0.00
Feb-12	1.73	1.55
Mar-12	0.00	0.00
Apr-12	0.00	0.00
May-12	0.00	0.00

Appendix B

R Statistical Scripts

Linear Regression

```
# Read in File with Results
x<-read.csv("Results_2.csv")
attach(x)

#Build Regression Lines
fit<-lm(thorn.2009~observed.2009)
fit1<-lm(pen.2009~observed.2009)
fit2<-lm(thorn.2010~observed.2010)
fit3<-lm(pen.2010~observed.2010)
fit4<-lm(thorn.2011~observed.2011)
fit5<-lm(pen.2011~observed.2011)
fit6<-lm(thorn.2012~observed.2012)
fit7<-lm(pen.2012~observed.2012)

# Create Plot Space
par(mfrow = c(2,2))

# Plot 2009 Results
plot(observed.2009,observed.2009, type='l', lwd=2, col="black", xlab="Observed
Weekly Average Water Levels (m)",ylab="Predicted Weekly Average Water
Levels (m) ")

par(new=T)
plot(observed.2009,thorn.2009, type='p', pch=16, col="red", xlab=" ",ylab=" ",
axes =F)
abline(fit,lwd=2,col="red")

par(new=T)
plot(observed.2009, pen.2009, type='p', pch=16, col="blue", xlab=" ",ylab=" ",
axes=F)
abline(fit1,lwd=2,col="blue")
title("October - December 2009")
```

```
# 2009 Legend
legend(locator(1), c("Equal Value (observed levels)", "Thornthwaite Advanced
Model", "Penman Advanced Model"),
col = c("Black", "red", "blue"), lty=c(1,1,1))

# Plot 2010 Results
plot(observed.2010,observed.2010, type='l', lwd=2, col="black", xlab="Observed
Weekly Average Water Levels (m)",ylab="Predicted Weekly Average Water
Levels (m) ")

par(new=T)
plot(observed.2010,thorn.2010, type='p', pch=16, col="red", xlab=" ",ylab=" ",
axes=F)
abline(fit2,lwd=2,col="red")

par(new=T)
plot(observed.2010, pen.2010, type='p', pch=16, col="blue", xlab=" ",ylab=" ",
axes=F)
abline(fit3,lwd=2,col="blue")
title("January - December 2010")

# 2010 Legend
legend(locator(1), c("Equal Value (observed levels)", "Thornthwaite Advanced
Model", "Penman Advanced Model"),
col = c("Black", "red", "blue"), lty=c(1,1,1))

# Plot 2011 Results
plot(observed.2011,observed.2011, type='l', lwd=2, col="black", xlab="Observed
Weekly Average Water Levels (m)",ylab="Predicted Weekly Average Water
Levels (m) ")

par(new=T)
plot(observed.2011,thorn.2011, type='p', pch=16, col="red", xlab=" ",ylab=" ",
axes=F)
abline(fit4,lwd=2,col="red")

par(new=T)
plot(observed.2011, pen.2011, type='p', pch=16, col="blue", xlab=" ",ylab=" ",
axes=F)
abline(fit5,lwd=2,col="blue")
```

```
title("January - December 2011")

# 2011 Legend
legend(locator(1), c("Equal Value (observed levels)", "Thornthwaite Advanced
Model", "Penman Advanced Model"),
col = c("Black", "red", "blue"), lty=c(1,1,1))

# Plot 2012 Results
plot(observed.2012,observed.2012, type='l', lwd=2, col="black", xlab="Observed
Weekly Average Water Levels (m)",ylab="Predicted Weekly Average Water
Levels (m) ")

par(new=T)
plot(observed.2012,thorn.2012, type='p', pch=16, col="red", xlab=" ",ylab=" ",
axes=F)
abline(fit6,lwd=2,col="red")

par(new=T)
plot(observed.2012, pen.2012, type='p', pch=16, col="blue", xlab=" ",ylab=" ",
axes=F)
abline(fit7,lwd=2,col="blue")
title("January - May 2012")

# 2012 Legend
legend(locator(1), c("Equal Value (observed levels)", "Thornthwaite Advanced
Model", "Penman Advanced Model"),
col = c("Black", "red", "blue"), lty=c(1,1,1))
```