Evaluating a Process-based Mitigation Wetland Water Budget Model

Matthew A. Gloe

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

Master of Science

in

Biological Systems Engineering

Theresa M. Wynn, Chair
W. Cully Hession
W. Lee Daniels

August 08, 2011
Blacksburg, Virginia

Keywords: wetlands, modeling, mitigation, modflow, water budget

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ABSTRACT

Correctly predicting water levels is key to the success of created wetlands. The Pierce method is a commonly used technique for modeling and designing mitigation wetlands that assumes minimal groundwater interaction with the wetland. This technique for mitigation wetland design relies primarily on surface water inputs, assuming a relatively impermeable substrate (perched system), and level pool routing. The Pierce method was applied utilizing two different evapotranspiration estimation methods: Thornthwaite (IPM) and FAO-56 Penman-Monteith (IPM-FAO). A second process-based model, utilizing MODFLOW-2005, was constructed to better predict water levels in mitigation wetlands. Modeled processes included groundwater movement and vegetative resistance to flow, which can be a significant factor in wetland water levels. The two versions of the Pierce method were compared to the process-based wetland representation developed in MODFLOW-2005 using data from an existing mitigation wetland.

Output from these models were compared to observed data from an existing mitigation wetland near Manassas, VA, USA. Results indicate the use of Thornthwaite's method to estimate wetland evapotranspiration (ET) does not capture the timing or magnitude of wetland ET losses, leading to over-prediction of wetland water levels during the growing season. The Modflow-based approach resulted in more accurate hydroperiod predictions on a yearly basis than the Pierce Method. However, the Integrated Pierce method model, utilizing the FAO-56 Penman-Monteith method of estimating potential evapotranspiration instead of Thornthwaite's method most accurately predicted water levels during the growing season (March-October).

to my family: Alan, Patti, Katie, and Marcus

I am fortunate and grateful for your support, encouragement, love, and guidance

Acknowledgments

I would like to thank my advisor Tess Wynn for taking me on as a graduate student, for her great contributions and help over the past few years of my undergraduate and graduate education. I must also thank my committee Cully Hession and Lee Daniels. Together, Tess, Cully, and Lee provided me with an unrivaled experience in the implementation of the Stroubles Creek restoration, and taught me more than I ever thought possible about streams, wetlands, and engineering.

I am indebted to Wetland Studies and Solutions Inc for their help and generosity with this project. Together with the Piedmont Wetland Research Program they provided funding for this study. I am thankful for the modeling guidance and field assistance of many individuals, including Zach Agioutantis, Robert Winston, Denton Yoder, Mike Mobile, Laura Teaney, Nicole Troyer, Candice Piercy, and Karen Hall.

I must acknowledge the other BSE faculty who have played a pivotal role in my education, specifically John Cundiff, Robert Grisso, and Brian Benham; thank you all for the advice and the patient ear when I needed it most.

Last but not least I cannot forget my fellow graduate students: Dan Laird, Jenae Pinney, Mike Nassry, Javier Osorio, Andrea Ludwig, and all the other students I’ve had the privilege to interact with. Thank you for the great times: the long days at Stroubles, the impromptu trips, the late nights at the Cellar, the many hours spent studying, and a graduate experience I could not imagine having in any other way.

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Introduction

Worldwide, wetlands are identified by a vast assortment of names that differ across wetland type, and geographic locations. Common terms include bogs, lagoons, marshes, swamps, and fens (Mitsch, 2007). As defined by the U.S. Army Corps of Engineers, a wetlands are “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” (USACE, 1987).

Wetland ecosystems provide benefits such as wildlife habitat, groundwater recharge, water purification and biomass production (Mansell et al., 2000). These critical areas supply or support the food, shelter, and/or reproduction of numerous species of reptiles, amphibians, birds, and mammals. Wetlands also serve as chemical buffers between uplands and deeper-water systems, cleansing the water (Mitsch et al., 1988). Throughout history, these lands have served as sources of nourishment and production for humans. Numerous plants and animal products, such as rice, are harvested from wetlands across the globe (Mitsch, 2007).

The alteration of wetland habitats by natural and anthropogenic processes is an issue of worldwide concern (Restrepo et al., 2006). These areas were once seen as wastelands, and were often diked and drained (Mitsch et al., 1988). However, the value of these lands has since been recognized, and efforts made to restore, enhance, and create wetland systems are on the rise.

“Natural” wetlands are lands which were historically considered wetlands, and formed independent of anthropogenic influence, while created wetlands are those which were constructed by humans in areas which were traditionally persistent upland or shallow open water areas (Mitsch, 2007). Generally speaking, when a specific type of wetland is destroyed, federal law mandates that the same type of wetland be created for mitigation. However, studies have shown that created wetlands frequently do not look or function like the natural system they were designed to replace (Campbell et al., 2002).

Under the Clean Water Act, any adverse impacts to wetland or other aquatic resources must be avoided and minimized to the greatest extent practicable. For impacts that are unavoidable, compensatory mitigation is required by law to replace the loss of a wetland. Compensatory mitigation can consist of restoration, establishment (creation), enhancement, or preservation of wetlands (USEPA, 2011). This legislative policy, based on the “no net loss” goal, have led to the development of a new industry in support of wetland mitigation (Brown and Lant, 1999). This industry primarily creates wetlands in previously wetland deficient areas to satisfy mitigation requirements. Wetland creation is regulated through a permitting process with the U.S. Army Corps of Engineers (USACE). The USACE evaluate pre-construction modeling to approve created wetland mitigation plans, as well as evaluate the post-construction "success" of a site.

Past indicators of mitigation "success" included vegetative success, animals witnessed, and water table monitoring. However, in recent years, these indicators of success have come under scrutiny, based on the idea that these mitigation wetlands were not functioning as well as the wetlands they intended to replace (Campbell et al., 2002; Mitsch and Wilson, 1996). Evidence of this can be seen in the issues that have plagued many mitigation wetlands, including: sedimentation, problematic hydric soil development, and the development of hydrology different from the target-wetland hydroperiod (Whittecar and Daniels, 1999). As a result of the development of this new industry and the desire for improved mitigation wetlands, the need for improved predictive models of wetland hydrology has increased.

Correctly predicting water levels is key to the success of created mitigation wetlands. A common water budget modeling technique for mitigation wetland design relies primarily on surface water inputs, assuming a relatively impermeable substrate and little groundwater interaction (the "Pierce method"). Hydrologic processes typically modeled include precipitation, evapotranspiration, infiltration, surface water additions, and outflow through hydraulic structures. It is generally assumed that the wetland acts as a level pool, with water levels controlled by the outlet structure. In reality, vegetative resistance to surface flow can be a significant factor in altering water levels (Kadlec, 1996). These assumptions can result in inaccurate wetland water budgets, ultimately leading to failure to achieve the desired wetland type. To address these deficiencies, a process-based model was developed including groundwater movement and vegetative resistance to flow, to better predict water levels in mitigation wetlands.

Goals and Objectives

The overall goal of this research was to determine the accuracy of a Pierce water balance method model and MODFLOW-2005 model for use in designing mitigation wetlands and, based on the results, make recommendations for improved modeling to increase success rates of mitigation wetlands. To achieve this goal, three main objectives were completed:

1. Determine the accuracy of water-level predictions by a Pierce-based water balance method model, and a process-based MODFLOW-2005 model
2. Evaluate seasonal effects in model performance.
3. Determine the sensitivity of the models to select model inputs.

The water balance of Cedar Run 3, a created mitigation wetland near Manassas, VA, USA was simulated utilizing both the Pierce water balance method and a new MODFLOW-based process model. Monthly results were compared to observed water levels for the wetland using regression analysis and Nash-Sutcliffe model efficiency coefficients. Additionally, model error of typical inputs was evaluated, and a sensitivity analysis was conducted to determine model response to changing parameter values. Model calibration was not conducted, as these models will be used for the design of mitigation wetlands.

Literature Review

Wetland Hydrology

Wetland hydrology is the result of interactions between various processes and site factors, including precipitation, surface inflows and outflows, evapotranspiration, and groundwater inputs and losses. Together, these components make up the entire water budget for the wetland, ultimately driving the hydrology. This hydrology is critical for maintaining the structure and function of the wetland (Mitsch, 2007). This is especially important with respect to created wetlands, as they must meet the U.S. Army Corps of Engineers definition of a wetland, as follows:

> *"Those areas that are inundated or saturated by surface or groundwater 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."*
> (USACE, 1987)

Biogeochemical processes and benthic-bacterial functions, such as nutrient retention and carbon sequestration, are heavily influenced by wetland hydrology (Ishida et al., 2006; Pierce, 1993). Nutrient and sediment removal cannot occur if hydrologic conditions do not permit adequate residence time for detention and water depths to support aquatic vegetation (Hunter et al., 2008; Ishida et al., 2006). Thus, understanding hydrologic processes of wetlands is fundamental in their effective ecosystem restoration and creation (Zhang and Mitsch, 2005).

In a broader sense, the water budget for a wetland is a result of a number of variable factors, including the balance between water inflows and outflows, topography, soils, geology, and groundwater conditions (Mitsch, 2007). These factors result in a unique set of conditions of water depth and flood frequencies and duration, which vary across wetland types and locales (Dugan, 1993). A simplified water budget is shown in (1) (Mitsch, 2007):

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

where $\Delta V/\Delta t$ is the change in volume of water storage in the wetland per unit time, P_n is net precipitation, S_i is surface inflows, including stream flooding, G_i is groundwater inflows, ET is evapotranspiration, S_o is surface outflows, G_o is groundwater outflows, and T is tidal inflows or outflows (Mitsch, 2007). If the wetland dimensions are known, an average water depth can be calculated based on this equation.

Precipitation

Precipitation is a vital component to wetland hydrology, as most wetlands occur in areas where precipitation (rain and snowfall) is higher than the wetland water losses (Mitsch, 2007). When calculating precipitation for a water budget, only the net precipitation must be considered. This means interception by trees and other vegetation must be accounted for, as significant volumes of water can be prevented from reaching the wetland surface (Mitsch, 2007). For example, in a lowland hardwood dominated riparian wetland corridor in southwest Georgia, interception was shown to be 17% of the total precipitation (Bryant et al., 2005).

Evapotranspiration

In a wetland, evapotranspiration consists of direct surface evaporation (either from open water or soil), and transpiration by vascular plants. Together, these two processes can have a significant effect on the water budget of a wetland (Lott and Hunt, 2009). Three factors that highly influence the rate of evapotranspiration are solar radiation, relative humidity, and surface temperature. Secondary factors include wind speeds and soil moisture supply.

Evapotranspiration can be a major factor influencing water levels in a wetland, even being the primary cause of water loss (Drexler et al., 2004). In one study, a seasonal water drawdown of 1.0 m to 2.5 m was recorded, corresponding to spring leaf-out (Whittecar and Daniels, 1999). Currently, simple meteorological models of offsite ET data are often used to estimate ET (eg. Thornthwaite's method, Penman-Monteith); these rough estimates (further discussed in the Modeling Concepts section) often lead to inaccurate estimations and corresponding inaccurate water budgets (Galvão et al., 2010; Lott and Hunt, 2009).

In a study of a constructed subsurface flow wetland in southern Portugal, evapotranspiration played a major role in influencing predicted water levels. When the wetland was modeled without evapotranspiration effects, flows were significantly overestimated and exhibited smaller variations. Comparatively, when a constant daily evapotranspiration rate was used, smoother flow curves resulted, with outflows being overestimated during daylight hours and underestimated during the night (Galvão et al., 2010).

Surface Water

Surface water enters wetlands either through overland flows or channelized stream flows. Overland flow is non-channelized sheet flow that often occurs immediately during or after a precipitation event or thaw. Stream flows can be quantified simply by taking the product of the cross-sectional area of the stream and the average flow velocity (Pierce, 1993).

Surface water flow represents the sum of all overland, stream, and base flow from upstream of the calculation point. It is critical to accurately quantify and incorporate surface flows for a wetland water budget, as surface flows can be the primary water source for the wetland (Chaubey and Ward, 2006). Additionally, proper residence time calculation for surface flows within the wetland is critical for nutrient and suspended sediment removal (Raisin and Mitchell, 1995). One source of potential error in representing these flows is failure to account for vegetative resistance to flow. It has been shown that drag attributed to plants reduces flow velocities as compared to unvegetated flowpaths, and can lead to an increase in water depth and residence time in the wetland (Nepf, 1999). These impacts have implications for wetland water budget modeling and may introduce error into water level estimates.

Groundwater

Groundwater can have a large impact on wetland hydrology and has often been cited as an important attribute of wetlands (Mitsch, 2007). Groundwater movement in wetlands is a product of five main factors: inputs from precipitation, seepage losses to surface water, transpiration losses, evaporation losses, and groundwater inflows and outflows (Mitsch et al., 1988). In some wetlands, groundwater is the primary contributor to the hydrologic budget. A fen studied by Gilvear and others (1993) located near Cambridge in the United Kingdom is one example of this. In this region evapotranspiration often exceeds annual rainfall, thus groundwater maintains hydrology within the system (Gilvear et al., 1993). The fen was monitored for two years, from 1988 to 1989, during which groundwater was the primary water contributor. Groundwater accounted for up to 95% of the total water influx in some months(Gilvear et al., 1993). In other instances where groundwater is not the main driver of hydrology, groundwater can nonetheless contribute a significant amount of water to the system (Chaubey and Ward, 2006).

Modeling Concepts

The utilization of both conceptual and simulation modeling provides a tool to describe, quantify, and predict the behavior of wetland systems (Mitsch et al., 1988). A major drawback of using predictive models is that the future conditions cannot be estimated with great certainty. Nevertheless, such models can provide valuable insights into the mechanisms and processes that drive wetland systems (Restrepo et al., 2006).

Precipitation and Evapotranspiration

Precipitation data used in models are typically measured at nearby meteorological observation stations, or through direct measurement onsite. Previously established meteorological stations, such as those run by the National Oceanic and Atmospheric Administration (National Climatic Data Center), or the United States Geological Survey (USGS), provide historic records of rainfall, temperature, and wind speeds. These data can be incorporated into the hydrologic modeling of wetlands.

Equations have been developed to estimate evapotranspiration using commonly measured weather parameters. One commonly used method for estimating evapotranspiration is Thornthwaite's equation (Thornthwaite, 1948) for potential evapotranspiration (Mitsch, 2007). In this case, potential evapotranspiration (PET) is the amount of water that could potentially evaporate and transpire from a vegetated landscape with no soil moisture limitations (Lu et al., 2005). Thornthwaite's empirical equation determines monthly potential evapotranspiration utilizing mean monthly temperature and a local heat index. One commonly used form of Thornthwaite's equation (Drexler et al., 2004) is shown in (2).

$$PET_i = 1.6 L_i \left(\frac{n_i}{30}\right)\left(10\frac{T_i}{I}\right)^A \tag{2}$$

where:

PET = monthly potential evapotranspiration (cm/month)
L_i = monthly mean day length given in 12 hour units
T_i = monthly mean temperature (°C)
n_i = number of days for the ith month
$A = \left(\left(6.75 \cdot 10^{-7} \cdot I^3\right) - \left(7.71 \cdot 10^{-5} \cdot I^2\right) + 0.49\right)$
$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514}$

However this formulation for calculating PET estimates the evaporative demand of the atmosphere, and not wetland evapotranspiration directly (Drexler et al., 2004).

A second common algorithm for calculating evapotranspiration is the Penman equation (Penman, 1948). This equation is more commonly used in hydrologic applications, and less so with wetland investigations (Mitsch, 2007). This equation calculates potential evapotranspiration from open water, on a daily basis, using vapor pressures, solar radiation, and wind speed. This relation is widely used, physically-based, and shows robustness even when using monthly-averaged weather data (Chaubey and Ward, 2006).

A third algorithm, based on the Penman equation, is the FAO-56 Penman-Monteith Model Equation (3), which is utilized by the Food and Agriculture Organization of the United Nations (FAO). This method determines the daily potential evapotranspiration rate of a hypothetical reference crop. This reference crop has fixed physical parameters that are very similar to grass including a height of 12 cm and a fixed canopy resistance of 70 s/m (Mao et al., 2002).

$$ET_o = \frac{0.408\Delta(r_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where:

ET_o = evapotranspiration (mm day^{-1})

Δ = slope of saturation vapor pressure curve (kPa °C^{-1})

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

G = soil heat flux density (MJ m^{-2} day^{-1})

γ = psychometric constant (kPa °C^{-1})

U_2 = wind speed at 2 m height ($m \cdot s^{-1}$)

e_s = Saturation vapor pressure (kPa)

e_a = Actual Vapor Pressure (kPa)

Since the FAO model estimates PET for a reference crop, a corresponding crop coefficient would normally be applied (as a multiplier) to estimate ET for wetland vegetation. Crop coefficients help describe the rate at which water is removed soil and plant surface for a specific crop (Ward and Trimble, 2004). This coefficient corrects for the difference between ET from a cropped surface and PET (Towler et al., 2004). However, there are no reliable crop coefficients available for wetlands, and thus the FAO-56 approach has generally been limited when used with wetland systems (Drexler et al., 2008; Zhou and Zhou, 2009). As with standard crop coefficients, the limited data available indicates wetland crop coefficients are dependent on location and meteorological conditions (Drexler et al., 2008). In a three year study by Drexler and others (2008) at the Sacramento-San Joaquin Delta in California, the average crop coefficient for a tidal marsh was 0.95. Overall, the coefficient ranged from 0.73 to 1.18, showing variability between months across all years. Both wind direction and temperature of standing water in the wetland were particularly important in determining ET rates and the crop coefficients (Drexler et al., 2008).

The FAO method was evaluated against three other methods (pan evaporation method, Penman-Monteith, Priestley-Taylor) for estimating the predominantly wetland vegetated upper St. Johns River Basin in Florida (Mao et al., 2002). The study showed monthly mean evapotranspiration rates for all methods were very similar; thus, data intensive mathematical methods for estimating ET were, from a practicality standpoint, just as effective as direct pan evaporation measurements (Mao et al., 2002).

A fourth common model used for determining potential evapotranspiration is the Preistley-Taylor (1972) method. This equation is a modified version of the Penman method, requiring only solar radiation data. Instead of utilizing all the inputs as Penman, an empirically approximated constant is used. This is shown in (4**)**.

$$PET = \frac{\alpha}{\lambda}\frac{\Delta}{\Delta + \gamma}\left(R_n - G\right) \tag{4}$$

where:

PET = potential evapotranspiration (mm day^{-1})

Δ = latent heat of vaporization (MJ kg^{-1})

α = 1.26

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

γ = psychometric constant (kPa °C^{-1})

G = soil heat flux density (MJ m^{-2} day^{-1})

A study conducted in the southeastern United States (Georgia), compared the FAO Penman-Monteith method with the Priestley-Taylor method of estimating evapotranspiration. They found that the Priestley-Taylor method was less accurate than the FAO Penman-Monteith for reference evapotranspiration calculation in the southeastern humid climate.(Suleiman and Hoogenboom, 2007).

Surface Flow

Surface flows into wetlands are a combination of direct storm runoff into the wetland and channelized stream flow. For modeling purposes, flumes (or weirs) are sometimes installed for easy measurements of surface inputs to a wetland (Gilvear et al., 1993; Pierce, 1993). In the event installing a flume is prohibitive, stream flows must be quantified through other means for accurate measurement of surface inputs.

Stream flow can be broken down into two major components, storm runoff and base flow. Generally, storm runoff is the portion of precipitation which flows over the soil and land surface, making its way to surface waters. Base flow is the water that enters the stream through groundwater (Chow, 1964). A hydrograph (discharge vs. time) analysis can be conducted to differentiate between the two components of stream flow. If stream flows are measured before and after rainfall events, a distinct rising and falling limb will be seen on the hydrograph, indicating the beginning and decreasing levels of runoff, respectively. By determining the hydrograph separation line, it is possible to distinguish between groundwater base flow and runoff associated with a storm event (Ward and Trimble, 2004).

Storm runoff can be estimated through a number of different methods, with the Soil Conservation Service Curve number method being the most common. The SCS Curve number method was developed by the United States Department of Agriculture's Soil Conservation Service, now known as the Natural Resources Conservation Service (NRCS) (Kent, 1973). This method uses an empirical coefficient which can be used to predict runoff and infiltration. This "curve number" is based on soil, land use, hydrologic, and topographic characteristics of a site. The curve number is then related to precipitation and infiltration, resulting in an estimated precipitation excess (Ward and Trimble, 2004).

Groundwater

The current industry standard for modeling wetland water budgets for mitigation wetland design often discounts any influence of groundwater, mainly because measuring, mapping, and modeling groundwater sources for wetland construction can be time consuming and difficult (Favero et al., 2009; Pierce, 1993). In some instances, any groundwater fluxes are estimated as a residual term in the water budget (Favero et al., 2009).

Currently, most mitigation sites are lined with a compacted clay layer, creating a theorized perched system independent of any groundwater upwelling or seepage. Despite this compacted sublayer, many mitigation wetlands in Virginia have been described as “too wet”, resulting in outlet structure adjustments to decrease water levels (Whittecar and Daniels, 1999). In a study of a 2 ha reed swamp in Victoria, Canada (Raisin et al., 1999), 97% of all surface water leaving the natural wetland site was from groundwater discharge. Thus, groundwater may be a vital component to accurately modeling any wetland water budget.

Traditionally, groundwater flows have been modeled using Darcy’s Law and measured groundwater gradients from water level observation wells and piezometer arrays (Galvão et al., 2010; Gerla, 1999; Hunt et al., 1996). In one study (Bradley, 2002), groundwater flows were modeled using MODFLOW for a floodplain wetland in Great Britain. In combination with evapotranspiration, precipitation, and river stage data, the MODFLOW representation successfully reproduced the observed wetland water table and reflected the broader trends of water movement through the wetland (Bradley, 2002).

Wetland Water Budget Modeling

The current practice for modeling and constructing mitigation wetlands utilizes the Pierce (1993) methodology. This consists of designing a perched wetland through subsoil compaction and clay lining. This practice reduces the total parameters of the wetland water budget and allows water level control via an outlet structure, which is easily manipulated. To model a system designed in this manner, Pierce (1993) recommends calculating a monthly water budget for typical, dry, and wet years utilizing precipitation data from the previous 30 years.

Poiani and Johnson (1993) developed a simulation model for wetland hydrology and vegetation dynamics. Within this model, a process-based hydrologic sub-model was created to estimate seasonal and yearly water levels. Factors considered included precipitation and runoff, snowmelt, and previous stage. Evapotranspiration was calculated using Thornthwaite’s method, but groundwater was not directly addressed as it was beyond the scope of the project to measure and simulate these interactions. The model was developed and evaluated using field measurements for a semi-permanent prairie wetland located in North Dakota. Runoff inputs for this model were estimated using regression prediction. Precipitation values were plotted against a number of observed runoff volume values, and fitted with a non-linear exponential curve (Poiani and Johnson, 1993). Overall, their model closely simulated the hydrologic changes in the wetland during the test period. Even with simplified estimates of hydrologic parameters, water levels calculated by the model were within a narrow range of the observed values, showing differences between calculated and observed water levels to be within 10 cm 75% of the time (Poiani and Johnson, 1993).

Restrepo et al. (Restrepo et al., 1998), a package was created for MODFLOW to simulate three dimensional wetland flow hydroperiods and wetland interactions with aquifers and slough channels. The purpose of this model was to accurately predict changes in hydrology that would occur as a result of anthropogenic impacts. At the time, most surface water and groundwater models had been developed separately, and interactions between the two had not been simulated with an integrated model. The wetland simulation module represents the wetland using two layers. The upper layer models surface flows through vegetation and the upper soil substrate (peat). The secondary layer is modeled as an unconfined aquifer, which is connected to the upper layer, allowing the water surface to change from one level to another dependent on conditions. Surface sheet flows through dense vegetation are described in the model as cells with high equivalent hydraulic conductivities, and sloughs are modeled as channelized flows (Restrepo et al., 1998). A hypothetical wetland was modeled to verify the model code. The results of this modeling showed close matches between modeled and numeric answers. However, the model has yet to be used for a real wetland system (Restrepo et al., 1998).

Krasnostein and Oldham (2004) developed a bucket-style conceptual model to describe interactions between a wetland, the surrounding catchment, and local groundwater. A conceptual model was developed because it was deemed a more flexible tool for understanding and predicting wetland hydrology, as opposed to the difficulties of parameterizing a numeric model. The model is set up into three main regions: the catchment, underlying groundwater, and open water. Areas which are vegetated incorporate an evapotranspiration factor into the model. Parameters needed can be easily ascertained through a single site visit or through literature. The bucket concept dictates that water storage in the bucket varies over time relative to rainfall. Once water storage in the wetland exceeds the field capacity, water discharges laterally in the model as subsurface flow. Then, when the bucket fills completely, meaning inputs to the bucket greatly exceed outputs, the bucket “spills”, resulting in surface outflows. This model was applied to Loch McNess, a permanent open water body on the Swan Coastal Plain in Western Australia. It was shown to be effective in determining if a wetland is surface or groundwater-dominated (Krasnostein and Oldham, 2004).

Lee and others (2002) designed the WETLAND model to model free water surface and sub surface flow wetlands, simulating the hydrologic, nitrogen, carbon, bacteria, dissolved oxygen, vegetative, phosphorus, and sediment cycles of a wetland system, with each cycle having a dedicated submodel. The model was calibrated and validated using data from a free-water surface wetland near Benton, Kentucky, USA. The hydrologic sub model was adapted from Kadlec (1996). The budget includes: watershed runoff additions (SCS method) , point source additions, daily outflow rate, daily precipitation rate, percolation and infiltration rates (which was negated due to an impermeable clay lining), and daily estimated evapotranspiration rate (Pan method or Thornthwaite’s method).

Model Assessment

Verification and Validation

Model verification and validation are two vital components for assessing the function of a newly developed model. However, there are no specific tests that can be easily applied to calculate the “correctness” of a model (Sargent, 2005). For the purposes of this modeling investigation, verification will be defined as a demonstration that the model formulation is correct. Verification, in its most fundamental form, relates to how accurately ideas are represented with computer code or mathematical equations (Anderson, 2001), meaning that the model runs without errors or bugs in the programming, and that all algorithms have been used appropriately. Verification is usually conducted for a model being run under normal circumstances, thus any model application that deviates from these conditions is assumed erroneous.

Validation can be defined as the method for determining if model output is sufficiently accurate for the purpose of the model (Sargent, 2005). This highlights that the model is not a predictor of absolute truth, as this is never possible, but rather predicts a parameter within a set margin of acceptable error.

Statistical Analysis

Absolute Relative Error

Absolute relative error determination allows for an easily understood comparison of modeled water levels to observed water levels. Absolute relative errors were calculated using (5).

$$RE\% = \left|\frac{Modeled - Observed}{Observed}\right| \times 100\% \tag{5}$$

Mean Absolute Error

Mean absolute error (MAE) is another dimensioned metric to quantify how well a model predicts values as compared to observed values. The mean absolute error is an average of the absolute value of the errors (Willmott and Matsuura, 2005). MAE can be calculated as shown in (6), where *P* is the model predicted value, *O* is the true value, and *n* is the number of total paired values. As shown in Table 7, Modflow had the lower mean absolute error, although only less than the IPM-FAO by 0.17 cm, as compared to the IPM by 10.9 cm. On average, the best models (MODFLOW and IPM-FAO) had mean absolute errors of 14.9 cm.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|P_i - O_i\right| \tag{6}$$

Root Mean Square Error

The root mean square error (RMSE) is a common statistic used in the comparison and evaluation of simulation models (Willmott et al., 1985). Root mean square error is calculated by taking the square root of the average sum of the squares of the residuals, as shown in (7) where X_i is the i*th* observed value, Y_i is the i*th* simulated value, and *n* is the number of pairs of comparisons

$$RMSE = \sqrt{\frac{\Sigma(X_i - Y_i)^2}{n}} \tag{7}$$

RMSE-observations Standard Deviation Ratio (RSR)

While the root mean square error (RMSE) is typically used in error analysis, with a lower RMSE indicating better model performance, there is nothing that defines what is a "low" RMSE (Moriasi et al., 2007). One way to account for this, is to normalize the RMSE using the standard deviation of the observed data, as shown in (8), where X_i is the i*th* observed value, Y_i is the i*th* simulated value, n is the number of pairs of comparisons, and X_{mean} is the average observed value. In this case, the RMSE values previously calculated were divided by the standard deviation of the observed water levels, providing an RSR statistic. This resulting statistic has an optimal value of 0, indicating perfect model performance.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\frac{\Sigma(X_i - Y_i)^2}{n}}}{\sqrt{\Sigma(X_i - X_{mean})^2}} \tag{8}$$

Nash-Sutcliffe Model Efficiency

To provide a quantitative estimate of the ability of a model to reproduce historic and future wetland behavior (Krause et al., 2005), a model efficiency can be calculated based on a method proposed by Nash and Sutcliffe (1970). This parameter gives an indication of how well a model reproduces observed values. Efficiencies can vary from $-\infty$ to 1. A value of 1 indicates a perfect match of modeled values to observed data. A value of 0 indicates that modeled values are as accurate as the mean of the observed data, and any efficiency less than 0 indicates that the mean of the observed data is a better predictor than the modeled values.

The efficiency is defined as one minus the sum of the absolute squared differences between predicted and observed values normalized by the variance of the observed values under the period of investigation (Krause et al., 2005). This formulation is shown in (9), and is analogous to a coefficient of determination.

$$NSE = 1 - \frac{\Sigma(O-P)^2}{\Sigma(O-O_{mean})^2} \tag{9}$$

Sensitivity Analysis

To determine the sensitivity of a model to given model inputs, a sensitivity analysis is conducted. A sensitivity analysis is the process through which the rate of change of model outputs with respect to changes in model inputs is determined (Moriasi et al., 2007). It describes how model output changes over a range of given inputs. Alone, this analysis is useful, but provides no basis for comparing sensitivity values of parameters with different units. Thus, a more practical approach is to determine the dimensionless relative sensitivity of a parameter, as shown in (10), where S_r is relative sensitivity, O is output, and P is input (Byne, 2000; Haan et al., 1995; Staley, 2006). Resulting relative sensitivity values indicate the type of correlation each parameter has with the model. Positive values indicate a direct correlation, while negative values indicate an inverse correlation with the parameter. Additionally, absolute values of less than 1 indicate a damped model response to the parameter change, while absolute values of greater than 1 indicate an exaggerated model response (Byne, 2000).

$$S_r = \left(\frac{\frac{\partial O}{O}}{\frac{\partial P}{P}} \right) \tag{10}$$

Methods

The overall study goal was to improve current methods of conducting hydrologic budgets for mitigation wetland design. To accomplish this, results from an existing design model, developed by Wetland Studies and Solutions, Inc. (WSSI) using the Pierce (1993) method, were compared to water level monitoring data from an actual mitigation wetland. This model was adapted to include a different model of evapotranspiration, as well as flow connections between wetland cells. The wetland was also modeled using MODFLOW 2005, including both the revised evapotranspiration and resistance of wetland vegetation to surface water flows. Comparisons were drawn utilizing statistical analysis and inferences drawn from model results.

Study Site

Data from an existing 99-ha wetland bank located near Manassas, in Prince William County, VA, USA (Figure 1) was used to test the models. Two specific wetland cells, the North and South, were used for this study (Figure 5). The North and South cells have areas of approximately 5.5 ha and 5.9 ha, respectively.

Cedar Run was completed in October of 2001 by Wetland Studies and Solutions Inc. of Gainesville, VA.

Manassas, VA has a temperate climate with monthly average temperatures ranging from 0.5 °C in January to 25 °C in July, with monthly average precipitation ranging from 6.3 cm in February to 9.4 cm in May (NCDC, 2011). Located in the Piedmont Physiographic Province of Virginia, the underlying site geology consists of upper Triassic stone and siltstone, with Triassic shale also in the vicinity (USGS, 2005). Soils onsite before Cedar Run 3 was constructed consisted predominantly of Albano silt loam, Delanco fine sandy loam, and Dulles silt loam (Figure 2, Table 1). Albano series are deep, poorly-drained soils with slow infiltration and permeability (USDA, 2005). The Delanco series is a very deep, moderately to somewhat poorly drained soil with low permeability (USDA, 2006a). Formed from the underlying sandstone, Dulles series soils are moderately well and somewhat poorly drained, with slow to very slow permeability (USDA, 2006b).

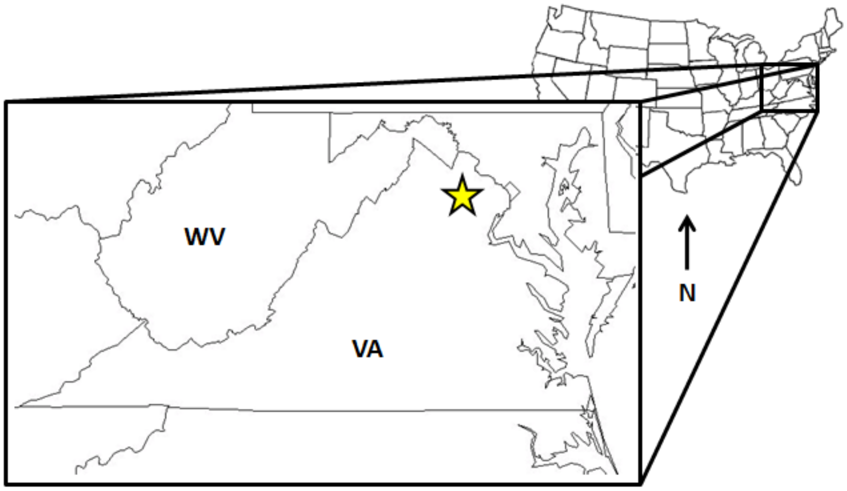

Figure 1. Prince William County, VA, USA, location of the Cedar Run wetland mitigation bank

Table 1. Original soils on site before the construction of Cedar Run 3 (Web Soil Survey, 2011)

Map Unit	Map Unit Name
1A	Aden silt loam
3A	Albano silt loam
11B	Calverton silt loam
16A	Delanco fine sandy loam
17A	Dulles silt loam
46B	Panorama silt loam
W	Water

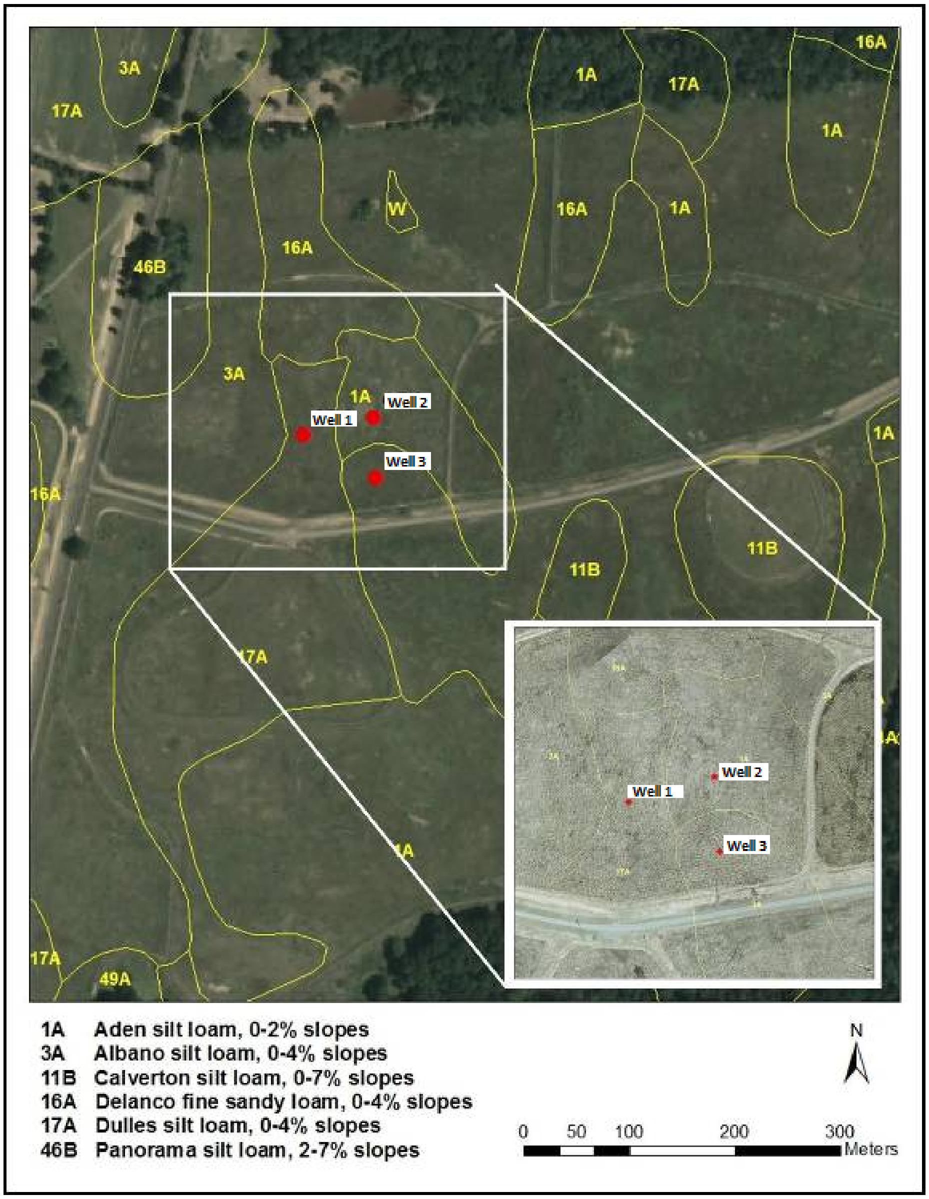

Figure 2. Original soils on site before the construction of Cedar Run 3 (Web Soil Survey, 2011), with the three monitoring wells shown in red, courtesy Nicole Troyer

Cedar Run was designed, modeled, and constructed as a forested wetland utilizing an Integrated Pierce approach (Pierce, 1993); it consists of individual cells, surrounded by berms and connected through a series of weirs (Figure 3). These weirs were designed as compound Cipoletti style weirs, and are lined with stone and volunteer vegetation. The original design of Cedar Run 3 only utilized two weirs, one to connect the north and south cells, and one to drain the south cell. After construction it was found that water levels were too high to develop forested vegetation. Thus, three additional weirs were added to reduce water levels (two to connect the cells, and an additional to drain the South cell). Vegetation commonly found within the wetland is shown in Table 2.

Utilizing the Pierce approach, Cedar Run was designed to simplify the overall water budget of a wetland system. This was accomplished by grading the site to the clayey subsoils, leveling each cell, and creating a perching system through subsoil compaction. Only 30 cm of elevation change exists between the north cell and south cell. This simplification reduced the overall wetland water budget to four basic factors: inflow, outflow, precipitation, and evapotranspiration (Figure 4). By creating this perched system, the wetland becomes strictly surface water and precipitation fed, as groundwater exchange is minimized. Using this technique, water levels can theoretically be controlled utilizing an outlet structure.

Table 2. Common plant species found within the Cedar Run Wetland Bank

Species	Indicator Status*
Scirpus atrovirens (Bulrush)	OBL
Juncus effusus (soft rush)	FACW+
Carex lurida (sedge)	OBL
Leersia oryzoides (rice cut grass)	OBL
Tripsacum dactyloides (gama grass)	FACW+
Quercus phellos (willow oak)	FAC+
Fraxinus pennsylvanica (green ash)	FACW+
Quercus bicolor (swamp white oak)	FACW+
Rosa palustris (swamp rose)	OBL
Carex vulpinoidea (fox sedge)	OBL

*OBL – Obligate; FACW – Facultative Wet; FAC - Facultative

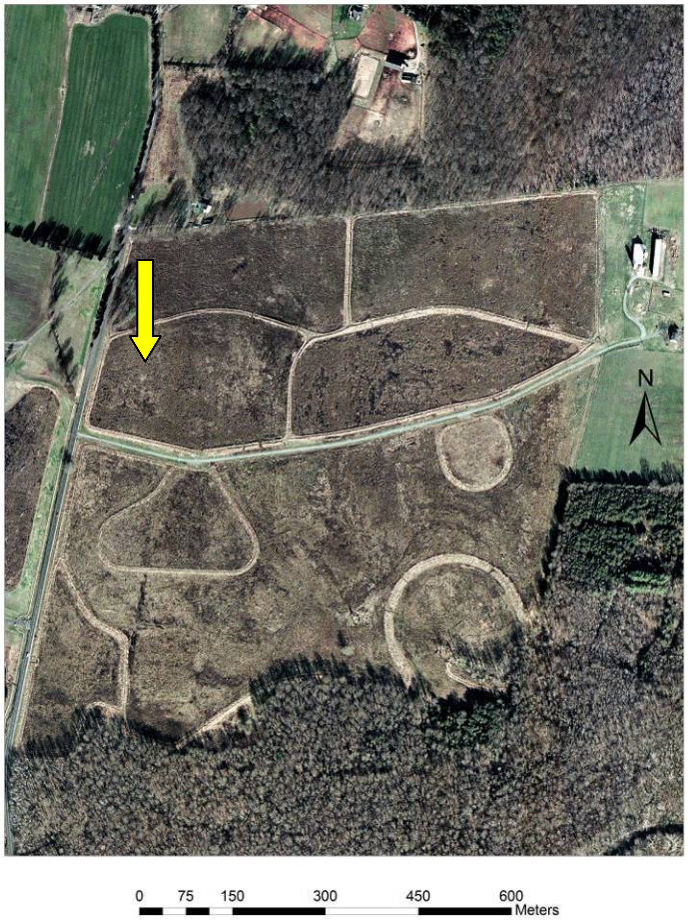

Figure 3. Cedar Run Phase 3 wetland mitigation site near Mannassas, VA, USA (38°37’27.47” N, 77°33’00.75” W), arrow indicates general flow direction from North cell to South cell

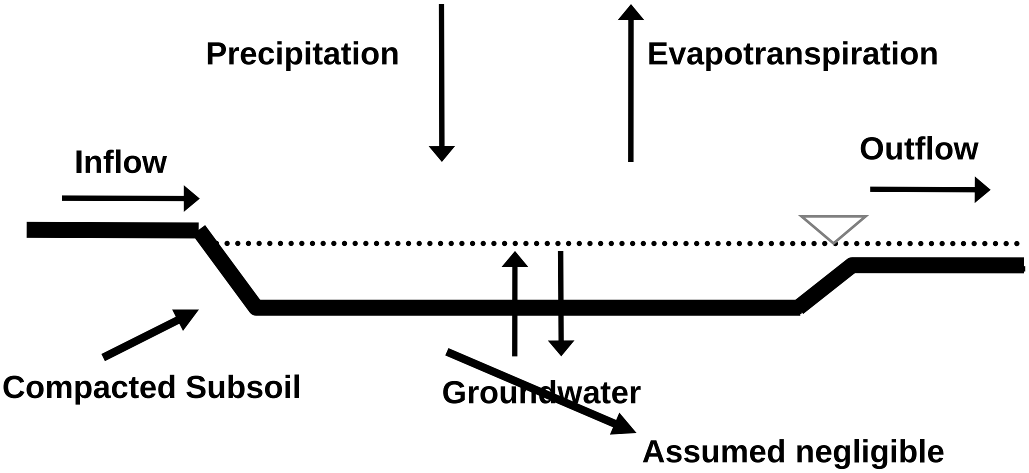

Figure 4. Simplified water budget of wetland designed with compacted subsoil

Overview of Weather and Water-Level Data Collection

Meteorological Data

Weather data were collected on-site by a weather station installed by WSSI. These data are downloaded monthly, and include daily summary values of precipitation and air temperature. Solar radiation and wind speed data were downloaded from the Northern Piedmont Agricultural Research and Extension (AREC, Site 2039), located in Orange, VA, approximately 83 km from Cedar Run 3.

Water-Level Data

For this study, water-level data were collected in the southern cell (Figure 5) as part of a separate study. Water levels within the wetland were monitored from 1 September 2009 to 31 August 2010 (courtesy Dr. W. Lee Daniels and Nicole Troyer) utilizing an array of U.S. Army Corps of Engineers standard observation wells (USACE, 2005). These three wells were outfitted with water-level data loggers (Remote Data Systems WL40, Navassa, NC), which recorded water levels every ten minutes for the monitoring period. For analysis purposes, water levels from all three wells were averaged to one single monthly value. The location of the observation wells are shown in Figure 6.

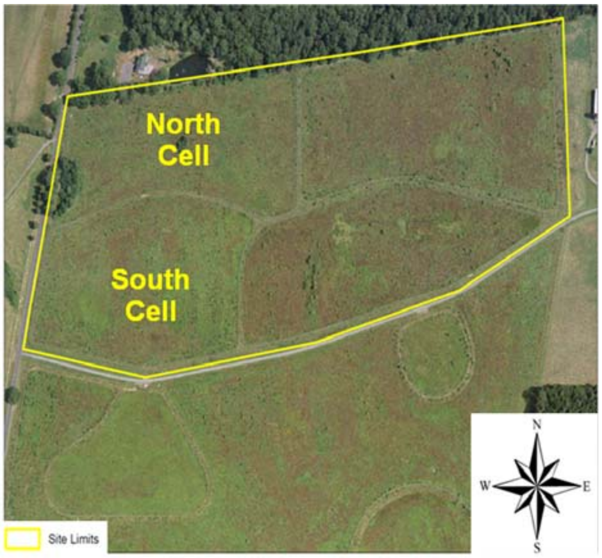

Figure 5. The north and south cell of Cedar Run 3were the main focus of this study, with data being collected in the southern cell (courtesy WSSI)

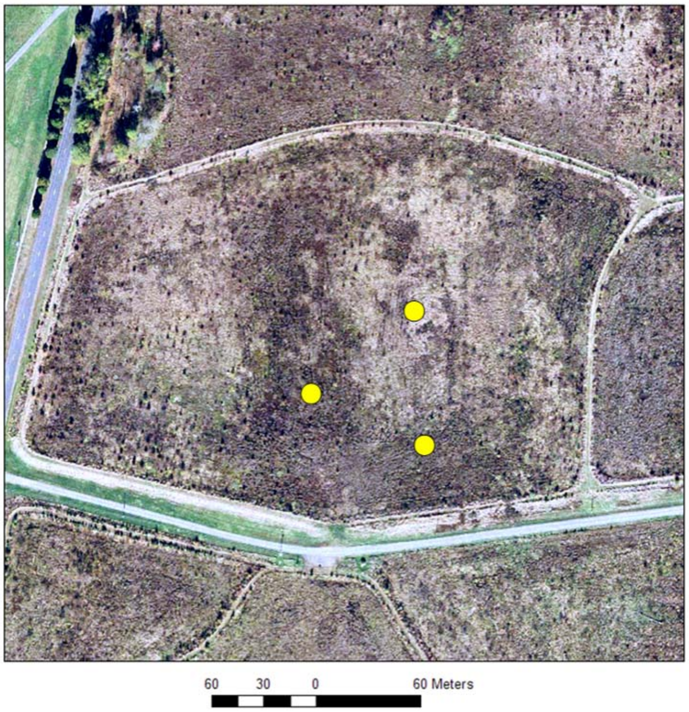

Figure 6. Water table observation well locations within the South wetland cell

The Current Design Model – The Integrated Pierce Approach

The current practice for designing, modeling, and constructing mitigation wetlands utilizes the Pierce methodology. This consists of creating a perched wetland through subsoil compaction and clay lining. This practice reduces the total parameters of the wetland water budget and allows water level control via an outlet structure, which is easily manipulated. To model a system designed in this manner, Pierce (1993) recommended calculating a monthly water budget for typical, dry, and wet years utilizing precipitation data from the previous 30 years.

WSSI developed a proprietary version of a wetland water budget model to predict monthly water levels utilizing the Pierce methodology (Figure 7). The individual sub-models include methods for modeling runoff, precipitation, and evapotranspiration. Because groundwater is difficult to estimate without extensive field data, current design practice seeks to minimize or ignore groundwater interactions.

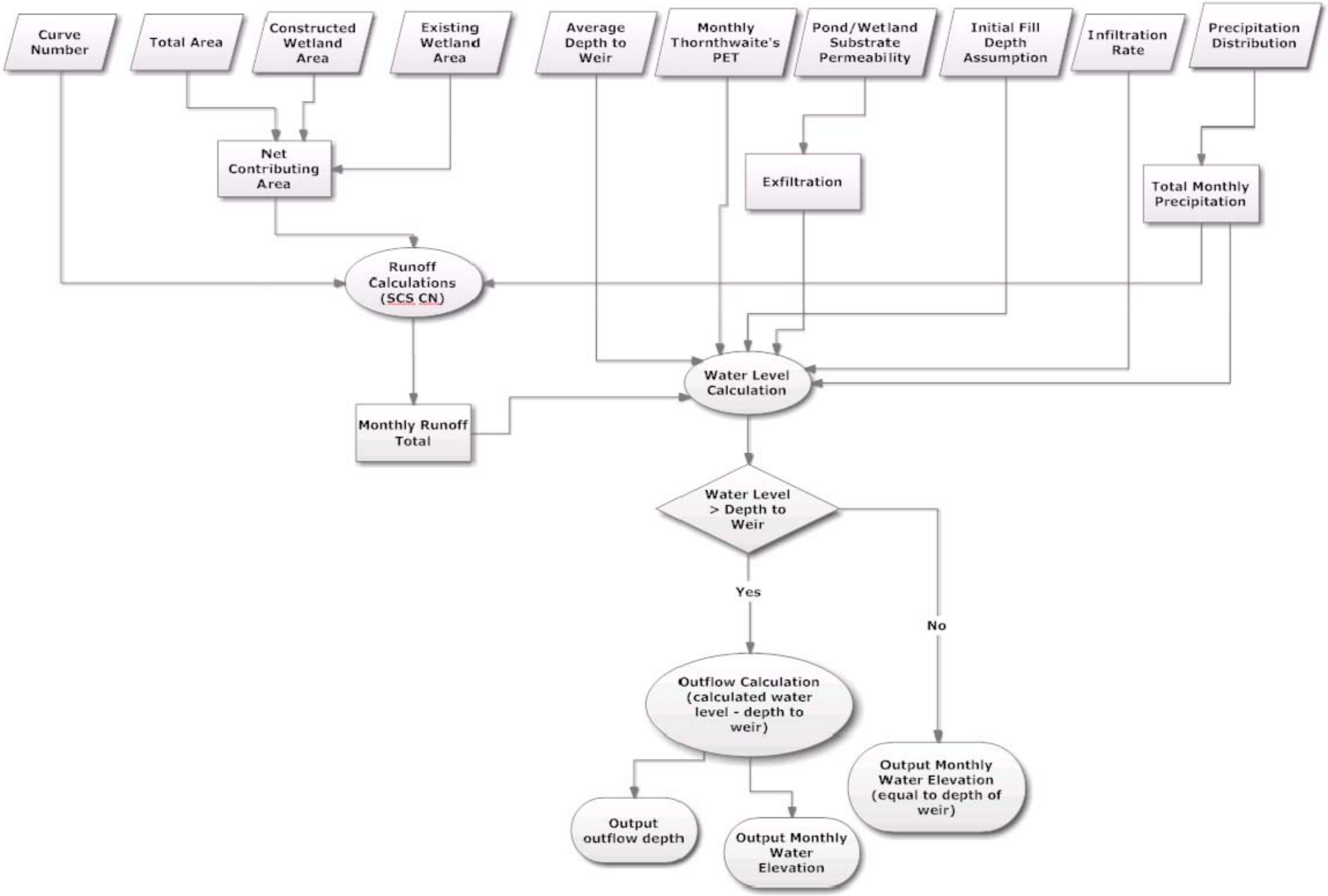

Figure 7. Simplified flowchart of Wetland Studies and Solutions Inc. wetland water budget model

Runoff Sub-Model

The Integrated Pierce method model which WSSI developed utilizes the SCS Curve Number method for determining surface inputs to a wetland. This sub-model relates upstream catchment characteristics such as landuse, slope, soil types, and precipitation to calculate an excess rainfall volume, which discharges into the wetland.

The SCS Curve Number method was developed by the United Stated Department of Agriculture to predict runoff and infiltration from excess rainfall (Mockus, 1972; USDA, 1973). This method uses an equation to relate rainfall with the maximum soil retention capability (based on a curve number) and an initial abstraction to determine total runoff (Ward and Trimble, 2004) (11).

$$Q = \frac{\left(P - I_a\right)^2}{P - I_a + S} \tag{11}$$

Where:

P = 24 hour precipitation expressed in mm

$S = 254 \cdot \left(\frac{100}{CN} - 1 \right)$

$I_a = 0.2S$

A curve number is an empirical parameter that is integral for predicting runoff from the catchment draining into the wetland. This number is based on physical characteristics of the catchment area feeding the wetland, including soil type, antecedent moisture conditions, and landcover. This curve number must be calculated external to the model by the user, and entered as one of the required inputs.

With inputs of total area, constructed wetland area, and existing area, a total net hydraulic contributing area is determined. Using this area, an input Curve Number value, and the precipitation data for the site, the SCS Curve Number equations (Ward and Trimble, 2004) can be utilized. Thus, the runoff sub-model calculation results in monthly values of surface water contributions to the wetland from the upstream watershed (Figure 8).

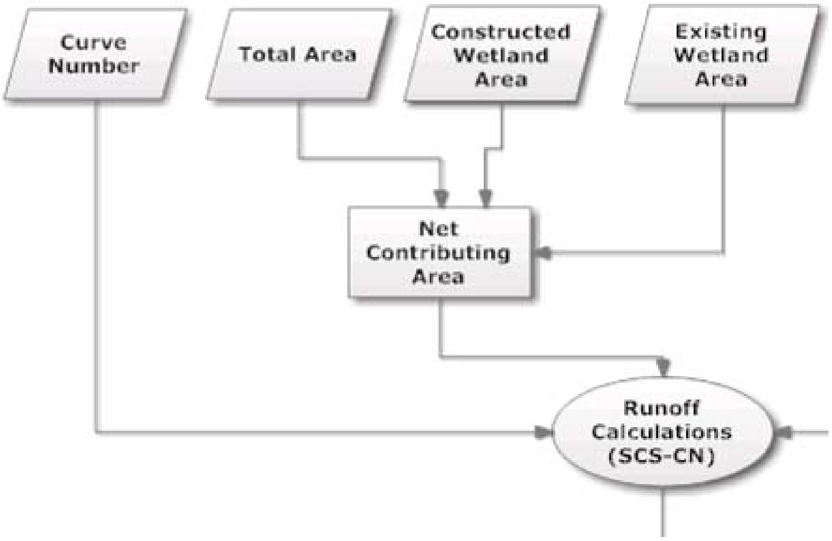

Figure 8. Runoff sub-model of the Integrated Pierce water budget model

Thornthwaite's PET

One commonly used method for determining potential evapotranspiration is Thornthwaite's method. In this case, potential evapotranspiration (PET) is the amount of water that could potentially evaporate and transpire from a vegetated landscape, specifically a well-watered grass reference crop, with no soil moisture limitations (Lu et al., 2005). Thornthwaite's empirical equation determines a monthly potential evapotranspiration utilizing mean monthly temperature and the local heat index (Lott and Hunt, 2009). For the Integrated Pierce method model, Thornthwaite's PET was calculated external to the model and input directly.

Water-Level Prediction Routine

The Integrated Pierce model predicts monthly water levels within the wetland by combining surface runoff contributions, direct precipitation, evapotranspiration, and exfiltration additively. The wetland is treated as a level pool. If the predicted water level is greater than the elevation of the outlet, then the difference of the two is calculated. The excess depth is assumed to flow directly out of the wetland. Given the monthly time step, the assumption that any excess water in the wetland above the weir elevation is removed from the wetland is reasonable. Thus, when the wetland is "full" of water, the model reports the predicted water level as equal to the outlet elevation. If the predicted water level is less than the elevation of the outlet, then the model reports the calculated water level (Figure 9).

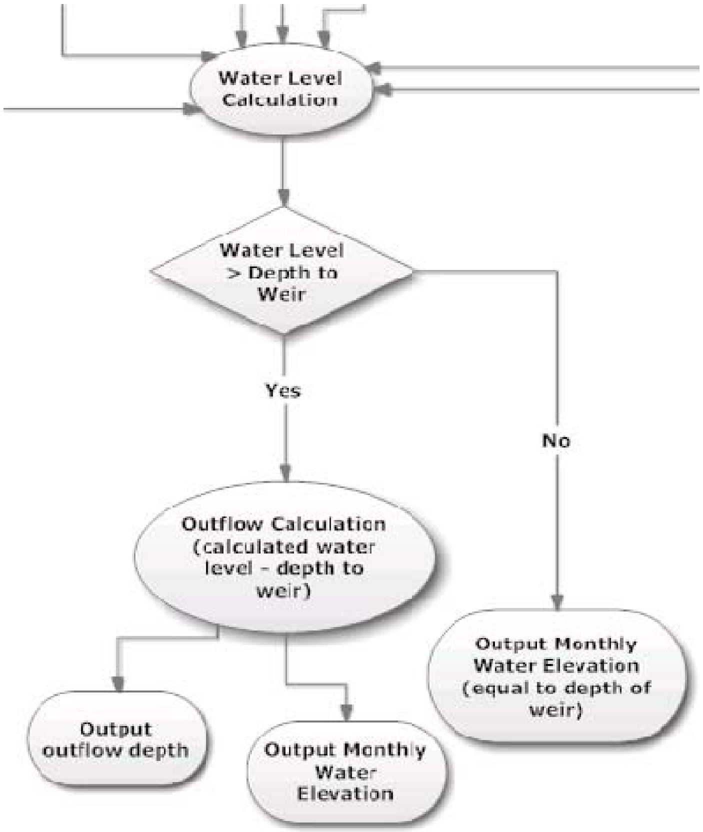

Figure 9. Water level prediction routine of the Integrated Pierce water budget model

Integrated Pierce Model Evaluation

To evaluate the standard mitigation design model, the Integrated Pierce model was run two different times, each with slight variations. The first execution consisted of running the model “off the shelf” as it was provided by WSSI. Based on comparison of these preliminary results to actual water-level measurements, the model was altered slightly to improve the predictive power without making substantial changes to the Pierce methodology.

One alteration made to the Integrated Pierce model was to account for soil porosity, which significantly affects prediction of water levels below the soil surface. Thus, a secondary model was formed to incorporate soil porosity. A third version of the model was also completed, utilizing the FAO-56 Penman-Monteith method for calculating evapotranspiration, while maintaining the updated soil porosity (Figure 10).

Daily evapotranspiration rates were calculated external of the model using weather data collected at the Northern Piedmont Agricultural Research and Extension Center (AREC, site

2039), which were available through the Natural Resources Conservation Service National Water and Climate Center (NRCS NWCC). Daily values were summed to determine monthly wetland ET.

When designing a mitigation wetland, Wetland Studies and Solutions run individual water budgets for each cell on their mitigation site, routing runoff from the wetland catchment into the site. However, this model does not account for the hydraulic linkages which exist between cells. As seen in Figure 11, the precipitation from the wetland catchment flows into the north cell directly; however, direct inputs of runoff into the southern cell must come from outflow of the northern cell. To accurately represent this, the Integrated Pierce model was modified to run a budget for the northern cell, and then use the outflow values from the northern cell as inflow values for the southern cell (Figure 12 and Figure 13). To translate calculated water depths in the northern cell to a depth for the southern cell, water volumes were determined using stage-volume relationships. These relationships were developed using AutoCAD and an as-built survey of the two wetland cells.

Each of the three model versions were run for a time period spanning January 2009 to December 2010. Since measured water levels were only available from September 2009 to August 2010, model evaluation was only conducted for this time period.

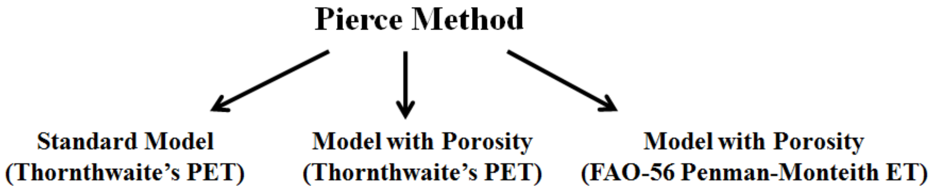

Figure 10. Three model versions of the Pierce Method model were run, the standard model, a model incorporating porosity, and a model incorporating porosity and the FAO-56 P-M reference evapotranspiration

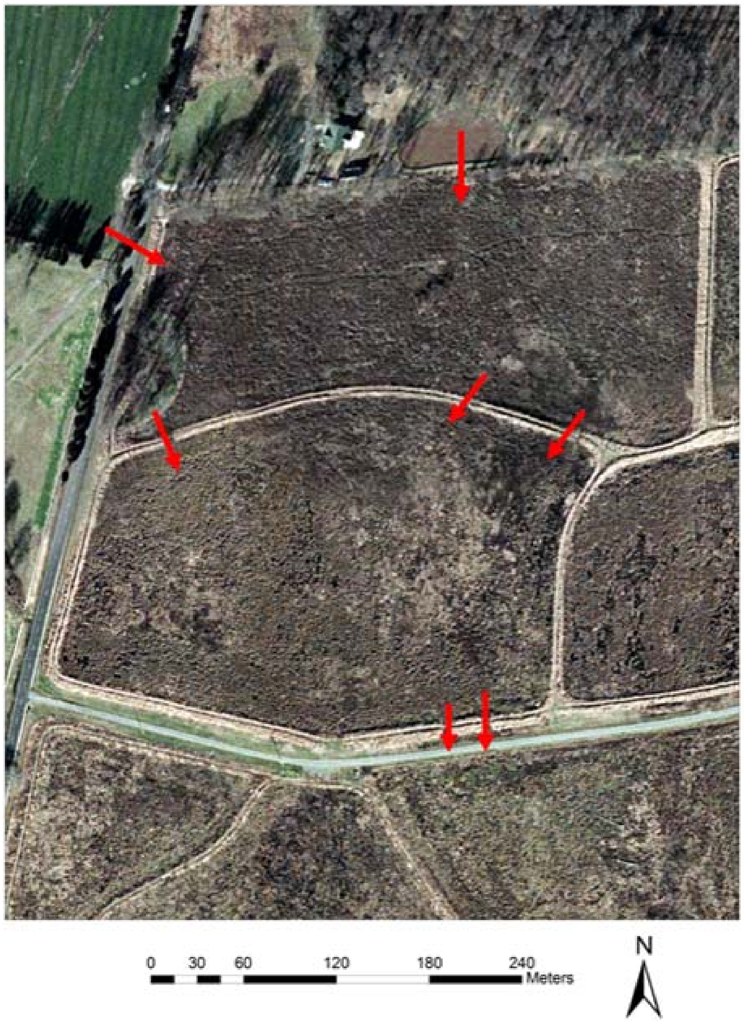

Figure 11. Inlet and outlet locations for the north and south cell

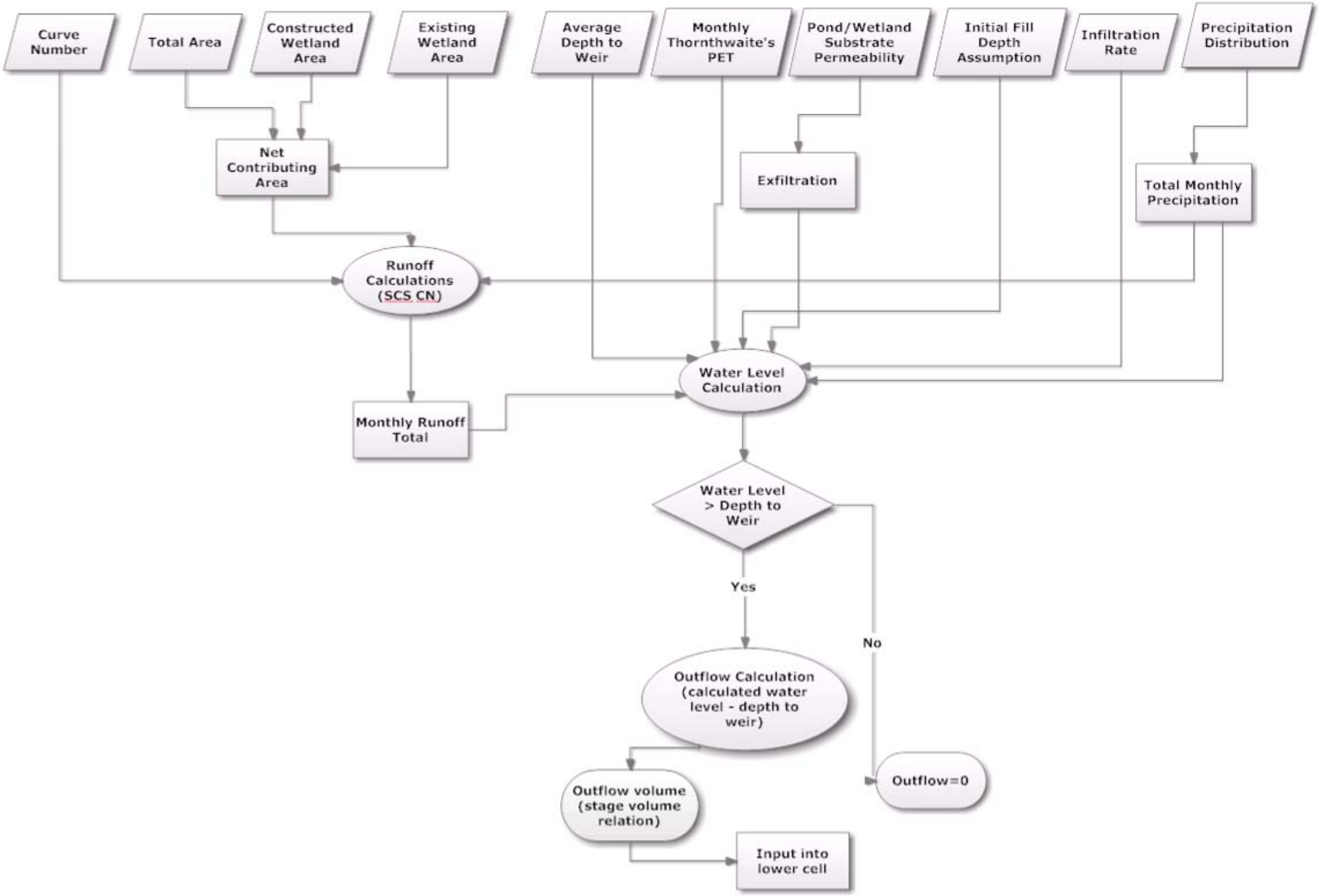

Figure 12. Flowchart of the first half of the Integrated Pierce Method model incorporating flow routing

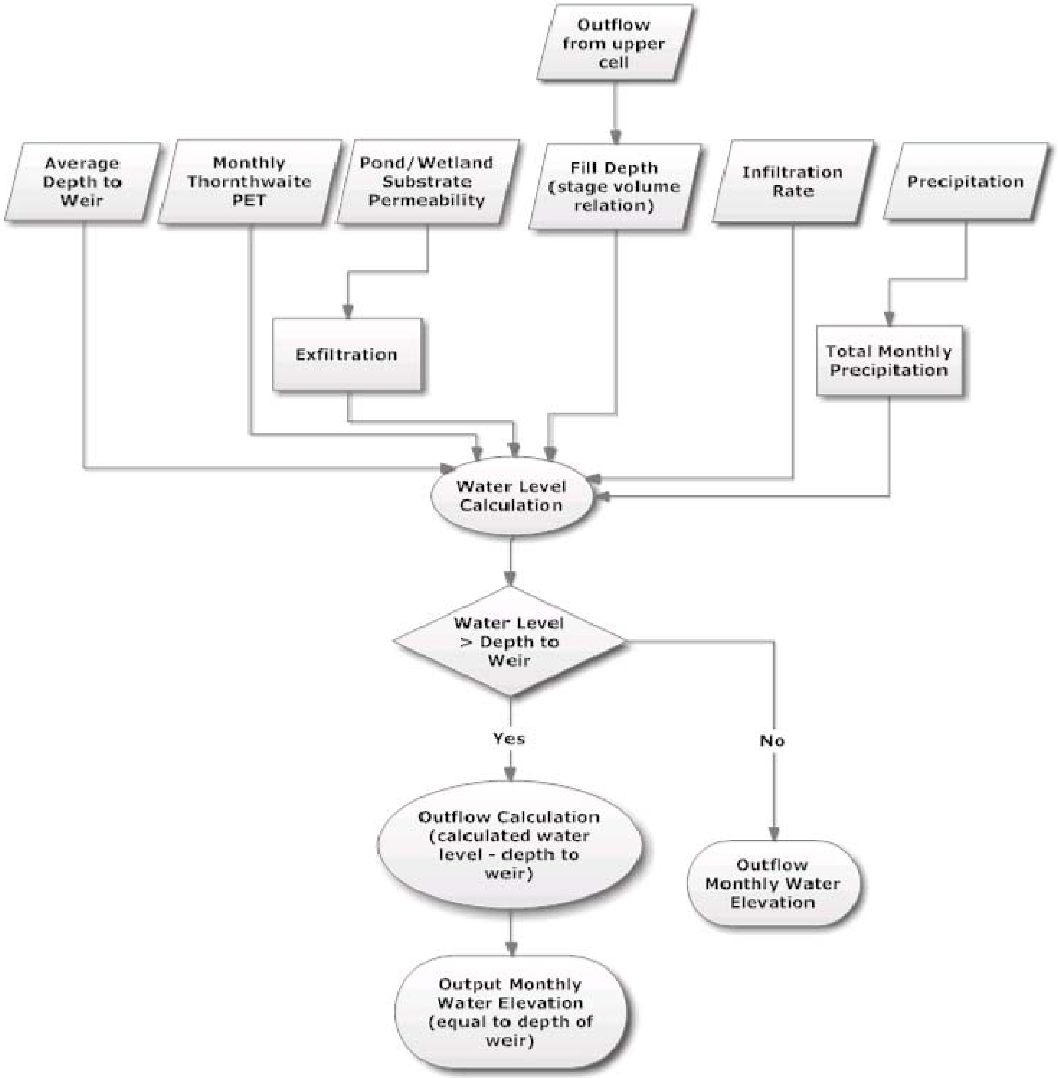

Figure 13. Flowchart of the second half of the Integrated Pierce Method model incorporating flow routing

MODFLOW 2005 – Process Based Model

To evaluate the Integrated Pierce method of modeling against a more process-based approach, two cells of Cedar Run 3 were modeled using the United States Geological Survey's (USGS) modular finite difference model, MODFLOW-2005. The MODFLOW model was initially set up using the USGS' graphical user interface, ModelMuse. Later in the project, the model was converted for use with the Aquaveo graphical user interface, Groundwater Modeling System (GMS ver. 8.0, Aquaveo, Provo, UT).

Model Construction

Cedar Run 3 was simulated in MODFLOW-2005 as a four-layer system. The layer elevations were set by importing topographic data from Cedar Run 3 into the graphical user interface, and interpolating elevations between points. The bottommost layer represented the underlying soil, which was assumed homogenous. This substrate was defined as having an assumed drainable specific yield of 0.4, as well as a storage coefficient of 0.4, which is analogous to specific yield (Todd and Mays, 2005). The upper three layers represented specific ranges of surface water depth, from 0-10 cm, 10-20 cm, and 20-30 cm (Figure 14). All four layers were modeled as confined/unconfined layers. The surface water layers utilized a drainable specific yield of 0.98 (accounting for plant volume), and a storage coefficient of 0.98 (Todd and Mays, 2005). The model was run on a daily time step for 2009 and 2010 data. However, based on available observed well data, model performance was only evaluated for the period of September 2009 to August 2010.

MODFLOW-2005 is a modular software package, incorporating a number of packages which can be turned on or off to model specific processes or features. In the Cedar Run 3 representation the Recharge, Evapotranspiration, Well, and Drain Return packages were utilized.

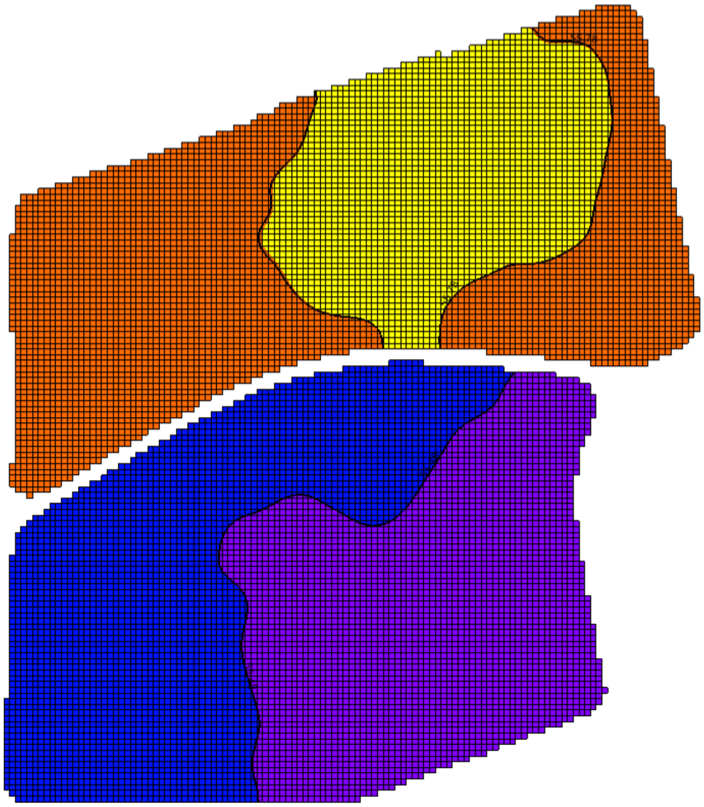

Figure 14. GMS representation of the north and south cells at Cedar Run 3 with example heads colored

Precipitation – Recharge Package

The recharge package in MODFLOW-2005 allows for the specification of a specific recharge rate over a given area (USGS, 2010). This package was utilized to simulate the influx of water from precipitation. Daily precipitation rates in meters per day (m/day) were entered for the stress periods corresponding to precipitation events.

Evapotranspiration – Evapotranspiration Package

MODFLOW-2005 contains a number of packages specifically tailored for simulating different head-dependent fluxes. The Evapotranspiration package is designed to simulate the effects of direct evaporation and plant transpiration at a rate that depends on the water head in a cell. In this package, if the water head is above a defined elevation (the evapotranspiration surface), then water leaves the system at a constant rate. However, if the head drops below this level, then the rate varies linearly from the maximum rate (at the evapotranspiration boundary) to zero (at the extinction depth) (USGS, 2010). Daily potential evapotranspiration estimates utilizing the FAO-56 Penman-Monteith method were calculated externally from Modflow using temperature, solar, wind, and humidity data from the Northern Piedmont Agricultural Research and Extension Center (NPAREC), resulting in a meter per day (m/day) potential evapotranspiration rate. The evapotranspiration surface was set at the soil surface, , the ET Layer Indicator was set to the fourth layer, and the extinction depth was set at 30 cm below the soil surface, corresponding to typical wetland plant rooting depth (Kadlec, 1996).

Surface Inflow – Well Package

Surface water flux into the wetland was represented as a discharging well, located at the inflow point of the North cell. Daily injection flow values were assigned to this well based on the flows from the contributing watershed, as estimated using the SCS runoff curve number method, which was also used in the Integrated Pierce model.

Flow Between Cells – Drain Return Package

As was noted in the evaluation of the Integrated Pierce model, the northern cell of Cedar Run 3 flows into the southern cell via three trapezoidal (Cipoletti type) weirs (Figure 11). These flow connections were modeled using the Drain Return package. This package allows water to leave the system when the head in a cell rises above the elevation of the drain boundary. Additionally, it allows some or all of the water exiting through the drain to return at some other location (USGS, 2010). Accordingly, a drain was placed in the three weir locations in the north cell, and their corresponding returns were placed at the weir locations in the south cell.

In standard use, the Drain Return package calculates the volume of water leaving the system based on the dimensions of the model object used to identify the drain. To represent the compound trapezoidal weirs, a rating curve was formulated using the Cipoletti weir equations (12), where L is the bottom length (in meters) of the trapezoidal weir, and H is the head above the bottom of the weir (in meters).

$$Q = 1.84LH^{3/2} \tag{12}$$

Based on this equation, flow rates (Q in m^3/day) were calculated for the range of potential head values that could exist in the wetland (0.76 cm to 50 cm). Utilizing Darcy’s Law (13), where Q is the flow rate, k is hydraulic conductivity, and i is the hydraulic gradient, a hydraulic conductivity can be determined by dividing the flow rate by the cross sectional area of the weir and dividing by the hydraulic gradient, resulting in *k* values from 6.8 m/day to 16,000 m/day.

$$Q = k \cdot i \cdot A \tag{13}$$

To calculate flow rates through the weirs using MODFLOW, an equivalent conductance had to be determined. As defined in MODFLOW-2005, conductance (*C*) has units of L^2/t, and is a function of hydraulic conductivity (*k*), cell length (*L*), cell width (*W*), and cell thickness (*M*) (14). By substituting the calculated hydraulic conductivities with the drain dimensions, a range of equivalent conductance's was found. A range of conductance values were attempted in the model, with the model successfully converging utilizing a conductance of 600-800 m^2/day, around the median value (787 m^2/day) of all calculated conductance values across the range of potential head values that could exist in the wetland.

$$C = \frac{KLW}{M} \tag{14}$$

Vegetative Resistance to Flow – Layer Conductivity Determinations

To account for vegetative resistance to surface flow, field observations of plant communities were made, and corresponding collections of plant material were used to calculate hydraulic conductivity values for the three upper layers of the model. Utilizing aerial photography, the southern cell was visually delineated into three different zones of similar vegetation (Figure 15). On May 24, 2010 and February 11, 2011, samples of plants were collected in each of the three zones: two samples in zone 1, two samples in zone 2, and one sample in zone3. A one square meter sampling quadrat (Figure 16) was randomly placed on the ground surface, and all plants within this block were cut at ground level and stored in a cooler until measured.

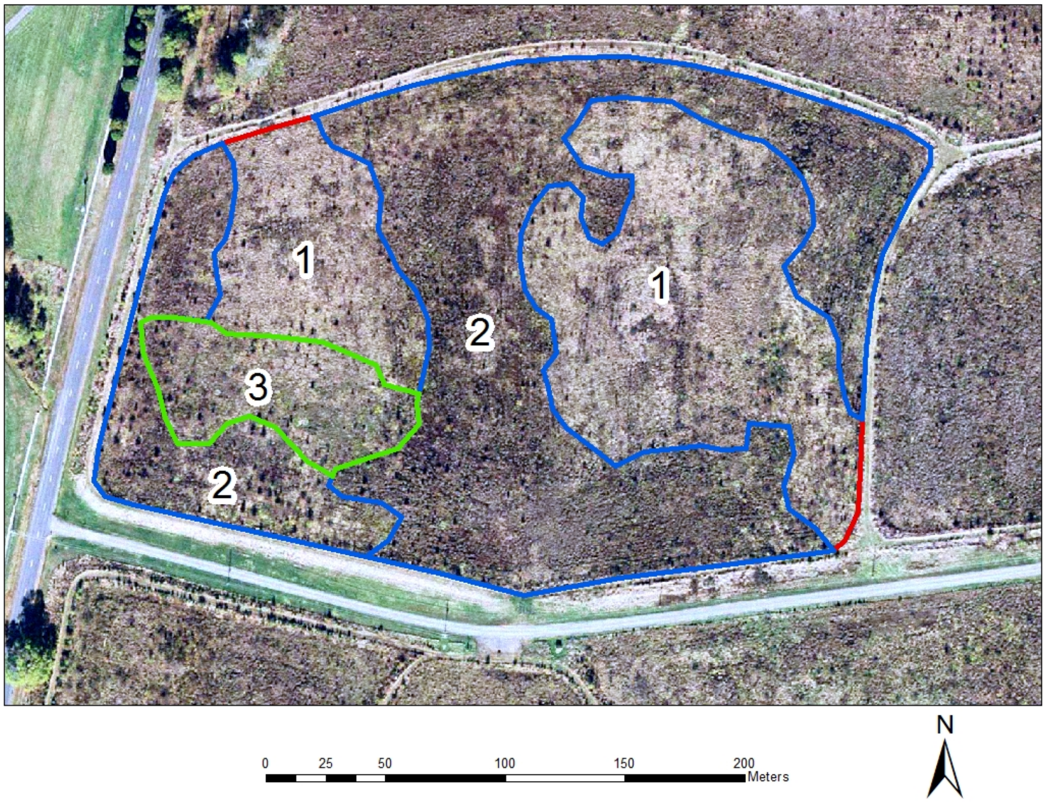

Figure 15. Visually delineated vegetation communities

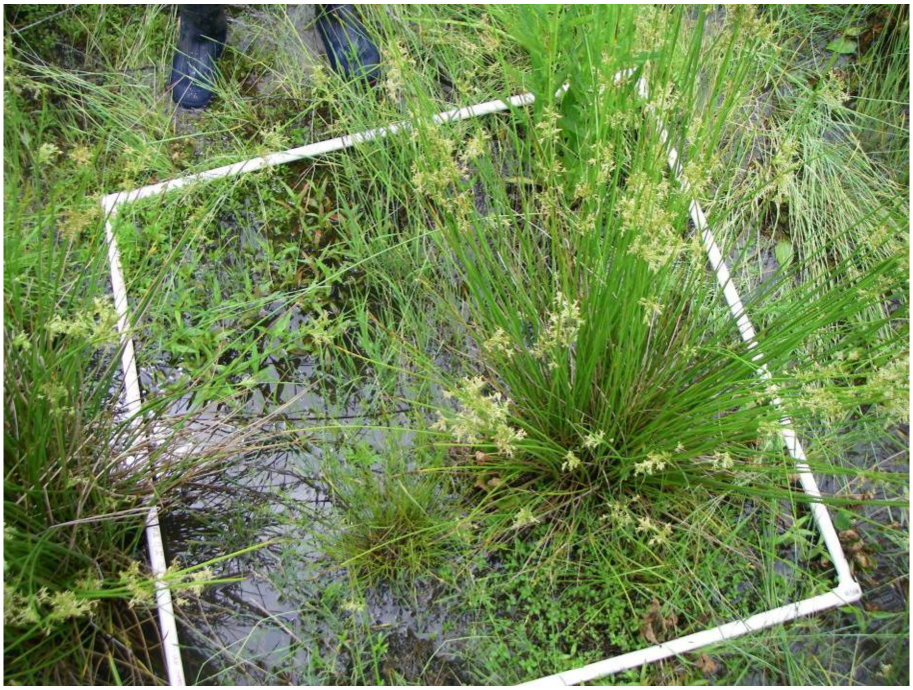

Figure 16. Square meter quadrat plot before plant harvesting

Utilizing a procedure similar to that of Piercy (2010) all the collected plants were counted to determine stem density. These plants were then cut into increments of 10 centimeters (cm). All of the stems for each height class (from 0-10 cm, 10-20cm, 20-30cm) were scanned using an area meter (LI-COR Inc. LI-3100 Area Meter, Lincoln, NE) to determine the frontal area. Average stem diameter for each height class in each vegetative community was determined by dividing the total stem area by the stem count. With these data, the momentum absorbing area (*maa*) per centimeter of plant height (for each height class) was determined by taking the total surface area and dividing by the 10-cm height increment. Utilizing (15**)** (Piercy, 2010) with an assumed laminar stem Reynolds number an initial laminar friction factor was calculated as follows:

$$f = 10^{4.98}(maa \cdot d)^{0.47}\,\mathrm{Re}^{-1.52} \tag{15}$$

where *maa* is the momentum absorbing area, and *d* is the average stem diameter by height class.

Friction factor is a common measure for describing hydraulic resistance in vegetated flow paths. For the purposes of utilizing MODFLOW-2005, however, this value must be transformed into a value of conductivity (*K*). This is accomplished by utilizing the Reynolds Equation (16) and a transformed version of the Darcy-Weisbach equation.

In a steady-state modeling case, such as Piercy (2010), a single *K* value may be determined iteratively as the head within the wetland is constant. However, in the transient case, head will vary. The groundwater flow equations in MODFLOW use a Darcian flow assumption, and Darcy's law dictates that the calculated flow rate of water is linearly proportionate to the hydraulic head (flow decreases as pressure decreases), with *K* (conductivity) being the proportionate constant (Piercy 2010). The Darcian flow assumption is consistent for laminar flow conditions. Beyond this, flow is no longer linearly proportional, meaning *K* is no longer a constant value, but instead varies with flow via an unknown site-specific relationship (Piercy 2010). Coupled with the flat wetland gradients, the Reynolds equation was utilized to determine a laminar flow velocity for the average stem diameter of each height class, by plant zone.

$$V = \frac{\mathrm{Re} \cdot \mu}{\rho \cdot D}$$

(16)

By rearranging and equating terms from the Darcy equation and the Darcy-Weisbach equation, the final conductivity value can be determined. The traditional Darcy equation at its most basic form is:

$$Q = KA\frac{dh}{dl} \rightarrow \frac{dh}{dl} = \frac{v}{K}$$

(17)

where *dh/dl* is the hydraulic head gradient, and *v* is the cross-sectionally averaged velocity (Piercy, 2010). Accordingly, the Darcy-Weisbach equation for open channel flow is:

$$\frac{dh}{dl} = \frac{fv^2}{8gR}$$

(18)

By equating the two formulations by the hydraulic head gradient term, and rearranging the equation to solve for *K*:

$$K = \frac{8gR}{fv}$$

(19)

where *R* is assumed equal to the water depth, *h* (Piercy, 2010). Using this method, conductivity (*K*) values were determined for each 10 centimeter height class of plants for each plant community zone. Conductivity values varied slightly across the height classes, and in some instances conductivities were higher in the lowest layer than the middle and upper layers. This may be attributed to the presence of broad leafed plants that were sampled (increased surface areas due to leaves at the ends of stems), as well as general sampling/quantification variances from stem harvesting, counting, and scanning. The final conductivities are shown in Table 3 and Table 4, and are similar to values determined by Piercy (2010).

Table 3. Spring/Summer conductivity values by height class for the three plant communities in the southern cell

***K* (m/s) Spring/Summer**			
	Zone 1	*Zone 2*	*Zone 3*
0-10 cm	2.67	1.49	2.26
10-20 cm	2.55	1.50	2.22
20-30cm	2.40	1.42	2.22

Table 4. Fall/Winter conductivity values by height class for the three plant communities in the southern cell

K (m/s) Fall/Winter			
	Zone 1	*Zone 2*	*Zone 3*
0-10 cm	2.38	2.00	2.63
10-20 cm	2.79	1.84	2.82
20-30cm	2.96	2.82	2.42

Wetting Option

In MODFLOW-2005, when the head level drops below the lower elevation of a model cell, this cell converts from an “active” cell, to a “no flow” cell. This conversion is known as “cell drying”. By itself, MODFLOW-2005 has no way of re-activating cells when water heads increase beyond the lower elevation of a no-flow model cells. To allow for reconversion of no flow cells to active cells, the Wetting option was incorporated (Harbaugh, 2005). This iterative option allows for re-wetting of cells based on surrounding head values. User-specified values of wetting iteration (how often cells are checked for re-wetting), and threshold values (level which water head must exceed to re-wet) can be specified. This capability is critical in modeling wetlands, where cells dry and rewet frequently.

In the model of CR3, the wetting option was activated and initialized with a wetting interval of 3, and a threshold of -0.1. This means that every third iteration in attempted solution convergence, MODFLOW-2005 attempts to re-wet cells. A threshold of -0.1 indicates that head values must exceed the bottom elevation of the above cell by 0.1 meters before it will re-wet, with the negative indicating a cell can only be re-wetted by an underlying cell, and not an adjacent cell. A fine balance must be found between the wetting iteration and wetting threshold/flag, as this option can lead to model instability and non-convergence.

Results and Discussion

Overview

Using water level data from a mitigation wetland, this study evaluated a common mitigation wetland design model. Study results are shown in Table 5. Evaluation parameters included analysis of absolute relative error (RE), mean absolute error (MAE), root mean square error (RMSE), RMSE-observations standard deviation ratio (RSR), Nash-Sutcliffe model efficiency (NSE), and regression analysis.

The Integrated Pierce model (IPM) was evaluated first. Model results showed overall poor estimation of observed water levels. The Pierce method consistently under-predicted monthly water levels during the winter when observed water levels were above the soil surface, and consistently over-predicted water levels during the growing season when actual water levels were subsurface. This combination of over and under predictions has implications for the success of the mitigation wetland once completed. Utilizing a model that under predicts water levels can result in a wetland design that will hold an excess volume of water, which can result in vegetative failure or a change in wetland type. Conversely, utilizing a model which over predicts water levels during the growing season, can result in a mitigation wetland that cannot support the targeted wetland vegetation community. During the growing season, the IPM model over-predictedover-predicted water levels by 16 to 36 cm, with July 2010 having the largest over prediction at 36.8 cm.

Based on these results, a second Integrated Pierce model (IPM-FAO) was evaluated using a different evapotranspiration sub model, the FAO-56 Penman-Monteith PET method. This model showed marked improvement in predictive power for determining water levels as compared to observed levels. The IPM-FAO model better reflected the cyclic nature of the wetland hydroperiod, rising and falling with the observed levels across the year (Figure 17). While the IPM-FAO was a better predictor than the IPM, it consistently under-predicted water levels that existed in Cedar Run 3, suggesting ET rates for actual wetland vegetation in the Virginia Piedmont are less than ET rates for a well-watered reference crop.

Overall, changing the evapotranspiration model from Thornthwaite’s PET to the FAO-56 Penman-Monteith PET produced a noticeable change in predicted wetland water levels. Figure 17 visually shows how each model predicted water levels across the 12-month period. From

September 2009 to February 2010 both the IPM and IPM-FAO under-predicted water levels. The two then diverged in March, with the IPM over predicting water levels. The IPM-FAO under-predicted water levels during the growing season across a range from -0.13 cm to -19.9 cm, with June having the largest under prediction at -19.9 cm.

Lastly, Cedar Run 3 was modeled utilizing MODFLOW-2005 (Modflow). Modflow better reflects the rapid rise that occurred in the observed water levels in the late Fall and winter, which the IPM model failed to do (Figure 17). From January 2010 to April 2010 Modflow consistently under-predicted water levels. From June 2010 to August 2010 the model over-predicted water levels. Compared to the IPM and IPM-FAO, Modflow showed the best overall predictive power. While the IPM had wide swings in amplitude of over and under prediction and the IPM-FAO consistently under-predicted water levels, Modflow showed the most mediated response. Modflow both over and under-predicted water levels across the year, with most over predictions occurring primarily when observed levels dropped 8 cm below the soil surface.

The overall water budget components shown in Figure 18, Figure 19, and Figure 20 shows that evapotranspiration is a dominant controlling factor for hydrology at the Cedar Run 3 mitigation wetland. This component accounted for 91%, 94%, and 66% of the water losses in the IPM, IPM-FAO, and Modflow models respectively.

Table 5. Observed and predicted mitigation wetland water levels for the Integrated Pierce models and the MODFLOW-2005 model

Month	*Observed Water Level (cm)*	*Integrated Pierce (Thornthwaite) (cm)*	*Integrated Pierce (FAO 56 P-M) (cm)*	*MODFLOW-2005(cm)*
Sep	-48.6	-83.0	-67.1	-32.8
Oct	-40.5	-78.0	-62.0	-20.4
Nov	7.4	-53.3	-38.6	14.5
Dec	9.8	-18.4	-8.8	16.2
Jan	6.8	-5.8	-4.8	-3.9
Feb	10.3	1.1	-4.0	-5.0
Mar	8.5	7.6	1.2	-7.0
Apr	-2.0	7.1	-16.0	-18.7
May	-20.0	7.1	-20.1	-7.2
Jun	-13.6	3.1	-33.5	-10.1
Jul	-33.8	3.0	-39.1	-10.0
Aug	-38.0	-2.5	-40.9	-8.0

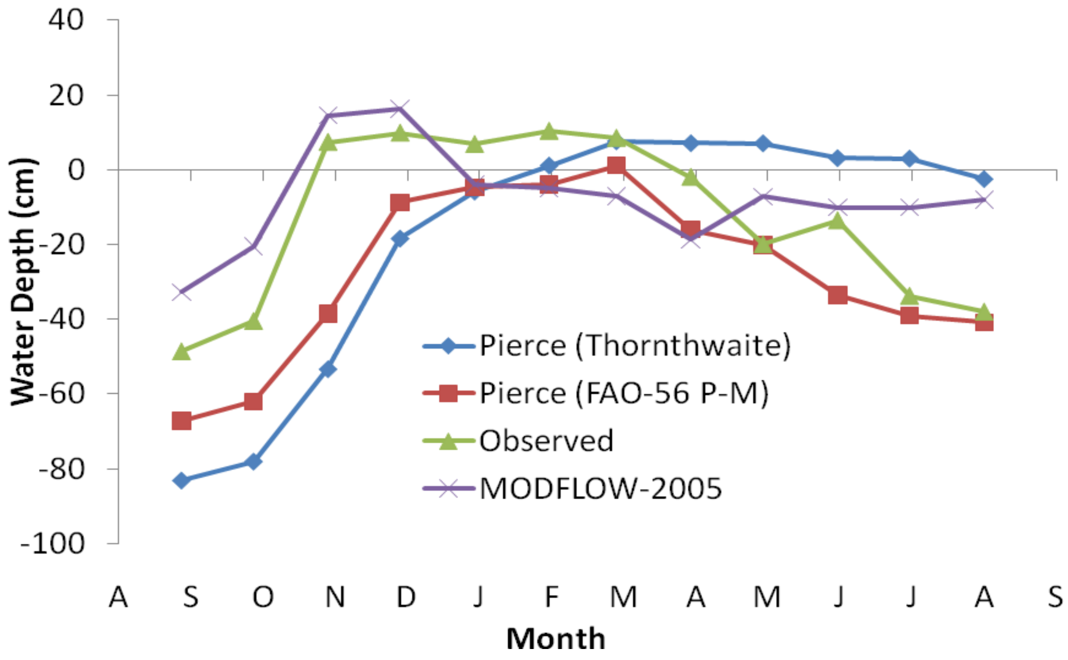

Figure 17. Monthly observed and predicted water levels in Cedar Run 3 mitigation wetland from September 2009 to August 2010

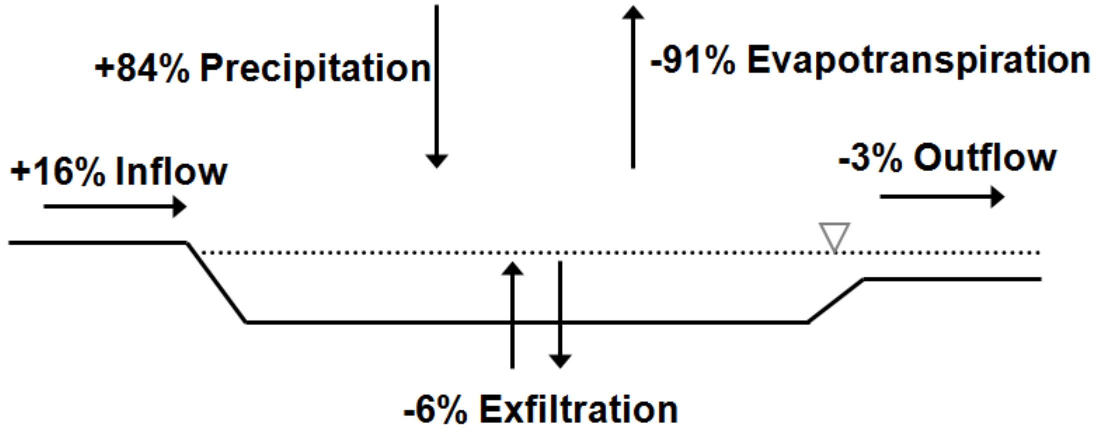

Figure 18. Water budget components as calculated by the Integrated Pierce Method model using Thornthwaite's method (IPM).

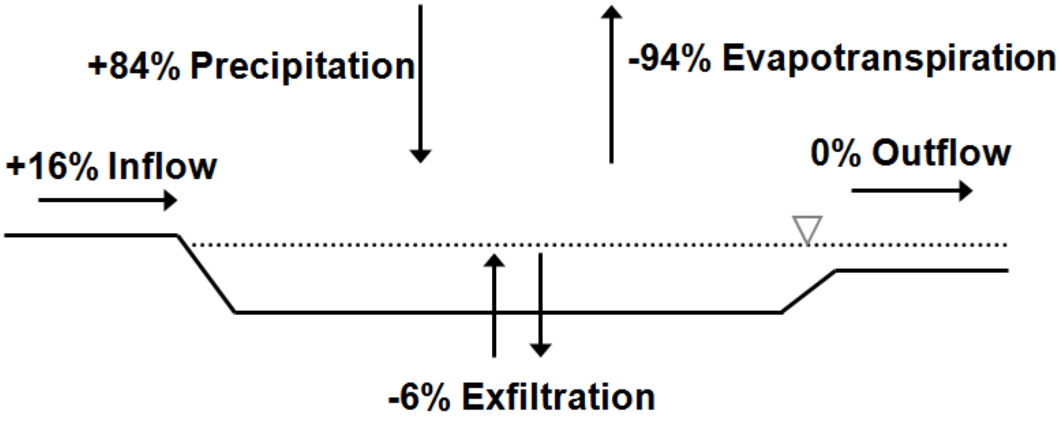

Figure 19. Water budget components of Cedar Run 3 as calculated by the Integrated Pierce Method model using the FAO Penman-Moneith method (IPM-FAO).

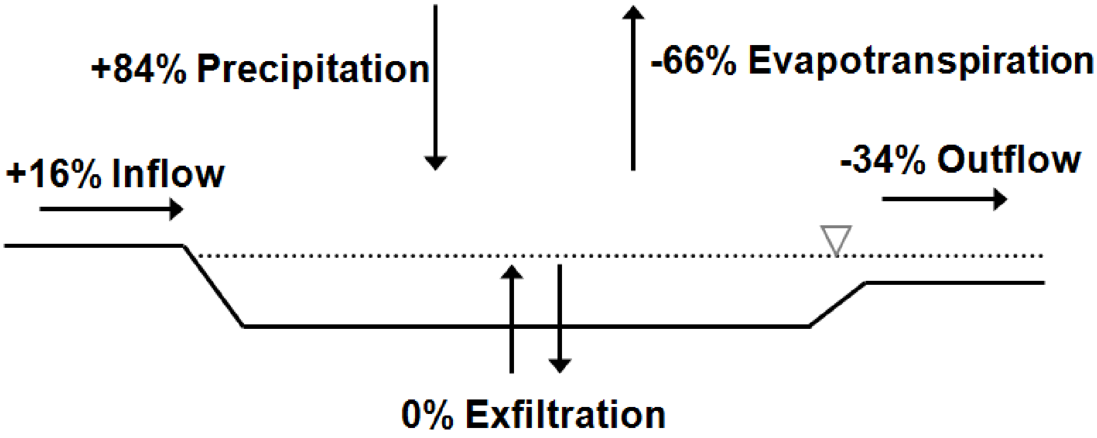

Figure 20. Water budget components of Cedar Run 3 as calculated by MODFLOW-2005

Error Analysis

Absolute Relative Error

Absolute relative error determination allows for an easily understood comparison of modeled water levels to observed water levels. Absolute relative errors were calculated using

(5). These errors ranged from 1% to +841%, showing a wide range in model accuracy. The computed absolute relative errors for the modeled and observed water levels are shown in Table 6. On a yearly basis, MODFLOW-2005 showed the best absolute relative error, with a mean of 151%. In comparison, the IPM-FAO had a mean absolute relative error of 181% and the IPM had a mean absolute relative error of 206%.

Table 6. Computed percent absolute relative errors of predicted water levels

Month	*Integrated Pierce (Thornthwaite)(%)*	*Integrated Pierce (FAO-56 P-M)(%)*	*MODFLOW-2005 (%)*
Sep	71	38	32
Oct	92	53	50
Nov	823	623	97
Dec	287	189	65
Jan	185	170	157
Feb	89	139	148
Mar	10	86	182
Apr	457	705	841
May	135	1	63
Jun	123	147	25
Jul	109	16	70
Aug	94	7	79
Mean	*206 %*	*181 %*	*151 %*

Mean absolute error (MAE) is another dimensioned metric to quantify how well a model predicts values as compared to observed values. As shown in Table 7, Modflow had the lower mean absolute error, although only less than the IPM-FAO by 0.17 cm, as compared to the IPM by 10.9 cm. On average, the best models (MODFLOW and IPM-FAO) had mean absolute errors of 14.9 cm.

The computed RMSE for all models is shown in Table 7. Modflow had the lowest root mean square error (16.4 cm), which was 2.4 cm and 13.8 cm lower than the IPM-FAO and the IPM, respectively.

While the root mean square error (RMSE) is typically used in error analysis, with a lower RMSE indicating better model performance, there is nothing that defines what is a "low"

RMSE, thus a root mean square error standard deviation ratio is used. In this case, the RMSE values previously calculated were divided by the standard deviation of the observed water levels, providing an RSR statistic. This resulting statistic has an optimal value of 0, indicating perfect model performance.

The calculated RSR statistics for all three models are shown in Table 7. As a basis of comparison, Moriasi and others (2007) indicated that an RSR value of 0.6 to 0.7 was considered satisfactory for calibrated model performance, with 0.0 to 0.5 being the best. Accordingly, the Modflow model performed near the satisfactory threshold, despite it being an uncalibrated design model.

Nash-Sutcliffe model efficiency (NSE), as shown in (9), is an indicator of how well a comparison of observed and predicted values fit an equal value line. It is a commonly used statistic for evaluating model performance, and is recommended for use by the American Society of Civil Engineers (Engineers, 1993).

Calculated values for Nash-Sutcliffe model efficiency are shown in Table 7. Results show that between the two versions of the Integrated Pierce model, the IPM-FAO model performed the best, with Modflow the best between all three models. The IPM had a negative NSE (-0.97), indicating that taking the mean of the observed values is a better predictor than the simulated value. Thus, this model exhibited unacceptable performance. The second version of the IPM, the IPM-FAO resulted in a positive value for NSE (0.23). Generally, NSE values greater than zero are viewed as acceptable (Moriasi et al., 2007). While this model exhibited an NSE greater than zero, it was still relatively low as compared to NSE results from the Modflow model (0.42). These results indicate the Modflow model produces markedly better predictions than the Integrated Pierce model incorporating FAO-56 P-M.

Moriasi and others (2007) summarized NSE values and their associated performance ratings from a literature review. They determined that models with NSE values less than 0.5 performed unsatisfactorily or poor, with values from 0.5 to 0.65 being satisfactory, and those ranging from 0.65 to 1.0 being good/very good. NSE values from this investigation showed that all values calculated for the Integrated Pierce models would be considered unsatisfactory or poor. It should be noted however, that the summarized values from the Moriasi and others (2007) study report NSE values for calibrated models. As the Integrated Pierce models are design models, no direct comparisons can be made to the NSE performance rating for these models.

However, the study results strongly support that IPM-FAO was a better predictor of wetland water levels than the mean of the observed values.

Summary

Overall, on all error metrics (RE, MAE, RMSE, RSR, and NSE), MODFLOW-2005 performed the best on a yearly basis out of all three water budget models. Summarized error metrics for Modflow are shown in Table 7. Accordingly, for modeling a mitigation wetland hydroperiod from a yearly standpoint, MODFLOW-2005 would be the best choice. However, due to the seasonality of wetland water levels and regulatory requirements, seasonal differences were also explored.

Table 7. Summary error statistics for all models on a yearly basis

	RE	MAE	RMSE	RSR	NSE
Integrated Pierce (Thornthwaite)	206%	25.7 cm	30.3 cm	1.34	-0.97
Integrated Pierce (FAO-56 P-M)	181%	15.0cm	18.9 cm	0.83	0.23
MODFLOW-2005	151%	14.8cm	16.4cm	0.73	0.42

Seasonal Model Performance

Created mitigation wetlands are regulated on a seasonal basis, with the growing season being the main focus. The U.S. Army Corps of Engineers delineates wetlands based on three factors: hydrophytic vegetation, hydric soils, and hydrology (USACE, 1987). For an area to be an accepted regulatory wetland, all three factors must be present for a significant period during the growing season (March to October for the Virginia Piedmont) of the prevalent vegetation (USACE, 1987).

Accurately predicting the seasonal hydroperiod for a mitigation wetland is important for proper vegetative establishment and success. A mitigation wetland system is usually designed to develop a specific hydroperiod and plant species composition (wetland type). However, if the constructed hydroperiod differs from that of the design, a shift in successful plant species and even wetland type can occur. Past studies have shown that changes to a wetland hydroperiod can directly result in a shift of plant communities to new communities adaptable to the new hydroperiod (Reinelt et al., 1998). Development of a correct hydroperiod is especially important in the spring, as many plant species have specific germination requirements and are sensitive to flooding once they have established.

Accordingly, the wetland water budget models were evaluated on a seasonal basis to determine the predictive power of each during the growing season. Seasons were divided into Spring (March, April, May), Summer (June, July, August), Fall (September, October, November), and Winter (December, January, February). For each season, absolute relative error, mean absolute error, root mean square error, and Nash-Sutcliffe model efficiency were calculated for the three models (IPM, IPM-FAO, Modflow). Additionally, error metrics were calculated for the growing season, consisting of data from March through October.

Absolute Relative Error

Overall, MODFLOW-2005 and the IPM-FAO had similar absolute relative errors (RE) during the summer. While MODFLOW-2005 over-predicted water levels during the peak summer months and the IPM-FAO appeared to be a better estimator (Figure 17, Table 5), they had similar absolute summer relative errors (57% and 58%, respectively). Examining the mean absolute relative error of the extended growing season (March-October), IPM-FAO had the lowest overall error at 132%, with the IPM model had the next best error at 136%. Modflow exhibited a high error (362%) during the springtime. This is a result of the large magnitude of water level changes which occurred in the wetland. Large spring rain events caused water levels in the wetland to rise quickly, and quickly drain and dry down due to the spring evapotranspiration. This cycle of wetting and drying of model layers causes model instability and can introduce error. As noted in the *Methods* section (*Wetting Option*) a wetting threshold is needed and must strike a balance between fine resolution and model stability. The threshold of 0.1 m was the smallest value possible in this instance with which the model could converge. Based on this value there could be instances when water levels were actually above soil surface and Modflow has not yet re-activated the surface layer. The model will re-activate the layers once the wetting conditions are met, but cyclic activating/deactivating of layers can introduce error, and explains Modflows high springtime errors.

Table 8. Computed seasonal absolute relative error (%) of predicted water levels for the Integrated Pierce and MODFLOW-2005 models

*Season**	*Integrated Pierce (Thornthwaite) (%)*	*Integrated Pierce (FAO-56 P-M) (%)*	*MODFLOW-2005(%)*
Spring	194	263	362
Summer	108	57	58
Fall	328	238	59
Winter	187	165	123
Growing Season	136	132	168

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

Mean Absolute Error

As the computed seasonal mean absolute error (MAE) values show in Table 9, the IPM-FAO performed better than Modflow during the summer months, with an MAE 9.3 cm and 19.1 cm, respectively. When considering the entire growing season, the IPM-FAO again performed the best with an MAE of 11.2 cm, an increased accuracy of 6 cm over Modflow.

Table 9. Computed seasonal mean absolute error (cm) of predicted water levels for the Integrated Pierce and MODFLOW-2005 models

*Season**	*Integrated Pierce (Thornthwaite) (cm)*	*Integrated Pierce (FAO 56 P-M) (cm)*	*MODFLOW-2005 (cm)*
Spring	12.3	7.2	14.9
Summer	29.7	9.3	19.1
Fall	44.2	28.6	14.4
Winter	16.7	14.8	10.8
Growing Season	24.7	11.2	17.2

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

Root Mean Square Error

Seasonal RMSE for all models was also explored, and the results are shown in Table 10. These results confirm what was illustrated by the RE and MAE results, that the IPM-FAO has the lowest error during the peak summer months, with an RMSE of 12.0 cm. Looking at the entire growing season, the IPM-FAO model had the lowest RMSE of all three models (13.6 cm).

Table 10. Calculated seasonal RMSE (cm) of predicted water levels for the Integrated Pierce and MODFLOW-2005 models

*Season**	*Integrated Pierce (Thornthwaite) (cm)*	*Integrated Pierce (FAO 56 P-M) (cm)*	*MODFLOW-2005 (cm)*
Spring	16.5	9.1	15.1
Summer	31.1	12.0	22.2
Fall	45.7	31.2	15.3
Winter	18.6	15.1	11.4
Growing Season	28.1	13.6	18.7

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

RMSE-Standard Deviation Ratio

In conjunction with the RMSE calculations, the RMSE-standard deviation ratio (RSR) was also determined on a seasonal basis. This metric also confirms that the IPM-FAO model performed the best during the summer growing season. During the extended growing season (March-October), the IPM-FAO again performed best, with an RSR of 0.68, with 0 being ideal (Table 11).

Table 11. Calculated seasonal RSR values of predicted water levels for the Integrated Pierce and MODFLOW-2005 models

*Season**	*Integrated Pierce (Thornthwaite)*	*Integrated Pierce (FAO-56 P-M)*	*MODFLOW-2005*
Spring	1.15	0.63	1.05
Summer	2.38	0.92	1.7
Fall	1.51	1.03	0.51
Winter	9.79	7.94	6.00
Growing Season	1.39	0.68	0.93

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

Nash-Sutcliffe Model Efficiency

As was conducted on an annual basis, Nash-Sutcliffe model efficiency was calculated seasonally for the three wetland water budget models as well as for the extended growing season (Table 12).

Table 12. Seasonal Nash-Sutcliffe model efficiency coefficients for the Integrated Pierce models and MODFLOW-2005

*Season**	*Integrated Pierce (Thornthwaite)*	*Integrated Pierce (FAO-56 P-M)*	*MODFLOW-2005*
Spring	-0.96	0.39	-0.64
Summer	-2.41	-0.58	-3.34
Fall	-7.5	-0.27	0.61
Winter	-142.92	-93.67	-53
Growing Season	-1.22	0.48	0.01

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

Summary

Overall, the Integrated Pierce model incorporating FAO-56 Penman-Monteith PET performed the best seasonally, especially during the extended growing season (March-October) despite MODFLOW-2005 being a physically based, process-oriented model. Cedar Run 3 was designed and built as a Pierce method mitigation wetland, and thus it is not surprising that the IPM-FAO model was accurate for predicting water levels during the growing season. The design of Cedar Run 3 incorporates compacted subsoil, and the site was graded level. Thus, the physical site closely resembles the assumptions made by the IPM-FAO model, allowing for accurate modeling. Error metrics during the extended growing season for the IPM-FAO model are summarized in Table 13.

Based on these results, it can be expected that wetland water levels predicted by the IPM-FAO will fall within ±11.2 cm to ±13.6 cm of observed levels. This is a similar predictive range as compared to other models. Poiani and Johnson's (1993) calibrated simulation model for wetland hydrology and vegetation dynamics resulted in a similar error range. Their predictions fell within 10 cm of observed values 75% of the time. In another hydrological modeling study of a wetland in Saskatchewan, calibrated model water level predictions for 28 years of data resulted in a standard error of 19 cm (Su et al., 2000).

The ability to model water levels within the 11.2 cm to ±13.6 cm range should provide effective predictive data to design and construct a system that will maintain proper hydrology and vegetation. A study by Valk and others (1994) showed that increases in water depth within a wetland by 30 cm or more can transition emergent vegetation cover to submersed free-floating types by as much as 40%. The errors associated with the IPM-FAO model fall under this range.

Table 13. Summarized error metrics during the extended growing season for the IPM-FAO model

RE	*MAE*	*RMSE*	*RSR*	*NSE*
132%	11.2 cm	13.6 cm	0.68	0.48

Regression Analysis

In conjunction with analysis of the different error metrics in model predictions, linear regression analysis of predicted versus measured water levels was also conducted to evaluate the predictive power of the different models. If a model were to perform ideally, observed water levels and simulated water levels would exhibit an equal value relationship with a regression line having an intercept of zero and a slope of one (Hession et al., 1994). The coefficient of determination, or r^2, describes the ability of the regression to account for variations in the predicted water levels. However, it must be noted that the coefficient of determination does not describe how well the regression relationship matches the ideal equal value relationship (Haan, 1977; Hession et al., 1994). Regressions for each set of predicted water levels (one set per model), were evaluated as a function of observed water levels. Analysis of the linear regression residuals indicated they were heteroskedastic, so a nonparametric linear regression (Theil-Sen) analysis was conducted.

Theil-Sen Analysis

A Theil-Sen nonparametric linear regression analysis is similar to a parametric linear regression analysis, but does not make any assumptions about the population distribution of data. This method is median-based, thus it is not affected by outlying data points. The results of this analysis are shown in Table 14, and a plot of water levels (observed vs predicted) with the corresponding Theil-Sen regression line are shown in Figure 21. Results of the robust Theil-Sen analysis showed that MODFLOW-2005 had lowest overall error of all three models. MODFLOW-2005 had a non-significant regression intercept, indicating the intercept is not statistically different than zero. MODFLOW-2005 also had a statistically significant slope of 0.42. While this value is not the ideal one to one slope, it was a better overall result as compared to the Integrated Pierce models. While the Pierce model incorporating FAO-56 P-M evapotranspiration had a better 1:1 fit, it had a statistically significant intercept of -14.0. This is far from the ideal intercept of 0, indicating consistent under prediction by the model. The significant intercept of -14.0 indicates that, on average, IPM-FAO under-predicted water levels by 14.0 cm. This is similar to the RMSE value of 13.6 cm. The combination of lower intercept and near 1:1 fit (0.95) is indicative that model predictions may be corrected with a systematic adjustment.

As was noted in the study-site description (*Methods* section), additional weirs were added to Cedar Run 3 shortly after construction to solve the problem of excess water volume in the system. When the Theil-Sen regression for the original design model (IPM) is plotted against the one to one line of observed water levels (Figure 21), it can be seen that the IPM under predicts water levels when observed levels are above the soil surface. The intersection point (from over to under predicting) for the IPM model occurs where observed water levels are at 0 cm. Thus, there was no statistically significant relationship between predicted and observed water levels for the IPM, confirming the Nash-Sutcliffe model efficiency (-0.97) that the mean of the observed values is a better predictor than the IPM model.

Table 14. Summary of the Theil-Sen Analysis

	Intercept	*p-value*	*Slope*	*p-value*	*Relative Error*
Integrated Pierce (Thornthwaite's)	2.28	0.51	0.22	0.03	38.39
Integrated Pierce (FAO-56 P-M)	-13.99	0.0005	0.95	1.8e-06	12.48
MODFLOW-2005	-3.95	0.47	0.42	2.7e-05	10.37

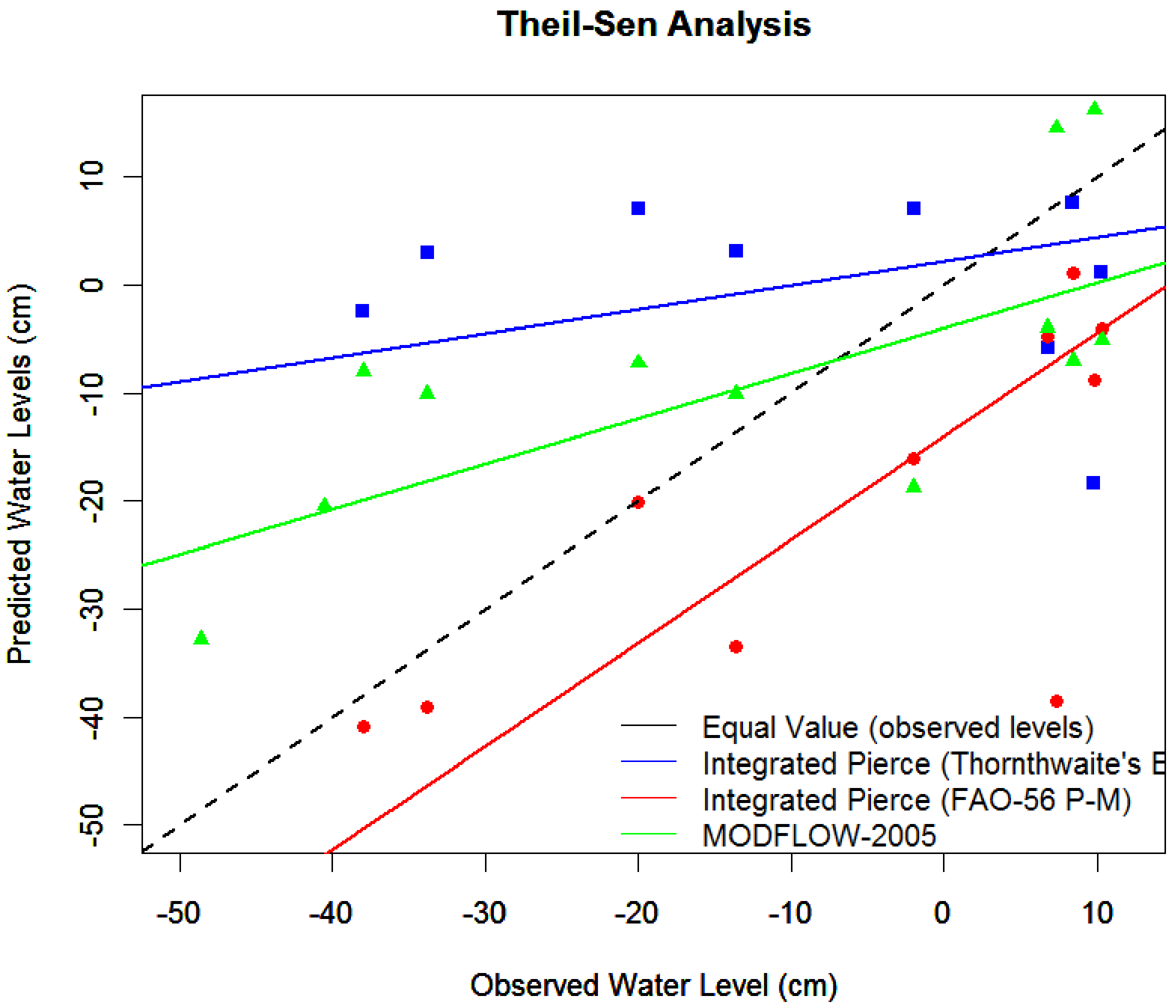

Figure 21. Theil-Sen regression lines of the Integrated Pierce and MODFLOW-2005 models as compared to the equal value line of observed water levels

Sensitivity Analysis

To determine the sensitivity of Modflow to changes in model inputs, a sensitivity analysis was conducted. The evapotranspiration rate (calculated external to Modflow) and the vegetative hydraulic conductivity in MODFLOW-2005 were changed by ±10%, ±25%, ±50%, and ±75% of the original model input in both wetland cells. Corresponding computed daily water levels were then compared against the water levels initially calculated by the model to determine the relative sensitivity and average water level change of each. The results of this analysis are shown in Table 16 and Table 17. At certain input levels, MODFLOW-2005 failed to converge upon a solution with the given wetting option parameters. To obtain sensitivity values for these changes, the wetting option parameters would have had to have been altered, resulting in inaccurate sensitivity comparisons.

As indicated in Table 16, the MODFLOW-2005 model was most sensitive to changes in evapotranspiration. Changes of 10% (within ET prediction errors) had the most exaggerated effect, with extreme changes showing less of an effect. There was an inverse relationship between ET and wetland water levels. Model response was less sensitive at more extreme ET amounts (±50%, ±75%). This damped response is due to the nature of water removal from the model. When water levels are above the ET extinction depth, but below the weir elevation, levels are controlled primarily by ET. Accordingly, as ET increases or decreases at extreme values, water level control transitions from being governed by ET to being either limited by the ET extinction depth, or controlled by outflow through the wetland weirs. Accordingly, the use of the evapotranspiration package's extinction depth interpolation functionality (*Methods* section) is evident during the winter months. When water levels fall below the soil surface, the evapotranspiration rate is linearly decreased from the full rate to zero at the extinction depth (-30 cm). Hence, as water levels in the wetland increase above the extinction depth, the full ET rate is utilized. The increased difference in water levels evident during the winter is caused by water levels moving from subsurface to above the soil as a result of the changed ET.

The model showed little sensitivity to variations in vegetative hydraulic conductivity (*k*). The negative values for relative sensitivity indicate an inverse correlation, implying that as hydraulic conductivity increases, water levels decrease. This is also reflected in the changes in percent water level shown in Table 17. On a monthly basis, at the extremes of *k* variance, water levels can change by ±15%, especially during the winter months when there is increased precipitation, and increased flow through the wetland. It should be noted that analyzing percent water level changes can be misleading, as this equates to very small changes in water level. As can be seen in Figure 23, high percentage increases in water levels equate to sub centimeter changes. Thus, while MODFLOW-2005 is not as sensitive to *k* values as ET, very large changes in vegetative hydraulic conductivity can influence water levels slightly. This is similar to findings in Piercy (2010).

To better understand this range of *k* parameters and how they relate directly to vegetation on the ground, stem densities were back calculated for the extreme range of *k* values. As *k* varies across the wetland, an area of wetland with higher conductivity (lower vegetation density) and an area of lower conductivity (higher vegetation density) were investigated. Each of the areas had a baseline stem density of approximately 700 stems per square meter and 2400 stems per square meter, respectively. The results of changing *k* are shown in Table 15. In a flume study conducted by Piercy (2010), stem densities of up to 9365 stems per meter square were considered to be very dense. Accordingly, it can be seen that the extreme stem densities determined by varying *k* may be unrealistic (up to 111,000 stems per meter square). Thus, it can be determined that slight errors in *k* will have little effect on water level predictions.

Table 15. Approximate stem density variations as a result of changing hydraulic conductivity

Percent Change in conductivity (k)	*700 stem/m^2*	*2400 stem/m^2*
-75%	200	1800
-50%	300	950
50%	3000	9800
75%	13800	111000

Table 16. Average daily sensitivity of MODFLOW-2005 to evapotranspiration and vegetative hydraulic conductivity (*k*)

Percent Change in Parameter	*ET*	*k*
-75%	1.26	NC*
-50%	1.52	-0.001
-25%	2.32	NC*
-10%	5.18	-0.020
10%	-5.24	-0.017
25%	-2.07	-0.015
50%	-0.93	-0.034
75%	-0.61	NC*

*Indicates model non-convergence

Table 17. Average daily percent water level changes from sensitivity analysis

Percent Change in Parameter	*ET(%)*	*k (%)*
-75%	121.0	NC*
-50%	67.8	1.76
-25%	26.4	NC*
-10%	10.5	0.06
10%	-7.92	-0.05
25%	-20.2	-0.14
50%	-35.7	-1.28
75%	-47.9	NC*

*Indicates model non-convergence

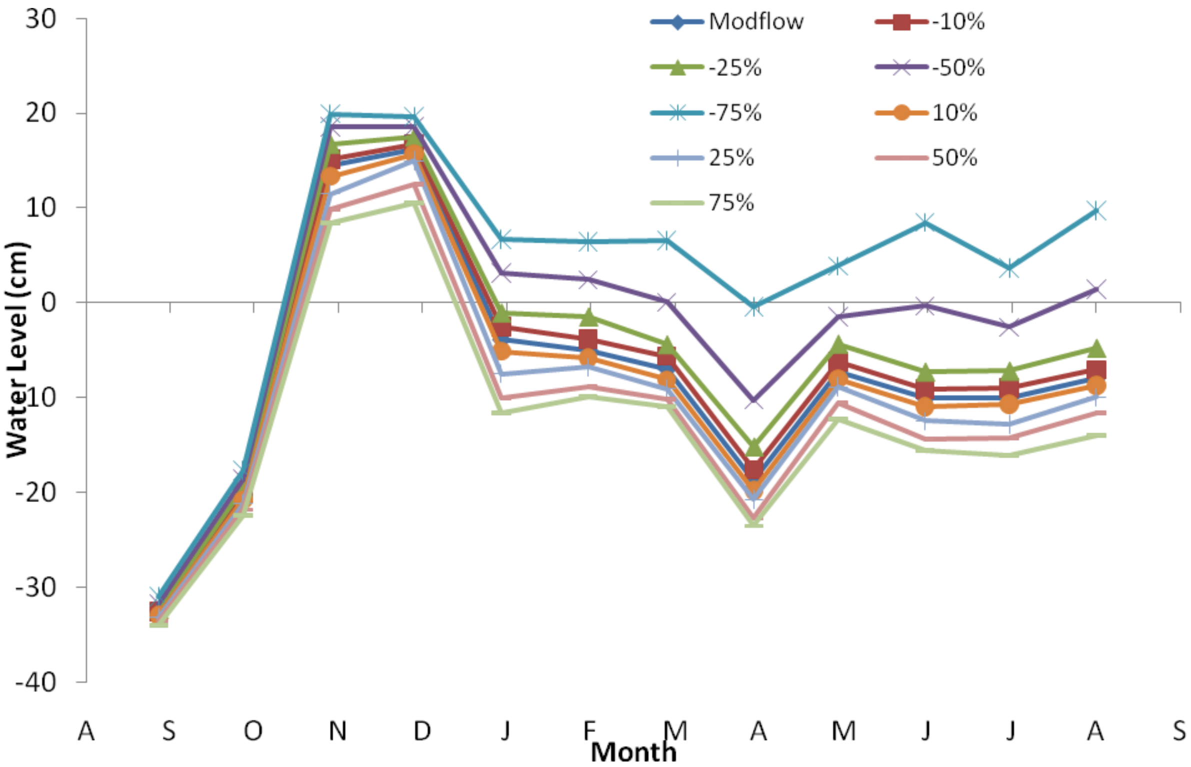

Figure 22. Water level changes from sensitivity analysis of evapotranspiration

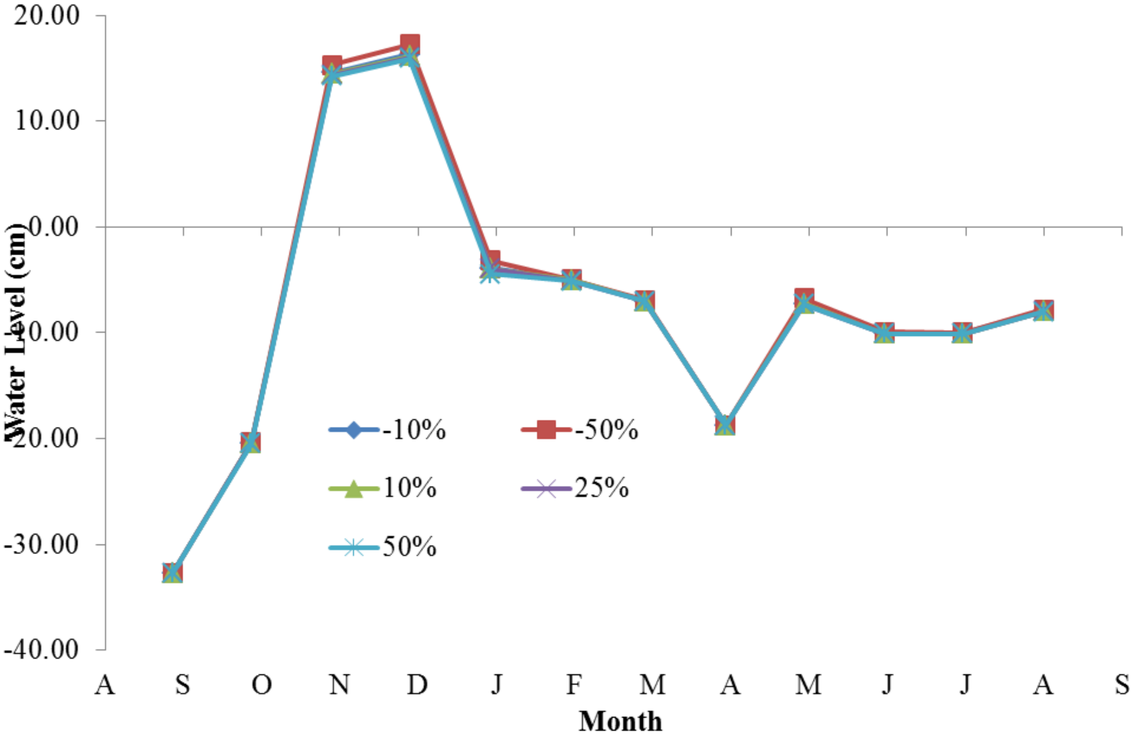

Figure 23. Water level changes from sensitivity analysis of vegetative hydraulic conductivity

Conclusions

The goal of this research was to determine the accuracy of water level predictions by a Pierce water balance method model and a process-based Modflow model. The IPM model on average had an error of 28.0 cm (average of RE, MAE) and exhibited consistent under-prediction of water-levels. The IPM had a Nash-Sutcliffe efficiency of -0.97, indicating the mean of the data is a better predictor of wetland water levels than the model. The IPM-FAO model under-estimated wetland water levels with an average (of RE and MAE) error of 16.9 cm, with a Nash-Sutcliffe efficiency of 0.21. MODFLOW-2005 generally over-predicted water levels with the lowest average (of RE and MAE) error of 15.6 cm. Modflow also had the highest Nash-Sutcliffe efficiency at 0.42, indicating this model was a better predictor on an annual basis than the two IPM models.

Comparing the two Integrated Pierce Method models, it was apparent that small changes to the original design model resulted in significantly improved water level predictions. Incorporating soil porosity resulted in a more realistic model. Additionally, it was readily apparent in all three models that evapotranspiration is the primary controlling factor for hydrology at the Cedar Run 3 mitigation wetland. Changing the ET sub model in the Integrated Pierce method models resulted in large differences in predicted wetland water levels. Studies by Owen (1995), and Drexler and others (2004) also indicated ET was an important process in wetlands.

While having an error range of up to 16 cm, MODFLOW-2005 provided a physically oriented, process-based model of Cedar Run 3, allowing for the ability to model flow through the system and incorporate physical parameters not accounted for in the Integrated Pierce models, such as vegetative resistance to flow. Even being uncalibrated, Modflow showed errors similar to calibrated models (Poiani and Johnson, 1993; Su et al., 2000). Thus, for modeling a mitigation wetland before construction, on a yearly hydroperiod basis, MODFLOW-2005 is the best model to utilize.

In a mitigation wetland, it is critical that a system have adequate water levels during a significant portion of the growing season (14-21 days), as outlined by the U.S. Army Corps of Engineers (USACE, 1987). Accordingly, it is most critical for a wetland water budget model to accurately predict water levels during this time period. Seasonally, MODFLOW-2005 and the IPM-FAO models had similar summertime absolute relative errors of 58% and 57%, respectively, with MODFLOW-2005 over predicting water levels, and the IPM-FAO model under predicting.

Overall, during the growing season, the IPM-FAO model had the best predictive power. Accordingly, the IPM-FAO model was best suited for modeling the Cedar Run 3 mitigation wetland during the growing season to ensure water levels meet regulatory requirements and support vegetative success. The construction design of Cedar Run 3 meets the assumptions of the Pierce method, thus it is not surprising that this model accurately predicted water levels in this wetland during the growing season. The constructed Cedar Run 3 site was graded flat, and the subsoils were compacted. Accordingly, the onsite conditions closely resemble the assumptions made by the IPM-FAO model. However, in a site where the wetland hydrology is strongly influenced by groundwater, the IPM-FAO may not be the better predictor. The ability of Modflow to model flows (head gradients, seepage etc.) may provide better water level estimations for these sites. Additional testing of the two wetland models in a groundwater-dominated wetland is needed.

To determine how changes in hydraulic conductivity (*k*) and evapotranspiration affected MODFLOW-2005, a sensitivity analysis was conducted. Modflow was generally not sensitive to changes in hydraulic conductivity (*k*); however, at the extremes of changes in *k* (75%), water levels could vary by ±15%. This finding is similar to that of Piercy (2010) and Jorge et al. (2001).

In contrast, the model was sensitive to change in evapotranspiration of ±10%. Considering ET represents a direct water loss from the wetland during the growing season, it is reasonable that ET plays a vital role in determining water levels in the Modflow model. As such, the ET estimation method needs to be carefully chosen and calculated with the most accurate and site-specific data available.

Study Implications

Ultimately, designing and modeling mitigation wetlands in MODFLOW-2005 has advantages over the monthly IPM-FAO model. The ability to model a system at a daily time step will allow for assessment of individual precipitation events and for the assessment of varying design changes to a system, such as varying outlet height, constructed topography, and varying soil types. The results of this research will inform and guide future wetland water budget modeling efforts and techniques, especially related to wetland mitigation. Improved pre-construction modeling will potentially increase mitigation success rates and progress the overall development of mitigation wetland systems.

Recommendations for Future Work

While this work lays a foundation for further investigation of modeling of mitigation wetland designs using MODFLOW-2005, additional work is necessary to streamline and improve model development prior to implementation by design practitioners. Evapotranspiration was a major hydrologic component influencing water levels within Cedar Run 3. Accordingly, improved methods for estimating evapotranspiration should be developed, including developing wetland crop-coefficients for the Virginia Piedmont. The quantification of crop-coefficients for specific wetland types, as well as for individual wetland plant species at different growth stages would increase modeling accuracy. Additionally, improved and more streamlined methods for determining vegetative resistance to flow should be researched for more densely vegetated wetlands. In addition, species-specific values should be quantified for different stages of growth and wetland development.

One hydrologic component that was not accounted for in the MODFLOW-2005 representation of Cedar Run 3 was groundwater additions/losses (assumed to be negligible based on local geology and the wetland design). Cedar Run 3 was designed to limit these effects and separate investigations have verified the assumption of no groundwater influence. Ultimately though, quantifying groundwater influences could lead to better prediction models and increased mitigation successes. The next step beyond understanding these influences at a site designed with the Pierce methodology, would be to model, design, and construct mitigation sites that utilize the local groundwater hydrology. Moving away from creating "perched" mitigation sites would allow better functional replacement of impacted or destroyed wetlands. While more difficult to accomplish, proper pre-construction investigation of hydrologic conditions could be used to inform the modeling needed to design a functional wetland site. Having the ability to accurately quantify groundwater fluxes, incorporate them into a model, and successfully construct a site is only the first step. The method would need to be accurate enough to minimize failure rates while being streamlined into a timely process to be economically feasible for mitigation consultants to design such sites. While this ideal model may be further down the pipeline than the current understanding and abilities to construct mitigation sites, through sound science and research it should one day be feasible.

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Appendix A. Model Documentation

Model Inputs

Precipitation

Table 18. Precipitation data (meters) for 2009, courtesy WSSI

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
1	0.000	0.000	0.006	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.026	0.000
2	0.000	0.001	0.005	0.004	0.002	0.012	0.000	0.000	0.000	0.000	0.000	0.012
3	0.000	0.002	0.002	0.010	0.028	0.037	0.000	0.000	0.000	0.000	0.000	0.002
4	0.000	0.000	0.000	0.000	0.016	0.009	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.006	0.023	0.000	0.000	0.000	0.000	0.000	0.008
6	0.017	0.000	0.000	0.003	0.059	0.000	0.000	0.000	0.000	0.000	0.000	0.015
7	0.025	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012
9	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.031
10	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.002	0.003	0.000	0.014	0.007	0.001	0.000	0.000	0.000	0.000	0.032	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.000
13	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.017
14	0.000	0.000	0.006	0.008	0.009	0.000	0.000	0.000	0.000	0.000	0.001	0.000
15	0.000	0.000	0.004	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.004	0.000	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.001	0.000	0.002	0.014	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.004	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000
20	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011
21	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.001	0.000	0.000	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	0.000	0.000	0.000	0.000	0.001	0.017	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.003	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.018
26	0.000	0.000	0.010	0.000	0.015	0.000	0.000	0.000	0.000	0.000	0.002	0.011
27	0.004	0.002	0.009	0.000	0.001	0.000	0.000	0.000	0.000	0.040	0.001	0.000
28	0.012	0.000	0.011	0.000	0.007	0.000	0.000	0.000	0.000	0.014	0.000	0.000
29	0.002	-	0.002	0.014	0.004	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	0.000	0.000	0.000	0.007	0.000
31	0.000	-	0.000	-	0.015	-	0.000	0.000	-	0.008	-	0.009
Total	0.066	0.012	0.061	0.098	0.203	0.099	0.000	0.000	0.000	0.071	0.129	0.146

Table 19. Precipitation data (meters) for 2010, courtesy WSSI

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug
1	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.001
2	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.007
3	0.000	0.011	0.001	0.000	0.003	0.035	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006
5	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.023
6	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000
7	0.000	0.017	0.000	0.000	0.000	0.000	0.000	0.000
8	0.001	0.000	0.000	0.016	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.001	0.000	0.002	0.000	0.000
10	0.000	0.005	0.000	0.000	0.000	0.002	0.017	0.000
11	0.000	0.004	0.002	0.000	0.004	0.000	0.000	0.000
12	0.000	0.000	0.013	0.000	0.001	0.010	0.010	0.039
13	0.000	0.000	0.024	0.003	0.000	0.004	0.074	0.001
14	0.000	0.000	0.015	0.000	0.000	0.001	0.001	0.000
15	0.000	0.002	0.001	0.000	0.000	0.001	0.000	0.006
16	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.000
17	0.013	0.000	0.000	0.000	0.028	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.019
19	0.000	0.000	0.000	0.000	0.001	0.000	0.004	0.000
20	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.000
21	0.008	0.000	0.000	0.006	0.000	0.000	0.000	0.000
22	0.010	0.004	0.009	0.000	0.021	0.015	0.000	0.001
23	0.000	0.000	0.001	0.000	0.029	0.000	0.000	0.000
24	0.003	0.000	0.000	0.006	0.000	0.000	0.000	0.000
25	0.012	0.000	0.000	0.002	0.000	0.000	0.008	0.000
26	0.000	0.000	0.009	0.021	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000
28	0.000	0.000	0.025	0.000	0.001	0.004	0.000	0.000
29	0.000	-	0.006	0.000	0.000	0.000	0.019	0.000
30	0.000	-	0.003	0.000	0.000	0.000	0.000	0.000
31	0.006	-	0.000	-	0.000	-	0.003	0.000
Total	0.053	0.044	0.110	0.054	0.099	0.094	0.136	0.102

Evapotranspiration

Table 20. Computed evapotranspiration values (meters) using Thornthwaite's method

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Thornthwaite's Method	0.000	0.007	0.020	0.056	0.096	0.128	0.136	0.138	0.086	0.045	0.025	0.001
FAO 56 P-M	0.034	0.038	0.080	0.125	0.110	0.142	0.156	0.106	0.113	0.076	0.050	0.043

Runoff

Table 21. Estimated runoff volume (cubic meters) for 2009 entering the north cell from the upslope landscape

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3151.60	0.00
2	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	1.56
3	0.00	0.00	0.00	0.00	4396.36	8838.21	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	360.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	2260.49	0.00	0.00	0.00	0.00	0.00	0.00
6	446.62	0.00	0.00	0.00	25599.83	0.00	0.00	0.00	0.00	0.00	0.00	184.18
7	2740.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5662.12
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	105.38	0.00	0.00	0.00	0.00	0.00	0.00	6064.84	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	933.99	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	446.62
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	811.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	64.62	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	4639.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	540.86	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	697.52
26	0.00	0.00	0.00	0.00	215.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11270.48	0.00	0.00
28	1.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	129.32	0.00	0.00
29	0.00	-	0.00	105.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.00	-	0.00	-	184.18	-	0.00	0.00	-	0.00	-	0.00
Total	3188.84	0.00	0.00	4850.48	31568.07	11163.34	0.00	0.00	0.00	11399.80	10691.30	6992.01

Table 22. Estimated runoff volume (cubic meters) for 2010 entering the north cell from the upslope landscape

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	7625.61	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1991.04	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	402.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	360.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	402.64	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	33.57	0.00	0.00	0.00	0.00	10437.94	0.00	0.00	0.00	0.00
13	0.00	0.00	2353.46	0.00	0.00	0.00	38944.24	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	155.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	47.87	0.00	0.00	0.00	4396.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	871.98	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	1419.72	215.04	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	4517.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	5.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	1574.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	3046.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.00	-	0.00	0.00	0.00	0.00	811.89	0.00	0.00	0.00	0.00	0.00
30	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.00	-	0.00	-	0.00	-	0.00	0.00	-	0.00	-	0.00
Total	53.59	402.64	5589.32	1935.28	10333.50	7840.66	40158.76	13300.97	0.00	0.00	0.00	0.00

Monthly Averaged Modflow Results

Table 23. Averaged monthly MODFLOW-2005 results

	MODFLOW-2005 Results	
	2009	*2010*
Jan	-1.72	-3.90
Feb	-23.34	-5.02
Mar	-8.53	-7.01
Apr	-7.30	-18.74
May	11.92	-7.23
Jun	-2.13	-10.09
Jul	-31.30	-10.05
Aug	-32.30	-7.95
Sep	-32.78	-32.38
Oct	-20.43	-21.95
Nov	14.53	5.50
Dec	16.23	3.90

Daily Modflow Results

Table 24. Daily Modflow predicted water levels for 2009

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
1	18.50	-14.19	5.02	-2.89	1.57	6.36	-30.87	-32.03	-32.64	-32.89	36.79	4.77
2	13.21	-18.71	7.93	4.68	1.55	16.29	-29.62	-32.03	-32.65	-32.89	30.39	17.12
3	8.39	-8.69	5.99	15.62	27.06	35.30	-30.04	-32.03	-32.65	-32.90	25.33	14.79
4	3.72	-16.60	2.56	-11.74	31.10	34.97	-30.25	-32.04	-32.66	-32.91	17.31	9.47
5	2.14	-20.61	-3.45	-23.32	29.58	43.32	-30.47	-32.07	-32.66	-32.92	12.47	15.29
6	17.83	-22.33	-14.82	-19.87	60.79	35.99	-30.56	-32.10	-32.69	-32.93	5.89	23.19
7	31.37	-24.75	-21.78	-25.80	57.59	29.74	-30.69	-32.10	-32.72	-32.94	1.88	18.66
8	25.20	-27.60	-26.14	-27.47	47.81	23.03	-30.82	-32.11	-32.72	-32.94	-6.17	24.71
9	19.24	-28.78	-28.61	-28.57	39.14	17.48	-30.95	-32.11	-32.75	-32.96	-9.38	39.17
10	18.77	-29.28	-29.52	-29.21	28.00	12.85	-31.04	-32.14	-32.75	-32.97	-13.55	31.68
11	16.49	-19.69	-29.72	7.49	24.28	8.55	-31.10	-32.18	-32.77	-32.99	27.76	25.98
12	12.50	-25.17	-30.07	-12.46	19.52	4.94	-31.14	-32.22	-32.79	-33.01	33.36	19.00
13	8.19	-27.99	-25.07	-15.59	13.45	-4.34	-31.19	-32.26	-32.79	-33.02	32.53	27.37
14	3.26	-28.89	6.58	7.19	15.99	-14.97	-31.28	-32.29	-32.79	-33.03	28.06	22.56
15	-6.86	-29.20	7.67	17.37	12.16	-21.29	-31.37	-32.30	-32.80	-33.03	23.74	18.31
16	-13.40	-29.56	9.95	11.89	24.79	-22.76	-31.45	-32.30	-32.80	-33.03	18.57	13.41
17	-15.59	-29.66	8.32	3.27	20.73	9.21	-31.54	-32.31	-32.80	-33.03	13.94	8.25
18	-18.83	-14.75	5.90	-15.13	5.35	8.08	-31.61	-32.34	-32.82	-33.03	8.11	4.62
19	-21.46	-13.06	-9.10	-21.97	-8.67	2.83	-31.67	-32.37	-32.83	-33.04	17.46	3.66
20	-23.84	-20.75	-11.57	23.13	-18.85	-5.46	-31.72	-32.41	-32.83	-33.04	12.01	16.86
21	-25.05	-24.10	-17.12	19.11	-24.77	-19.75	-31.76	-32.42	-32.83	-33.04	7.94	11.39
22	-26.52	-23.27	-22.28	15.40	-27.34	-25.61	-31.79	-32.42	-32.83	-33.04	4.79	7.58
23	-27.52	-26.24	-26.57	6.96	-28.57	-28.23	-31.82	-32.43	-32.83	-28.17	19.54	5.36
24	-28.64	-27.46	-28.24	-13.92	-29.24	-28.96	-31.85	-32.46	-32.83	1.32	18.17	3.69
25	-29.13	-28.39	-28.79	-22.24	-29.45	-29.71	-31.87	-32.49	-32.84	-8.76	17.16	19.79
26	-29.28	-29.00	5.48	-27.90	11.81	-29.98	-31.90	-32.51	-32.84	-14.29	15.55	25.21
27	-8.99	-21.53	15.30	-29.38	9.25	-30.13	-31.93	-32.54	-32.84	30.58	13.38	20.60
28	13.30	-23.18	19.59	-29.84	14.65	-30.36	-31.96	-32.55	-32.85	34.48	8.39	15.45
29	9.70	-	17.13	4.06	14.45	-30.52	-31.99	-32.57	-32.87	28.45	4.16	10.72
30	6.29	-	-11.57	2.24	7.84	-30.73	-32.02	-32.59	-32.87	23.82	10.19	7.74
31	-6.39	-	-17.30	-	17.84	-	-32.02	-32.61	-	24.92	-	16.74
Mean	**-1.72**	**-23.34**	**-8.53**	**-7.30**	**11.92**	**-2.13**	**-31.30**	**-32.30**	**-32.78**	**-20.43**	**14.53**	**16.23**

Table 25. Daily Modflow predicted water levels for 2010

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
1	12.20	-3.64	-27.26	-18.05	-28.09	-0.69	-29.11	-18.92	-30.48	-33.34	29.80	2.99
2	7.21	-9.13	-17.88	-25.41	-29.11	-9.27	-29.97	2.68	-30.81	-33.37	23.49	13.84
3	3.43	12.30	-14.81	-27.51	-21.52	26.25	-30.24	-8.85	-31.00	-33.39	18.07	10.84
4	-3.10	8.02	-18.91	-29.09	-23.60	21.06	-30.48	2.78	-31.32	-33.40	14.39	7.37
5	-8.38	9.23	-23.29	-29.82	-27.35	14.52	-30.75	20.40	-31.51	-33.40	11.16	14.07
6	-13.60	6.97	-25.86	-30.24	-28.95	13.61	-30.98	14.34	-31.62	-33.42	5.35	21.78
7	-17.17	20.62	-27.53	-30.76	-29.86	-14.48	-31.24	-14.83	-31.73	-33.44	-7.10	16.01
8	-14.74	16.57	-28.86	-1.95	-30.23	-22.18	-31.49	-22.35	-31.84	-33.48	-11.87	21.76
9	-18.06	13.20	-29.49	-4.98	-30.72	-20.60	-31.61	-26.31	-32.03	-33.52	-19.23	35.21
10	-20.50	14.55	-29.94	-17.84	-30.89	-16.27	11.57	-28.32	-32.11	-33.55	-23.02	27.57
11	-21.97	13.46	-22.25	-24.44	-15.54	-25.11	4.27	-29.41	-32.19	-33.60	23.53	20.48
12	-23.93	7.64	12.09	-27.69	-14.99	4.71	10.82	27.20	-32.23	-33.66	28.75	15.14
13	-24.78	3.78	26.48	-19.90	-17.53	6.17	56.17	22.09	-32.25	-33.74	26.05	23.44
14	-25.81	-6.10	31.19	-21.59	-19.31	-11.72	46.41	15.35	-32.35	-33.76	19.14	16.63
15	-27.04	-3.63	26.15	-24.05	-25.13	-16.65	36.42	15.50	-32.51	-33.79	13.50	8.14
16	-27.70	-7.81	20.23	-26.85	-27.21	2.52	28.09	9.58	-32.56	-33.83	10.47	-7.74
17	10.87	-12.93	12.92	-28.92	21.78	-4.06	17.06	4.21	-32.68	-33.86	6.50	-15.55
18	7.38	-17.20	-10.01	-29.51	17.98	-19.60	6.08	19.56	-32.76	-33.86	-7.19	-19.30
19	4.14	-21.33	-21.31	-29.85	14.08	-23.62	-6.20	14.50	-32.80	-33.86	7.67	-23.59
20	2.48	-24.62	-26.41	-30.20	10.25	-26.53	-18.42	8.56	-32.85	-33.87	3.22	5.38
21	11.61	-26.66	-28.54	-9.85	-11.73	-28.31	-21.63	-10.12	-32.95	-33.87	-5.51	-8.66
22	17.00	-12.43	0.48	-12.02	15.19	8.40	-26.54	-17.86	-32.99	-33.91	-8.71	-17.07
23	12.78	-13.36	-11.49	-21.44	31.42	3.55	-28.59	-22.66	-33.02	-28.64	15.78	-22.36
24	12.64	-16.80	-18.62	-5.04	26.10	-15.79	-29.88	-24.45	-33.08	-4.27	6.03	-24.78
25	20.55	-18.86	-23.71	-2.36	20.41	-23.68	-16.96	-26.00	-33.19	-12.92	4.88	13.89
26	13.71	-22.15	4.13	19.69	14.51	-27.29	-25.19	-26.79	-33.28	-16.24	6.22	17.13
27	7.05	-24.30	-11.12	7.80	17.25	-28.60	-27.71	-28.31	-33.29	30.03	-4.83	9.01
28	1.32	-25.95	22.40	-13.90	11.30	-16.05	-28.64	-28.78	-33.30	33.47	-11.95	-7.48
29	-9.49	-	22.33	-21.00	6.95	-24.81	10.20	-29.31	-33.32	23.78	-15.02	-16.36
30	-12.99	-	18.06	-25.33	-5.46	-28.27	-16.96	-29.64	-33.32	16.35	5.46	-20.99
31	4.03	-	3.66	-	-14.28	-	-16.19	-30.16	-	17.77	-	4.24
Mean	**-3.90**	**-5.02**	**-7.01**	**-18.74**	**-7.23**	**-10.09**	**-10.05**	**-7.95**	**-32.38**	**-21.95**	**5.50**	**3.90**

Appendix B. Statistical Scripts for R

Mean Absolute Error

```
# mean absolute error

setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)

mae<-function(obs,model) {
        diff<-abs(model-obs)
        n<-length(model)
        mae<-(sum(diff))*(1/n)
        return(mae)
        }

mae.por<-mae(observed.level,pierce.porosity)
mae.pen<-mae(observed.level,pierce.penman)
mae.mod<-mae(observed.level,modflow)
```

Relative Error

```
# relative error

setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)

RE<-function(obs,model) {
        RE<-(abs(((model-obs)/obs)))*100
        return(RE)
        }
RE(observed.level,pierce.porosity)
RE(observed.level,pierce.penman)
RE(observed.level,modflow)

mean(abs(RE(observed.level,pierce.porosity)))
mean(abs(RE(observed.level,pierce.penman)))
mean(abs(RE(observed.level,modflow)))

# seasonal RE
```

```
spr.porosity<-pierce.porosity[7:9]
fal.porosity<-pierce.porosity[1:3]
sum.porosity<-pierce.porosity[10:12]
win.porosity<-pierce.porosity[4:6]

spr.penman<-pierce.penman[7:9]
fal.penman<-pierce.penman[1:3]
sum.penman<-pierce.penman[10:12]
win.penman<-pierce.penman[4:6]

spr.obs<-observed.level[7:9]
fal.obs<-observed.level[1:3]
sum.obs<-observed.level[10:12]
win.obs<-observed.level[4:6]

spr.mod<-modflow[7:9]
fal.mod<-modflow[1:3]
sum.mod<-modflow[10:12]
win.mod<-modflow[4:6]

#SEASONAL PIERCE.POROSITY
mean(RE(spr.obs,spr.porosity))
mean(RE(fal.obs,fal.porosity))
mean(RE(sum.obs,sum.porosity))
mean(RE(win.obs,win.porosity))

# SEASONAL PIERCE.PENMAN
mean(RE(spr.obs,spr.penman))
mean(RE(fal.obs,fal.penman))
mean(RE(sum.obs,sum.penman))
mean(RE(win.obs,win.penman))

# SEASONAL MODFLOW
mean(RE(spr.obs,spr.mod))
mean(RE(fal.obs,fal.mod))
mean(RE(sum.obs,sum.mod))
mean(RE(win.obs,win.mod))
```

Nash Sutcliffe Model Efficiency

```
setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)
```

```
nash.sut<-function(obs,model) {
	num<-sum((obs-model)^2)
	denom<-sum((obs-mean(obs))^2)
	E<-1-(num/denom)
	return(E)
	}

#seasonal Nash.sut

spr.pierce<-pierce.level[7:9]
fal.pierce<-pierce.level[1:3]
sum.pierce<-pierce.level[10:12]
win.pierce<-pierce.level[4:6]

spr.porosity<-pierce.porosity[7:9]
fal.porosity<-pierce.porosity[1:3]
sum.porosity<-pierce.porosity[10:12]
win.porosity<-pierce.porosity[4:6]

spr.penman<-pierce.penman[7:9]
fal.penman<-pierce.penman[1:3]
sum.penman<-pierce.penman[10:12]
win.penman<-pierce.penman[4:6]

spr.obs<-observed.level[7:9]
fal.obs<-observed.level[1:3]
sum.obs<-observed.level[10:12]
win.obs<-observed.level[4:6]

spr.mod<-modflow[7:9]
fal.mod<-modflow[1:3]
sum.mod<-modflow[10:12]
win.mod<-modflow[4:6]

#Pierce.level
nash.sut(spr.obs,spr.pierce)
nash.sut(fal.obs,fal.pierce)
nash.sut(sum.obs,sum.pierce)
nash.sut(win.obs,win.pierce)

#Pierce.porosity

nash.sut(spr.obs,spr.porosity)
nash.sut(fal.obs,fal.porosity)
nash.sut(sum.obs,sum.porosity)
```

```
nash.sut(win.obs,win.porosity)

#Pierce.penman

nash.sut(spr.obs,spr.penman)
nash.sut(fal.obs,fal.penman)
nash.sut(sum.obs,sum.penman)
nash.sut(win.obs,win.penman)

#Modflow

nash.sut(spr.obs,spr.mod)
nash.sut(fal.obs,fal.mod)
nash.sut(sum.obs,sum.mod)
nash.sut(win.obs,win.mod)
```

Root Mean Square Error

```
setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)

#Porosity
z<-pierce.porosity-observed.level
a<-z^2
sqrt(sum(a)/length(pierce.porosity))

#Penman
z<-pierce.penman-observed.level
a<-z^2
sqrt(sum(a)/length(pierce.penman))

#Modflow
z<-modflow-observed.level
a<-z^2
sqrt(sum(a)/length(modflow))
```

RMSE-Observations Standard Deviation Ratio

```
# RSR - rmse-observations standard deviation ratio (moriasi 2007)

setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)
```

```
RSR<-function(obs,model) {
z<-model-obs
a<-z^2
rmse<-sqrt(sum(a)/length(obs))
sdev<-sd(obs)
RSR<-rmse/sdev
return (RSR)
}

RSR(observed.level,pierce.level)
RSR(observed.level,pierce.porosity)
RSR(observed.level,pierce.penman)
RSR(observed.level,modflow)
```

Mean Absolute Error

```
# mean absolute error

setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)

mae<-function(obs,model) {
        diff<-abs(model-obs)
        n<-length(model)
        mae<-(sum(diff))*(1/n)
        return(mae)
        }

mae.por<-mae(observed.level,pierce.porosity)
mae.pen<-mae(observed.level,pierce.penman)
mae.mod<-mae(observed.level,modflow)
```

Theil-Sen Regression

```
# theil-sen plots

setwd("z:/dropbox/matthew gloe/project models/Data")

x<-read.csv("pierce_results.csv")
attach(x)
```

```
library(mblm)

a<-pierce.level
b<-pierce.porosity
c<-pierce.penman
d<-observed.level
e<-modflow

fit.por<-mblm(b~d, repeated=FALSE)
fit.pen<-mblm(c~d, repeated=FALSE)
fit.mod<-mblm(e~d, repeated=FALSE)

fit<-lm(pierce.penman~observed.level)
fit2<-lm(pierce.porosity~observed.level)
fit4<-lm(modflow~observed.level)


plot(observed.level,pierce.porosity,pch=15, xlim=c(-50,12), ylim=c(-50,15), col="blue",
xlab="Observed Water Level (cm)", ylab = "Predicted Water Levels (cm)", main="Theil-Sen
Analysis")
par(new=T)
plot(observed.level,pierce.penman,pch=16, xlim=c(-50,12), ylim=c(-
50,15),col="red",xlab="Observed Water Level (cm)", ylab = "Predicted Water Levels (cm)",
main="Theil-Sen Analysis")
par(new=T)
plot(observed.level,modflow, pch=17, xlim=c(-50,12), ylim=c(-
50,15),col="green",xlab="Observed Water Level (cm)", ylab = "Predicted Water Levels (cm)",
main="Theil-Sen Analysis")



abline(0,1, lwd=2, lty="dashed")
abline(fit.por, lwd=2,col="blue")
abline(fit.pen, lwd=2, col="red")
abline(fit.mod, lwd=2, col="green")
legend(locator(1), c( "Equal Value (observed levels)", "Integrated Pierce (Thornthwaite's ET)",
"Integrated Pierce (FAO-56 P-M)", "MODFLOW-2005"), bty="n", col=c("black", "blue", "red",
"green"), lty=c(1,1,1,1))
```