ABSTRACT

PHILLIPS, BRIAN DAVID. Methods to Predict the Lateral Effect of a Drainage Ditch on Adjacent Wetland Hydrology. (Under the direction of Dr. R. Wayne Skaggs).

Four methods were studied to predict the lateral effect of a drainage ditch on wetland hydrology – a field method based on threshold drainage conditions, long-term simulations in both DRAINMOD and WATRCOM, and the approximate method (also known as the Skaggs Method). As defined in this study, the lateral effect is the width of a strip of land drained such that it no longer meets the wetland hydrologic criterion as set forth in the U.S. Army Corps of Engineers Wetland Delineation Manual.

Three years (2002 – 2004) of data were collected at field sites located at the Mildred Woods mitigation site in Edgecombe County, North Carolina and the ABC mitigation site located in Beaufort County, North Carolina. Hourly water table depths were recorded at several locations on transects perpendicular to one drainage ditch (1.2 m depth) at Mildred Woods and a shallow ditch (0.9 m depth) and deep ditch (1.3 m depth) at the ABC site. Rainfall was recorded at each site and temperature data were collected from nearby weather stations.

DRAINMOD simulations were performed for a 54-year period for each ditch to determine the threshold drain spacing, i.e. a spacing associated with water table fluctuations that would just barley satisfy the wetland hydrologic criterion in one half of the years. Next DRAINMOD was used with the threshold ditch spacing and depth along with recorded rainfall data for 2002-2004 to predict the maximum consecutive duration that the water table would be above the 30 cm depth for those specific years. Based on the measured durations

for each year the estimated lateral effect was 41 m for Mildred Woods, <3.75 m for the ABC shallow ditch, and 12 m for the ABC deep ditch.

DRAINMOD and WATRCOM were calibrated for each study transect by comparing model predicted water table depths and observed water table depths. The calibrated models were then used to simulate water table depths at each observation well for a 54-year period, and the results were analyzed to determine the distance from the ditch where the criterion was satisfied in exactly one-half of the years. Based on these simulation results the lateral effect was estimated to be 38.6 m for Mildred Woods, <3.75 m for the ABC shallow ditch, and 18.0 m for the ABC deep ditch. Simulation results with WATRCOM estimated a lateral effect of 41.5 m for Mildred Woods, and 8.9 m and 20.3 m ABC shallow and deep ditches, respectively.

Results of the approximate method estimated the lateral effect to be 42.6 m for the ditch at the Mildred Woods site. This was close to the values obtained from the observed data and the two simulation models. A lateral effect of 14.1 m was estimated for the ABC deep ditch using the approximate method. This value is slightly larger than obtained from the field data, 12 m, 3.9 m less than the value predicted by DRAINMOD, and 6.2 m less than the value predicted by WATRCOM. The approximate method estimated a lateral effect of the ABC site shallow ditch of 7.2 m, 1.7 m less than that predicted by WATRCOM, which is two times greater than results from the field method and predicted by DRAINMOD. The ABC site shallow ditch resides in a tight clay layer that apparently cut off most of the drainage from the lower, higher conductivity layer. Additional research is needed to determine how the method should be modified for shallow ditches confined in a low conductivity layer.

METHODS TO PREDICT THE LATERAL EFFECT OF A DRAINAGE DITCH ON ADJACENT WETLAND HYDROLOGY

By

BRIAN DAVID PHILLIPS

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Minor Representative

DEDICATION

To Mom and Dad

Without their love and support during my long academic journey, in no way would I have accomplished so much or developed in to the person I am today.

Thank you, and know that I love you both deeply.

BIOGRAPHY

Brian D. Phillips was born March 16, 1974 to David and Barbara Phillips. Both parents grew up in the town of Concord, NC. His dad received his B.S. in Mechanical Engineering from NCSU in 1972 and is currently the Deputy Supervisor of Shipbuilding and Repair for the US Navy in Jacksonville, FL. His mom works as an office manager for a real estate appraiser. Both parents are still happily married and enjoy all the time they can spare at the beach in Florida.

Brian spent the first 20 years of his life in Newport News, VA. He graduated high school in 1992 and attended Christopher Newport University from 1992- 1994. He then spent several years living in the suburbs of Washington DC, and he spent several semesters attending George Mason University.

He moved to North Carolina in the summer of 1998, enrolled at NCSU in the spring of 2000, and began working towards his B.S. in Biological and Agricultural Engineering. Along the route to receiving his B.S., Brian was able to achieve many successes. He served as President of the NCSU student branch of the American Society of Agricultural Engineers and the Biological and Agricultural Engineering honor society, Alpha Epsilon. He received numerous scholarships and awards including the College of Engineering Senior Award for Leadership.

After graduating Summa Cum Laude in 2003, Brian went on to pursue his M.S. in Biological and Agricultural Engineering under the direction of Dr. R. Wayne Skaggs. While there, he worked on developing methods to predict the lateral effect of drainage ditches on adjacent wetland hydrology.

ACKNOWLEDGEMENTS

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I would like to thank first my committee chair, Dr. R. Wayne Skaggs. I approached Dr. Skaggs about pursuing a M.S. under his direction at the beginning of my final undergraduate semester. Knowing that I would receive his teaching and mentoring was the deciding factor for entering into the NC State graduate program. It never ceases to amaze me at the breadth and command of his knowledge in the areas of agriculture and environmental engineering. I have had the pleasure of attending conferences and presentations with Dr. Skaggs, and I am always impressed by the respect others extend to him.

Dr. Skaggs exhibited extreme patience and generosity during the three years of my Master’s work. He allowed flexibility in my work schedule and promoted independence in completing tasks. Completing my thesis took several months longer than originally planned. Again, Dr. Skaggs was very patient and supportive, and I never felt he had lost faith in my ability to successfully complete the work.

This study represents only a small portion of the overall lateral effect projects. I have been very fortunate to be involved in many aspects of the projects. As a result, I have had great exposure in the professional community. I have been listed as a co-author on a referred journal article, listed as the main author and presented a paper at an international conference on forested wetland hydrology, and worked directly with representatives at the NCDOT. Dr. Skaggs also allowed me to do a DRAINMOD teaching session at a firm in Raleigh. I look forward to continuing to work on the lateral effect projects as a research engineer under Dr. Skaggs' direction. I also look forward to modeling myself after his image. Although those shoes can never be filled, it is a highly desirable goal.

I owe thanks to Dr. George "Chip" Chescheir for serving as a committee member and for all his help along the way to completing this study. Chip was instrumental in Chapter two of this study and in assisting in the DRAINMOD modeling of my field sites. I remember Chip sitting with me for several hours during the first attempts at calibration modeling. Chip's command of DRAINMOD and his understanding of drainage processes were greatly appreciated. I also owe thanks to Chip for getting to me a copy of RAINSIM and for fielding a multitude of general questions about the study and other projects.

I would like to thank Dr. Michael Vepraskas. Dr. Vepraskas served as the minor representative on my committee. I first met Dr. Vepraskas in the fall of 2003 while taking his wetland soils class. I was impressed by his knowledge of wetland soils and by his dynamic presence in the classroom. Although we only met a few times during my Master's program, I am thankful for his constructive input to this study.

Dr. John Parsons passed away during the fall semester of 2005. His passing was a tremendous loss to the department and to the engineering community. I am very fortunate to have known Dr. Parsons as a professor during my undergraduate days and to have received his help with the WATRCOM model during my graduate study. Without his help, my knowledge of and efficiency using WATRCOM would not be at the current level.

Without the next two people, my life in the field and the management of data would have been very difficult. Wilson Huntley and Jay Frick installed equipment on my study sites in late 2001, and they continued to monitor the sites until I took over in the summer of 2003. When I received the data sets from Jay, all spreadsheets for rainfall and water table were up to date saving me an enormous amount of time compiling early project data. Jay was also there along the way to answer questions I had regarding the measurement data. Wilson was always my go to guy for anything related to the field. Need logger batteries, see Wilson. Need parts for field equipment, see Wilson. Wilson was also with me to collect soils cores, to perform auger hole tests, and to drill down to find the impermeable layers. He also showed me how to perform soil tests in the lab. I am indebted to Jay and Wilson for their help with the study sites and data management.

My good friend, Chad Poole, has been there since my first undergraduate semester in BAE. It would be easy to argue that my strength as a student and as an engineer is due in large part to our friendship, our ability to work together, and our invigorating conversations about life and academics. I place a very high value on my friendship with Chad. Chad has also been my officemate during the past three years, and we have had countless productive discussions regarding our projects. I think we both have a better understanding of our own projects and each other's projects because of those talks.

I would like to also thank Dr. Glen Fernandez for providing help with the DRAINMOD model. Although, Dr. Fernandez left the department at the inception of my Master's program, he was always available via phone or email.

To the staff of the BAE department, I say thank you for helping me with the little things and the big things (paychecks). Thank you for your patience and for working hard to solve my problems that arose during the past three years. In particular, I would like to acknowledge Kathy Logan, Heather Gordon, Dorothy Lee, Sherry Li, and Kristel Page.

Finally, I would like to thank the late Dr. Francis J. Hassler for endowing a fellowship I was fortunate to receive during the 2003-2004 academic year. I had the pleasure of meeting his wife, Mrs. Oneta Hassler, during an awards banquet for the BAE department. She is a very wonderful person who insisted on hugging the students rather than shaking their hands. I am very thankful for the financial support provided by the fellowship.

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CHAPTER 1: WETLANDS AND THE LATERAL EFFECT OF ROADSIDE DRAINAGE DITCHES

Introduction

The valuable functions of wetlands have become widely acknowledged. Mitsch and Gooselink (2000a) grouped the values of wetlands in to three main categories: population – e.g. waterfowl, timber, fish; ecosystem- e.g. flood mitigation, storm abatement; and biosphere – e.g. nitrogen and phosphorus cycle. Highway construction adjacent to wetlands is often unavoidable. Roadside drainage systems associated with these highways can affect the adjacent wetland hydrology. When wetland hydrologic impact/loss is unavoidable, compensatory mitigation is required (MOA NCDENR/USACE, 1998). The hydrologic impact of drainage ditches on these adjacent wetland is of importance in quantifying losses and calculating mitigation fees (WRP/EEP, 2006). That is, a sound method of quantifying the lateral effect of a roadside ditch is required to complete the mitigation permit process, where lateral effect is defined as the width of a strip of land drained such that it no longer meets the wetland hydrologic criterion (USACE, 1987). An approximate method was developed by Skaggs et al. (2005) to predict the lateral effect of drainage ditches on adjacent wetland hydrology. The purpose of this study is to test the validity of the approximate method.

Wetlands

Wetlands represent transitional zones between dry, upland, conditions and wet, aquatic, conditions. The National Research Council (NRC) committee on wetlands concluded that a wetland can be defined as follows:

> "A wetland is an ecosystem that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristic of a wetland are recurrent , sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features reflective of recurrent , sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation. These features will be present except where specific physiochemical, biotic, or anthropogenic factors have removed them or prevented their development" (NRC, 1995).

Wetlands can be areas that receive direct overland flow, groundwater discharge or are purely driven by local precipitation, such as a Pocosin (Richardson, 2003; Skaggs et al. 1991). Geographically, wetlands can vary from depressional areas, i.e. Carolina bays (Sharitz, 2003; Lide et al., 1995), coastal lowlands subject to flooding, to interstream divides. The common property of all wetlands is the frequency of saturation or inundation. Wetland benefits to society and to ecosystems have been studied extensively. Benefits include, but are not limited to, waterfowl and wildlife habitat, flood control and attenuation, ground and surface water remediation and water quality enhancement, wastewater treatment, and shoreline protection.

There are approximately 103 million acres of wetlands in the United States (Dahl and Johnson, 1991). Approximately 6 million acres of these wetlands are located in North Carolina; with approximately 95% residing east of I-95 (Dahl and Allord, 1997). Mitsch and Gooselink (2000b) estimate that 53% of the original wetlands in the United States have been lost, primarily for agricultural uses. The conflict between the rights of landowners and the responsibility of public and ecological protection has led to several key legislative wetland policies. One of the most important federal regulations is Section

404 of the Clean Water Act (CWA). Through section 404 the federal government regulates wetlands by controlling discharge of dredged or fill materials into wetlands.

The United States Army Corps of Engineers (COE), under authority of the Environmental Protection Agency (EPA), enforces compliance with Section 404 of the CWA (33 CFR 320). In 1987, the COE's Environmental Laboratory issued a Wetlands Delineation Manual, commonly referred to as the 87 Manual, (USACE, 1987) as a guide to define a jurisdictional wetland. A wetland is defined in the 87 Manual as follows:

> "Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas".

The 87 Manual delineation procedures state that a wetland must possess three main parameters: wetland hydrology, hydric soils, and a dominance of hydrophytic vegetation. Wetland hydrology is the most difficult parameter to quantify and the most important parameter in wetland development (Owen, 1995; NRC, 2001). In order to determine the existence of wetland hydrology from on-site measurements, long-term water table data are required. Often these records are either unavailable or are available for only short durations. Therefore, regulatory judgment as to whether a site meets the jurisdictional wetland criteria is often based on presence of hydric soils, dominant hydrophytes, and topographic position. A current working definition of hydric soils (Richardson and Vepraskas, 2001) states that "A hydric soil is a soil formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part." The presence of hydric soils can be determined from on-site field indicators (USACE, 1987; NRCS, 2005.). However, the presence of hydric soil indicators does not necessarily indicate the presence of a wetland, because wetland hydrology and hydrophytic plants must also be present. Relict conditions, retaining features of a hydric soil, can remain on a site 30 years after removal of wetland hydrology (Richardson and Vepraskas, 2001). Nor does the presence of some hydrophytic plants indicate a wetland. The 87 Manual dictates that a prevalence of hydrophytic vegetation occur in order to satisfy the wetland plant criteria. This value can be difficult to quantify. The presence of hydrophytic vegetation is determined by site visits. Procedures for determining dominant vegetation can be found in the 87 Manual. Janisch and Molstad (2004) gives an overview of the procedure of hydrophytic vegetation wetland delineation methodology and states:

> "To determine dominant plant species, all species present at each data point, starting with the most abundant, were ranked in decreasing order for each stratum. Those species that cumulatively exceed 50% of the dominance for each stratum, plus any additional species making at least 20% of the total dominance measure qualified as dominant species."

Hydrology

The hydrology of a wetland is the most significant factor in wetland development. Hydrology influences the vegetation on a site and the chemical interactions that determine whether hydric soils will be developed or sustained. Wetland hydrology is usually the most difficult parameter of the criterion to quantify. This difficulty can lie in the inability to fully measure hydrologic parameters or in errors associated with those measurements (LaBaugh, 1986). Cole and Brooks (2000) stated that "…developing an understanding of wetland hydrology that is free from site-specific constraints remains one of the most vexing aspects of wetland ecology." Carter (1986) also stated, "As water is the primary driving force in the formation and maintenance of wetlands, wetland hydrology has become a research area of high importance." The hydrologic processes that determine the saturation / inundation regime of a wetland are determined by inputs and losses. Clearly defining the magnitude of the components of a water budget (water balance) for a specific wetland is a mathematical relationship that is often difficult to quantify. Additions to a wetland are mostly precipitation, groundwater discharge, overland flow, and subsurface flow (i.e. ditches). Losses from a wetland are mostly evapotranspiration (ET), groundwater recharge, or surface outflow. A wetland water balance can be defined as follows:

$$P + SI + GI - ET - SO - GO = \Delta STORO \qquad [1]$$

where P = precipitation, SI = surface flow in, GI = subsurface flow in, GO = subsurface outflow, ET = evapotranspiration, and ΔSTORO = the change in water stored.

Dooge (1975) suggested breaking the component of surface flow into fluxes due to streamflow and nonchannelized flow.

Hydrologic Criterion

For the purposes of this study, the wetland hydrologic criterion will be based on the 87 Manual and defined as follows:

> "Wetland hydrology exists if, during the growing season, the water table is normally within 30 cm (1 foot) of the soil surface for a continuous period of 5% to 12.5% of the growing season."

In order to fully quantify the above definition, terminology must be set for the growing season and "normally." The growing season is usually defined as the period between the average last day having an air temperature of 28F in the spring and the first day having an air temperature of 28F in the fall (50% probability of recurrence). Data for the growing season length can be found in published Natural Resources Conservation Service (NRCS) county soil surveys or from the internet at the NRCS Water and Climate Center. "Normally" is defined for this purpose by the COE as occurring on average in one-half or more of the years tested. The continuous period (5% to 12.5%) is generally taken as 5% for determination of presence of wetlands in North Carolina.

Although long-term water table fluctuations in a wetland may meet the required criterion definition, year-to-year variability makes it difficult to determine wetland hydrologic status. Due to annual variations in weather, a site may fail to meet the wetland hydrology criterion during one year or during a period of two or more consecutive years. Attempts to qualify a site as a jurisdictional wetland based on short-term hydrologic records can fail to provide accurate results. Point data, data taken at one or several times, of ground water levels will not provide adequate reliability as to the presence of wetland hydrology. Shaffer et al. (2000) suggest that a minimum of once daily water table measurements are required to accurately determine whether a site meets the hydrologic criterion.

Hydrologic Modeling

Of importance to this research is the effect of losses to wetland hydrology due to human disturbance. In particular, the influence of drainage ditches on adjacent wetland hydrology. In equation [1], this is considered a subsurface loss. Drainage ditches are used to manage water levels in an effort to, among other things, improve crop yields, prevent flooding, and prevent road damage. In order to calculate the water budget and the losses due to drainage ditches, the ability to simulate subsurface water movement is required. Water balance simulation models have been developed to predict effects of drainage systems on trafficability and crop yields (Skaggs, 1999; Evans and Fausey, 1999). Examples are DRAINMOD (Skaggs, 1978) and WATRCOM (Parsons et al., 1991a), which are commonly used to predict the effect of ditches on water table fluctuations. DRAINMOD was developed to predict the response of the water table due to surface and subsurface water management options (conventional drainage, controlled drainage, subirrigation). Of interest was the water table response at a point midway between two ditches (or tile drains). WATRCOM was developed to predict water table response to a system of irregular spaced drainage ditches. Other water balance models have been developed specifically to predict the hydrology of wetlands. Restrepo et al. (1998) integrated a wetland simulation model for MODFLOW that adjusted overland flow and ET for wetlands. FLATWOODS (Sun et al., 1998) and WETLANDS (Mansell et al., 2000) were developed to examine the hydrologic impact of silviculture practices in forested wetlands in the lower Southeast United States. All hydrologic models attempt to quantify the components of water balance equation [1] for a particular point on the landscape or for a generalized area. Differences exist among the various models in the numerical methods for calculating subsurface water fluxes in the saturated and unsaturated zones, ET, sheet and overland flow, channel flow, and infiltration. For the purposes of this study, the DRAINMOD and WATRCOM water balance models were utilized for hydrologic simulations. The models will be discussed further in Chapter 3.

Lateral Effect

Introduction

Drainage systems can impact adjacent lands. When drainage ditches are located adjacent to wetlands, the hydrology of the wetland will likely be modified to some extent. The lateral effect of a drainage ditch, as shown in Figure 1, will be defined as follows:

> "The width of a strip of land which is drained such that it no longer satisfies the wetland hydrologic criterion."

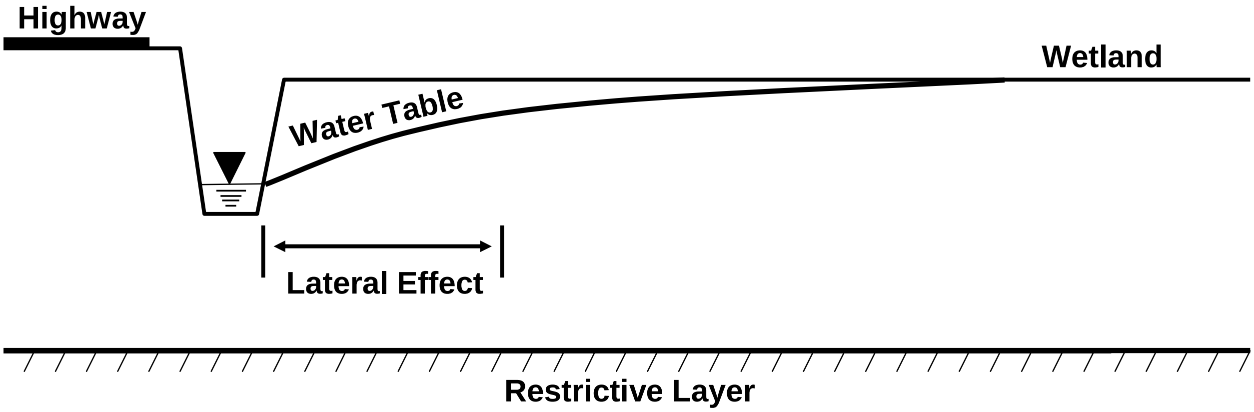

Figure 1. Schematic of highway ditch showing the lateral effect of the ditch on wetland hydrology

It is important to note that this definition defines the lateral effect purely based on the hydrologic impact of the drainage ditch as it relates to the jurisdictional wetland hydrologic criterion. Non-hydrological methods of determining the lateral effect have been explored. Hayes and Vepraskas (2000) proposed a method to determine the lateral effect of a drainage ditch based on Fe mass concentrations. Their research showed that subsurface drainage due to the ditch caused a migration of Fe masses in a direction towards the ditch. By examining cores for oxidized masses along a perpendicular transect leading away from the ditch, one can predict the lateral effect of the ditch. It must be noted that the definition of lateral effect, as it applies to this study, is solely based on the influence on the hydrology of the adjacent wetland hydrology. Analysis of the influence of a drainage ditch on modifications to the functional values of the wetland is neither analyzed nor researched in the scope of this thesis.

Current Methods of Calculating Lateral Effect

One method that has been used to determine the lateral effect of a roadside drainage ditch on adjacent wetland hydrology is based on the "Scope and Effect Guide" for North Carolina hydric soils (NRCS, 1998). The guide groups together soils of similar soil properties and estimates the lateral effect of a particular drainage ditch depth / soil group combination. The method is based on the ellipse equation for flow to parallel drains with several simplifying assumptions. It does not consider the fact that the lateral effect of a single ditch is less than that of parallel drains. Effects of surface depressional storage are neglected in the guide.

Approximate Method Model Description

An approximate method was developed by Skaggs et al. (2005) to estimate the lateral effect of a drainage ditch on adjacent wetland hydrology. The method has been referred to as the "Skaggs Method" by the NCDOT (http://www.ncdot.org/doh/operations/dp%5Fchief%5Feng/roadside/fieldops/downloads). The method is based on the time required for water table drawdown in an initially saturated profile with the water table coincident with the surface. DRAINMOD simulation analyses showed that sites barely satisfying the wetland hydrologic criterion will have drainage intensities that provide water table drawdown from the surface to a depth of 25 cm in a specific time. This threshold draw down time, T_{25}, was found to depend moderately on ditch depth but was nearly constant among soils having a wide range of profile transmissivities and drainable porosities. T_{25} was found to depend strongly on surface depressional storage, decreasing as surface storage increased. T_{25} also depended strongly on location, which affects both the growing season and weather variables. Once the T_{25} values are determined, published solutions for water table drawdown due to a single drain (Skaggs, 1976) can be used to estimate the lateral effect of a drainage ditch or subsurface drain on wetland hydrology. This method is currently being employed by the NCDOT to predict the lateral impact of borrow pits. The purpose of this study was to test the validity of the method.

Objectives

1. Collect water table, climate, and soil data from three well transects located near drainage ditches adjacent to wetlands.
2. Determine the lateral effect (location of boundary between upland and wetland conditions) for each transect, based on field data.
3. Predict the lateral effect of the drainage ditches using long term simulations with calibrated models
4. Compare lateral effects predicted by the approximate (Skaggs) method with values determined from field data and from long term calibrated model simulations.

CHAPTER 2: FIELD STUDY

Study Site Description

Field testing of the method was conducted at two wetland mitigation sites in Eastern North Carolina. These sites are managed by the North Carolina Department of Transportation's Office of Natural Environment. The first study site is located in Edgecombe County at Mildred Woods Mitigation Site (NCDOT Natural System Unit Monitoring Report 2001 Mildred Woods, 2001; 35.87 N, 77.48 W), approximately five kilometers east of Tarboro. The second study site is located in the town of Pinetown, Beaufort County at the ABC Mitigation Site (NCDOT Natural System Unit Monitoring Report 2002 ABC, 2002; 35.62 N, 76.86 W).

Transects of seven water table wells were installed perpendicular to drainage ditches at the sites. A graphical depiction of the wells along a generalized transect is shown in Figure 1. Two transects were installed at the ABC site and one transect was installed at the Mildred Woods site. Lengths of the transects and distances between the wells vary depending on the ditch dimensions and the soil type adjacent to each ditch. Both sites were instrumented in late 2001 with data collection beginning at the start of 2002 and continuing until the end of 2004 at the Mildred Woods site and the end of May 2005 at the ABC site.

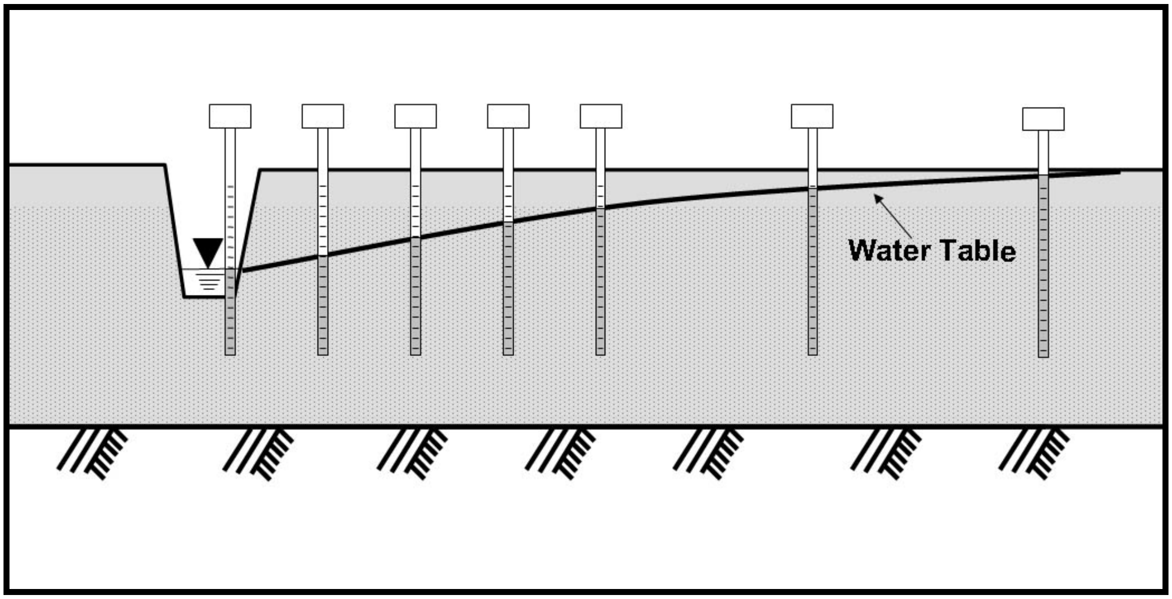

Figure 1. Generalized view of a transect of wells

Five of the seven water table wells were equipped with automatic recording mechanisms and the water levels in the remaining two wells were measured manually. Both manual and recording wells were used to determine water table depth. The wells consisted of slotted 4-inch diameter PVC pipe installed to a depth of 1.5 to 2.0 meters. Weatherproof boxes were placed atop recording wells. Elevations, in reference to the ditch bottom, were recorded at the top of the well and at ground surface.

The recording mechanisms consist of a float/counterweight pulley system coupled to a potentiometer (Figure 2). Voltages through the potentiometer were monitored and recorded by a data logger (Onset Computer Corporation HOBO H8 Logger) on an hourly basis. Water table depth was determined by a calibrated relationship between water table depth and voltage.

Figure 2. Image of pulley/float recording system showing the pulley, potentiometer, and the data logger

Collection of data from the field involved visiting each site on a regular basis, usually every two to four weeks depending on weather conditions. Depth to the water table was measured manually and recorded at each of the seven wells on each transect. Voltage data from the wells installed with recording mechanisms were downloaded to a computer. Paired values for the manually measured water table depth and the voltage at the time of the download were recorded for each automatic recording well. These data pairs for each visit were entered into a spreadsheet and a linear regression line fitted to the updated set of data pairs to develop an equation for the relationship between voltage and measured water table depth for each recording water table well. These calibration equations were then used to convert the hourly measured voltage data to hourly water table depths.

One manual rain gage and one recording rain gage were located at each study site. The fifteen centimeter (six inch) diameter recording tipping bucket rain gage (Onset Computer Corporation) was calibrated to 0.254 mm (0.01 inch) depth of precipitation per tip. The time of each tip of the bucket was recorded by a logger (Onset Computer Corporation HOBO Event Logger). During each field visit, the manual rain gage was read and then reset and the data from the automatic recording rain gage downloaded. The reading from the manual rain gage was compared to the total rainfall recorded by the automatic rain gage and the data adjusted as necessary.

The Mildred Woods Site

The Mildred Woods Mitigation Site was constructed in 1995 and is approximately 240 hectares (NCDOT Natural System Unit Monitoring Report 2001 Mildred Woods, 2001). One transect of wells was installed on the site as shown in Figure 3. The drainage ditch runs north to south at the location of the transect. The ditch dimensions at that point are shown in Table 1. Transect wells are located at 0 (located in the ditch), 7.5, 15, 30, 45, 60, and 90 meters away from the ditch. The wells located at 7.5 and 90 meters were manual observation wells (i.e. no recording mechanism). Wells located at 0, 15, 30, 45, and 60 meters were instrumented with recording mechanisms.

Table 1. Physical dimensions of drainage ditch at Mildred Woods Mitigation Site.

Mildred Woods Site	
Top Width	9.1 m
Bottom Width	6.1 m
Depth	1.2 m
Side Slopes	2:1
Profile Depth	4.8 m
Normal Depth Water in Ditch	0.9 m

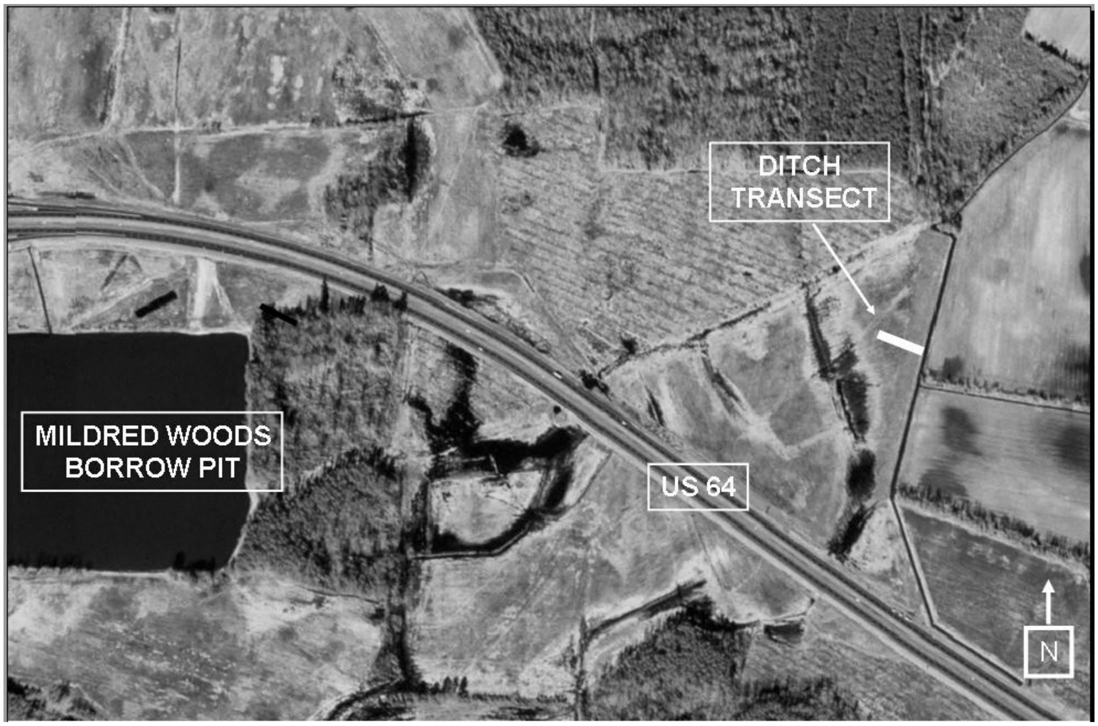

Figure 3. Ariel photograph of Mildred Woods field site (1998 IR)

Two dominant soil series are located within the transect area. Close to the drainage ditch, the dominant soil is the Cape Fear series (fine, mixed, semiactive thermic Typic Umbraquults). Beginning at approximately the midpoint of the transect, the dominant soil is the Roanoke series (fine, mixed, semiactive, thermic Typic Endoquult). The Cape Fear series is a very poorly drained soil, and the Roanoke series is a poorly drained soil. Auger hole tests to determine lateral hydraulic conductivity (van Beers, 1970) were performed on site in March 2004. Soil cores were collected in April 2004 to determine soil-water characteristics (soil water retention curves) and vertical hydraulic conductivity (Klute, 1986).

The ABC Site

The ABC Mitigation Site was constructed in 2001 and is approximately 75 hectares (NCDOT Natural System Unit Monitoring Report 2002 ABC, 2002). As part of the field testing of the method, two transects of wells were installed on the site as shown in Figure 4. Two main ditches are located on the ABC site. A shallow ditch is located on the western edge and runs north to south. A deeper ditch is located on the Northern side and runs east to west.

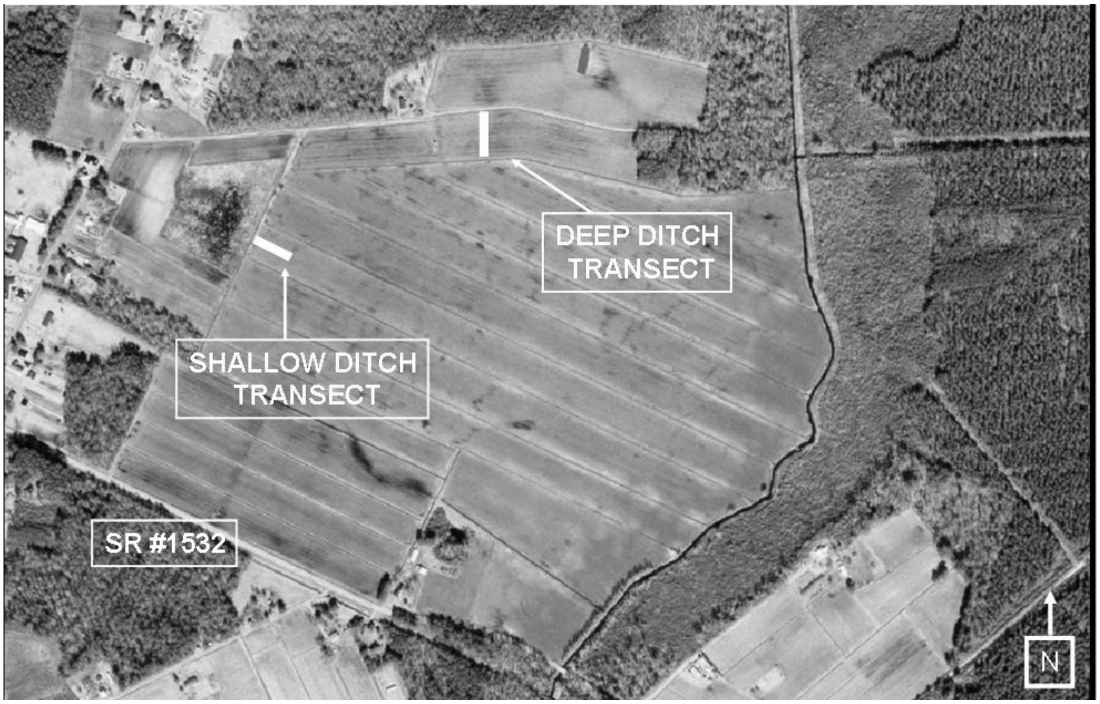

Figure 4. Ariel photograph of ABC field site (1998 IR)

Shallow Ditch

Observation wells on a perpendicular to the shallow ditch were at 0 (in the ditch), 3.75, 7.5, 11.25, 15, 22.5, and 30 meters away from the ditch. The well located 30 meters was a manual well (i.e. no recording mechanism). The remaining wells were instrumented with recording mechanisms. Dimensions of the shallow ditch are listed in Table 2.

Table 2. Physical dimensions of shallow ditch at the ABC Mitigation Site.

ABC Site Shallow Ditch	
Top Width	2.3 m
Bottom Width	1 m
Depth	0.9 m
Side Slopes	6 : 7
Profile Depth	6.4 m
Normal Depth Water in Ditch	0.8 m

Deep Ditch

Observation wells on the deep ditch transect were at 0 (in the ditch), 7.5, 15, 22.5, 30, 45, and 60 m away from the deep ditch. The wells located at 7.5, 60 meters were manual, and the remaining wells were recording wells. The remaining wells were instrumented with recording mechanisms. Dimensions of the deep ditch are listed in Table 3.

Table 3. Physical dimensions of deep ditch at the ABC Mitigation Site.

ABC Site Deep Ditch	
Top Width	4 m
Bottom Width	1.3 m
Depth	1.3 m
Side Slopes	1 : 1
Profile Depth	6.4 m
Normal Depth Water in Ditch	1.25 m

The dominant soil series in the transect areas is Leaf (fine, mixed, active, thermic Typic Albaquults). The Leaf series is a poorly drained soil. Auger hole tests to determine lateral hydraulic conductivity (van Beers, 1970) were performed on site in March 2004. Soil cores were collected in April 2004 to determine soil-water characteristics (soil water retention curves) and vertical hydraulic conductivity (Klute, 1986).

Weather and Hydrology

Precipitation

Mildred Woods

The annual rainfall for the study period ranged from 1110 mm in 2004 to 1418 mm in 2003 (Table 4, Figures 5 and 6). Annual rainfall for 2002 was somewhat larger than the long-term average annual rainfall (1157 mm) measured at the COOP weather station in Tarboro, NC. Year-to-year variability of rainfall for each month was greater on a percentage basis than year-to-year variability of annual rainfall (Figure 6). For example, rainfall for July ranged from 65 mm in 2004 to 216 mm for 2002 compared to the long-term average of 113 mm. High year-to-year variability of monthly rainfall amounts is typical for Eastern North Carolina and this variability causes difficulty in determining hydrological status of wetlands.

Table 4. Monthly rainfall (mm) at the Mildred Woods Site.

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Mildred Woods													
2002	139	38	108	36	32	62	216	140	136	171	116	96	1290
2003	45	131	97	151	135	44	148	191	207	104	44	122	1418
2004	29	80	53	73	125	152	65	244	126	54	79	31	1110
Avg (3yrs)	71	83	86	87	97	86	143	191	156	110	80	83	1272
Avg (30yrs)	108	90	107	78	95	95	113	122	125	81	65	78	1157

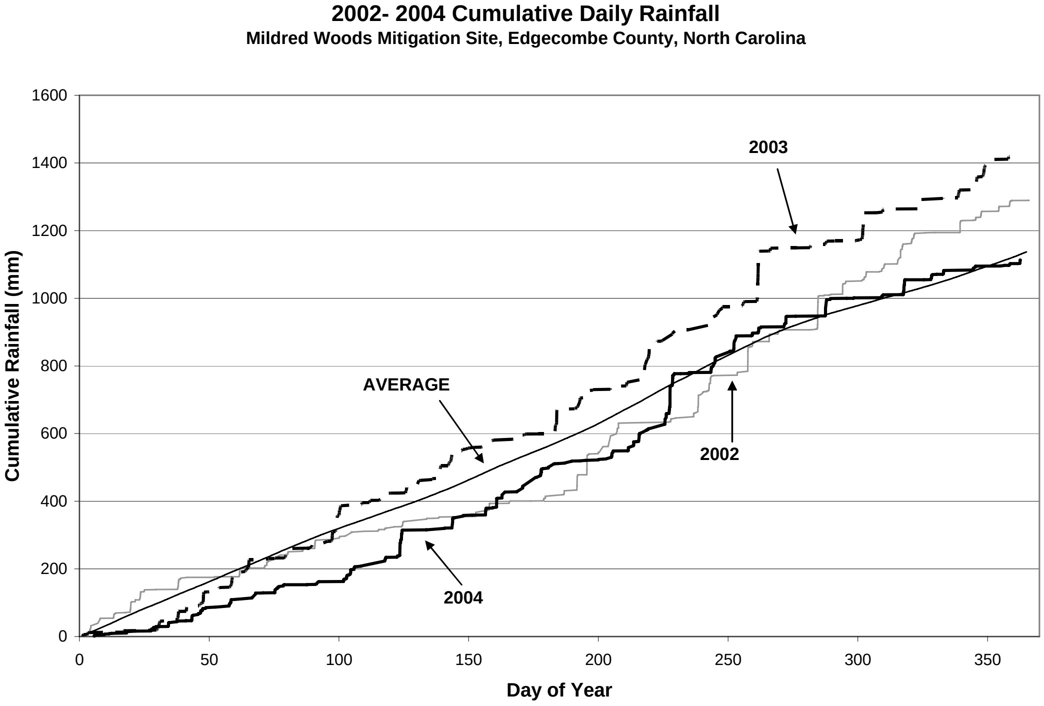

Figure 5. Cumulative rainfall for Mildred Woods site (2002 through 2004)

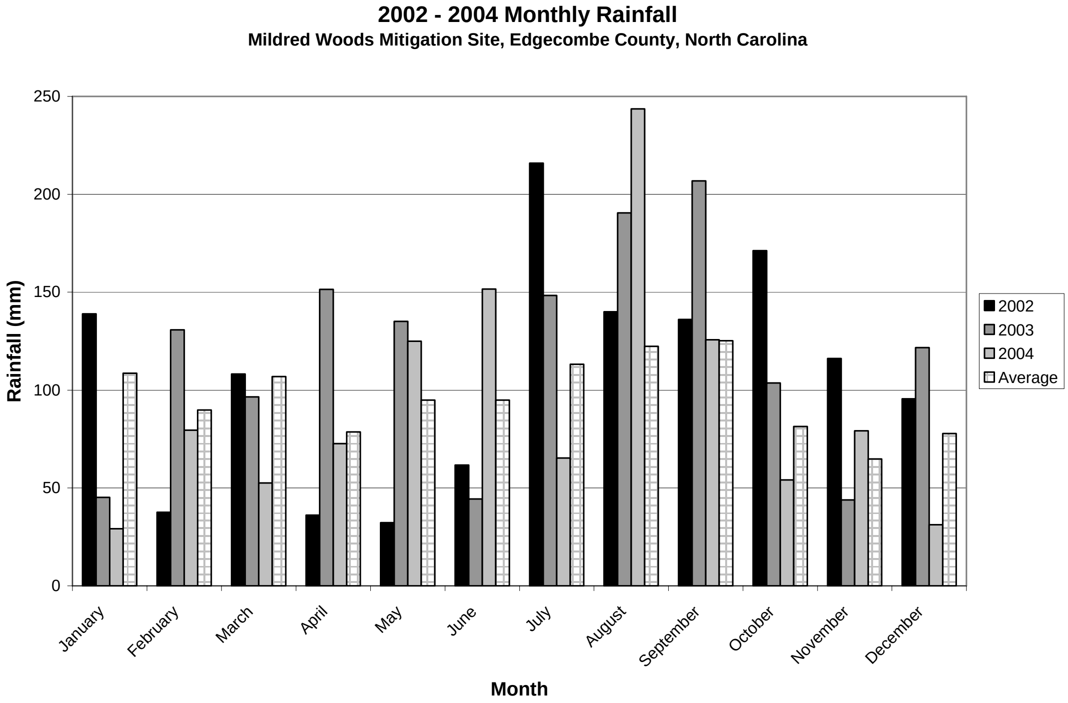

Figure 6. Monthly rainfall and long term average rainfall for Mildred Woods site

Short-term wetland determinations often define normal rainfall during a given month as any rainfall amount between the 30th and 70th percentiles for that month (see Figures 7 to 9) (Sprecher and Warne, 2000). Hunt et al. (2001) showed that defining normal rainfall in this way, and using observed water table data during months satisfying this definition for normal rainfall, resulted in errors that were biased toward defining wetland sites as upland. For example, as shown in Figure 8, the July 2003 rainfall was greater than the 70th percentile and would be considered wetter than normal month. However, the water table at the farthest well from the ditch only recorded a water table that was within 30 cm of the surface for 5 consecutive days. Therefore if a determination of wetland hydrology would have been made during this month, the site would have been incorrectly classified as upland. Data comparing site-specific rainfall and average rainfall are included in this study, but results indicate that the hydrologic status of a potential wetland site should be based on long-term water table records and/or projections.

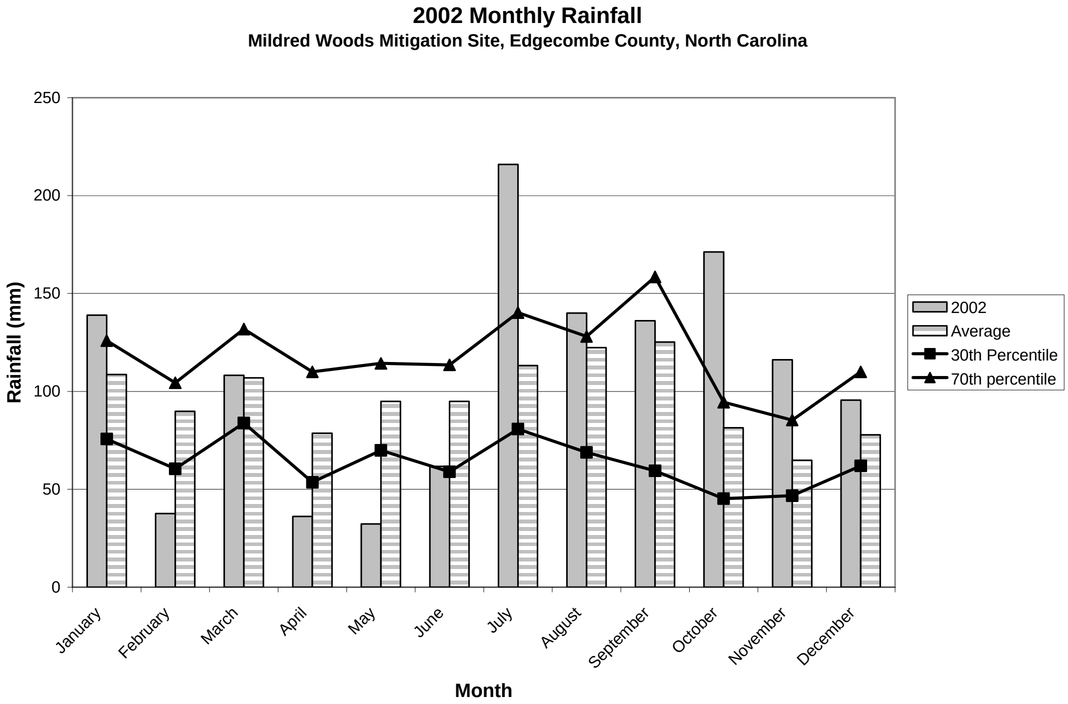

Figure 7. Monthly, long term and 30th and 70th percentile rainfall for2002 at Mildred Woods site

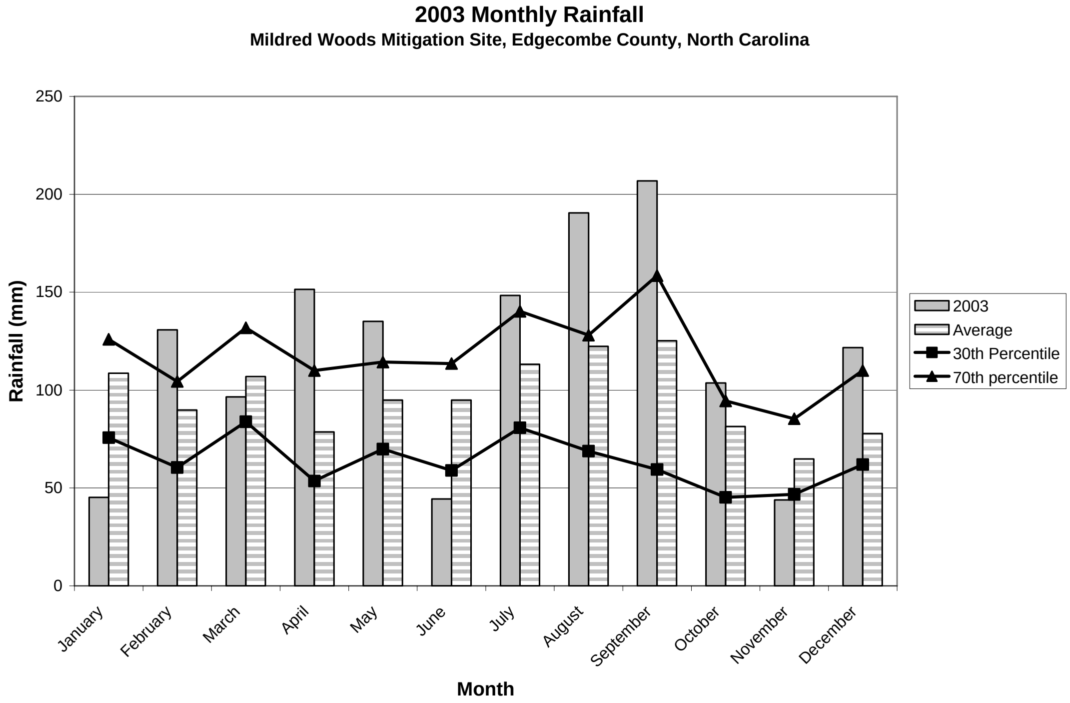

Figure 8. Monthly, long term and 30th and 70th percentile rainfall for 2003 at Mildred Woods site

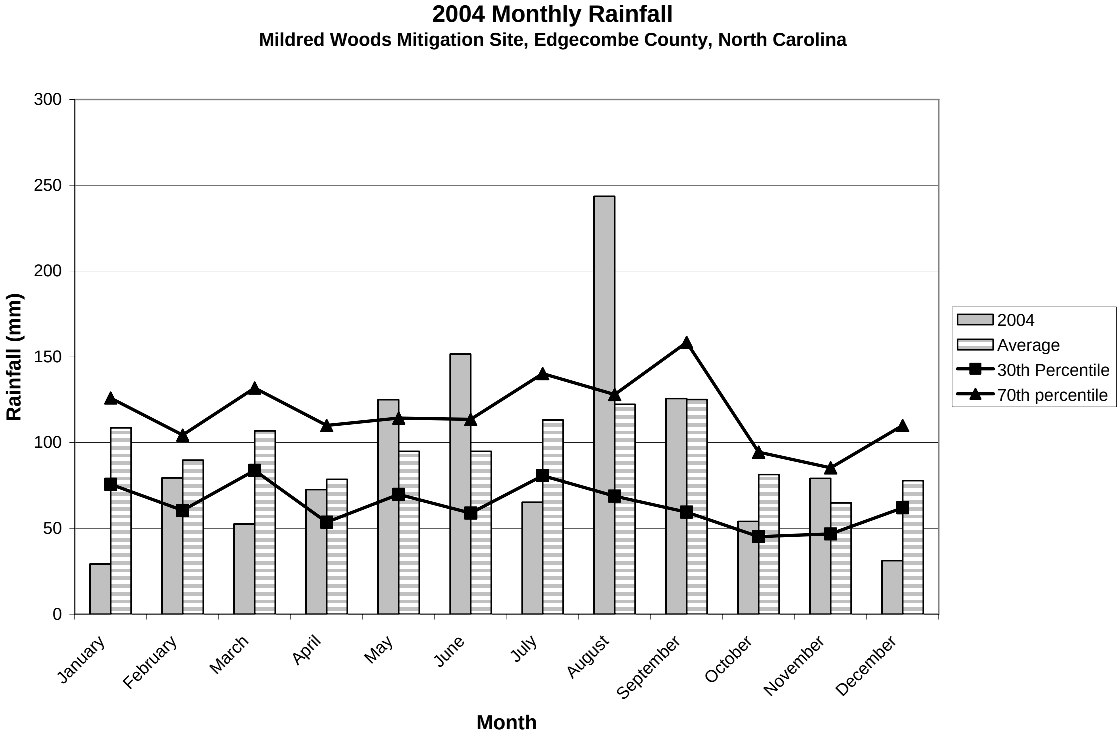

Figure 9. Monthly, long term and 30th and 70th percentile rainfall for 2004 at Mildred Woods site

ABC Site

The annual rainfall for the study period ranged from 1098 mm in 2004 to 1556 mm in 2003 (Table 5, Figure 10). Annual rainfall for two of the three years was below the long-term average annual rainfall (1226 cm) measured at the COOP weather station in Belhaven, NC. As at the Mildred Woods site, year-to-year variability of rainfall for each month was greater on a percentage basis than year-to-year variability of annual rainfall (Figure 11). For example, rainfall for September ranged from 89 mm in 2002 to 252 mm in 2003 compared to the long-term average of 129 mm. September is typically a month with high year-to-year variability of monthly rainfall amounts since it is in the peak of the hurricane season.

Table 5. Monthly rainfall (mm) at the ABC Site.

	Jan	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**
							ABC						
2002	122	50	167	70	56	72	75	145	89	104	125	96	1171
2003	19	121	111	141	222	34	174	133	252	107	72	170	1556
2004	44	98	52	104	95	150	46	196	132	47	90	46	1098
2005	60	58	131	93	116	84	--	--	--	--	--	--	--
Avg (3 or 4 yrs)	61	58	131	115	122	85	98	158	157	86	96	104	1275
Avg (30yrs)	108	78	105	81	114	121	140	148	129	87	74	81	1266

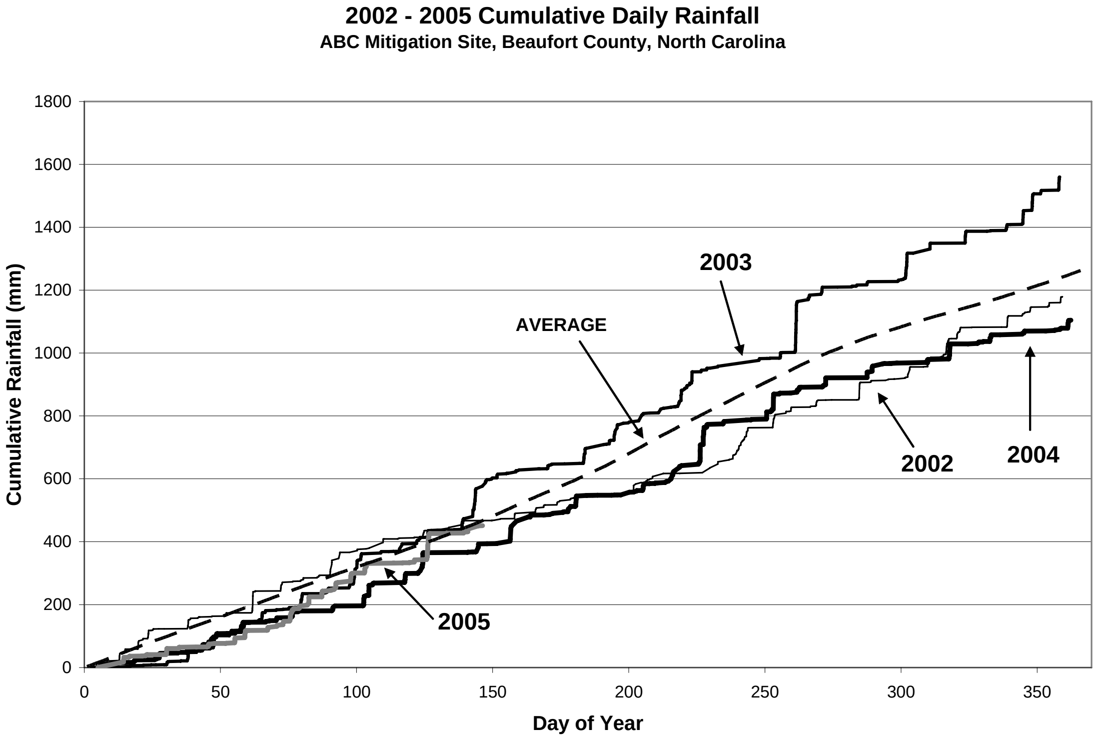

Figure 10. Cumulative rainfall for ABC Mitigation site (2002 through 2004)

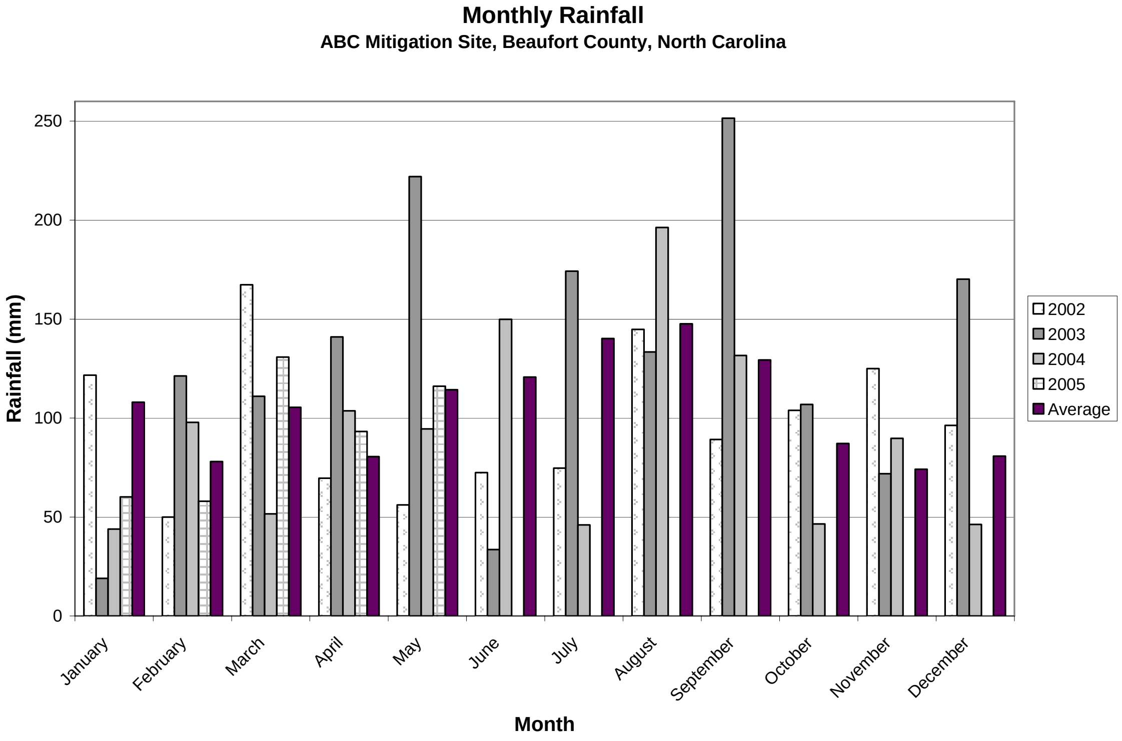

Figure 11. Monthly rainfall and long term average rainfall for ABC Mitigation site

Figures 12 to 15 show comparisons of monthly rainfall to long-term averages as well as the 30th and 70th percentiles

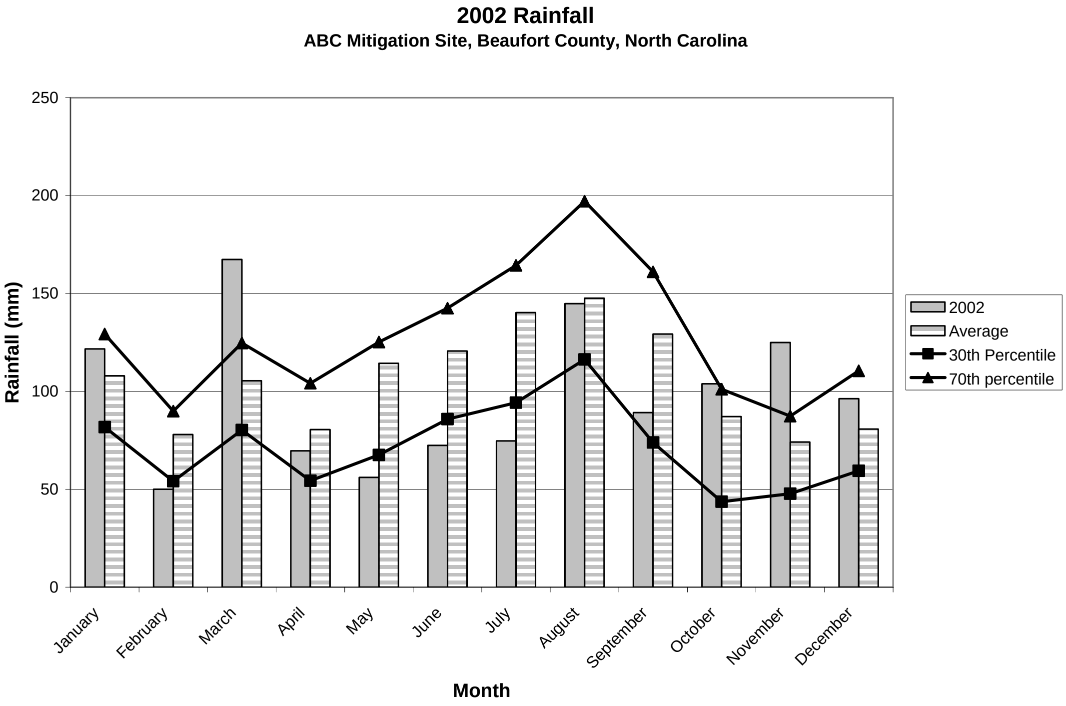

Figure 12. Monthly, long term, and 30th and 70th percentile rainfall for 2002 at ABC Mitigation site

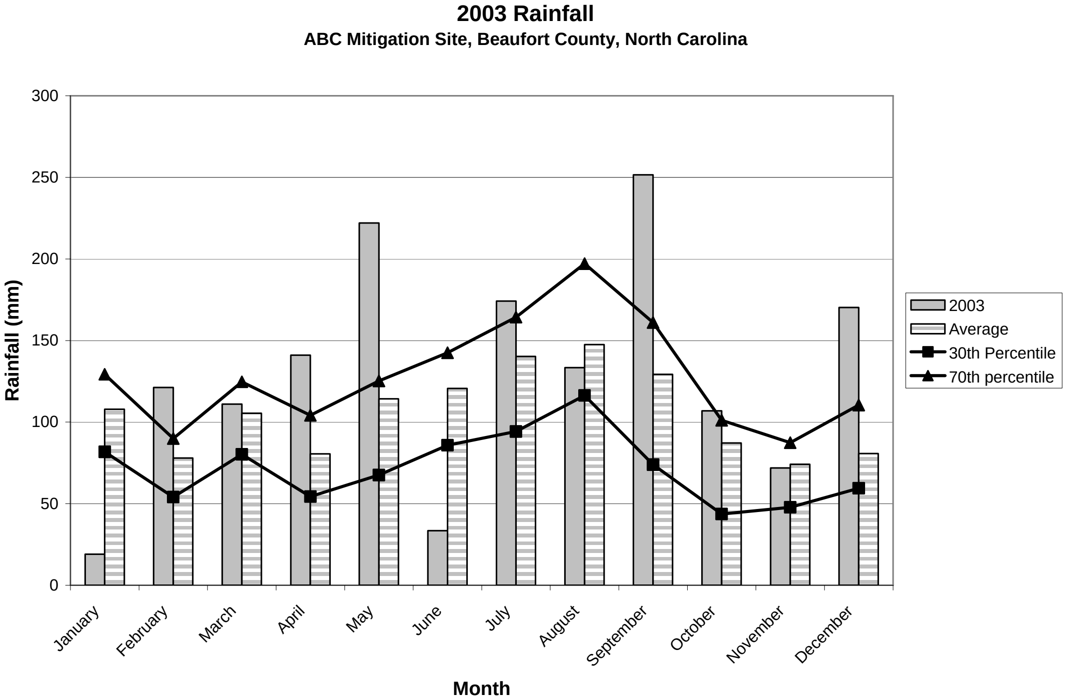

Figure 13. Monthly, long term, and 30th and 70th percentile rainfall for 2003 at ABC Mitigation site

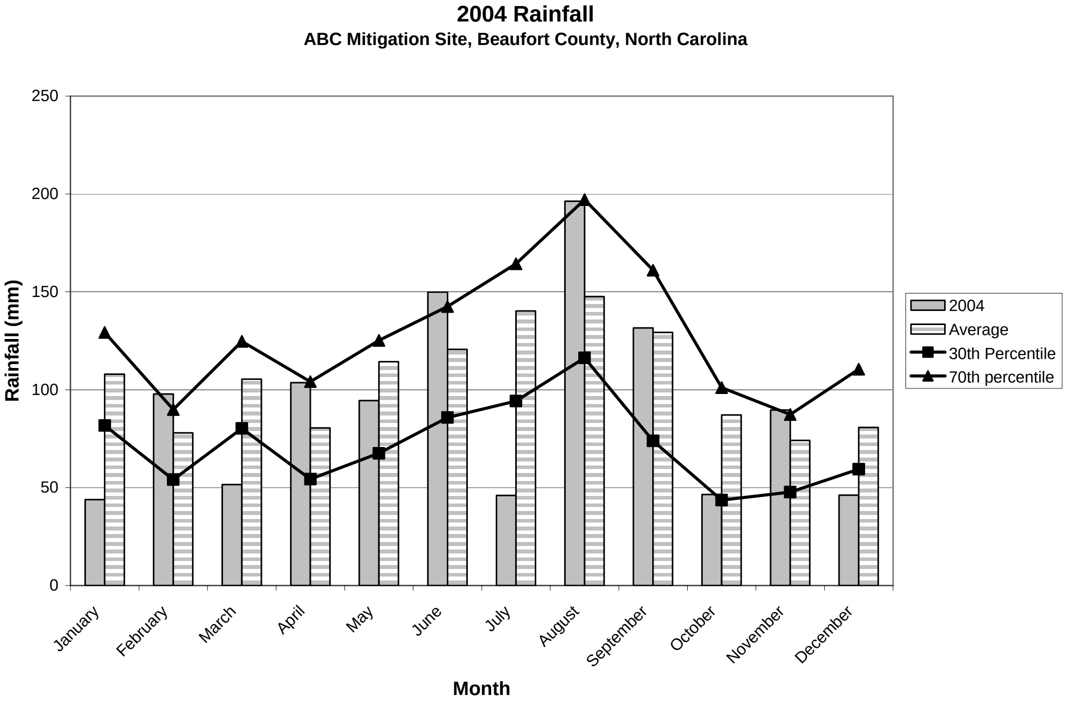

Figure 14. Monthly, long term, and 30th and 70th percentile rainfall for 2004 at ABC Mitigation site

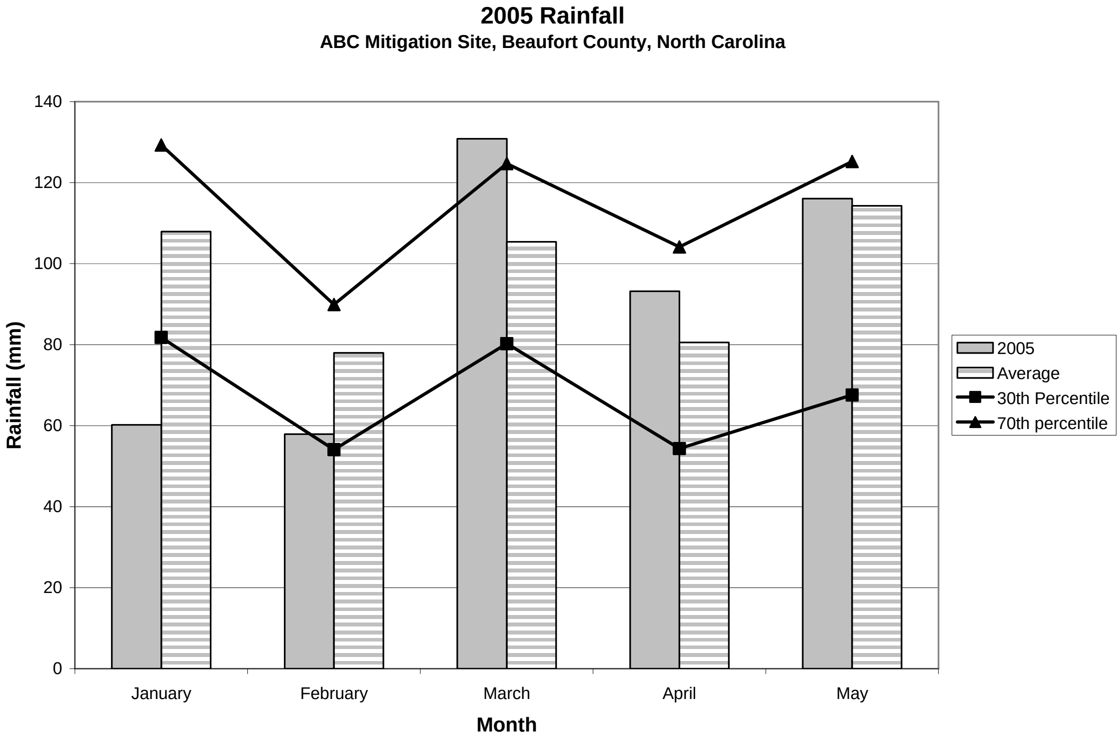

Figure 15. Monthly, long term, and 30th and 70th percentile rainfall for 2005 at ABC Mitigation site

Temperature

Mildred Woods

On site temperature was not recorded for this project. Temperature data were required for simulation purposes and were obtained from the COOP weather station in Tarboro, NC. Monthly averages for the study years and for the long-term period (1971 to 2000) are shown in Table 6. As expected, variability exists for each month when compared to long-term averages.

Table 6. Monthly temperature (ºC) at Tarboro, NC.

		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Tarboro, NC													
2002	Max	11.7	14.4	17.3	24.3	26.1	31.2	32.2	32.1	28.0	21.8	15.3	10.5
	Min	-0.6	0.5	4.0	10.1	12.2	18.7	20.8	20.1	18.2	12.3	3.9	-0.8
2003	Max	7.0	10.3	17.5	20.2	24.2	28.9	30.5	30.6	27.2	21.4	20.8	11.7
	Min	-3.3	-0.2	5.8	8.7	14.4	18.4	20.9	21.7	16.9	9.7	7.3	-1.0
2004	Max	8.9	10.3	17.5	22.2	28.1	29.5	31.4	28.9	26.9	21.6	18.8	12.3
	Min	-2.8	-0.8	4.1	8.7	16.8	19.4	21.6	19.5	17.6	11.3	5.5	-0.8
Avg (3yrs)	Max	9.2	11.7	17.4	22.2	26.1	29.9	31.4	30.5	27.4	21.6	18.3	11.5
	Min	-2.2	-0.2	4.6	9.2	14.5	18.8	21.1	20.4	17.6	11.1	5.6	-0.9
Avg (30yrs)	Max	10.0	11.5	16.1	20.8	25.3	29.2	31.3	30.6	27.7	22.4	17.2	12.2
	Min	-2.1	-1.5	2.7	6.9	12.9	17.6	20.3	19.3	15.7	8.7	3.4	-0.2

ABC Site

On site temperature was not recorded for this project. Again, temperature data were required for simulation purposes and were collected from the COOP weather station in Belhaven, NC. Monthly averages for the study years and for the long-term period (1971 to 2000) are shown in Table 7. As expected, variability exists for each month when compared to long-term averages. Analyses of data past May of 2005 were not performed, so temperature data past that date are not included in this study.

Table 7. Monthly temperature (ºC) at Belhaven, NC.

		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Belhaven, NC													
2002	Max	14.2	15.6	19.4	24.2	26.1	30.1	31.8	31.3	27.9	22.7	16.8	11.6
	Min	2.0	2.6	5.9	12.0	13.7	19.1	21.7	20.6	18.8	13.5	5.5	1.1
2003	Max	9.1	12.0	19.1	21.2	24.7	29.3	31.3	30.6	27.6	22.4	21.8	12.5
	Min	-1.6	1.2	7.1	9.9	15.0	19.8	22.4	22.5	17.2	10.8	8.1	0.1
2004	Max	10.4	11.5	17.4	22.8	28.9	30.1	31.5	28.6	27.3	22.7	18.5	13.5
	Min	-1.3	0.4	4.6	10.4	17.8	20.4	21.8	19.5	18.5	11.3	6.0	1.5
2005	Max	12.2	13.2	14.9	21.7	24.8	--	--	--	--	--	--	--
	Min	1.5	1.6	3.5	9.3	12.5	--	--	--	--	--	--	--
Avg (3yrs)	Max	11.5	13.1	17.7	22.5	26.1	29.7	31.5	30.2	27.6	22.6	19.0	12.5
	Min	0.2	1.5	5.3	10.4	14.8	19.7	22.0	20.9	18.2	11.9	6.5	0.9
Avg (30yrs)	Max	11.7	13.8	17.8	23.0	26.4	29.9	31.8	30.7	28.2	23.0	18.4	13.2
	Min	0.9	2.4	5.5	10.0	14.6	19.1	21.4	20.4	17.3	10.6	6.6	2.2

Water Table

Mildred Woods

Water table depths measured at the Mildred Woods site fluctuated with rainfall events and evapotranspiration (ET). Water table depths ranged from 1.3 to 1.5 meters in June of 2002 (Figure 16) to at or above the soil surface after rainfall events, particularly during the winter months (Figures 16 to 18). Water table depth generally decreased as the distance of the monitoring well from the ditch increased. For most of the observations, the water table was deepest at 15 m and shallowest at 90 m. The water table depths at 45 m were usually very close to those measured at 90 m. Water table depths at the 15 m well were rarely less than 30 cm deep, while water table depths at the 45 and 90 m wells were frequently less than 30 cm deep.

The water level in the ditch (presented in Figures 16 to 18 as depth below the soil surface at the top of the bank) also fluctuated with rainfall and ET; however, ditch levels fluctuated over a tighter range (0.45 m to 1.5 m) than the water table depths measured on the transects (0.0 to 1.5 m). The water level in the ditch was usually between 0.8 and 1.0 m below the top of the bank.

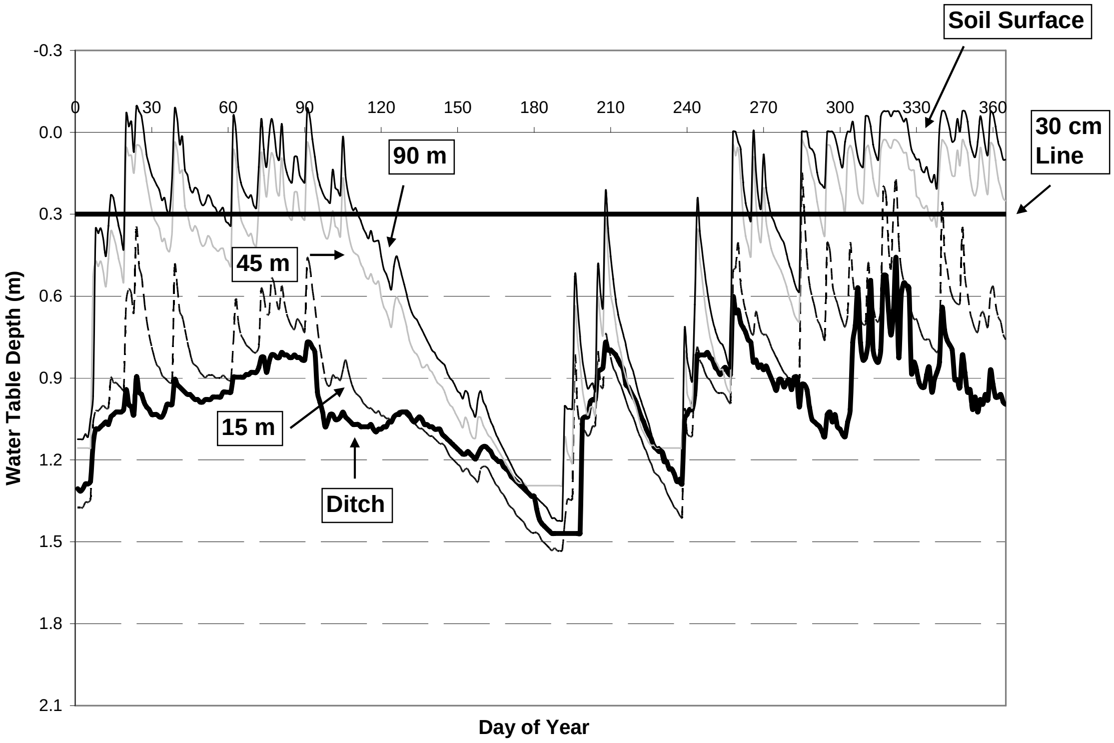

Figure 16. Observed daily water table depths in wells along a transect perpendicular to the ditch at the Mildred Woods site for 2002. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

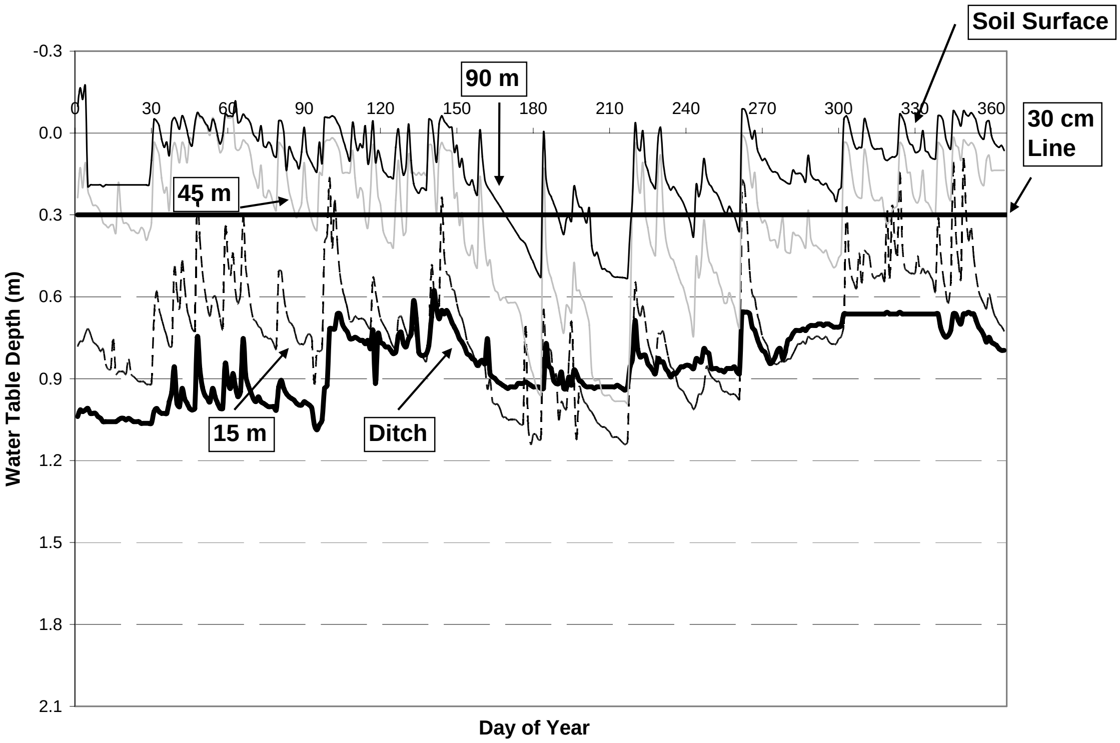

Figure 17. Observed daily water table depths in wells along a transect perpendicular to the ditch at the Mildred Woods site for 2003. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

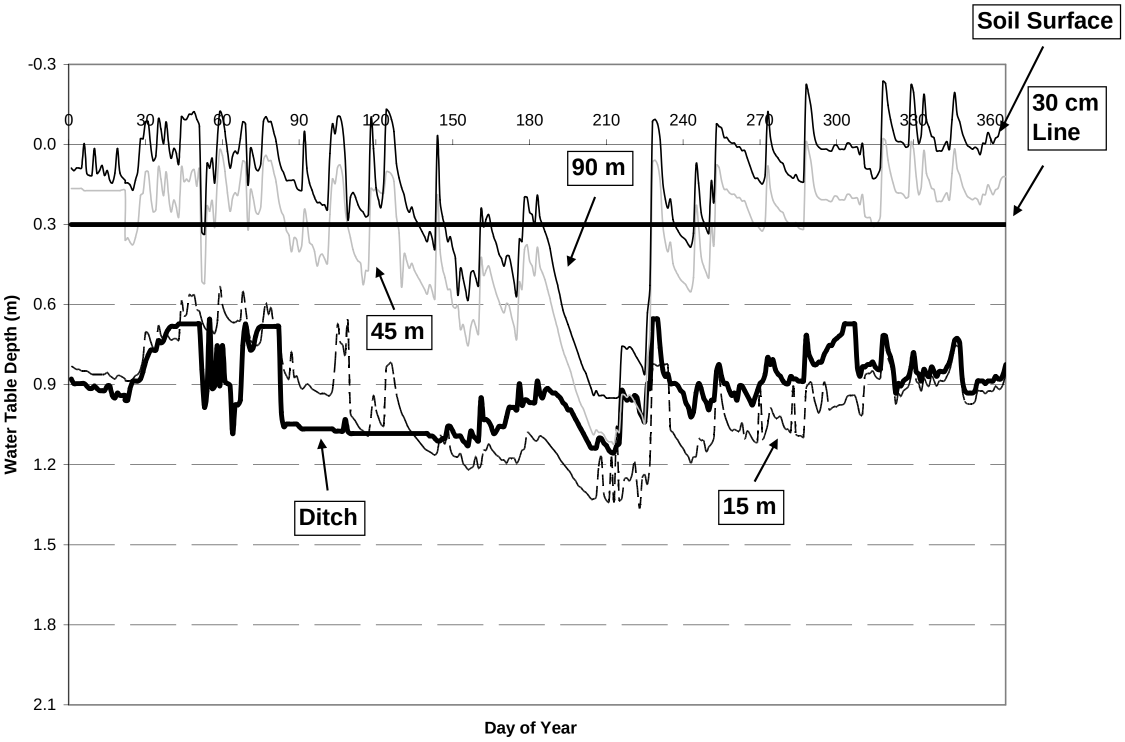

Figure 18. Observed daily water table depths in wells along a transect perpendicular to the ditch at the Mildred Woods site for 2004. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

There were periods during the 3-year study when the water level in the ditch was impacted by beaver dams (Figure 19). The beaver dam resulted in an additional 30 cm of head in the upstream portion (nearest well transect) of the ditch (i.e. the water level in the ditch was 30 cm higher than it would have been without the beaver dam).

Figure 19. Beaver dam at Mildred Woods site late 2003

Beaver activity is evident in water table data taken during late 2002 (Figure 16) and late 2003 (Figure 17). During much of this period, the level in the ditch was 0.6 to 0.7 m below the top of the bank. The water level in the ditch would likely influence the water table depths measured in the well transects, particularly in the wells close to the ditch.

Water table elevations (expressed in Figure 20 as elevation above the bottom of the ditch) usually increased as the distance of the well from the ditch increased. The shape of the water table was usually consistent with the theoretical shape shown Figure 1. Note that when the water table is high (e.g. Mar. 31), the water table beyond 45 m is relatively flat. These results indicate that the lateral effect of the ditch is between 30 and 45 m for this site. The water table shape near the ditch sometimes differed from the theoretical shape (see Nov. 11, Figure 20), but this was likely due to the fluctuating water level in the ditch. The theory assumes a constant water level in the ditch, so these differences are not surprising. Normal fluctuations of the ditch water levels caused by rainfall and ET would likely not affect the methods developed in the study. A rise in ditch water levels caused by beaver dams, however, is less variable and would greatly affect the accuracy of the methods. In this case, the effective depth to the water level in the ditch would be decreased and the lateral effect would be less than that predicted by the methods. The water table shape on Jul 31 occurred when the water table fell below the water level in the ditch during high ET summer conditions.

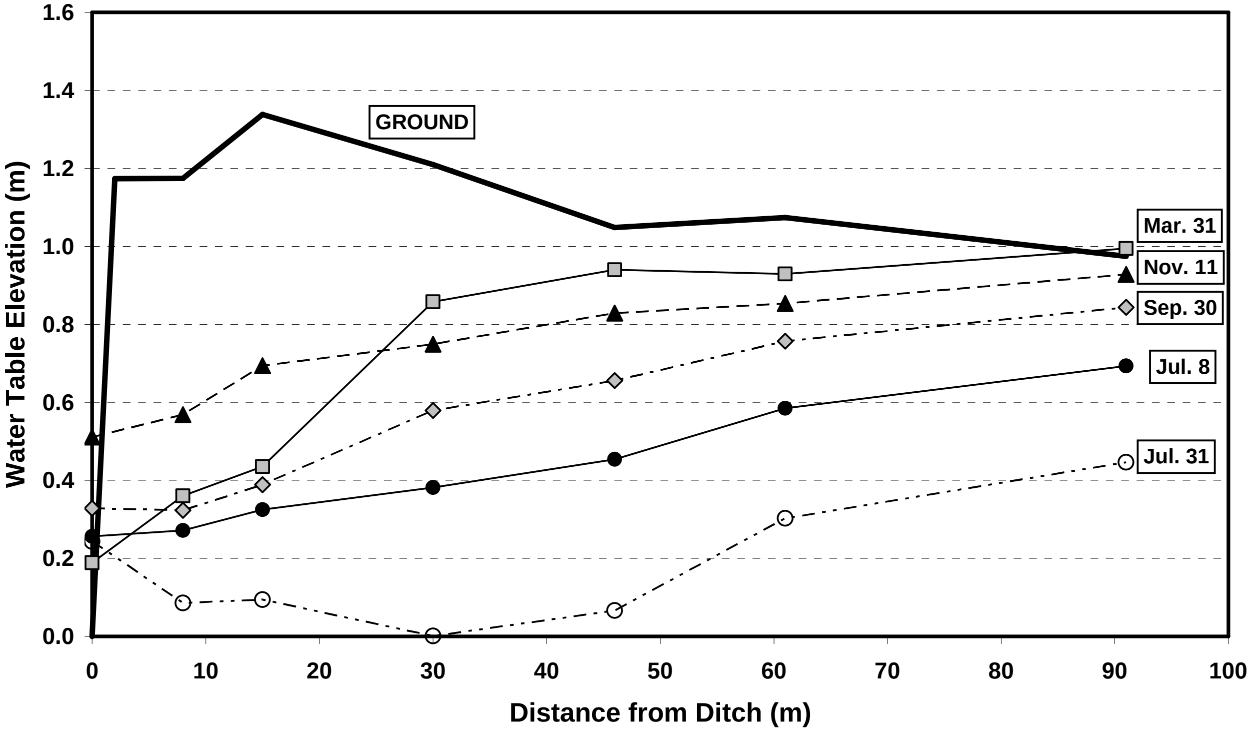

Figure 20. Water table depths observed on specific dates in wells along a transect perpendicular to the ditch at the Mildred Woods site in 2003. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

ABC Site

Shallow Ditch

Water table depths measured on the shallow ditch transect at the ABC mitigation site fluctuated with rainfall events and evapotranspiration (ET). Water table depths ranged from 1.0 to1.2 meters in August of 2002 (Figure 21) to at or above the soil surface after rainfall events particularly during the winter months (Figures 21 to 23). Water table depth generally decreased as the distance of the monitoring well from the ditch increased. For most of the observations, the water table was deepest at 3.75 m and shallowest at 30 m. The water table depths at wells 11.25 and 15 m from the ditch were usually between those at 3.75 and 30 m. Water table depths were often less than 30 cm deep for all of the wells in this transect.

The water level in the ditch (presented in Figures 21 to 23 as depth below the soil surface at the top of the bank) fluctuated with rainfall and ET; however, ditch levels fluctuated over a tighter range (0.6 m to 1.2 m) than the water table depths measured on the transects (0.0 to 1.2 m). There was no evidence of beaver activity in the ditch during the study period. The measured fluctuations of the water level in the ditch was not likely too greatly influence water table depths measured in the well transects.

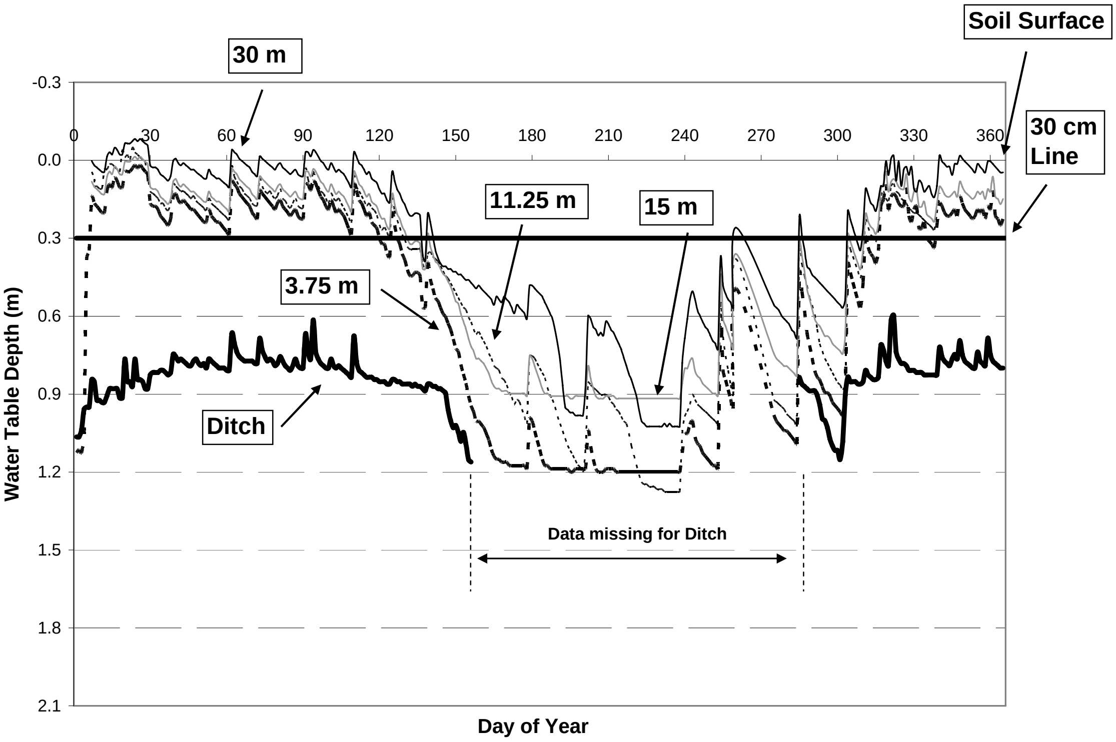

Figure 21. Observed daily water table depths in wells along a transect perpendicular to the shallow ditch at the ABC Mitigation site for 2002. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

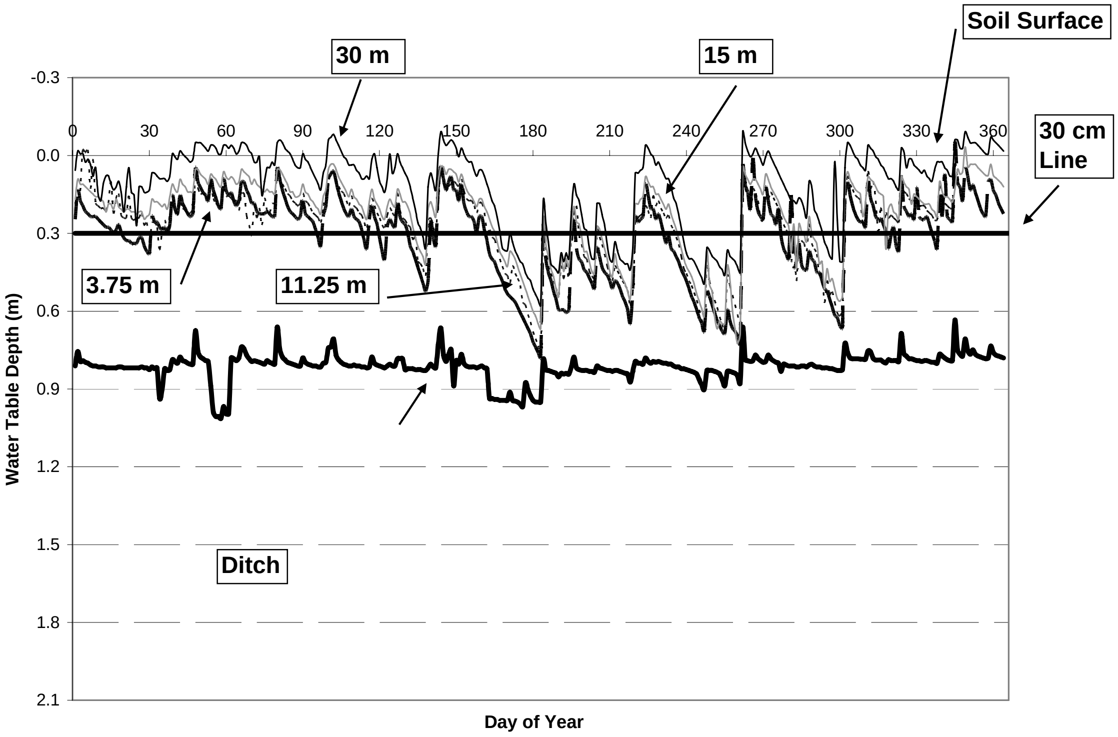

Figure 22. Observed daily water table depths in wells along a transect perpendicular to the shallow ditch at the ABC Mitigation site for 2003. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

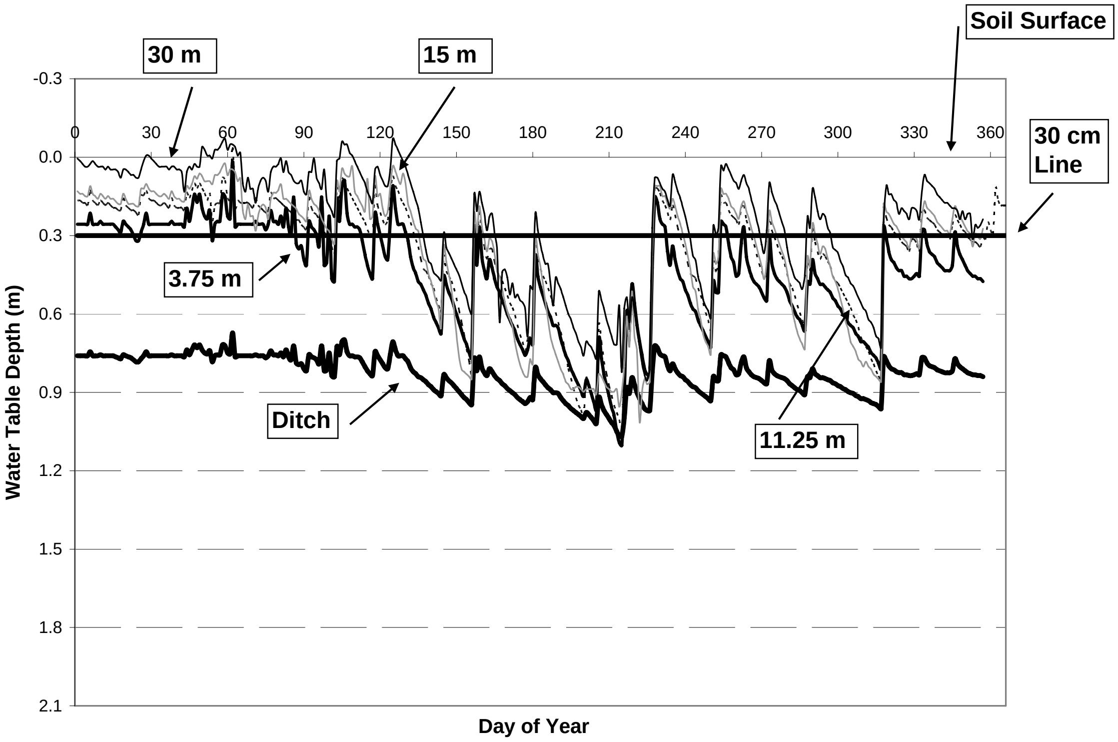

Figure 23. Observed daily water table depths in wells along a transect perpendicular to the shallow ditch at the ABC Mitigation site for 2004. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

Water table elevations (expressed in Figure 24 as elevation above the bottom of the ditch) increased with the distance of the well from the ditch for the first two wells (3.75 m and 7.5 m); however, differences in water table depths between 3.75 and 7.5 m were very small. The water table was mostly flat from 7.5 m to 30 m. Based on these data, it appears that the lateral effect of the ditch is less than 7.5 m, and possibly less than 3.75 m. The shape of the water table was consistent with the theoretical shape shown in Figure 1, but no points were available to define the shape of the at distances less than 3.75 m from the ditch. Fluctuations of the ditch water levels caused by rainfall and ET did not appear to affect the shape of the water table, however, if more wells had been installed between the ditch and the 3.75 m well, an effect of the ditch fluctuations might have been observed.

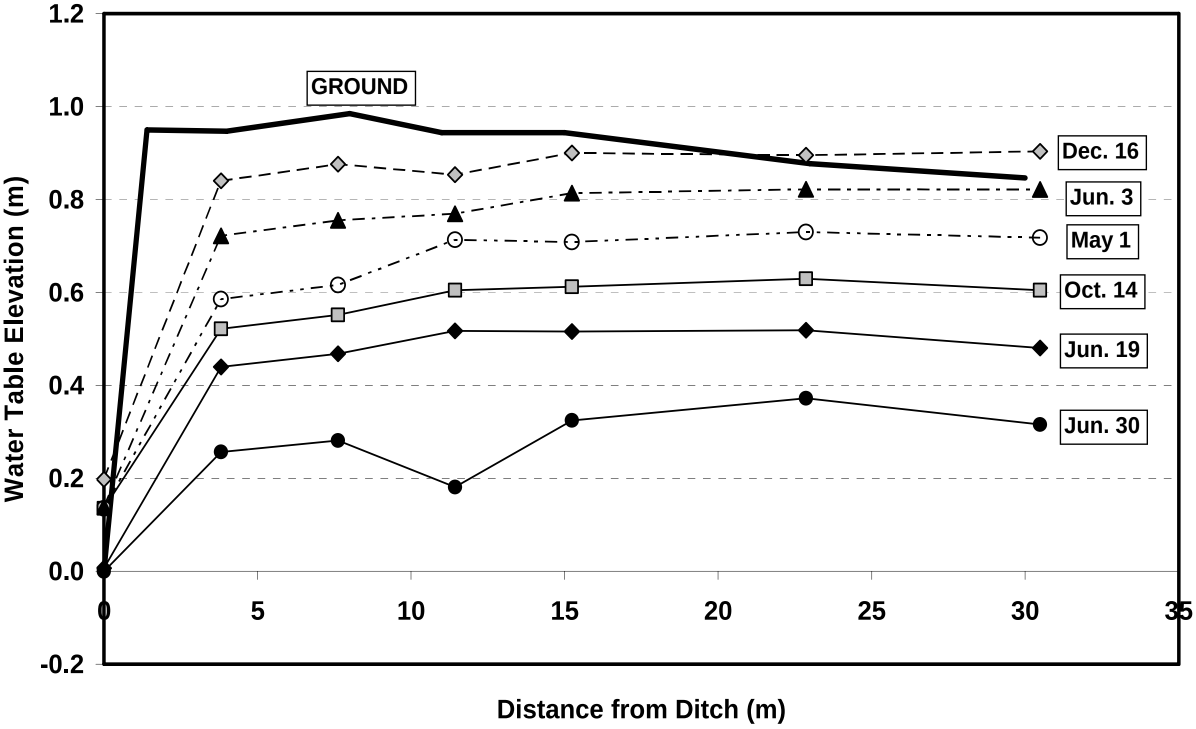

Figure 24. Water table depths observed on specific dates in wells along a transect perpendicular to the shallow ditch at the ABC Mitigation site in 2003. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

Deep Ditch

Water table depths measured on the deep ditch transect at the ABC Mitigation site fluctuated with rainfall events and evapotranspiration (ET). Water table depths ranged from 1.4 to 1.7 meters in August of 2002 (Figure 25) to at or above the soil surface after rainfall events, particularly during the winter months (Figures 25 to 27). Water table depth generally decreased as the distance of the monitoring well from the ditch increased. For most of the observations, the water table was deepest at 7.5 m and shallowest at 45

m. The water table depths at 15 and 22.5 m were usually between those at 7.5 and 45 m. Water table depths at the 7.5 m well were rarely less than 30 cm deep, while water table depths at the 22.5 and 45 m wells were frequently less than 30 cm deep.

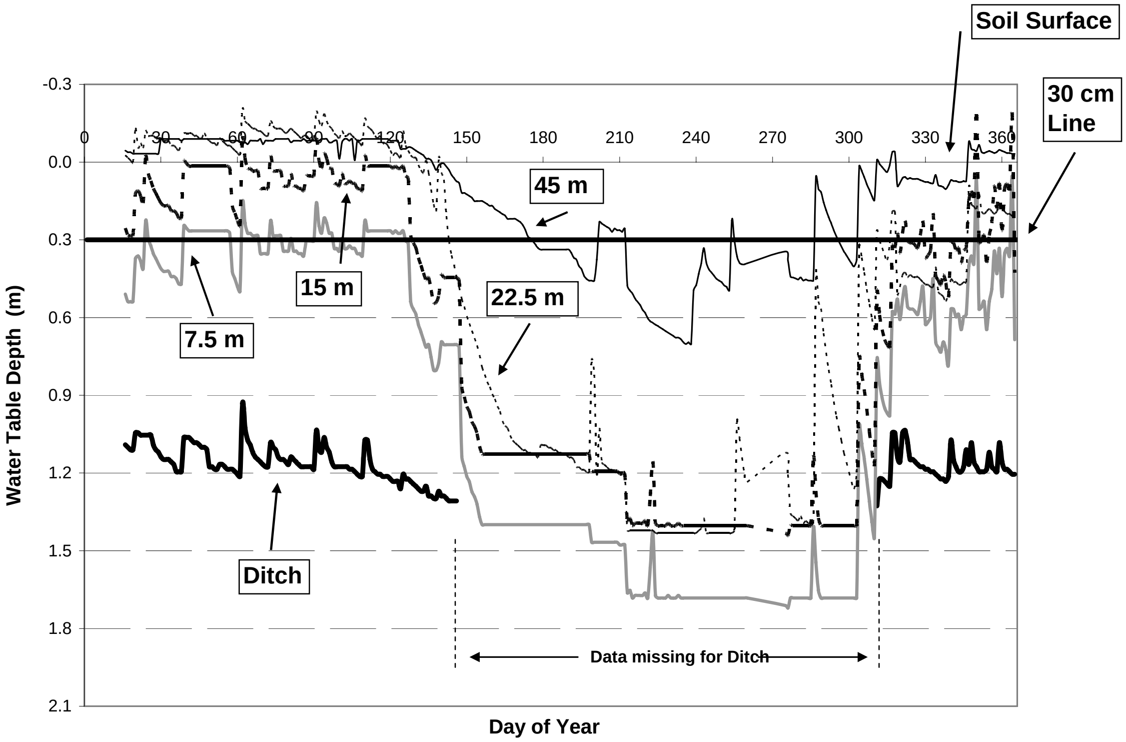

Figure 25. Observed daily water table depths in wells along a transect perpendicular to the deep ditch at the ABC Mitigation site for 2002. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

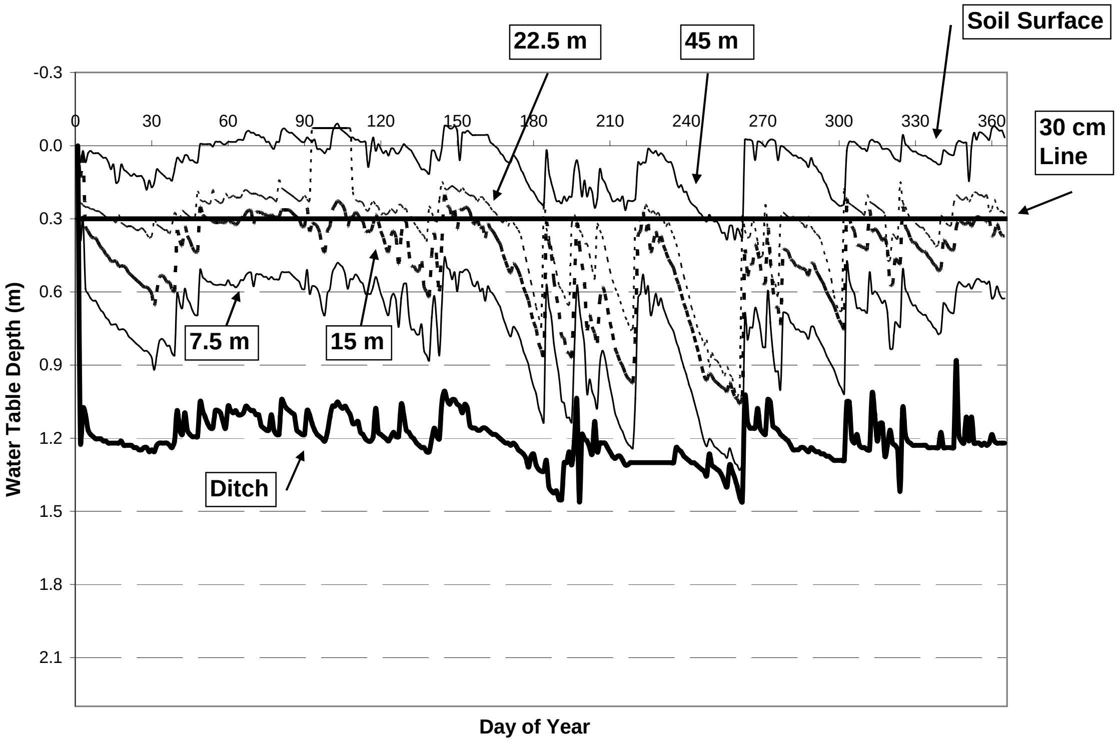

Figure 26. Observed daily water table depths in wells along a transect perpendicular to the deep ditch at the ABC Mitigation site for 2003. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

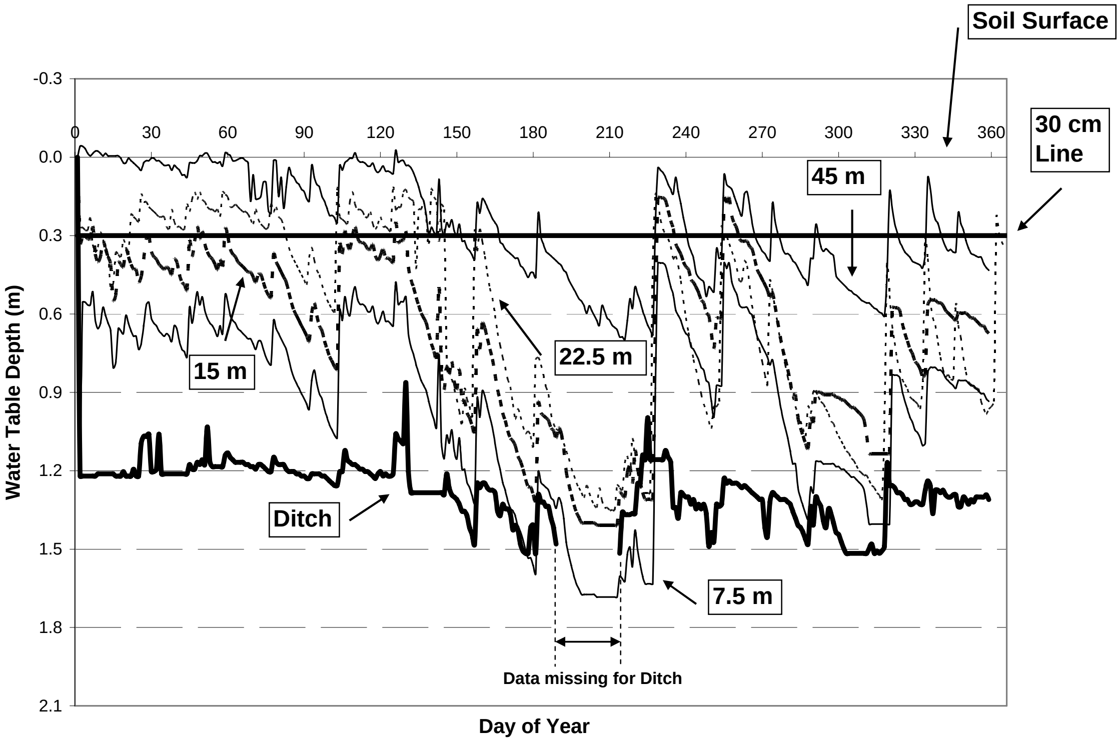

Figure 27. Observed daily water table depths in wells along a transect perpendicular to the deep ditch at the ABC Mitigation site for 2004. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

The water level in the ditch (presented in Figures 25 to 27 as depth below the soil surface at the top of the bank) fluctuated with rainfall and ET; however, ditch levels fluctuated over a tighter range (0.9 m to 1.5 m) than the water table depths measured on the transects (0.0 to 1.7 m). There was no evidence of beaver activity in the ditch during the study period. The water level in the ditch likely had little influence on the water table depths measured in the wells on this transect.

Water table elevations (expressed in Figure 28 as elevation above the bottom of the ditch) increased as the distance of the well from the ditch increased up to 30 m (100 ft). Most of this increase occurred within 15 and 22.5 m, especially during wet periods when the water table was shallow. The water table was mostly flat from 30 m to 60 m;

however the water table elevation at the 60 m well was less than at the 30 m well when conditions were dry. This may have been caused by a greater ET demand farther from the ditch. A change in vegetation occurred 45 m from the ditch and extended past the last transect well. From Figure 28, the ET demand in this area was probably greater than the demand closer to the ditch. The shape of the water table was consistent with the theoretical shape shown in Figure 1, except when the water table at 60 m was lower than at 30 m. Fluctuations of the ditch water levels caused by rainfall and ET did not appear to affect the shape of the water table. Results in Figure 28 indicate the lateral effect of the ditch is less than 30 m, and possibly less than 22 m. .

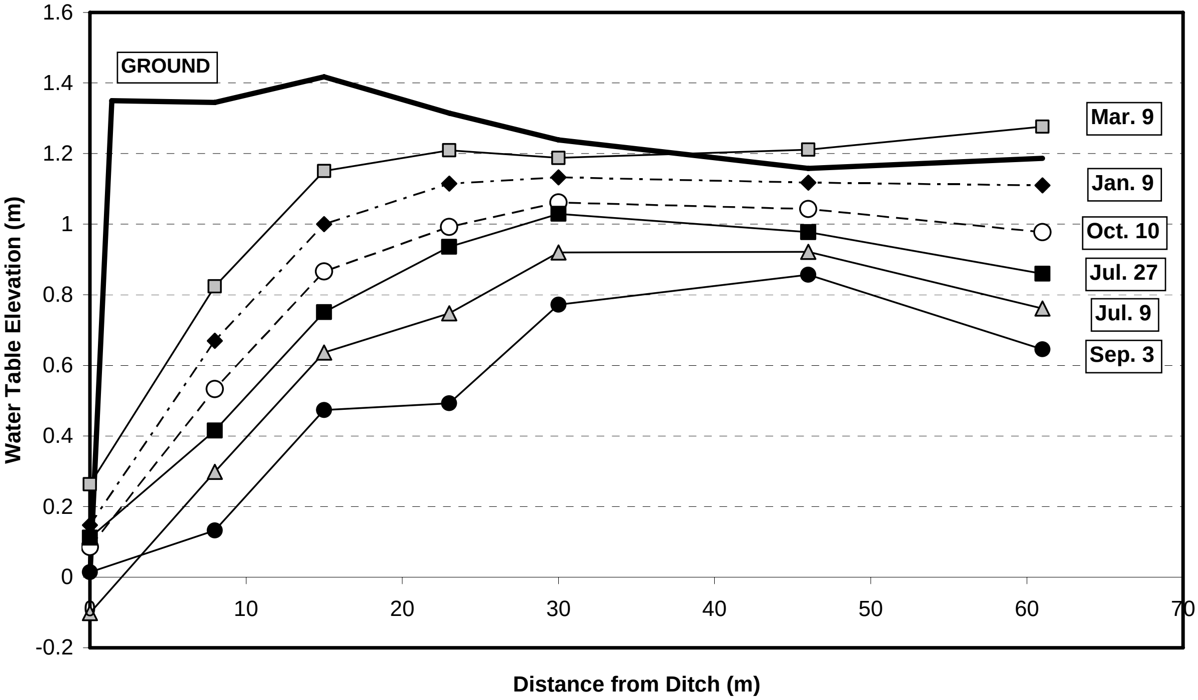

Figure 28. Water table depths observed on specific dates in wells along a transect perpendicular to the deep ditch at the ABC Mitigation site in 2003. Distances of the wells from the ditch are shown. Also shown is the water level in the ditch, expressed as a depth below the soil surface at the top of the bank.

Hydrologic Criterion Results & Lateral Effect

The data for all sites were analyzed to determine the maximum duration that the water table at each well stayed above the 30 cm depth during the growing season. Results varied from year-to-year (as expected) because of weather variability.

Mildred Woods

Maximum durations for each observation well at Mildred Woods are plotted in Figure 29. The critical duration at this site (5% of the growing season) is 12 days; so the lateral effect of the drainage ditch (call it x for convenience) is the distance from the ditch where the water table is within 30 cm of the surface for 12 consecutive days in 50% of the years. At distance x the water table will be within 30 cm of the surface for 12 or more consecutive days in 50% of the years, but not in every year. For any given year, the water table at x may remain in the top 30 cm for more or less than 12 days, depending on weather conditions. So it not possible to simply compare the measured number of consecutive days plotted in Figure 29 with 12 to determine the lateral effect, x. In order to define a reference duration for each year of observation, DRAINMOD was used to determine a threshold drain spacing for conditions of this site following procedures described by Skaggs et al. (2005). Simulations were conducted for a 54-year period (1951-2004) of local weather data and using site-specific soil data for multiple drain spacings. (Soil data can be found in Appendix 1). The threshold spacing for the Mildred Woods site was determined to be 96 m. This means that the land midway between ditches 96 m apart would satisfy the criterion in 50% of the years. Next DRAINMOD was used with the threshold ditch spacing and depth along with recorded rainfall data for 2002-2004 to predict the maximum consecutive duration that the water table would be above the 30 cm depth for those specific years. These threshold durations were 20 days fro 2002, 13 days for 2003, and 10 days for 2004, and are plotted as “threshold condition” in the bar plot of Figure 29.

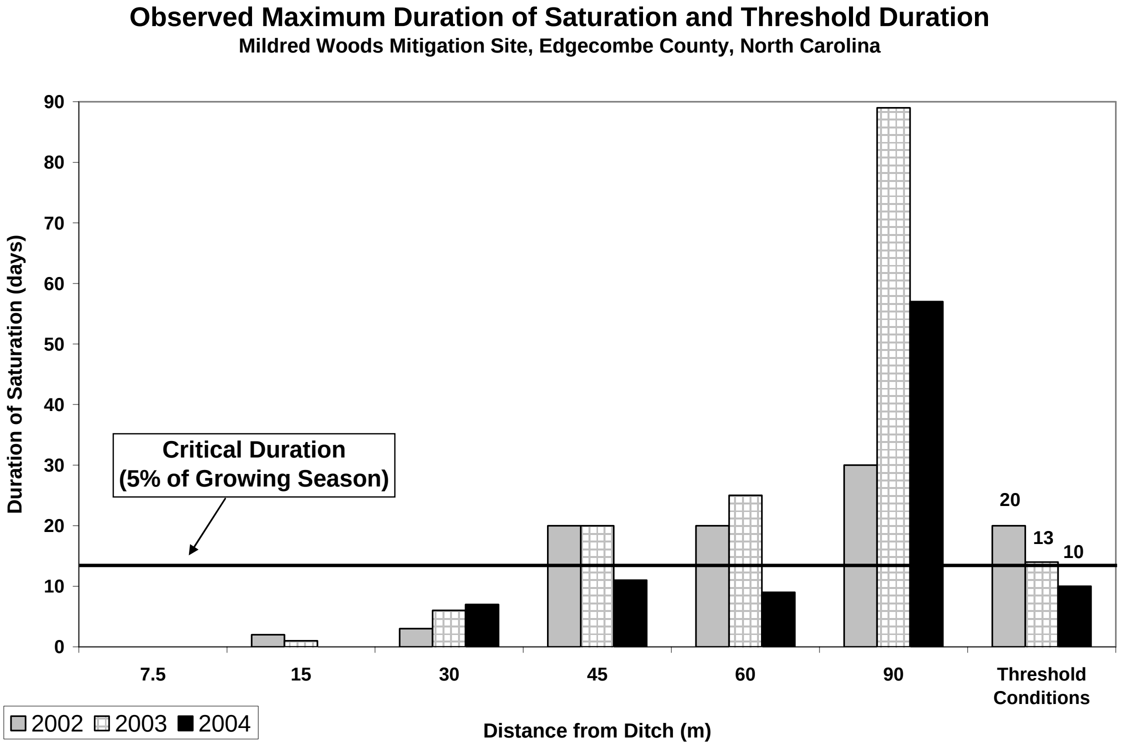

Figure 29. Observed and predicted number of consecutive days when water table was within 30 cm of the surface during the growing season plotted by year for the Mildred Woods site. Threshold conditions represent the number of days in each year for a site that barely satisfies the wetland hydrologic criterion.

Using these values as a reference, the durations plotted in Figure 29 can be analyzed to estimate the lateral effect. For example, the duration predicted for threshold conditions for 2002 was 20 days. This means that a site that would barely satisfy the wetland hydrologic criterion in 50% of the years over a 54-year period would have had the water table within 30 cm of the surface for 20 consecutive days during the growing season in 2002. This is very close to the measured duration at a distance of 45 m from the ditch in 2002 (Figure 29). So based on data from 2002, the estimate of the lateral effect is 45 m.

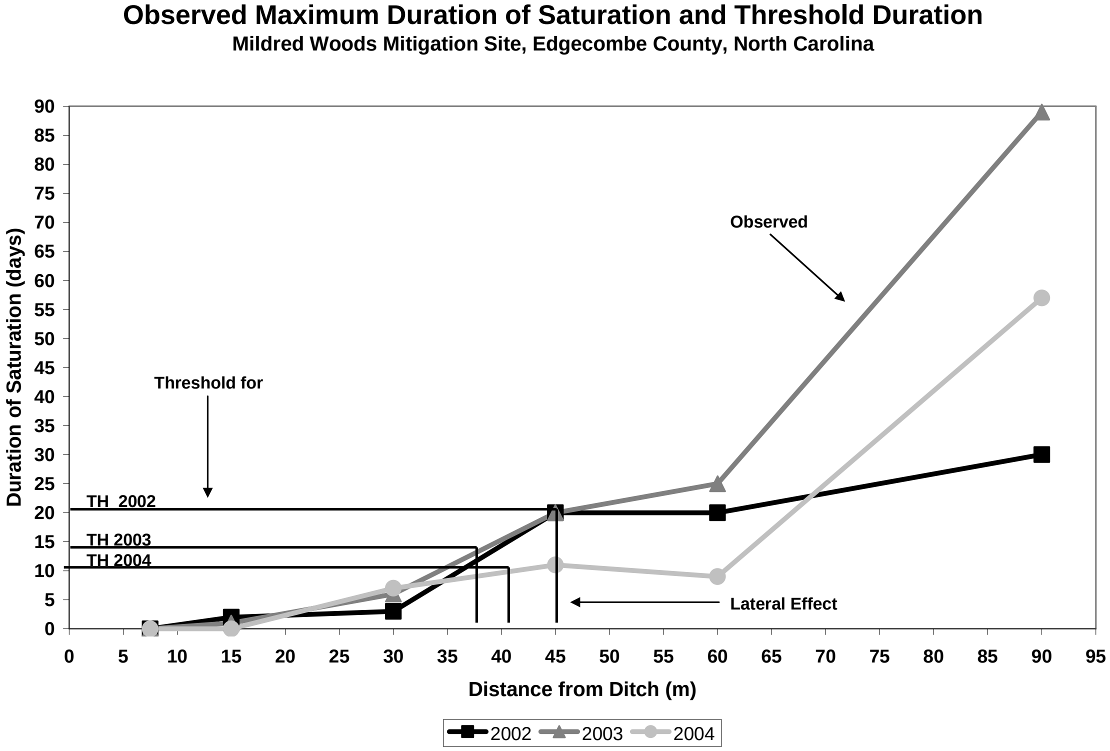

Figure 30. Observed consecutive number of days with water table within 30 cm of surface as a function of distance from ditch at the Mildred Woods site. Threshold (TH) values are the number of consecutive days that a site barely satisfies the criterion would have in each year.

Results in Figure 29 may be plotted by year as shown in Figure 30, for easy determination of the lateral effect. Once the measured duration is plotted versus distance from the ditch for a given year, the lateral effect can be estimated as the intercept of that curve and the duration predicted for the threshold ditch spacing for that year (Figure 30). Application of this method resulted in estimated lateral effects of 45 m for 2002, 37 m for 2003, and 41 m for 2004 (Figure 30).

ABC Site

Shallow Ditch

Maximum durations for each observation well at shallow ditch at the ABC site are plotted in Figure 31. The critical duration at this site (5% of the growing season) is 13 days. Simulations, using the method prescribed earlier, were conducted for the 54-year period (1951-2004) of local weather data for multiple drain spacings. The threshold ditch spacing and depth along with recorded rainfall data for 2002-2004 were used to predict the maximum consecutive duration that the water table would be above the 30 cm depth for those specific years. Those durations are plotted as “threshold condition” in the bar plot of Figure 31. They were 13 days for 2002, 16 days for 2003, and 5 days for 2004.

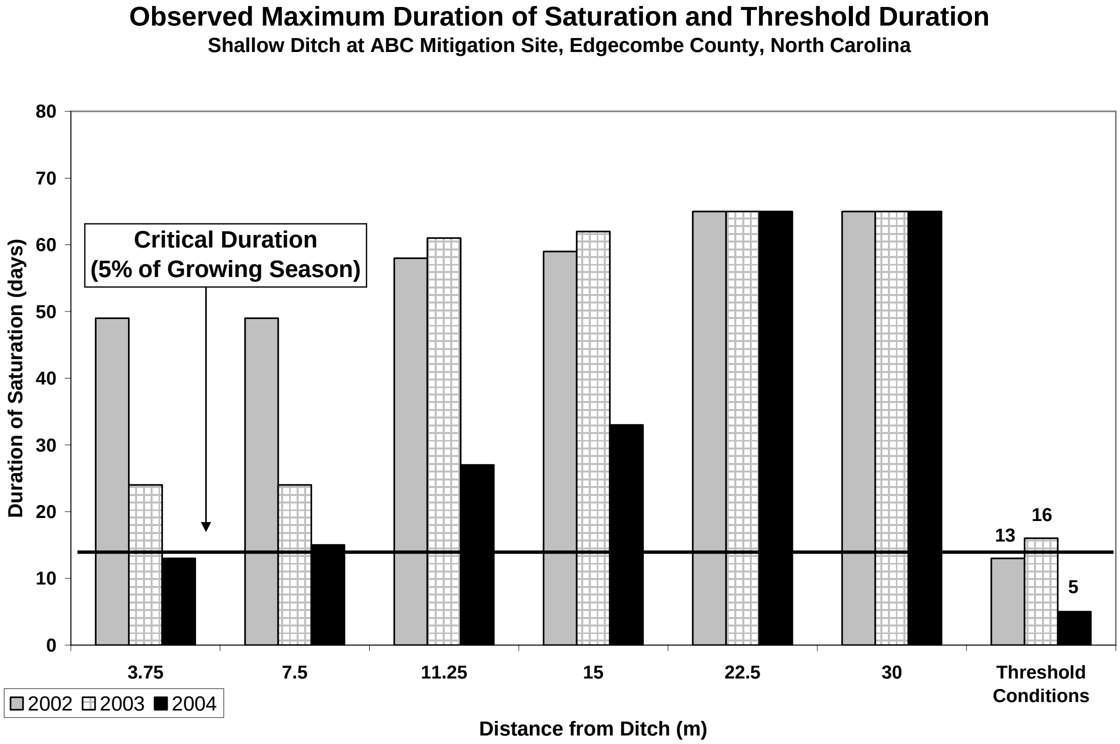

Figure 31. Observed and predicted number of consecutive days when water table was within 30 cm of the surface during the growing season plotted by year for the Shallow Ditch at the ABC site. Threshold conditions represent the number of days in each year for a site that barely satisfies the wetland hydrologic criterion.

In contrast to the Mildred Woods site, threshold conditions shown in Figure 31 are all below the maximum consecutive days for any given year / distance from the ditch combination. Based on the threshold conditions, it may be concluded that the lateral effect is less than 3.75 m for this ditch.

Deep Ditch

Maximum durations for each observation well at deep ditch at the ABC site are plotted in Figure 32. Threshold conditions for this ditch were simulated using the manner described previously. Those durations were 13 days for 2002, 18 days for 2003, and 6 days for 2004, and are plotted as “threshold condition” in the bar plot of Figure 32.

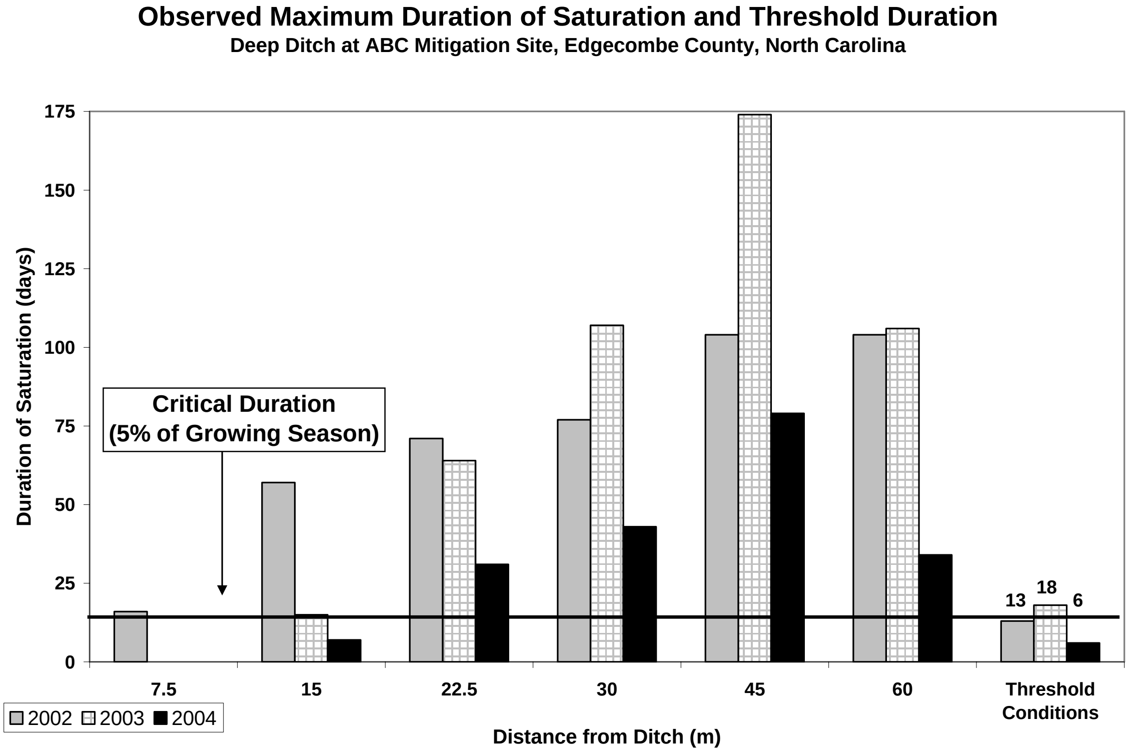

Figure 32. Observed and predicted number of consecutive days when water table was within 30 cm of the surface during the growing season plotted by year for the Deep Ditch at the ABC site. Threshold conditions represent the number of days in each year for a site that barely satisfies the wetland hydrologic criterion.

Using these threshold condition values as a reference, the duration plotted in Figure 32 can be analyzed to estimate the lateral effect. The duration predicted for threshold conditions for 2002 was 13 days, which is very close to the measured duration at a distance of 7.5 m from the ditch in 2002 (Figure 33). So based on data from 2002, the estimate of the lateral effect x = 7.5 m.

Results in Figure 32 may be plotted by year as shown in Figure 33, for easy determination of the lateral effect, as was done above for Mildred Woods. Once the measured duration is plotted versus distance from the ditch for a given year, the lateral effect was estimated as the intercept of that curve and the duration predicted for the threshold ditch spacing for that year (Figure 33). As shown, the predicted lateral effect was 15 m based on the data for 2003 and about 14 m for 2004, compared to 7.5 m based on data for 2002.

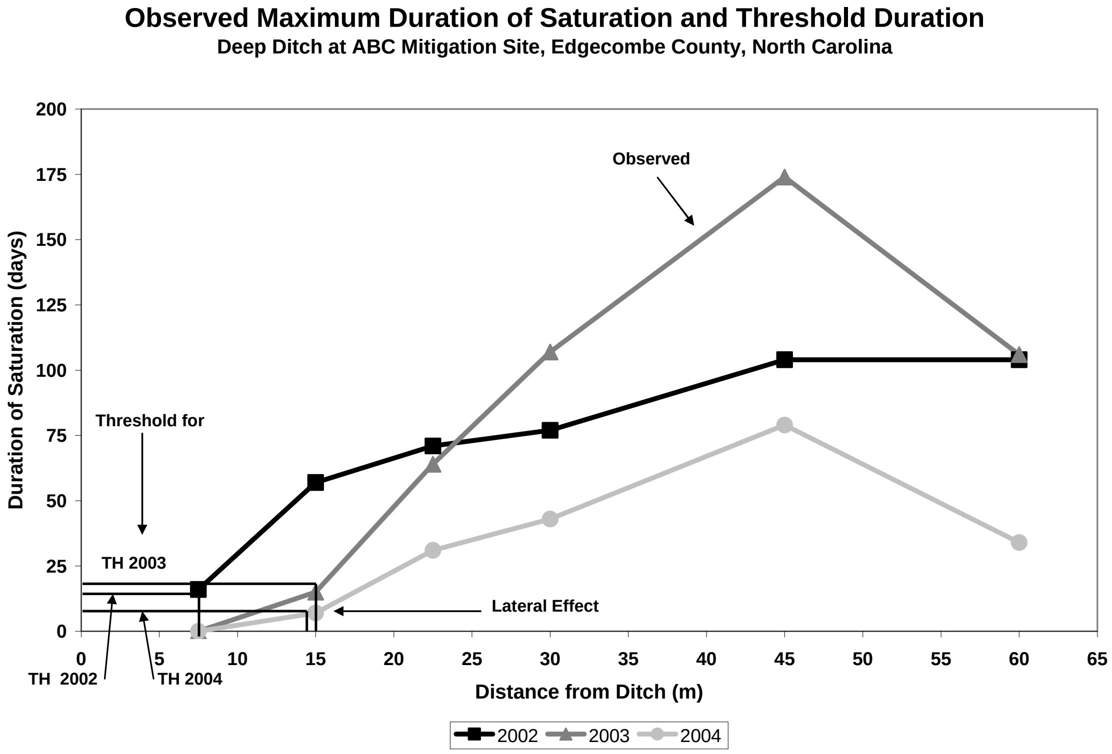

Figure 33. Observed consecutive number of days with water table within 30 cm of surface as a function of distance from ditch at the Deep Ditch at the ABC site. Threshold (TH) values are the number of consecutive days that a site barely satisfies the criterion would have in each year.

Results of estimations of the lateral effect for all sites are summarized in Table 8.

Table 8. Summary of results for lateral effect at drainage ditches based on 3 years of observations.

	Mildred Woods		**ABC Shallow Ditch**		**ABC Deep Ditch**	
	Threshold Condition (days)	**Lateral Effect (m)**	**Threshold Condition (days)**	**Lateral Effect (m)**	**Threshold Condition (days)**	**Lateral Effect (m)**
2002	20	45	13	< 3.75	13	7.5
2003	13	37	16	< 3.75	18	15
2004	10	41	5	< 3.75	6	14
Avg		41		< 3.75		12

Summary

Data to test the methods developed in this research were collected at two wetland mitigation sites in eastern North Carolina. One site was at Mildred Woods in Edgecombe County and the other near the town of Pinetown in Beaufort County. Water tables were measured at several locations on transects perpendicular to drainage ditches on both sites. Data were collected for the three-year period 2002-2004 on one transect at the Mildred Woods site and for the three and one half year period 2002-June 2005 on two transects at the ABC site. An analysis of the data indicated that the lateral effect of drainage ditches was between 37 and 45 m (121 to 150 ft) at the Mildred Woods site, less than 3.5 m for the shallow ditch (1.0 m deep) at the ABC site and between 7.5 and 15 m (25 to 50 ft.) at the deep ditch (1.3 m deep) site at the ABC site. Analysis of the data to both test the model and to determine the lateral effects based on long-term analyses will be presented in detail in Chapter 4 of this study.

CHAPTER 3: HYDROLOGY SIMULATIONS USING DRAINMOD AND WATRCOM

Introduction

Observed water table data were measured at each well on each transect for a period of three years. Simulations were conducted to determine whether the wetland hydrologic criterion would be satisfied in one-half or more of the years on a long-term basis for each well. The water balance simulation models DRAINMOD and WATRCOM were calibrated for each well by comparing model predicted water table depths and observed water table depths at every point in time. The calibrated models were then used to simulate conditions for a 54-year period in order to estimate the distance from the ditch where the criterion was satisfied in exactly one-half of the years.

DRAINMOD Model Description

The computer model DRAINMOD (Skaggs, 1978) is a water balance simulation model originally developed to evaluate the long term hydrologic response of a drainage system design in agricultural settings with a relative shallow depth to the impermeable layer and overall shallow water tables (Evans and Fausey, 1999). For a unit area of soil extending from the impermeable layer to the soil surface, the model describes water table fluctuations at the midpoint between parallel ditches or subsurface drains (often referred to as tile drains). An overview of the theory and inputs used in DRAINMOD is presented here.

Water Balance

Essential to a simulation model utilized to predict or evaluate a drainage system are the water balance calculations. The water balance refers to the mass balance of water into and out of a system with defined boundaries. Schematically, the system described by DRAINMOD is shown in Figure 1 (adopted from Burchell, 2003).

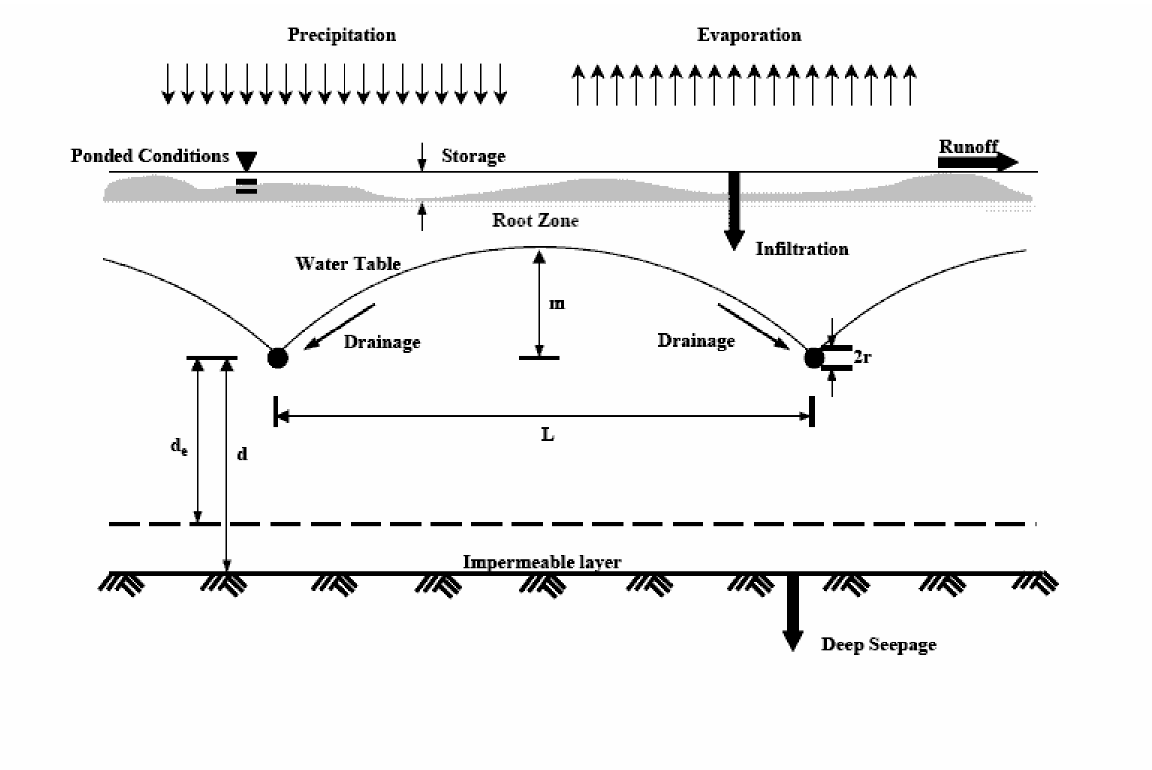

Figure 1. Schematic of drainage system described in DRAINMOD

DRAINMOD calculates fluctuations of the water table at a point midway between a parallel drain system. It does so on an hour-by-hour, day-by-day basis over a defined simulation period. The water balance equation for a section of the soil profile midway between drains is,

$$\Delta V_a = D + ET + DS - F \qquad [1]$$

where

ΔV_{a} = change in the water free pore space (cm),

D = drainage from or subirrigation to (cm),

ET = evapotranspiration (cm),

DS = deep seepage (cm),

and F = infiltration (cm).

Components of precipitation, runoff, and surface storage are not calculated in [1]. These variables are related in a water balance at the soil surface, as

$$P = F + \Delta S + RO \qquad [2]$$

where

P = precipitation (cm),

ΔS = change in surface storage (cm),

F = infiltration (cm),

and RO = runoff (cm).

The model assumes precipitation that falls during a time step is either infiltrated, stored in depressions on the surface, or is lost from the system by surface. Surface runoff is assumed to occur when surface depressions are filled with water and precipitation is greater than infiltration. The standard time step of the model is one hour. When precipitation is absent and the drainage from the system is so small as to produce minor changes in the water table depth, the time step is one day. Alternatively, when precipitation is so intense as to exceed the infiltration capacity the time step decreases to 0.05 hours (USDA, 1980).

Subsurface Drainage

Subsurface flow calculations within DRAINMOD are accomplished using analytical solutions for steady flow to the drains in two cases: ponded and non-ponded conditions. In the case of ponding (profile saturated and water ponded on surface), the model uses the solution for drainage flux developed by Kirkham (1957). Kirkham showed that under ponded conditions a majority of the flow to the drain enters the soil surface within a relatively short distance of the drain line.

In the case of non-ponded condition, DRAINMOD uses the Hooghoudt solution for drainage flux (Bouwer and van Schilfgaarde, 1963). The Hooghoudt equation is a steady state drainage flux equation that may be written as,

$$q = \frac{8Kd_e m + 4Km^2}{L^2} \tag{3}$$

where

q = drainage flux (cm/hr),

K = effective lateral hydraulic conductivity (cm/hr),

d_e = equivalent depth of the impermeable layer below the drain (cm),

m = midpoint water table height above the drain (cm),

and L = drain spacing (cm).

Use of the Hooghoudt equation assumes flow to the drain lines, for the most part, is in the lateral direction. The product of the drainage flux, q, from [3] and the time step provide the drainage value in [1]. The numerator of equation [3] contains two product components in an effort to account for the variance in the flux due to the position of the water table in soil profile. The left hand side, $8Kd_em$, accounts for drainage flux below the drain line. The left hand side, $4Km^2$, accounts for drainage flux above the drain line.

Surface Drainage

Storage of water on the soil surface is composed of two units with both units assumed to be evenly distributed over the ground surface. The first unit represents micro storage in isolated depressions caused by general surface roughness. The second represents macro storage caused by surface depressions, potholes, or berms. After available surface depressional storage is filled to capacity, any excess water is assumed to leave the site, i.e. it is considered runoff (RO) and is no longer available for infiltration in to the soil profile. A reduction of the time step during periods of intense precipitation allows for a more accurate calculation of infiltration rates and, consequently, runoff amounts when maximum surface storage is exceeded.

Evapotranspiration

Evaporative losses from the soil surface and subsurface and vegetative transpiration are combined in the evapotranspiration (ET) component of DRAINMOD. ET is calculated using a two step process (Skaggs, 1978). First, the daily potential evapotranspiration (PET) value is calculated for the day and distributed over a twelve-hour period (6:00 am to 6:00 pm). If rainfall occurs during one of these hours, the PET is set equal to zero for that hour. Second, the model checks to determine if soil water is available to meet the demands of PET. If water is available, ET is set equal to PET. If sufficient water is not available, ET is set equal to the amount available from the soil profile. Water availability is a function of depth of the water table, presence of water table in root zone, and depth of the dry zone. Water is first removed from surface storage, if any. Next, depending on the depth of the water table, water is supplied by upward flux of water from the water table. At some point, upward flux becomes less than PET and water must be removed from the root zone. This will create a dry zone that can extend from the soil surface down to the effective depth of the root zone. Water deficit in the root zone is the first to be recharged during a rainfall event. Therefore, it is possible for a lag to occur in the rise of the water table after a rainfall event. During drought periods, it is possible for all water potentially available to meet PET in the root zone to be depleted from the profile. At this point, the model will set ET equal to the upward flux rate which can become zero.

Values of PET are obtained using one of two methods. Daily values can be determined by any method chosen by the user and read as input directly. Often, all the input variables required to create daily PET values, as in Penman-Montieth method

(Jensen et al., 1990), are unavailable. DRAINMOD can also calculate PET using the Thornthwaite method (Thornthwaite, 1948). The Thornthwaite method uses a heat index value based on mean monthly temperature data. The equation for calculating the heat index follows:

$$I = \sum_{i=1}^{12} (\overline{T}_i / 5)^{1.514} \qquad [4]$$

where

I = heat index,

$\overline{\mathrm{T}}$ = monthly mean temperature (ºC).

Correction factors are applied to compensate for the day length and latitude. PET calculations using the Thornthwaite method require only temperature values and therefore would seem to lack the robustness, and perhaps accuracy, of the Penman Montieth method. Mohammad (1978) showed that the Thornthwaite method provides acceptable approximations of PET compared to pan evaporation values for North Carolina. The Thornthwaite method tended to over predict ET from July through November. Monthly correction factors to compensate for over and under predictions of the Thornthwaite method are inputs to the model.

Infiltration

DRAINMOD uses the Green-Ampt (Green and Ampt, 1911) equation to calculate the infiltration rate. The reader is referred to Hillel (1998) and Skaggs (1978) for details of the Green-Ampt equation and its application in DRAINMOD.

Input Parameters

DRAINMOD input parameters include

Weather Data – precipitation, maximum and minimum temperature, daily PET values or heat index and monthly PET correction factors, and latitude of site.

Soil Properties – soil water characteristics, hydraulic conductivities, crop rooting depths and lower limit water content (wilting point).

*Drainage Desig*n – drain spacing and depth, depth to impermeable layer, weir depths if in controlled drainage, surface depressional storage, drain radius, and depth of surface storage.

WATRCOM Model Description

The computer simulation model WATRCOM (Parsons, 1987; Parson et al., 1991b) is a finite element water management simulation model developed to quantify drainage and water table fluctuations on a watershed scale. Whereas the model DRAINMOD was designed to predict the water table response to a parallel drainage system design, the two dimensional model WATRCOM was designed to predict water table fluctuations for multiple intersecting drains of varying depths and slopes. The two dimensional version of the model was used in this study. A schematic of the water flows simulated in WATRCOM is shown in Figure 2.

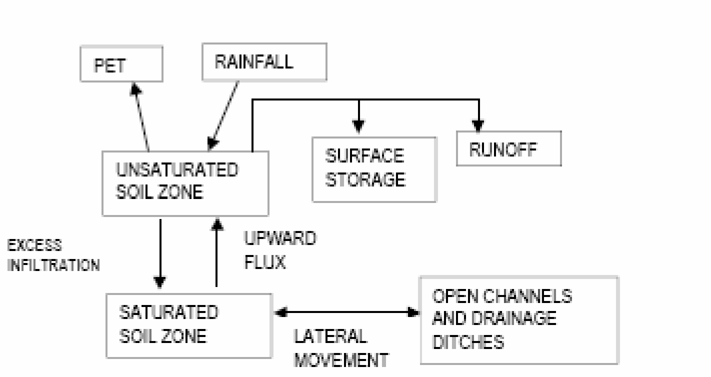

Figure 2. Schematic of water flows simulated in WATRCOM (adopted from Parsons and Trettin, 2001)

Water Balance

WATRCOM calculates water balances on an hour-by-hour day-by-day basis. During periods of precipitation, a time step of one hour is used, otherwise a time step of four hours is used. The overall water balance equation (Parsons et al., 1991a) used in the model is as follows:

$$\Delta SAT + \Delta UNS = RAIN - AET - OUTFLOW - RO - RSTOR - PSTOR \qquad [5]$$

where

ΔSAT = the change in the volume of water stored in the saturated zone per unit surface area (m),

ΔUNS = the change in the volume of water stored in the unsaturated zone per unit surface area (m),

RAIN = the amount of rainfall per unit surface area (m),

AET = the actual evapotranspiration per unit surface area (m),

OUTFLOW = the subsurface lateral flow across the boundaries per unit surface area (m),

RO = the amount of surface runoff from the region per unit surface area (m),

RSTOR = the change in potential runoff in retention storage per unit surface area (m),

and PSTOR = the change in detention storage per unit surface area (m).

Subsurface Drainage

WATRCOM fractionates subsurface water movement into two components: saturated flow and unsaturated flow. The change in the water table and water stored in the saturated zone is determined by solving the Boussinesq equation for one- or two-dimensional flow (van Schilfgaarde, 1974). The Boussinesq equation is based on the Dupuit-Forchheimer assumptions (Nieber and Feddes, 1999) and is as follows (Parsons and Trettin, 2001),

$$f(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K(h)h\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(h)h\frac{\partial h}{\partial y}\right) + R \qquad [6]$$

where

f(h) = drainable porosity function of water table height,

h = water table height above impermeable layer (m),

K = lateral saturated hydraulic conductivity function of water table height (m/day),

R = vertical recharge rate in m/day at the water table at each location in the region;

x,y = location coordinates of the region (m),

and x = time (days).

Movement of water in the unsaturated zone is assumed one-dimensional and in the vertical direction and is treated with methods similar to those in DRAINMOD.

Surface Drainage

WATRCOM treats water stored on the soil surface as retention storage and detention storage (Parsons et al., 1991a). Retention storage is water stored in depressions and as discussed for surface storage in DRAINMOD. For each time step, water remaining in retention storage is available for infiltration or ET. Detention storage represents storage greater than retention storage that can move, based on slope, to surrounding areas. Surface water movement crossing the boundary of the system is treated as runoff and is subsequently unavailable to the system.

Evapotranspiration

WATRCOM calculates the water balance to satisfy the demand of ET as follows (Parsons et al., 1991a):

$$AETi = WSPi + UPFi + RZWi \qquad [7]$$

where

i = the node number in the area,

AET = actual evapotranspiration (cm),

WSP = amount evaporated from water ponded on the surface (cm),

UPF = water moving vertically from the water table to the root zone to meet ET (cm),

and RZW = amount of water supplied from the root zone (cm).

To satisfy the ET demand, water is first removed from retention / detention storage, second from the water table, and third from the root zone. If the calculated PET value is greater than the total available stored on the surface plus available water from the water table, then water is removed from the root zone to a predefined lower limit. This method is similar to that used in DRAINMOD (Skaggs, 1978).

As with DRAINMOD, daily PET estimates may be entered directly or calculated using the Thornthwaite method.

Infiltration

WATRCOM calculates infiltration using the Green-Ampt equation similar to DRAINMOD. The Green-Ampt parameters are a function of the soil properties and calculations for infiltration are based on the depth of the water table in the profile. For each time step, rainfall intensity is calculated and compared to the Green-Ampt parameters. Based on this comparison, water is either infiltrated, ponded or lost to overland flow. In the event a dry zone has been developed, infiltrated water is first used to fill the dry zone. Then, infiltrated water is used to recharge the water table.

Input Parameters

The WATRCOM model version used in this report utilized DRAINMOD format rainfall and temperature files. WATRCOM input parameters include

Weather Data – precipitation, maximum and minimum temperature, daily PET values or heat index and monthly PET correction factors, and latitude of site.
Soil Properties – soil water characteristics, hydraulic conductivities, crop rooting depths and lower limit water content (wilting point), and drainable porosity.
*Drainage Desig*n – drain elevation, elevation of ground, weir elevation if in controlled drainage, surface depressional storage, drain radius, length of transect and measurement spacing along transect.

Modeling Input Data

Weather

On site precipitation data were collected at both the Mildred Woods and ABC field sites for a period of January 2002 to December 2004 (May 2005 at ABC site) as described in Chapter 2.The data were synthesized into hourly data for model input. The rainfall data set can be found in Appendix 1. Other weather parameters were not measured on site. Maximum and minimum daily temperature values were collected from nearby weather stations. The Tarboro (COOP ID 318500) station was used for the Mildred Woods site. The Belhaven (COOP ID 310674) station was used for the ABC site. Using these data, heat index values were calculated for use of the Thornthwaite method of calculating PET. The heat index for Mildred Woods and the ABC site were 75 and 76, respectively. Temperature data sets can be found in Appendix 2.

For long-term simulations, daily precipitation and maximum and minimum temperature values were collected from nearby weather stations for the period 1951 to 2001. Daily precipitation values from the COOP stations were disaggregated in to hourly values for use in the models using the computer program RAINSIM (Robbins, 1988). These data sets are not printed in this report due their excessive length. The long-term data are available online at the following: http://www.sercc.com/.

Soil Properties

Required soil inputs included the soil water characteristic curve, Green-Ampt coefficients, volume drained, depth to impermeable layer, lateral and vertical hydraulic conductivity, and upward flux values.

Soil cores from both sites were collected during March of 2004. Pressure plate tests (Klute, 1986) were performed on each core. Results of the pressure plate test give the soil water characteristic curve, also known as soil water retention curve. This curve is a plot of volumetric soil water content versus pressure head. Values for vertical hydraulic conductivity were obtained using a constant head test. For this test, a constant head of water was maintained on the surface of a fully saturated core and the flow rate measured. The vertical conductivity was then calculated using the time required for a volume of water to pass through the core. The equation used is a direct application of the Darcy equation for flow in a vertical column (Hillel, 1998) as follows:

$$K = \frac{qL}{\Delta H} \qquad [8]$$

where

K = vertical conductivity (m/hr),

q = flux (m/hr),

L = length of core (m),

and ΔH = difference in hydraulic head from top to bottom of core (m) .

The flux, q, was defined as the ratio of flow rate, Q, to cross sectional area, A, of the core. The hydraulic head drop, ΔH, was defined as the height of the soil core, L, plus the depth of water, δ , ponded on top of the core. This leads to the following equation:

$$K = \frac{QL}{[(L+\delta)A]} \qquad [9]$$

Within the DRAINMOD model, a soil prep subroutine is used to determine Green-Ampt coefficients, upward flux values, and volume drained information based on soil water characteristic data and vertical hydraulic conductivity. The reader is referred to The

DRAINMOD reference report (USDA, 1980) for an extensive discussion on calculations of Green-Ampt, upward flux and volume drained calculations as it applies to the models.

DRAINMOD Simulations

Statistical Measures

Three statistical measures were used to determine the goodness of fit of the predicted water table depths with observed values.

The first measure was the coefficient of determination, R^2 (Legates and McCabe, 1999). The coefficient of determination is defined as follows:

$$R^2 = \frac{\left(\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P}) \right)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2 \sum_{i=1}^{n} (P_i - \bar{P})^2} \qquad [10]$$

where

O = observed value,

P = predicted value,

and the overbar represents the average for the entire data set.

R^2 values indicate the strength of the "best fit" straight-line relationship between the predicted and the observed values, and it is the proportion of the total variation described by the model. For example, $R^2 = 0.80$ indicates that the model describes 80% of the variability of the observed data. For this study, R^2 values of 0.64 and above are considered a good.

The second statistical measure used was the coefficient of efficiency, E, (Legates and McCabe, 1999), (Nash and Sutcliffe, 1970). As stated in Fernandez et al (2005), "The coefficient of efficiency expresses the fraction of the error variance relative to the variance of the measured values." The equation for E is as follows:

$$E = 1.0 - \left\{ \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \right\} \qquad [11]$$

where

O = observed value for day i,

P = predicted value for day i,

and the overbar represents the average for the entire data set.

Values of E greater than 0.75 are considered good. Values between 0.36 and 0.75 are considered satisfactory (Motovilov et al., 1999).

The final statistical measured used in this study was the mean absolute error, MAE, (Fernandez et al., 2005). The MAE equation is as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left| P_i - O_i \right| \qquad [12]$$

where

O = observed value,

P = predicted value,

And n = total number of observations.

For this study, MAE values of less than 20 cm are considered satisfactory and values less than 10 cm are considered good.

Mildred Woods Site Calibrations

DRAINMOD was calibrated for Mildred Woods using observed water table data from January 2002 through August 2003 for the first three transect wells nearest the ditch. The three farthest wells were calibrated from January 2002 through December 2004. The discrepancy in calibration time was due to un-natural water table fluctuations near the ditch due to the influence of a downstream beaver dam beginning in September 2003 (See Chapter 2).

DRAINMOD was calibrated using known parameters and best estimates Parameters were then adjusted, within reason, to match observed water table plots for the calibration period. Soil boring performed in 2004 indicated a depth to the impermeable layer of approximately 4.8 meters. The boring was performed at one location approximately 400 m from the transect site. It was not possible to move the drill rig closer to the transect. For calibration purposes, the depth to the impermeable layer was originally set to 4.8 meters. This value was adjusted to 4.0 meters for calibration purposes. Drain depths were originally set to best match the depth from the soil surface to the bottom of the ditch. Drain depths were reduced for wells farther from the transect. The reduction in the drain depths allowed DRAINMOD to predict shallow water tables as resulting from perpendicular subsurface flow to the transect area. The effective drain radius was set to 20 cm or 10 cm and the drainage coefficient set to 2.0 cm to reduce the drainage constriction and allow for the open channel ditch design. Surface storage values were set originally to best describe surface conditions near the transect. These values were reduced for the last four wells to prevent extended periods of predicted ponding by the model. Based on site inspection during the time of auger hole measurements, there is a transition in soil series after the fourth well (30 m). Lateral conductivities were adjusted to account for this transition. DRAINMOD was designed to simulate the water balance between a system of parallel drains / ditches. Final DRAINMOD drainage design inputs for the Mildred Woods site are shown in Table 1. Soil input data can be found in Appendix 1.

Table 1. Final DRAINMOD calibration parameters for Mildred Woods.

	Distance from Ditch					
Model Parameter	**7.5 m**	**15 m**	**30 m**	**45 m**	**60 m**	**90 m**
Drain Spacing (m)	25.0	40.0	33.0	50.0	70.0	80.0
Drain Depth (m)	0.90	1.00	0.60	0.3	0.3	0.3
Depth to Impermeable Layer (m)	4.0	4.0	4.0	4.0	4.0	4.0
Max Surface Storage (cm)	2.5	2.5	1.25	1.25	1.25	1.25
Kirkham's Depth (cm)	1.25	1.25	0.75	0.75	0.75	0.75
Effective drain radius (cm)	20.0	20.0	20.0	10.0	10.0	10.0
Drainage coefficient(cm)	2.0	2.0	2.0	2.0	2.0	2.0
Lateral Conductivity(cm/hr)						
0 – 30 cm	30.0	30.0	30.0	3.0	3.0	3.0
30 – 120 cm	0.25	0.25	0.25	0.25	0.25	0.25
120 - Impermeable	3.0	3.0	3.0	3.0	3.0	3.0

Statistical measures for the DRAINMOD calibrations of the Mildred Woods site are summarized in Table 2.

Table 2. DRAINMOD calibration statistical results for Mildred Woods.

Mildred Woods Site Calibrations - DRAINMOD			
Distance of well from ditch	**Coefficient of Determination, R^2**	**Coefficient of Efficiency, E**	**MAE (cm)**
7.5 m	0.71	0.71	8.2
15 m	0.68	0.67	11.2
30 m	0.82	0.80	12.6
45 m	0.78	0.75	12.3
60 m	0.74	0.65	15.8
90 m	0.58	0.56	14.2

Values for the mean absolute error, MAE, increased as distance from the ditch increased. Values for the modeling efficiency, E, were in the high satisfactory range for the 7.5, 15, 45, 60, and 90 m wells. The efficiency was in the good range for the 30 m well. The topography of the landscape 20 meters past the last well was marked by very high surface storage. Water was ponded in this area several centimeters for extensive periods during the year. The model was unable to compensate for this change in topography and was not able to predict the dampened effects of ET due to a subsurface influx and therefore resulting in the highest MAE values farther out from the ditch. This is particularly evident in the summer of 2003 at the 60 and 90 m wells (Figures 7 and 8). Graphical representations showing the water table plots of the observed and calibration values are given in Figures 3 to 8. The influence of the beaver dam is evident, and noted, in Figures 3 to 5. Predicted water table depths are deeper than observed values for the fall and winter of 2003 - 2004 due to the un-natural rise in the water level in the ditch due to the downstream damming of the ditch. An inspection of Figures 3 to 5 shows the model predicted rapid rise and recession of the water table when large rain events occurred. An example of this “flashy” prediction can be observed in Figure 3 near April 26, 2003. These spikes may have been occurred at the site, but due an offset in the timing of the observed and predicted values, the plotted observed water table fluctuations did not produce similar trends. Therefore, the “flashy” predicted spikes in the figures should be discounted.

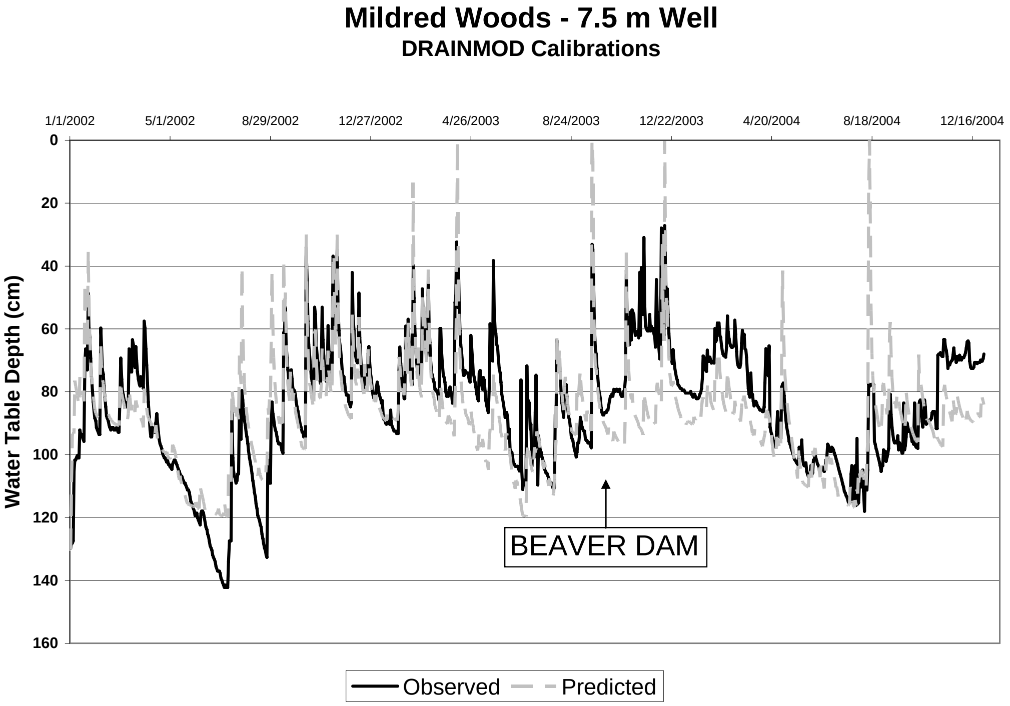

Figure 3. Water table plot for DRAINMOD calibration at Mildred Woods 7.5 m well

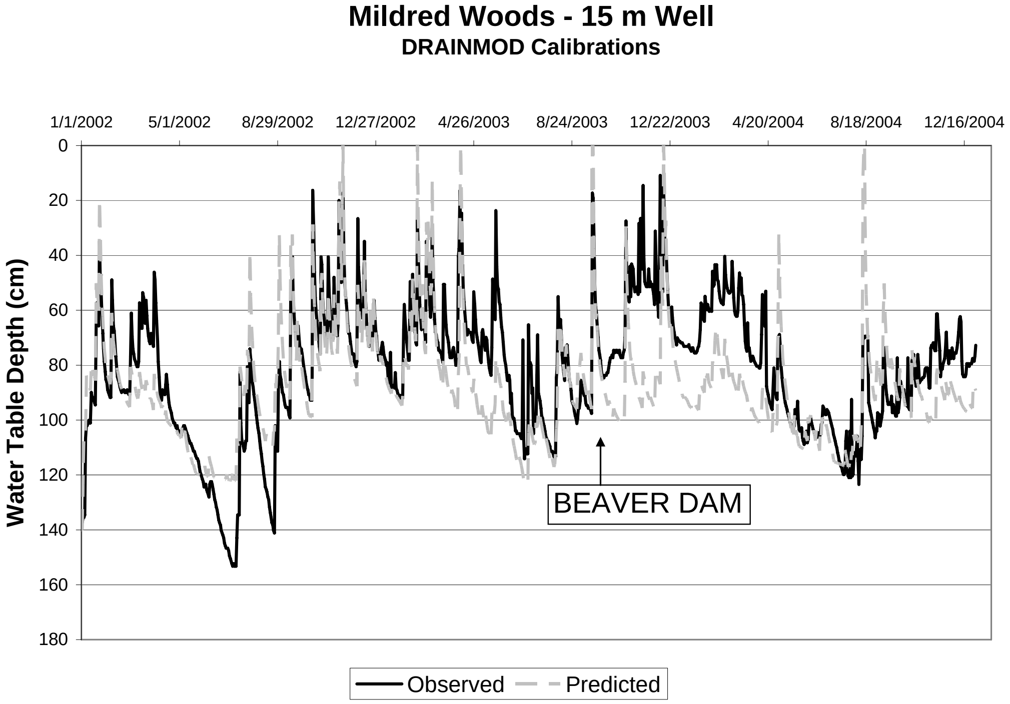

Figure 4. Water table plot for DRAINMOD calibration at Mildred Woods 15 m well

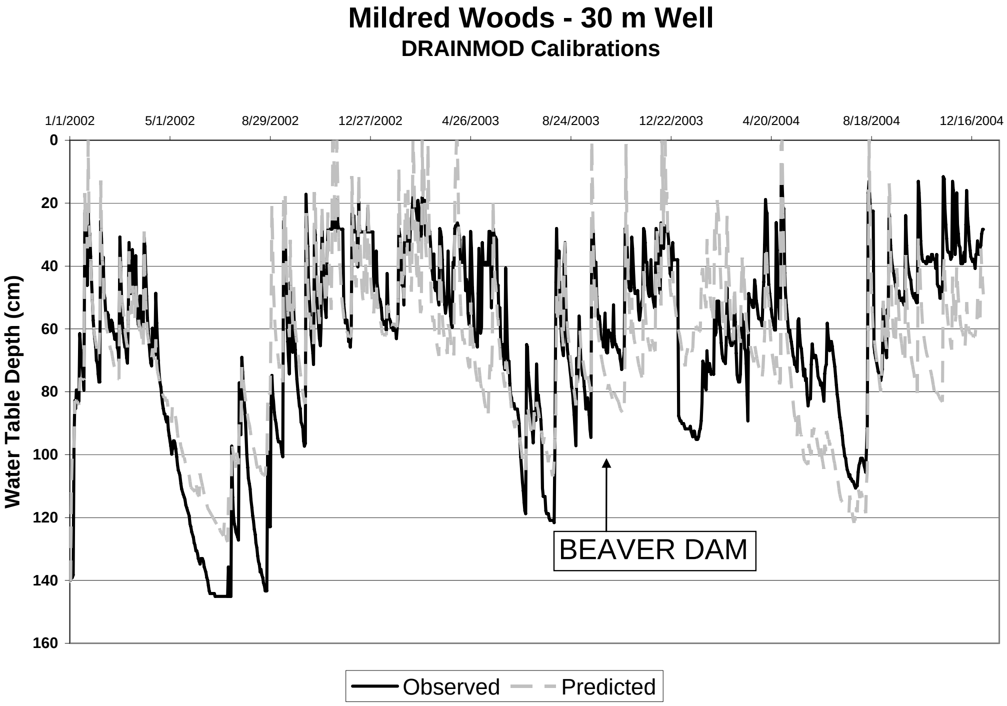

Figure 5. Water table plot for DRAINMOD calibration at Mildred Woods 30 m well

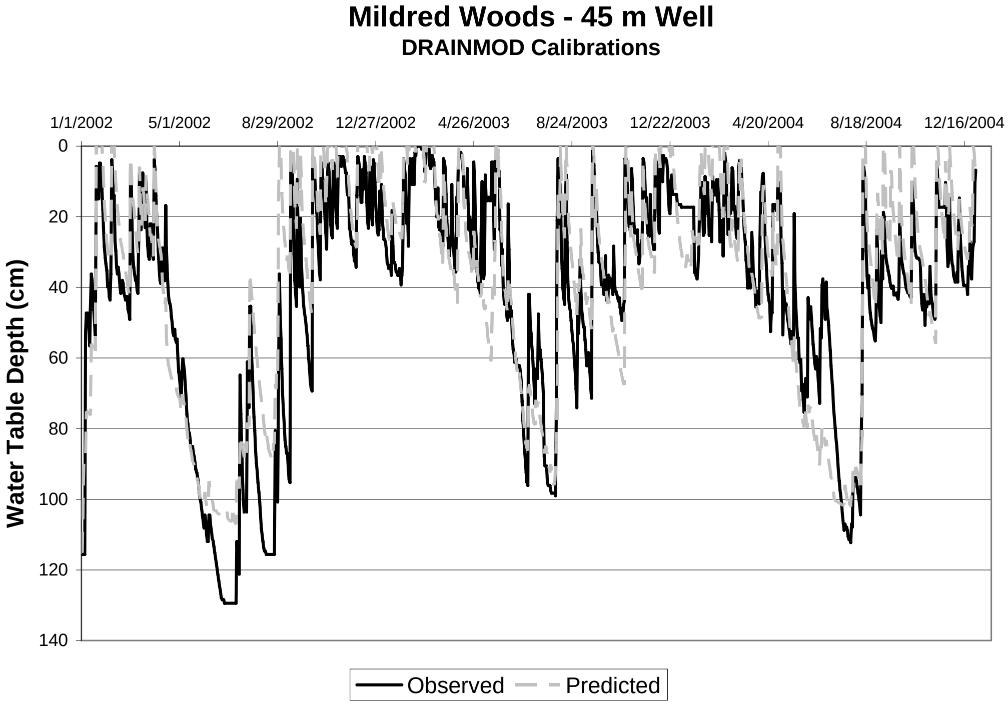

Figure 6. Water table plot for DRAINMOD calibration at Mildred Woods 45 m well

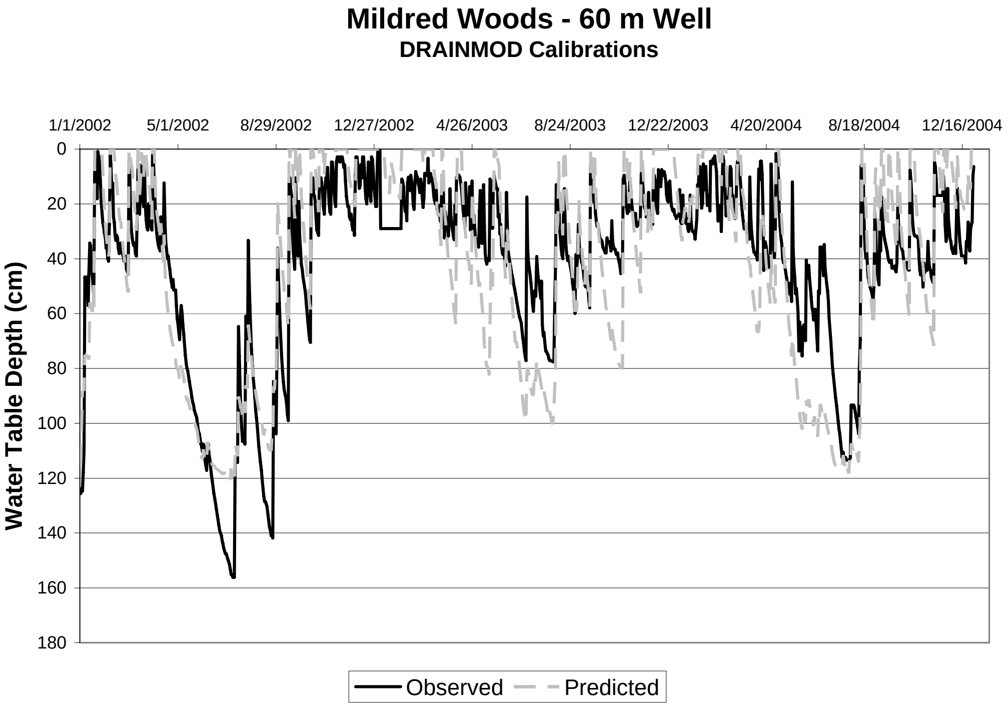

Figure 7. Water table plot for DRAINMOD calibration at Mildred Woods 60 m well

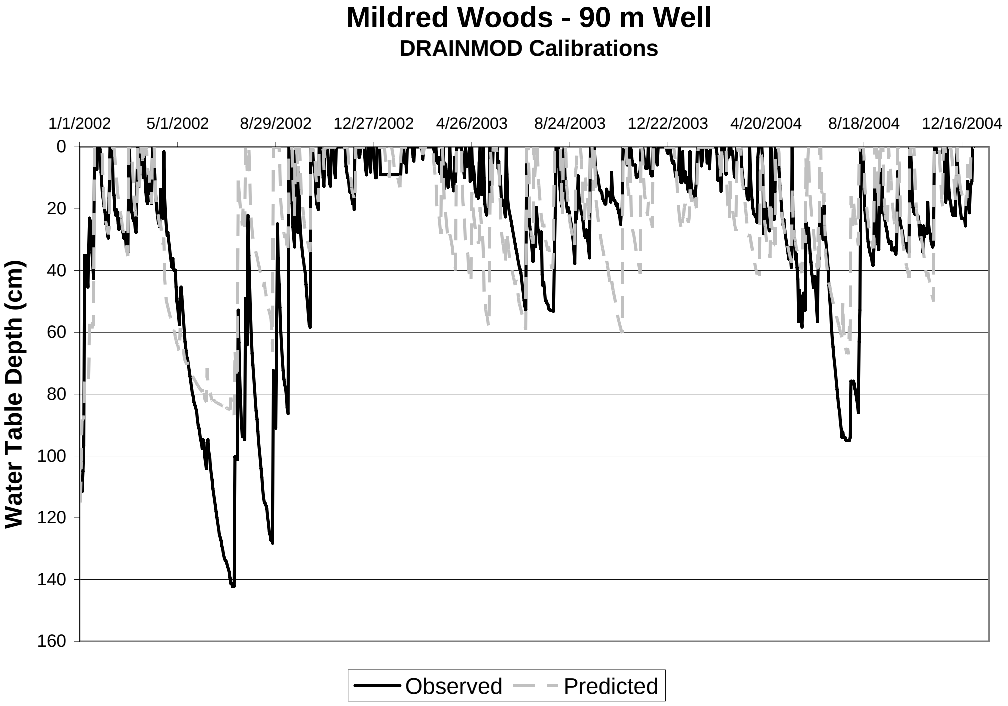

Figure 8. Water table plot for DRAINMOD calibration at Mildred Woods 90 m well

ABC Site Calibrations

Shallow Ditch

DRAINMOD was calibrated for the ABC shallow ditch using observed water table data from January 2002 through December 2004. Again, DRAINMOD was calibrated using known parameters and best estimates. Parameters were then adjusted, within reason, to match observed water table plots for the calibration period. Soil boring performed in 2004 showed a depth to the impermeable layer of approximately 6.4 meters. The boring was performed at one location approximately 200 m from the transect site. Field conditions prevented moving the drill rig closer to the transect. For calibration purposes, the depth to the impermeable layer was originally set to 6.4 meters from the soil surface. This value was adjusted to 6.0 meters during calibration. Drain depths were set to best match the depth from the soil surface to the bottom of the ditch. All drain depths were reduced by 20 cm for successful calibrations. The effective drain radius was set to 15 cm and the drainage coefficient set to 2.0 cm to allow for the open channel ditch design. Surface storage values were set originally to best describe surface conditions near the transect. Soil input data can be found in Appendix 1. Final DRAINMOD drainage design inputs are shown in Table 3.

Table 3. .Final DRAINMOD calibration parameters for ABC site shallow ditch.

	Distance from Ditch					
Model Parameter	**3.75 m**	**7.5 m**	**11.25 m**	**15 m**	**22.5 m**	**30 m**
Drain Spacing (m)	40.0	45.0	55.0	60.0	70.0	75.0
Drain Depth (m)	0.70	0.70	0.70	0.70	0.60	0.60
Depth to Impermeable Layer (m)	6.0	6.0	6.0	6.0	6.0	6.0
Max Surface Storage (cm)	2.0	2.0	2.0	2.0	4.0	4.0
Kirkham's Depth (cm)	1.0	1.0	1.0	1.0	2.0	2.0
Effective drain radius (cm)	15.0	15.0	15.0	15.0	15.0	15.0
Drainage coefficient(cm)	2.0	2.0	2.0	2.0	2.0	2.0
Lateral Conductivity(cm/hr)						
0 – 30 cm	25.0	25.0	25.0	25.0	25.0	25.0
30 – 120 cm	0.25	0.25	0.25	0.25	0.25	0.25
120 - Impermeable	0.5	0.5	0.5	0.5	0.5	0.5

Statistical measures for the DRAINMOD calibrations of the ABC site shallow ditch are summarized in Table 4.

Table 4. DRAINMOD calibration statistical results for ABC site shallow ditch.

ABC Site Shallow Ditch Calibrations - DRAINMOD			
Distance of well from ditch	**Coefficient of Determination, R^2**	**Coefficient of Efficiency, E**	**MAE (cm)**
3.75 m	0.78	0.76	12.1
7.5 m	0.75	0.71	12.3
11.25 m	0.79	0.77	10.3
15 m	0.82	0.80	9.5
22.5 m	0.80	0.57	10.3
30 m	0.80	0.68	9.5

Modeling efficiency, E, values for the 3.75, 11.25, and 15 m wells are considered good. E values for the remaining wells were satisfactory. Overall, MAE values were better than those for the Mildred Woods calibrations. Similar to Mildred Woods, DRAINMOD over-predicted the impact of ET during portions of the summer periods for the wells farthest from the ditch, therefore the coefficient of efficiency values for these wells were low compared to wells closer to the ditch. A graphical representation showing the water table plots of the observed and calibration values are given in Figures 9 to 14.

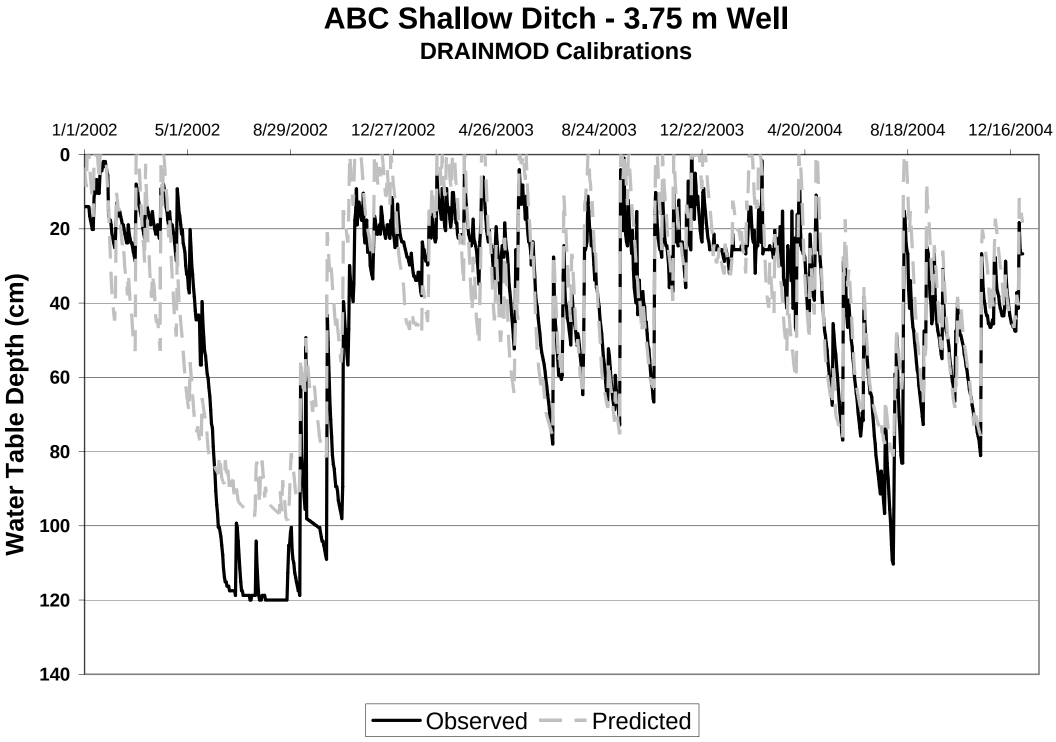

Figure 9. Water table plot for DRAINMOD calibration at ABC Shallow Ditch 3.75 m well

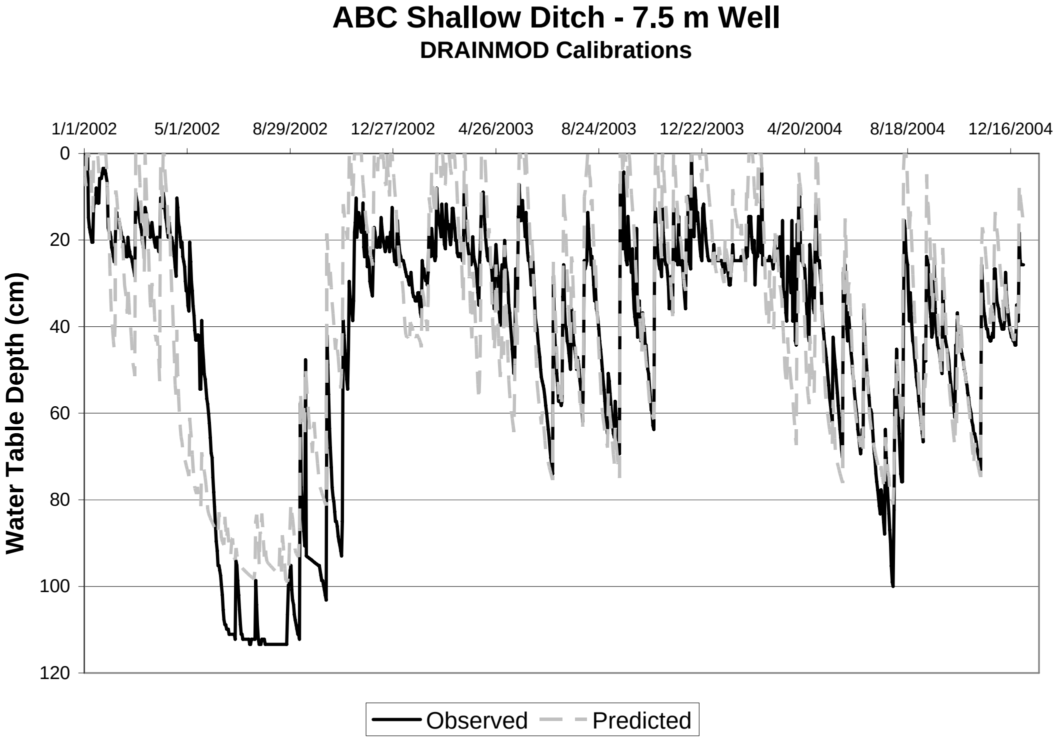

Figure 10. Water table plot for DRAINMOD calibration at ABC Shallow Ditch 7.5 m well

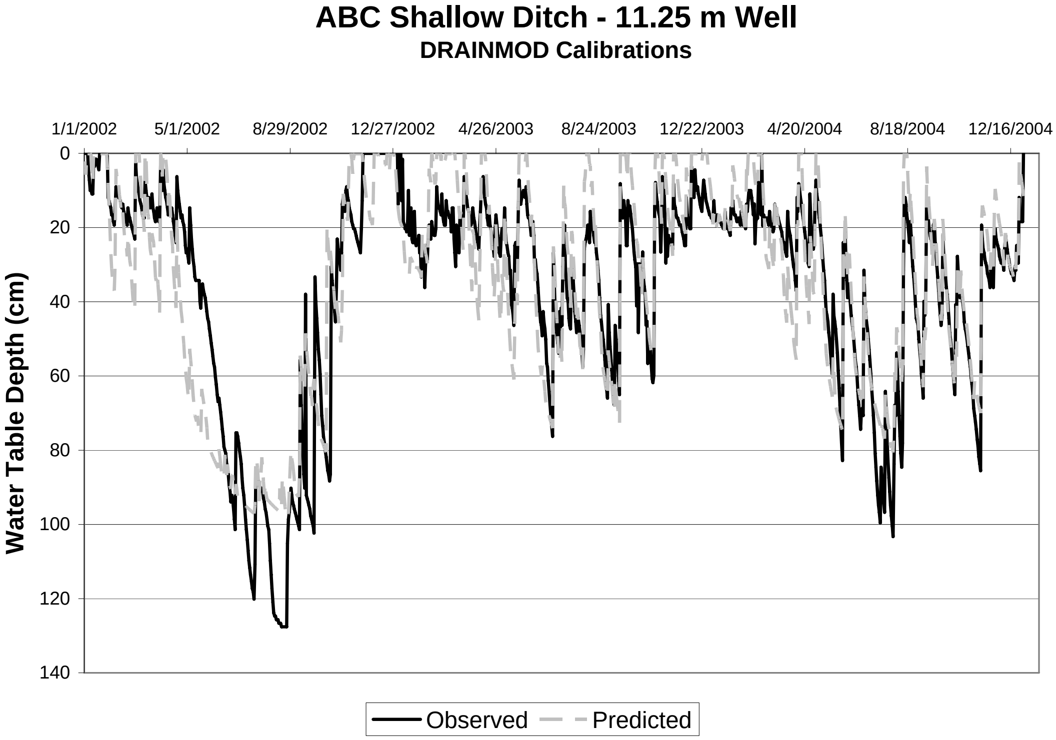

Figure 11. Water table plot for DRAINMOD calibration at ABC Shallow Ditch 11.25 m well

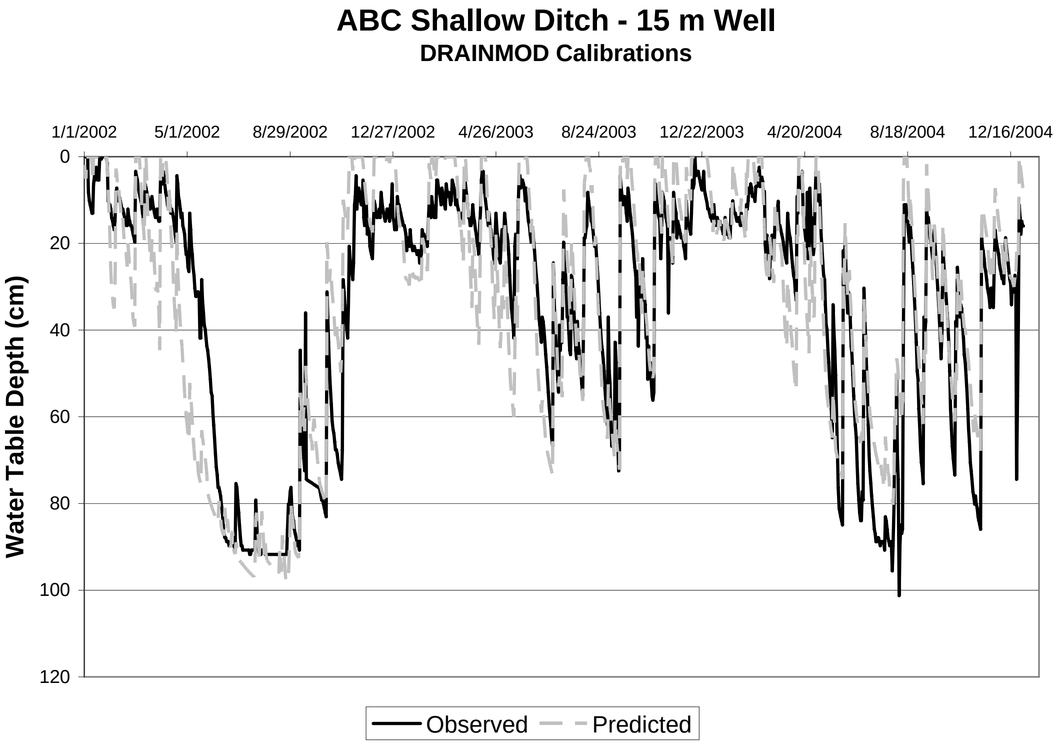

Figure 12. Water table plot for DRAINMOD calibration at ABC Shallow Ditch 15 m well

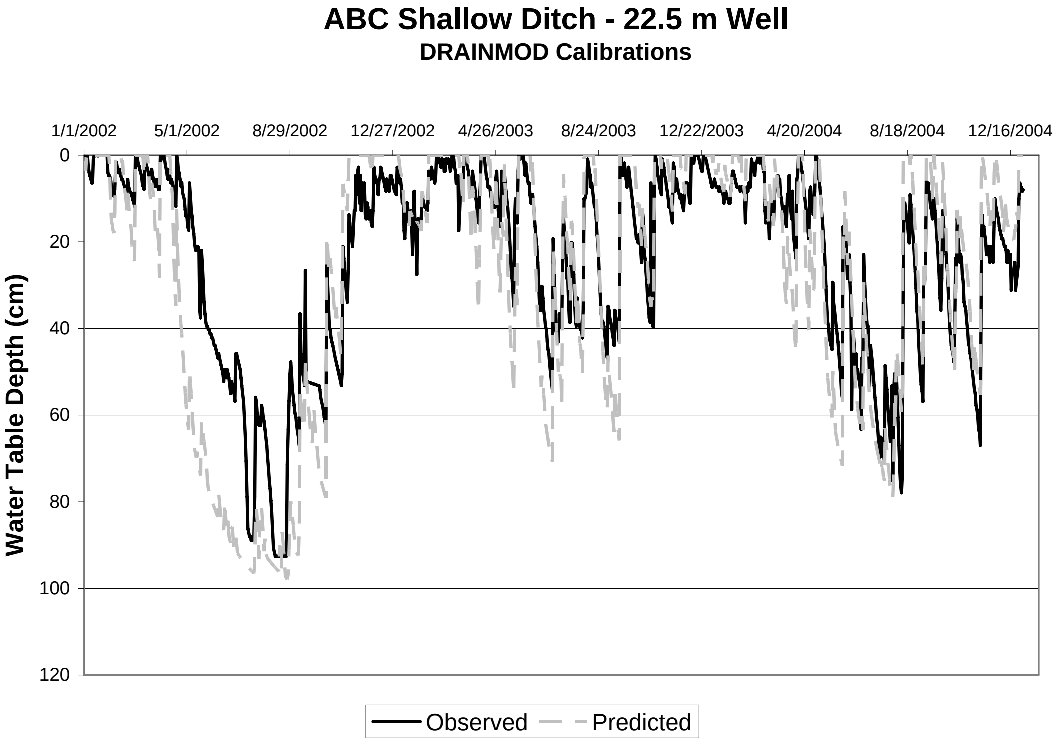

Figure 13. Water table plot for DRAINMOD calibration at ABC Shallow Ditch 22.5 m well

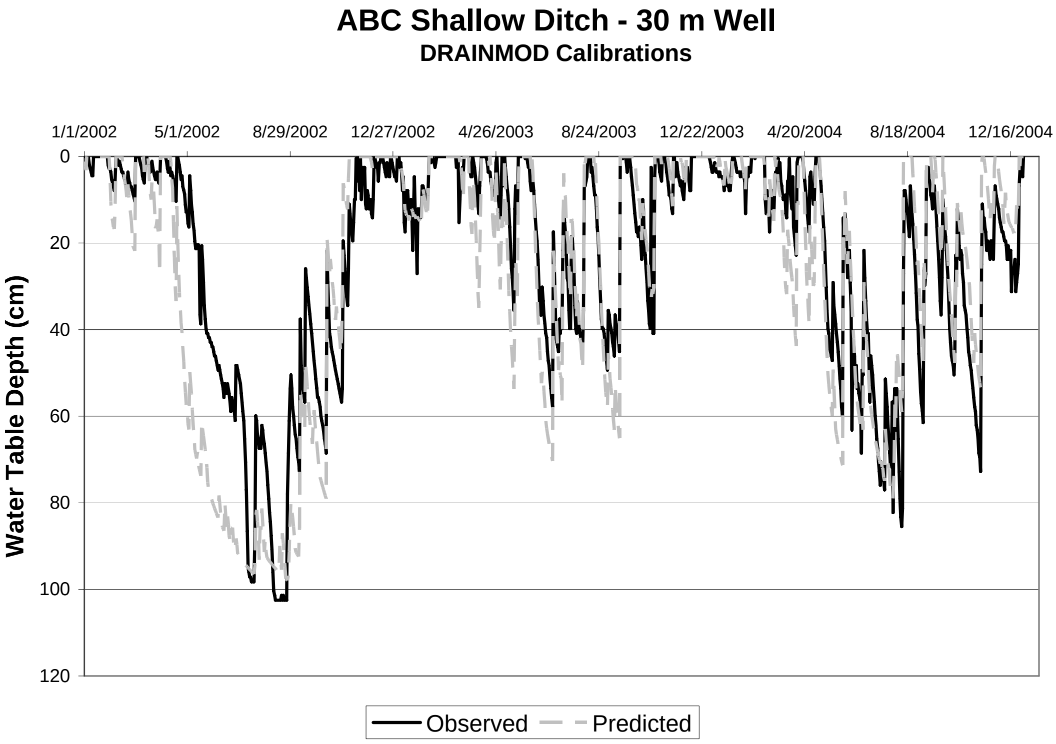

Figure 14. Water table plot for DRAINMOD calibration at ABC Shallow Ditch 30 m well

Deep Ditch

DRAINMOD was calibrated for the ABC site deep ditch using observed water table data from November 2002 through May 2005. Data for the first part of 2002 was determined to be unreliable due to complications with the initialization of field equipment. The calibration technique followed the methods described for the previous two transects. All wells were modeled using a conventional drainage design. Soil input data can be found in Appendix 1. Table 5 summarizes the main DRAINMOD calibration inputs for the ABC site deep ditch.

Table 5. .Final DRAINMOD calibration parameters for ABC site deep ditch.

	Distance from Ditch					
Model Parameter	**7.5 m**	**15 m**	**22.5 m**	**30 m**	**45 m**	**60 m**
Drain Spacing (m)	17.5	39.0	45.0	50.0	60.0	55.0
Drain Depth (m)	1.10	1.20	1.05	0.95	0.90	0.95
Depth to Impermeable Layer (m)	6.0	6.0	6.0	6.0	6.0	6.0
Max Surface Storage (cm)	1.0	5.0	4.0	4.0	6.0	12.0
Kirkham's Depth (cm)	1.0	2.5	2.0	2.0	3.0	6.0
Effective drain radius (cm)	10.0	10.0	10.0	15.0	15.0	15.0
Drainage coefficient(cm)	2.0	2.0	2.0	2.0	2.0	2.0
Lateral Conductivity(cm/hr)						
0 – 30 cm	30.0	30.0	30.0	10.0	10.0	10.0
30 – 120 cm	0.15	0.15	0.15	0.25	0.25	0.25
120 - Impermeable	0.25	0.25	0.5	0.5	0.5	0.5

The deep ditch proved to be an extremely difficult transect to model using DRAINMOD. Adjacent high surface storage provided subsurface flow to the transect area during the early part of 2003. This trend has also been noted at the Mildred Woods and ABC shallow transects. As stated previously, the high adjacent surface storage provides a source of available water and leads to a dampening of ET effects not predicted by the model. As shown in Table 6, the fit of the model data to observed values was the lowest of the three field transects, based on the coefficient of efficiency, E. No E values for the deep ditch were in the good range, although all values were in the satisfactory range of 0.36 and 0.75 (Motovilov et al., 1999).

Table 6. DRAINMOD calibration statistical results for ABC site deep ditch.

ABC Site Deep Ditch Calibrations - DRAINMOD			
Distance of well from ditch	**Coefficient of Determination, R^2**	**Coefficient of Efficiency, E**	**MAE (cm)**
7.5 m	0.61	0.60	14.3
15 m	0.71	0.68	12.3
22.5 m	0.66	0.64	15.5
30 m	0.70	0.67	9.0
45 m	0.70	0.68	6.4
60 m	0.66	0.66	8.2

A graphical representation showing the water table plots of the observed and calibration values are given in Figures 15 to 20.

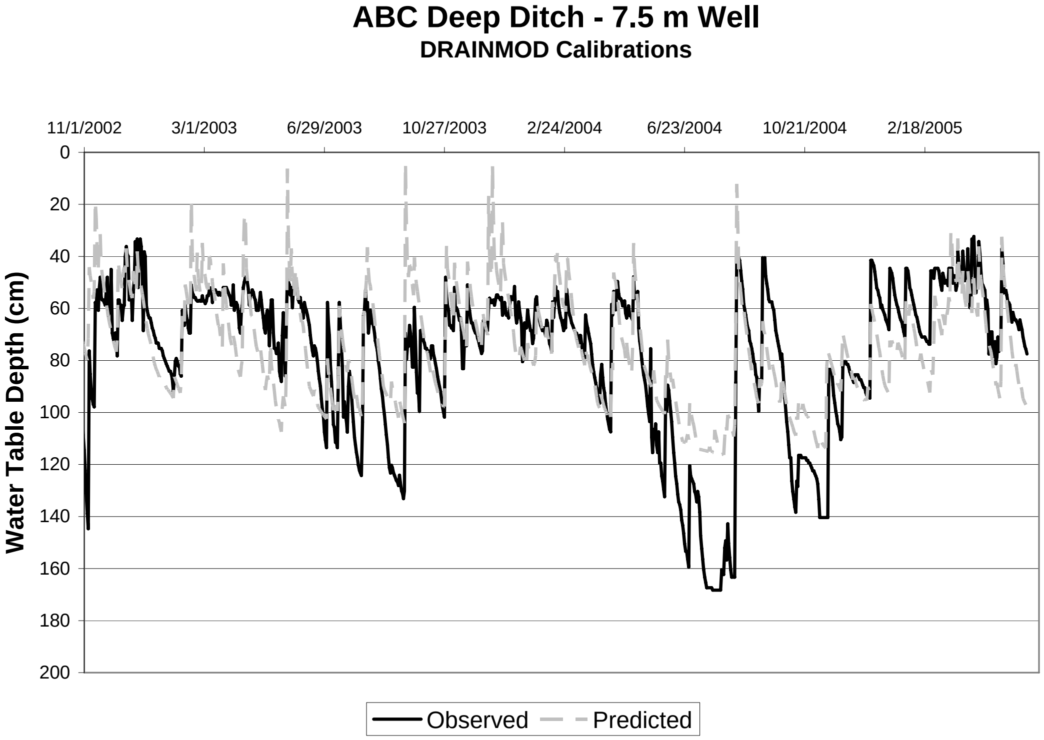

Figure 15. Water table plot for DRAINMOD calibration at ABC Deep Ditch 7.5 m well

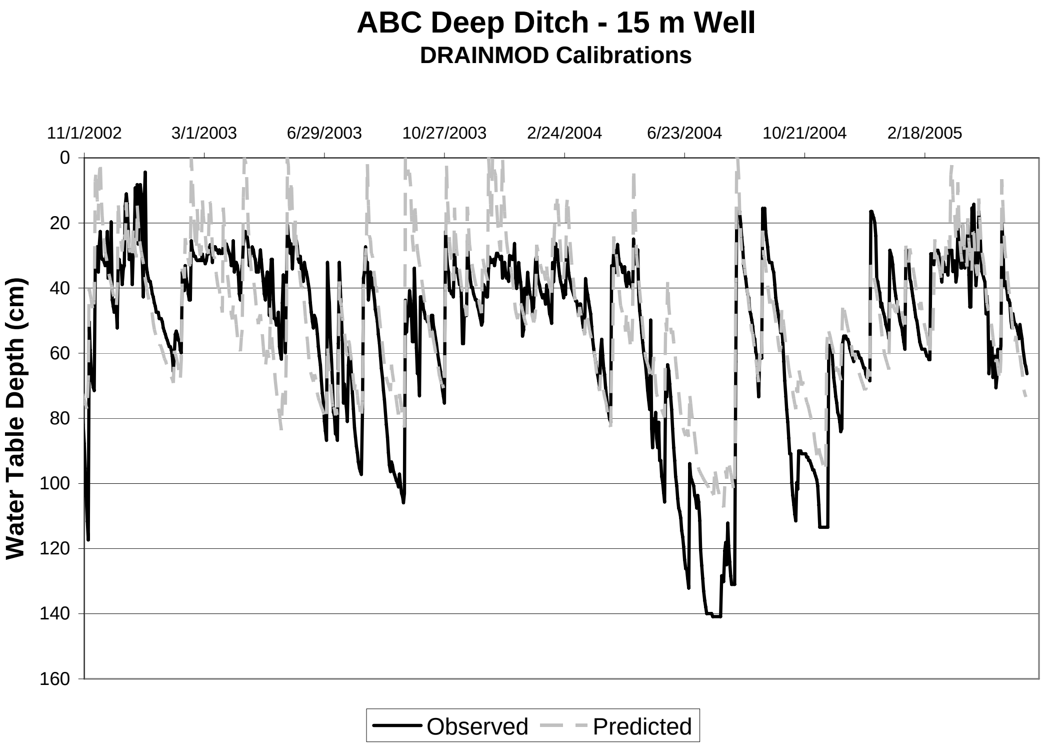

Figure 16. Water table plot for DRAINMOD calibration at ABC Deep Ditch 15 m well

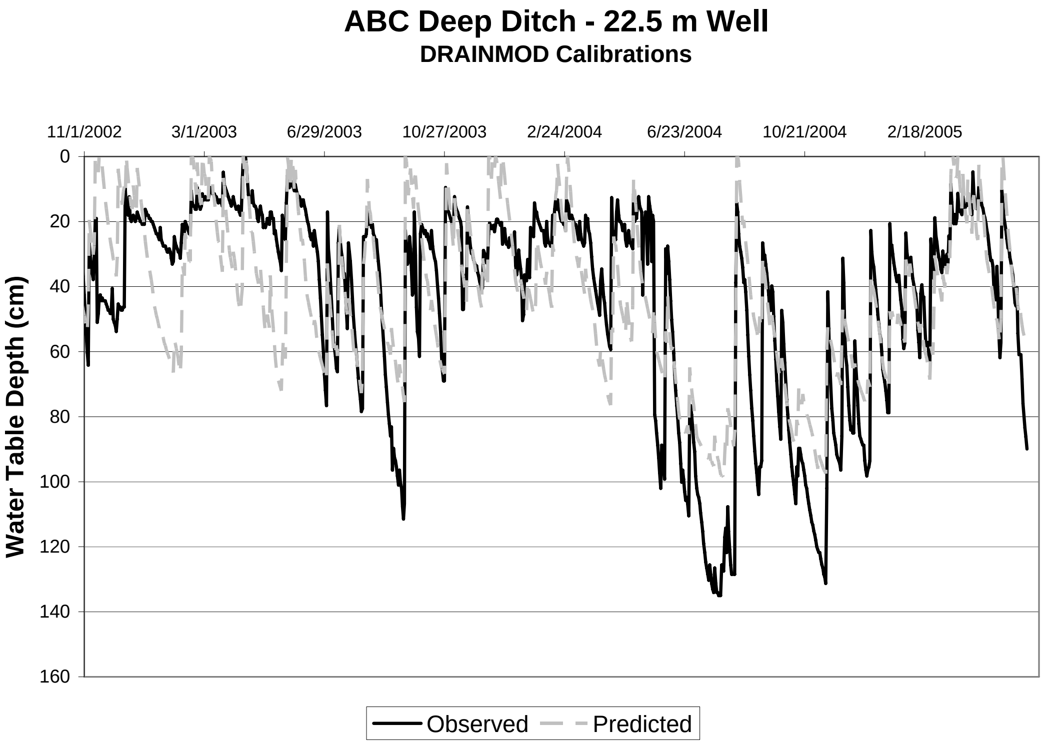

Figure 17. Water table plot for DRAINMOD calibration at ABC Deep Ditch 22.5 m well

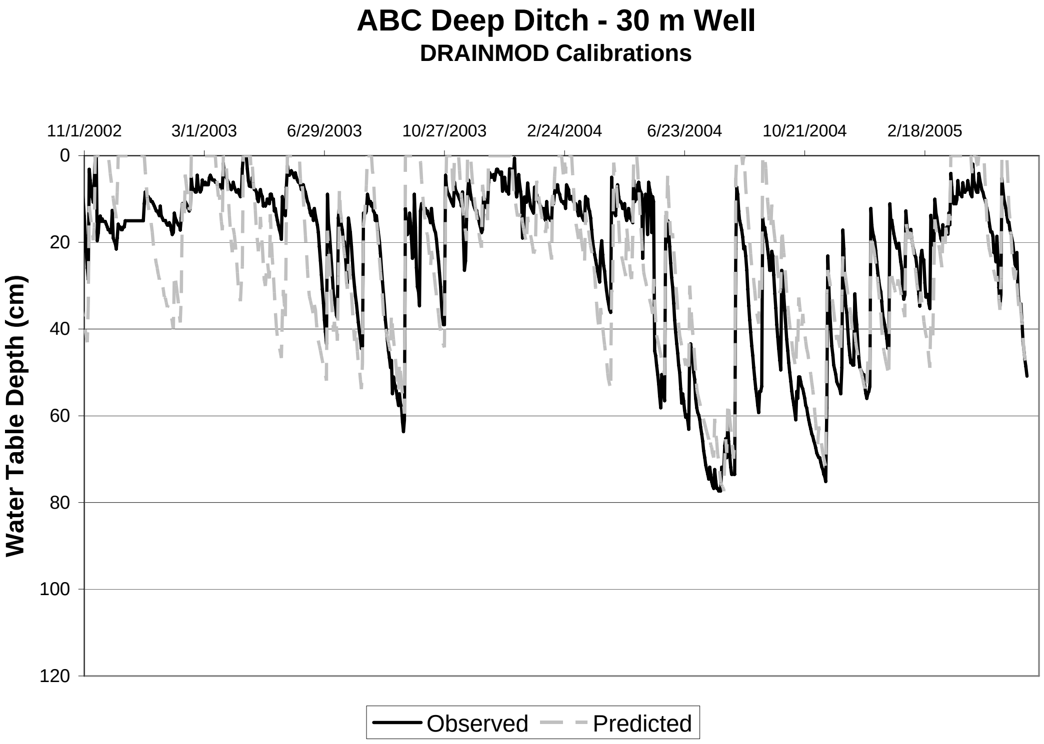

Figure 18. Water table plot for DRAINMOD calibration at ABC Deep Ditch 30 m well

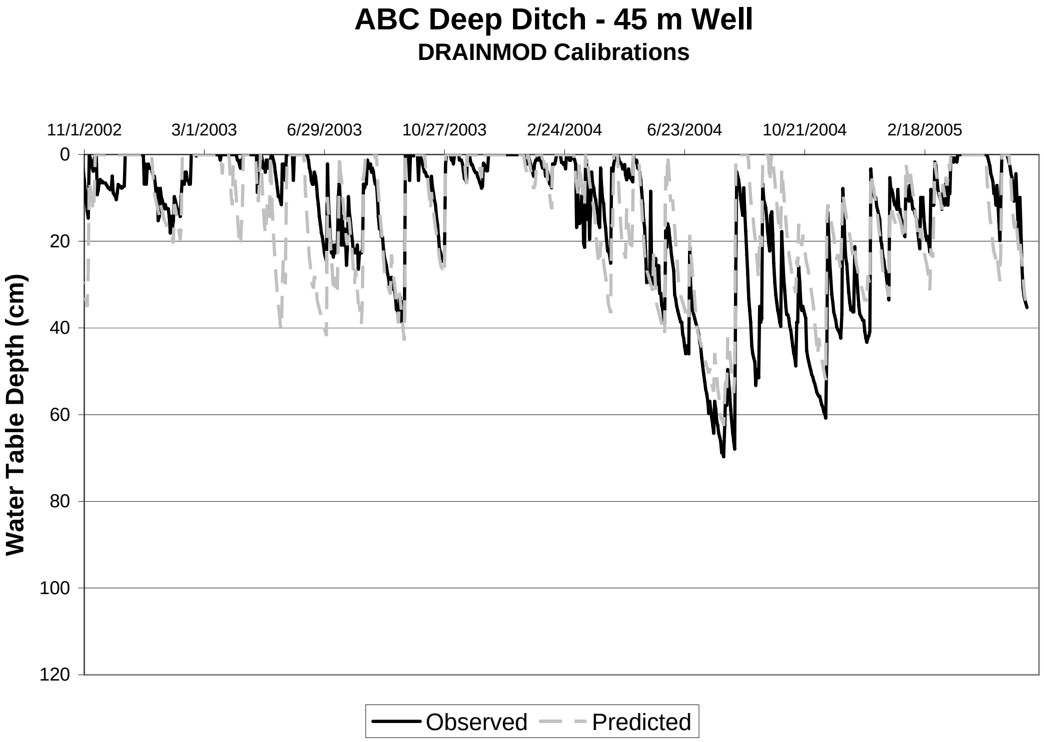

Figure 19. Water table plot for DRAINMOD calibration at ABC Deep Ditch 45 m well

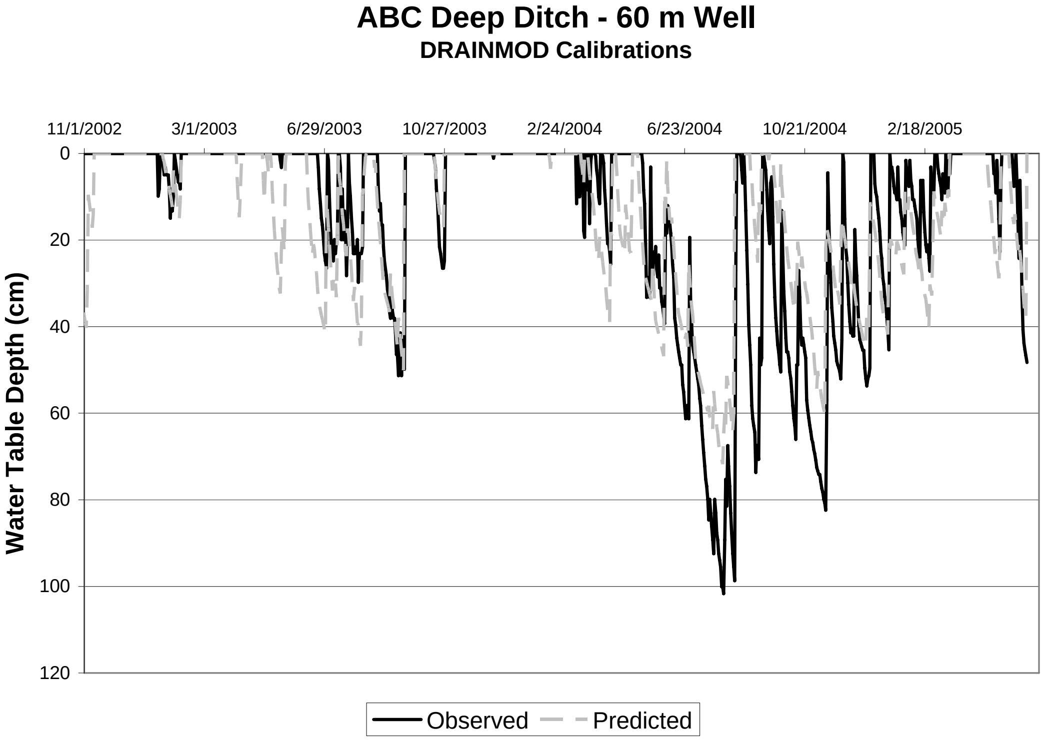

Figure 20. Water table plot for DRAINMOD calibration at ABC Deep Ditch 60 m well

DRAINMOD Long term Simulation Results

Long-term DRAINMOD simulations were performed for each well on each transect for a 54-year period from 1951 to 2004. Calibrated inputs were used for each well. It was possible to determine from measured data whether water table conditions at each well satisfied wetland hydrologic criterion. The purpose of the simulations was to determine whether the wetland criterion would be satisfied in one-half or more of the years on a long-term basis. The hydrologic criterion assumed a threshold duration of 5% of the growing season. This means that a site that would barely satisfy the wetland hydrologic criterion in 50% of the years over a 54 -year period would have the water table within 30 cm of the surface for a continuous period of time equal or greater than 5%

of the growing season (12 days at Mildred Woods, 13 days at the ABC site). Results of the long-term simulations are listed in Table 7.

Table 7. DRAINMOD long term simulation results.

Summary of long term simulations	
Mildred Woods	
Distance of well from ditch	Number of years out of 54 meeting criterion
7.5 m	0
15 m	0
30 m	0
45 m	47
60 m	42
90 m	54
ABC Shallow Ditch	
Distance of well from ditch	Number of years out of 54 meeting criterion
3.75 m	50
7.5 m	50
11.25 m	54
15 m	54
22.5 m	54
30 m	54
ABC Deep Ditch	
Distance of well from ditch	Number of years out of 54 meeting criterion
7.5 m	0
15 m	16
22.5 m	43
30 m	53
45 m	54
60 m	54

Based on these results, the lateral effect of the drainage ditches is between 30 and 45 m for Mildred Woods. Linear interpolation results in a lateral effect of 38.6 meters. Results of both field results and the model indicate the lateral effect is less than 3.75 m for the ABC shallow ditch. The lateral effect for the ABC deep ditch is between 15 and 22.5 meters. Linear interpolation would indicate an effect of 18 meters. A comparison between all methods in this study will be given in Chapter 4.

DRAINMOD Limitations

DRAINMOD was designed to predict the water table fluctuations at a point midway between a system of parallel drains. These field sites were bounded by one single drain running adjacent to a jurisdictional wetland. These sites were also marked by an extreme variation in surface conditions along the landscape. Small pockets of high depressional storage retained surface water for long periods of time. The presence of this water dampened the influence of ET and drainage on the water table and resulted in higher water table elevations (smaller water table depths) than predicted. As shown earlier in Figure 8, the model predicted greater water table drawdown than was observed at the wettest of the Mildred Woods wells (90 m from the ditch) in the summer of 2003. This error is attributed to water moving laterally from depressional storage in the vicinity of the well. The effect of such isolated pockets could not be adequately modeled in DRAINMOD. Limitations to modeling effects of these macro topographic variations resulted in discrepancies between observed and measured water table depths as indicated in the statistical measures.

WATRCOM Simulations

Statistical Measures

Statistical measures used in the calibration of the WATRCOM model are identical to the measures used in the DRAINMOD calibration: coefficient of determination, coefficient of efficiency, and MAE.

Mildred Woods Site Calibrations

WATRCOM was calibrated for Mildred Woods for the period of January 2002 to August 2003. Although data were collected through the end of 2004, the influence of a beaver dam affected water table fluctuations along the transect after August 2003. Depth to the impermeable layer was assumed to be 4.8 meters. A survey of the site provided ground elevations near each well in reference to the bottom of the ditch. These were used to determine elevations in reference to the impermeable layer. Initial water table elevations were based on January 1, 2002 water table data. The ditch elevation was set to the average value for the year, 3.88 meters above the impermeable layer. The nodes were spaced 7.62 meters apart and extended to a distance of 122 meters from the ditch. Extending the model transect past the last site well allowed for inputs of landscape features in that area. This was a limitation in the DRAINMOD model. All inputs to the WATRCOM model can be found in Appendix 2. Statistical measures for the WATRCOM calibrations of the Mildred Woods site are summarized in Table 8.

Table 8. WATRCOM calibration statistical results for Mildred Woods.

Mildred Woods Site Calibrations - WATRCOM			
Distance of well from ditch	**Coefficient of Determination, R^2**	**Coefficient of Efficiency, E**	**MAE (cm)**
7.5 m	***	***	***
15 m	0.74	0.61	14.6
30 m	0.77	0.58	15.8
45 m	0.81	0.78	7.1
60 m	0.83	0.67	6.7
90 m	0.83	0.83	5.8

*** - Model was unable to predict water table fluctuations for this well.

Plots of the observed and predicted water tables are given in Figures 21 to 25.

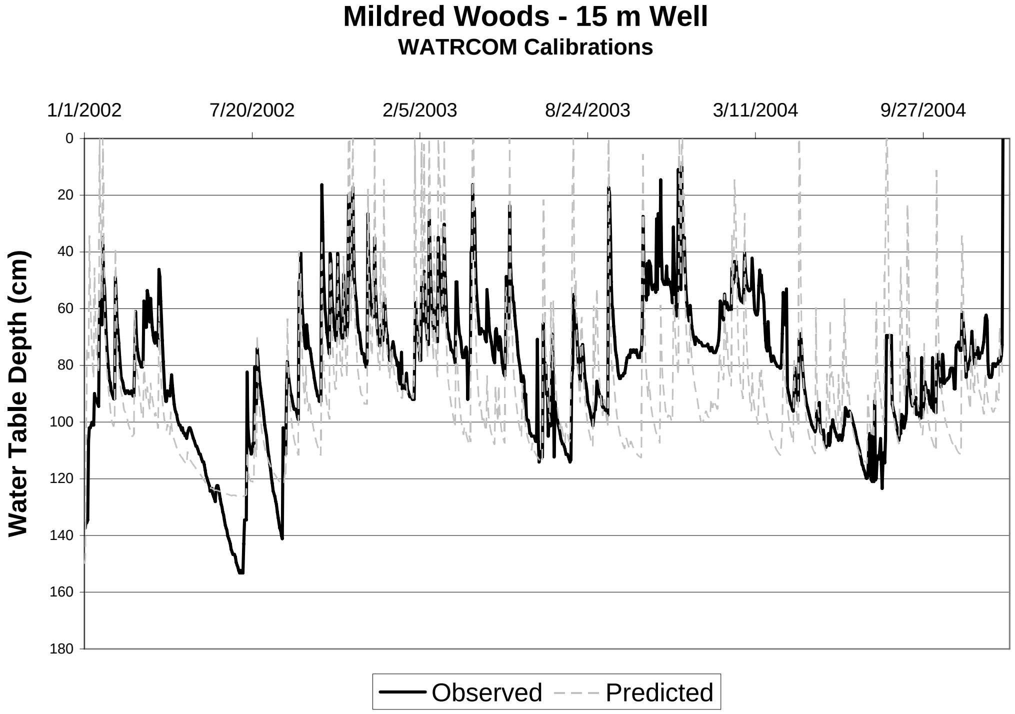

Figure 21. Water table plot for WATRCOM calibration at Mildred Woods 15 m well

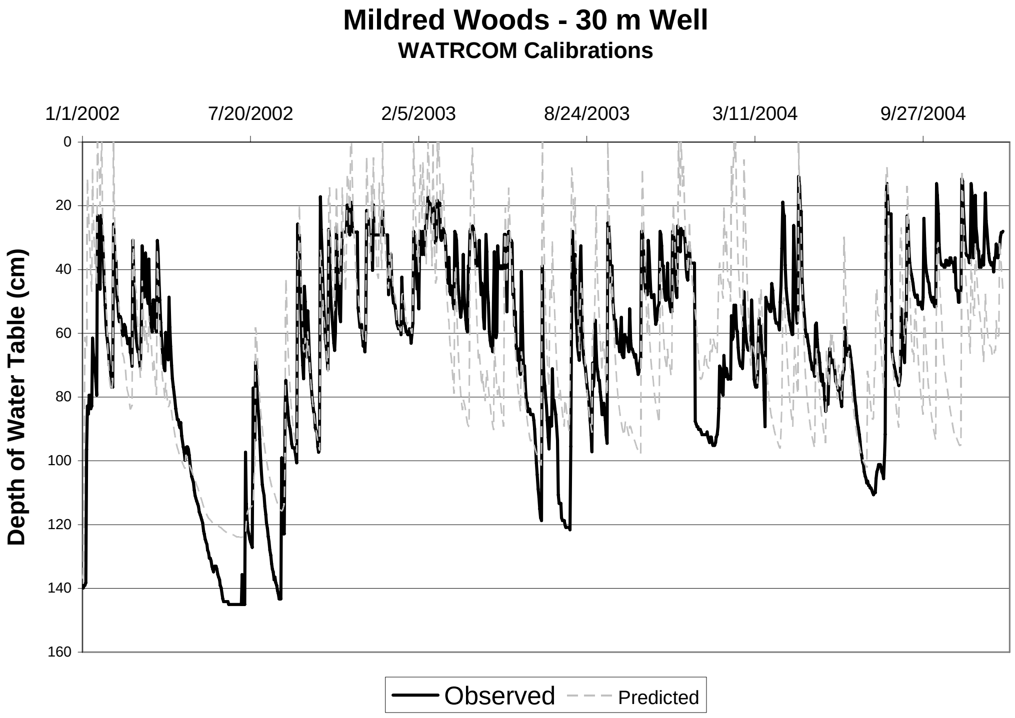

Figure 22. Water table plot for WATRCOM calibration at Mildred Woods 30 m well

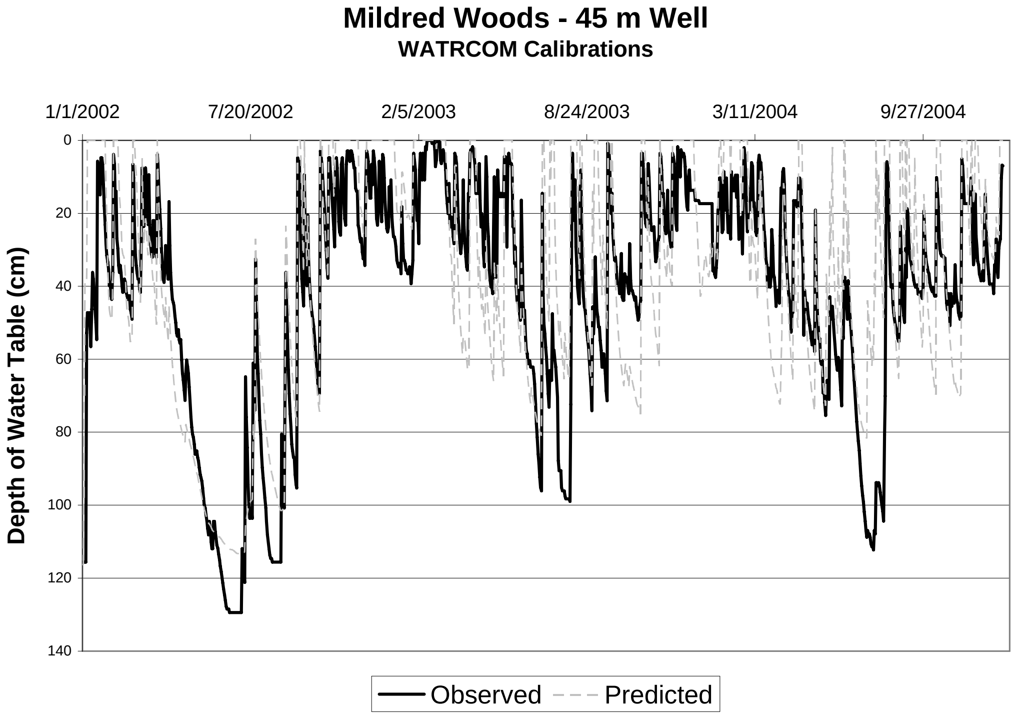

Figure 23. Water table plot for WATRCOM calibration at Mildred Woods 45 m well

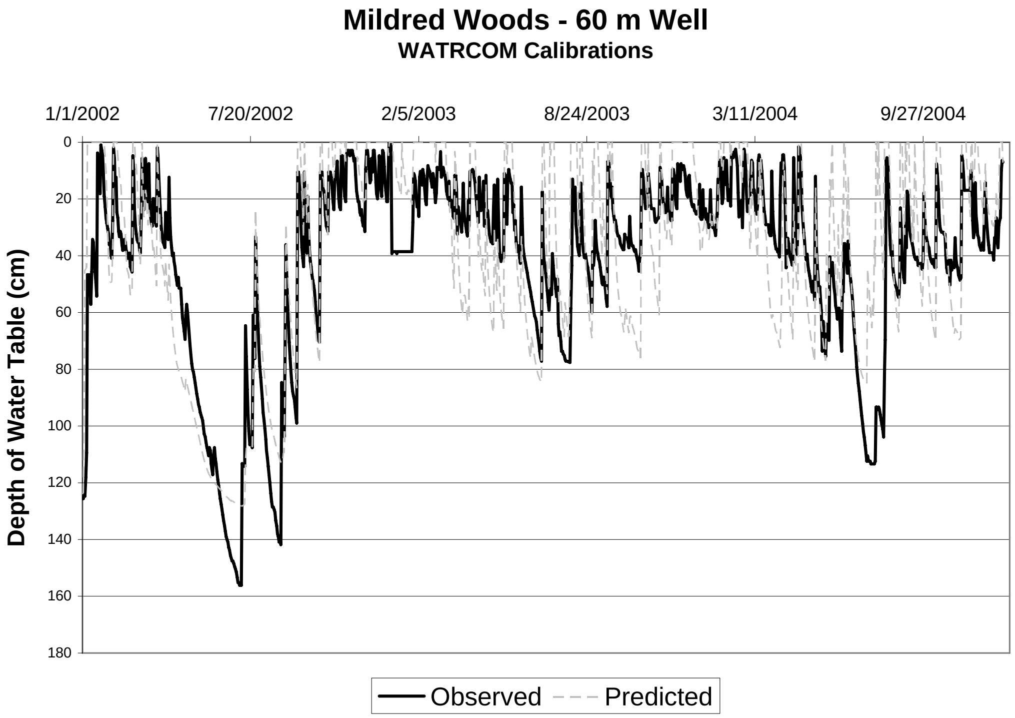

Figure 24. Water table plot for WATRCOM calibration at Mildred Woods 60 m well

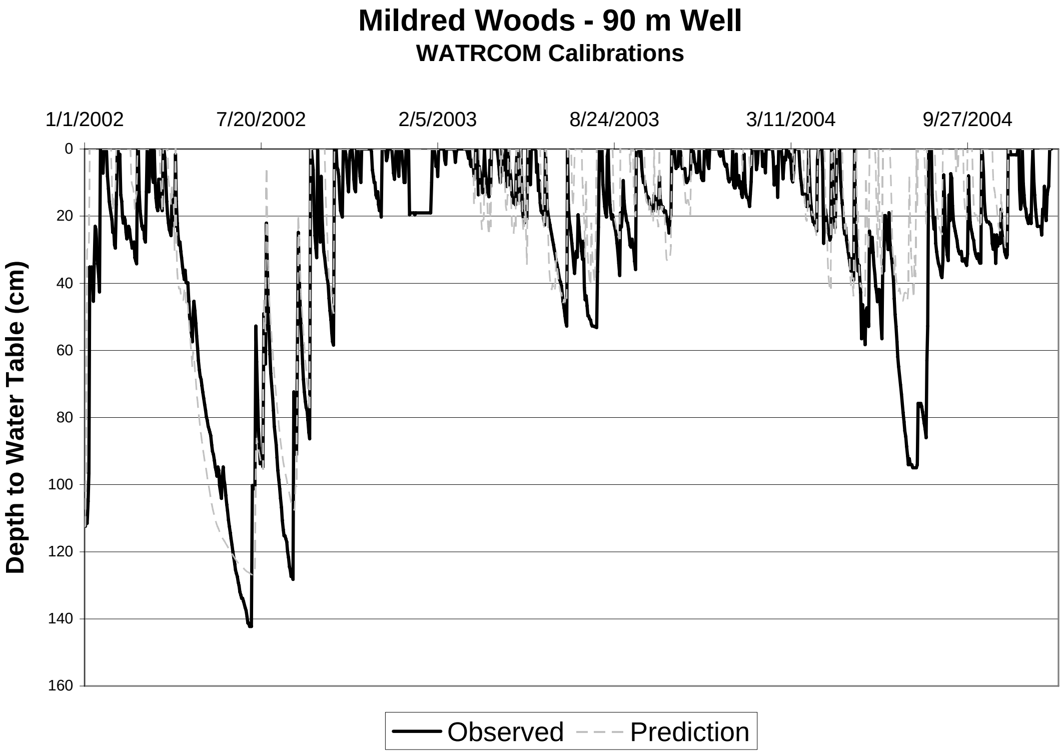

Figure 25. Water table plot for WATRCOM calibration at Mildred Woods 90 m well

ABC Site Calibrations

Shallow Ditch

WATRCOM was calibrated for the ABC shallow ditch for the period of January 2002 to December 2004. A depth to the impermeable layer of 6.4 meters was originally assumed based on a single boring on the site; it was adjusted to 6.0 meters in the calibration process. A survey of the site provided elevations of the ground near each well in reference to the bottom of the ditch. These were used to determine ground surface elevations in reference to the impermeable layer. Initial water table elevations were based on January 1, 2002 water table data. The ditch elevation was adjusted to 5.4 meters. The nodes were spaced 3.8 meters apart and extended to a distance of 61 meters which was 31 meters past the last well. This allowed consideration of landscape features in the transect beyond the wells. All inputs to the WATRCOM model can be found in Appendix 2. Statistics for the calibrations are summarized in Table 9.

Table 9. WATRCOM calibration statistical results for ABC site shallow ditch.

ABC Site Shallow Ditch Calibrations - WATRCOM			
Distance of well from ditch	**Coefficient of Determination, R^2**	**Coefficient of Efficiency, E**	**MAE (cm)**
3.75 m	0.64	0.47	15.6
7.5 m	0.69	0.68	11.5
11.25 m	0.71	0.70	11.4
15 m	0.83	0.81	8.8
22.5 m	0.85	0.71	9.0
30 m	0.83	0.77	8.4

WATRCOM more accurately predicted water table fluctuations in the wells farthest removed from the ditch than did DRAINMOD. The opposite occurred for the wells nearest the ditch, although all values for the coefficient of efficiency were within the satisfactory range for WATRCOM. Water table plots of the observed and predicted water tables are given in Figures 26 to 31.

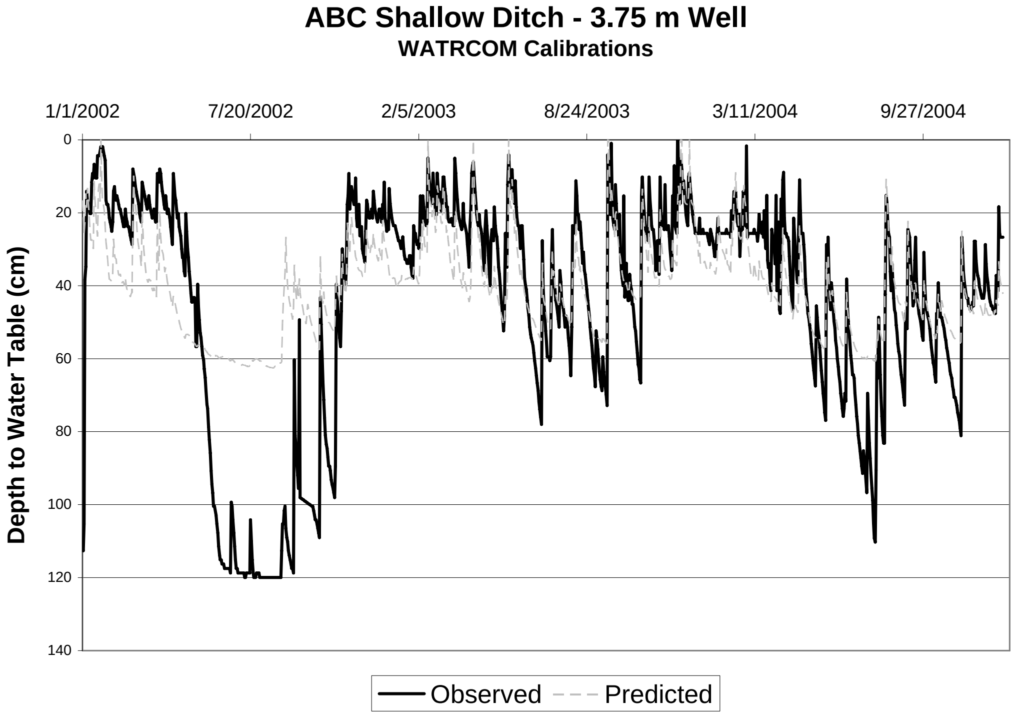

Figure 26. Water table plot for WATRCOM calibration at ABC shallow ditch 3.75 m well

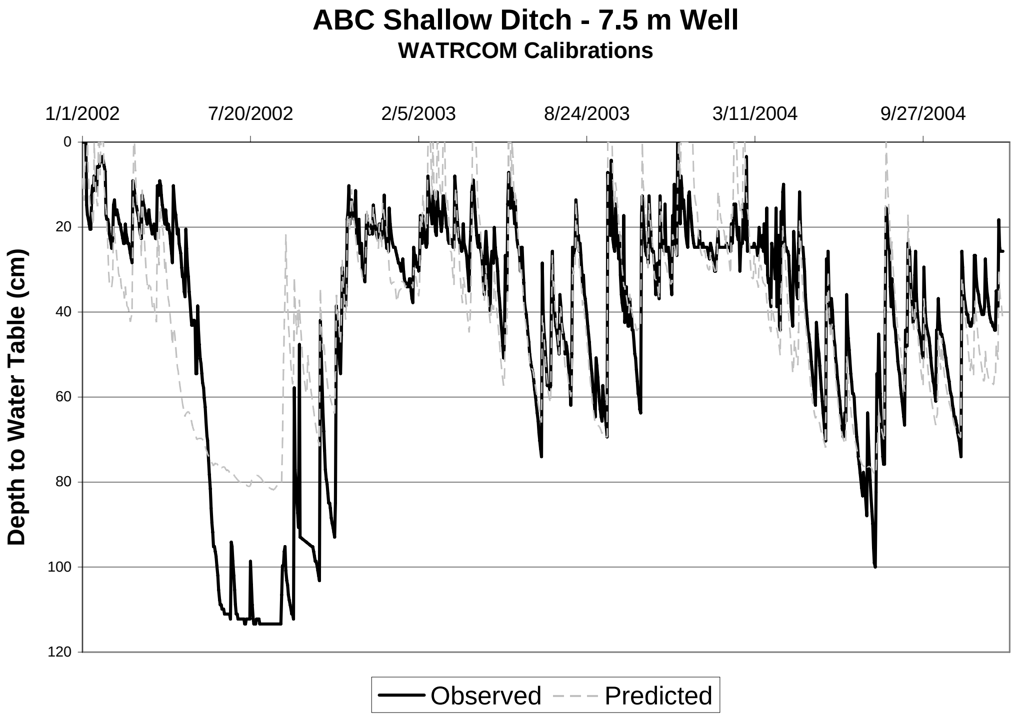

Figure 27. Water table plot for WATRCOM calibration at ABC shallow ditch 7.5 m well

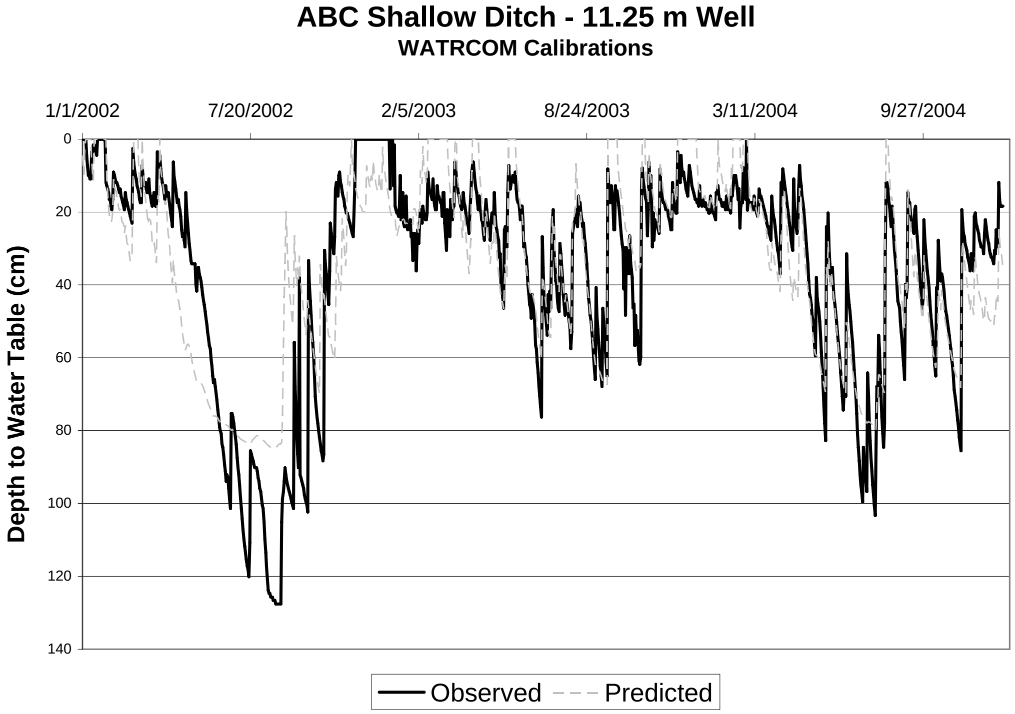

Figure 28. Water table plot for WATRCOM calibration at ABC shallow ditch 11.25 m well

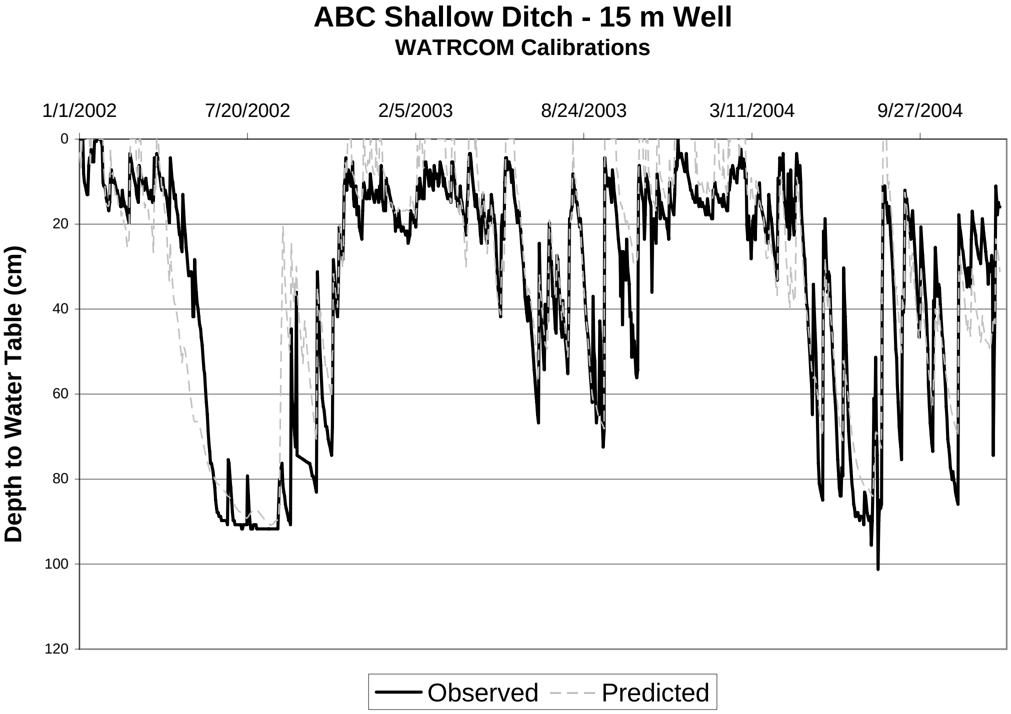

Figure 29. Water table plot for WATRCOM calibration at ABC shallow ditch 15 m well

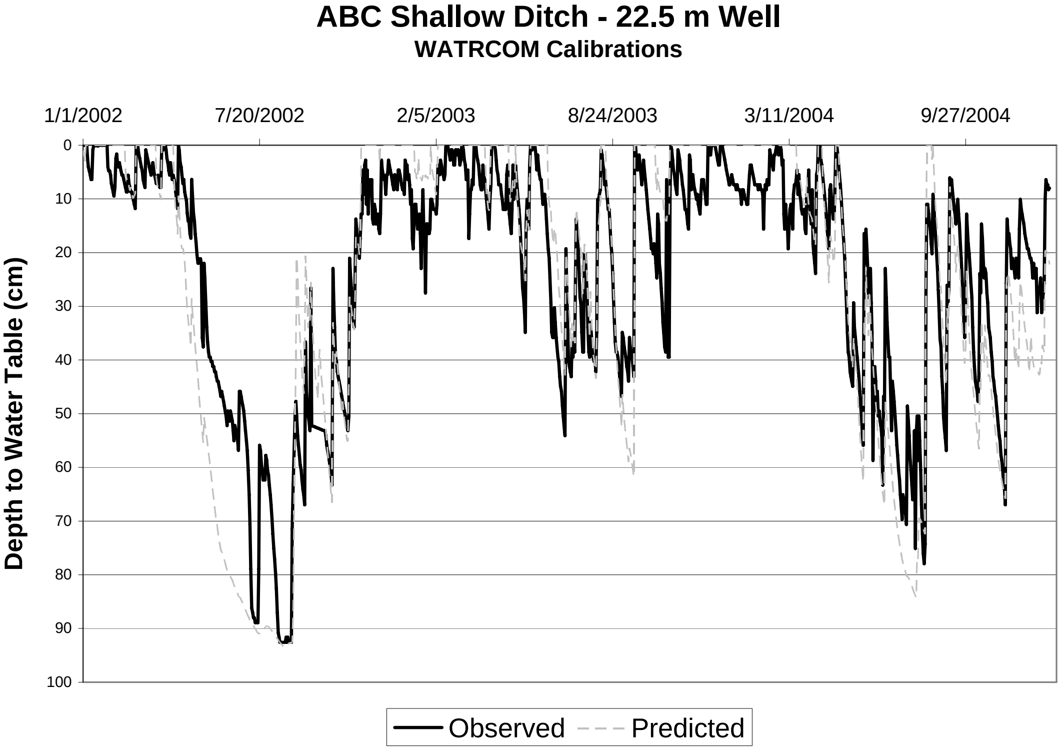

Figure 30. Water table plot for WATRCOM calibration at ABC shallow ditch 22.5 m well

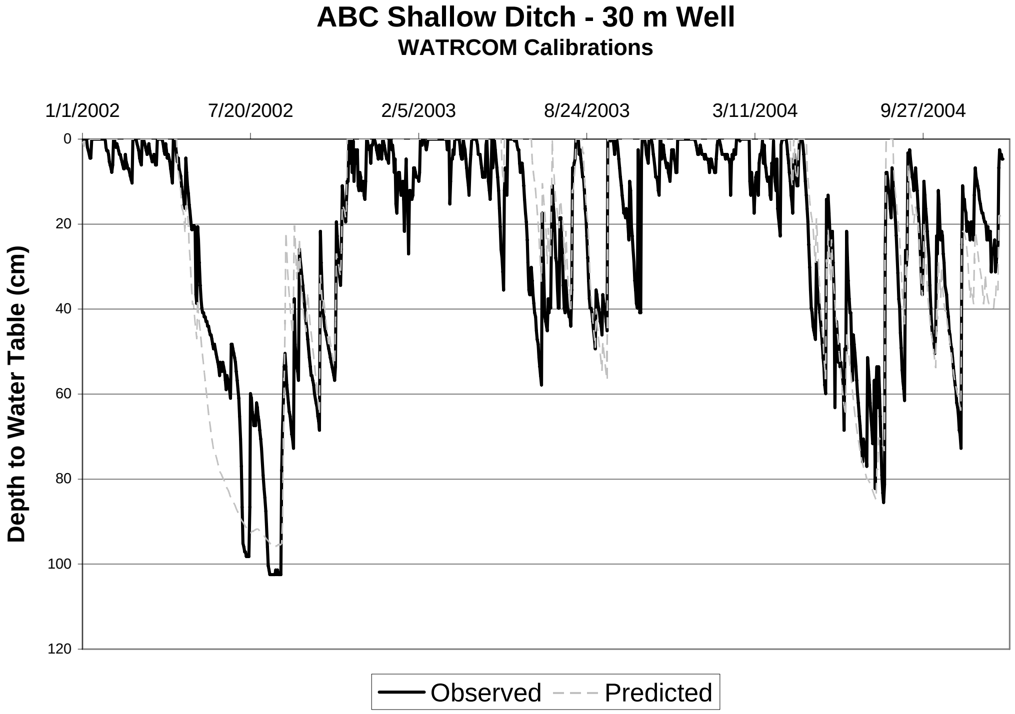

Figure 31. Water table plot for WATRCOM calibration at ABC shallow ditch 30m well

Deep Ditch

WATRCOM was calibrated for ABC site deep ditch for the period of November 2002 to May 2005. Discrepancies in data collected during the first part of 2002 prevented calibration using the entire 2002 data set. These discrepancies were due to problems with equipment initialization and maintenance during the initial period. A depth to the impermeable layer of 6.0 meters was used. A survey of the site provided elevations of the ground surface near each well as well as the bottom of the ditch. These data were used to calculate elevations in reference to the impermeable layer. Initial water table elevations were based on November 1, 2002 water table data. The ditch elevation was adjusted to 4.83 meters. The nodes were spaced 7.62 meters apart and extended to a distance of 122 meters. All inputs to the WATRCOM model can be found in Appendix

2. Statistics quantifying agreement between predicted and observed water table fluctuations are summarized in Table 10.

Table 10. WATRCOM calibration statistical results for ABC site deep ditch.

ABC Site Deep Ditch Calibrations - WATRCOM			
Distance of well from ditch	**Coefficient of Determination, R^2**	**Coefficient of Efficiency, E**	**MAE (cm)**
7.5 m	0.56	0.05	24.3
15 m	0.74	0.91	14.6
22.5 m	0.77	0.58	15.8
30 m	0.81	0.78	7.1
45 m	0.83	0.67	6.7
60 m	0.83	0.83	5.8

Water table depth in the first transect well (7.5 m) were not accurately modeled with WATRCOM. Predicted water tables were higher and conditions wetter than observed in the field. When model parameters were adjusted to lower the predicted water table at this well, water table depths were over-predicted (too deep) in the remaining wells. Fortunately, the observed water table data clearly indicated that the wetland hydrologic criterion would not be satisfied at the 7.5 m well. Therefore, predicted water table fluctuations at that well were not critical and the results were considered acceptable for this study. A graphical representation showing the water table plots of the observed and calibrated predicted values are given in Figures 32 to 37.

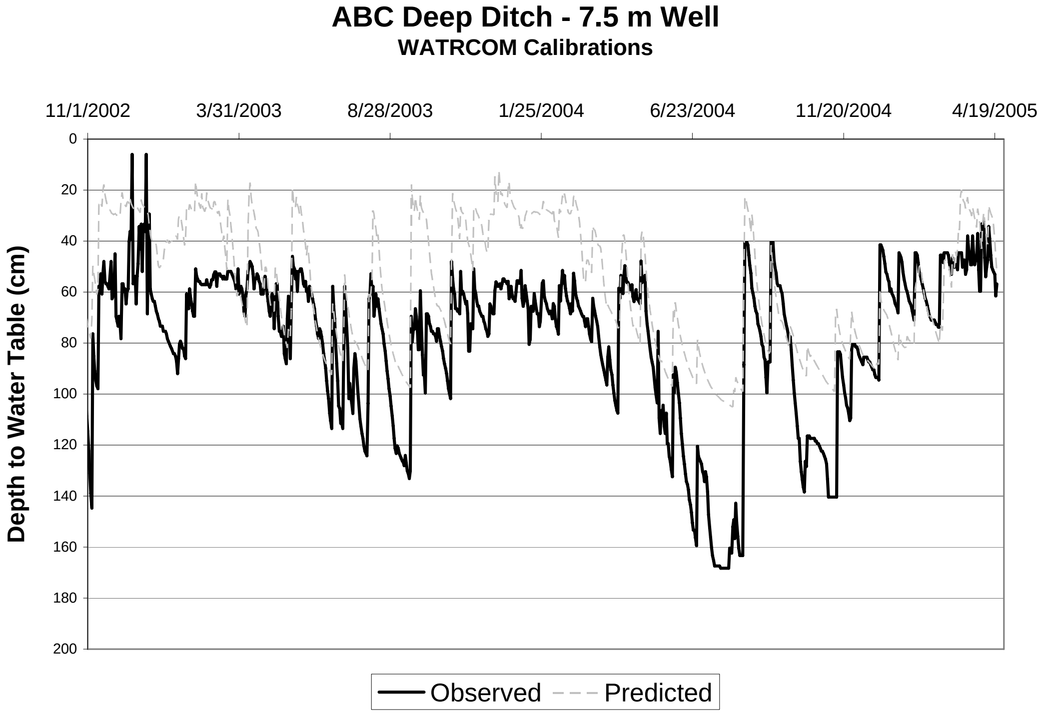

Figure 32. Water table plot for WATRCOM calibration at ABC deep ditch 7.5m well

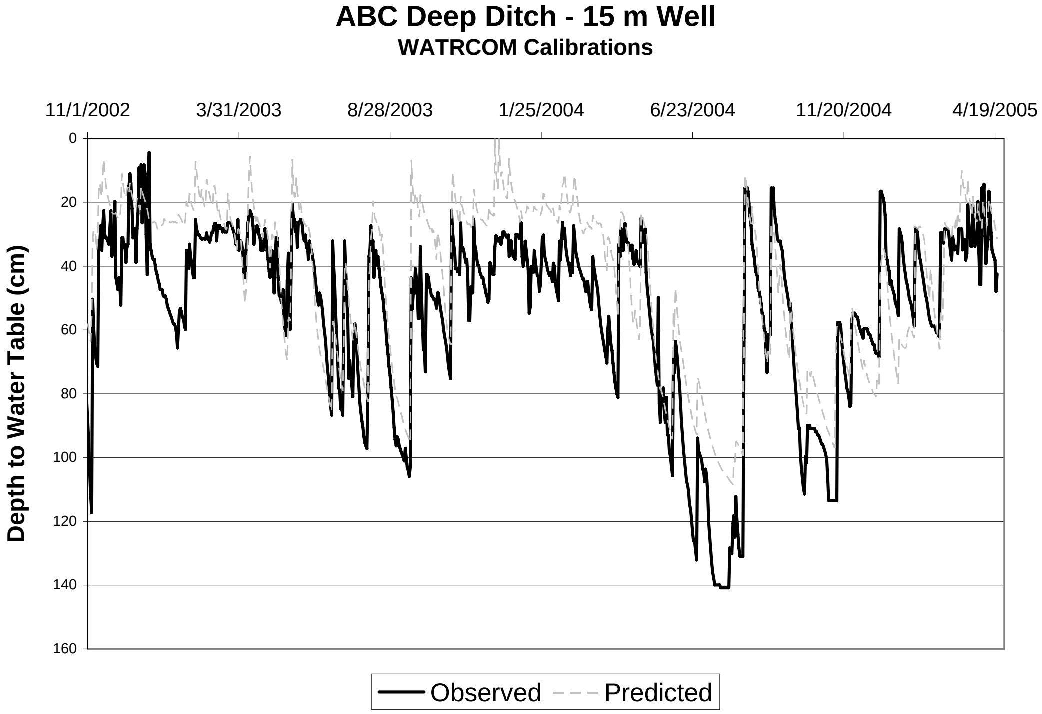

Figure 33. Water table plot for WATRCOM calibration at ABC deep ditch 15 m well

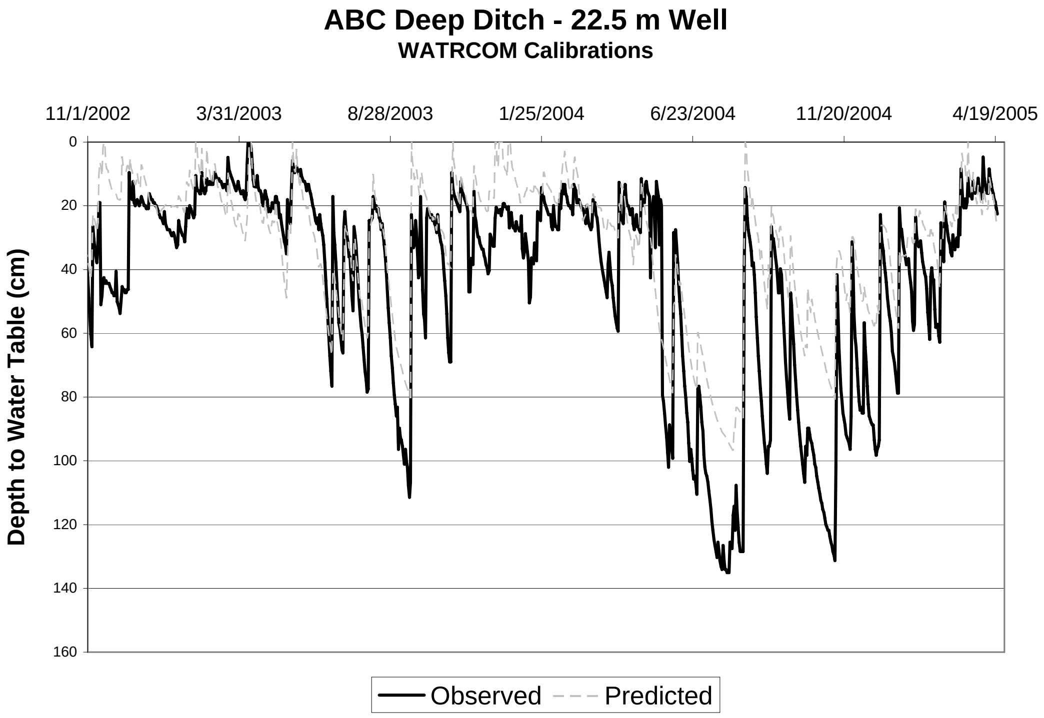

Figure 34. Water table plot for WATRCOM calibration at ABC deep ditch 22.5 m well

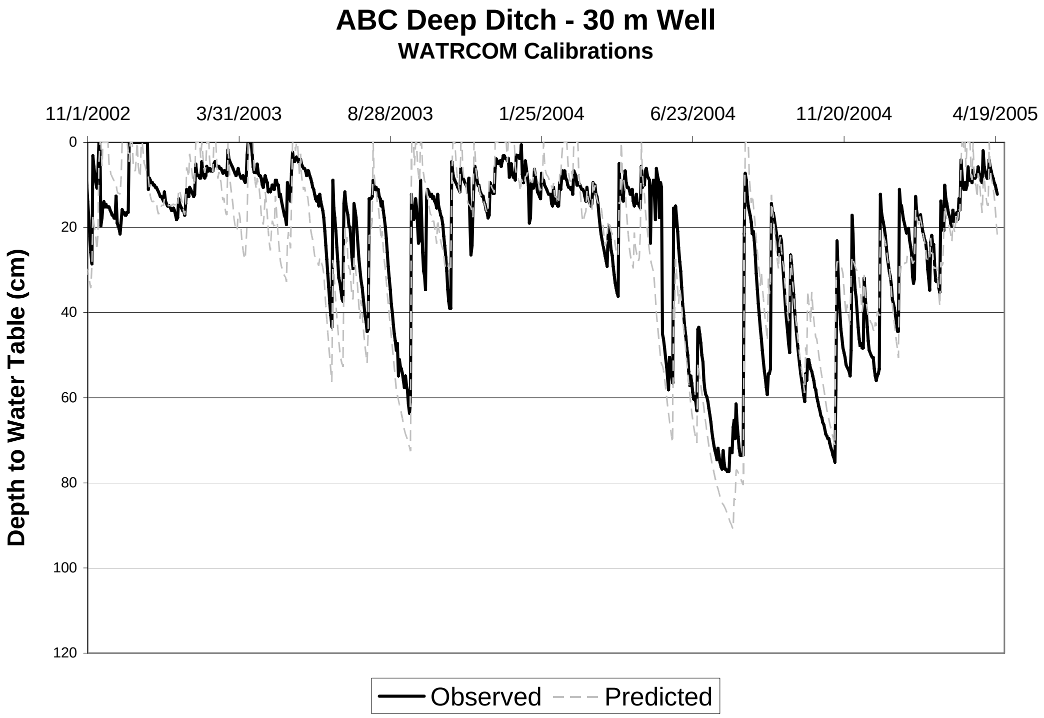

Figure 35. Water table plot for WATRCOM calibration at ABC deep ditch 30 m well

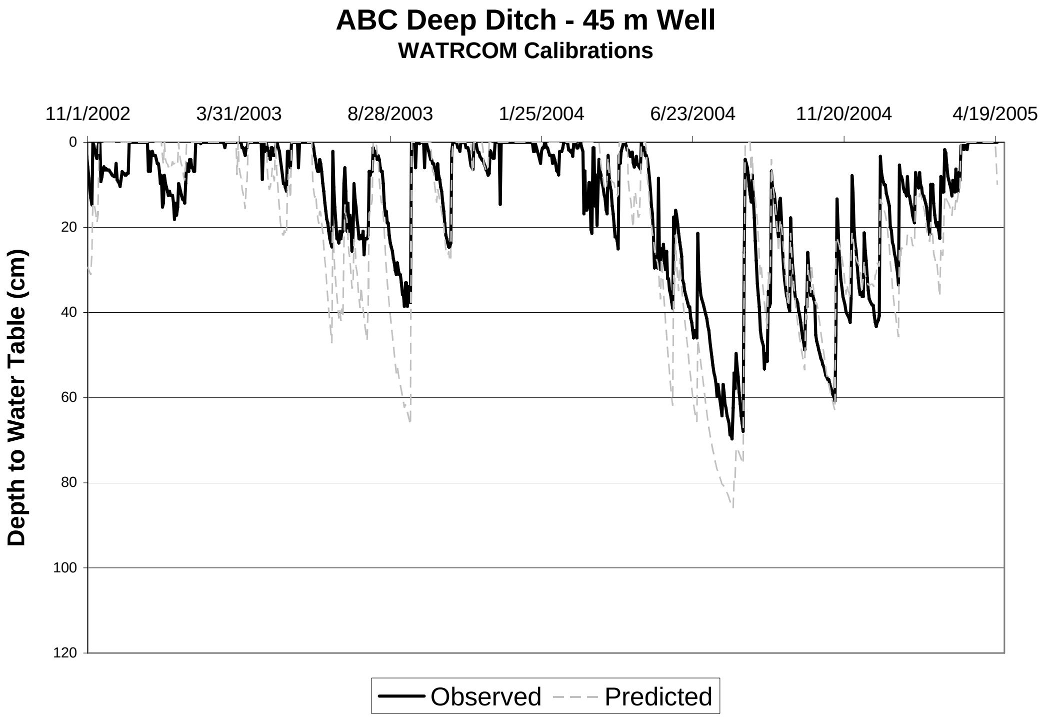

Figure 36. Water table plot for WATRCOM calibration at ABC deep ditch 45 m well

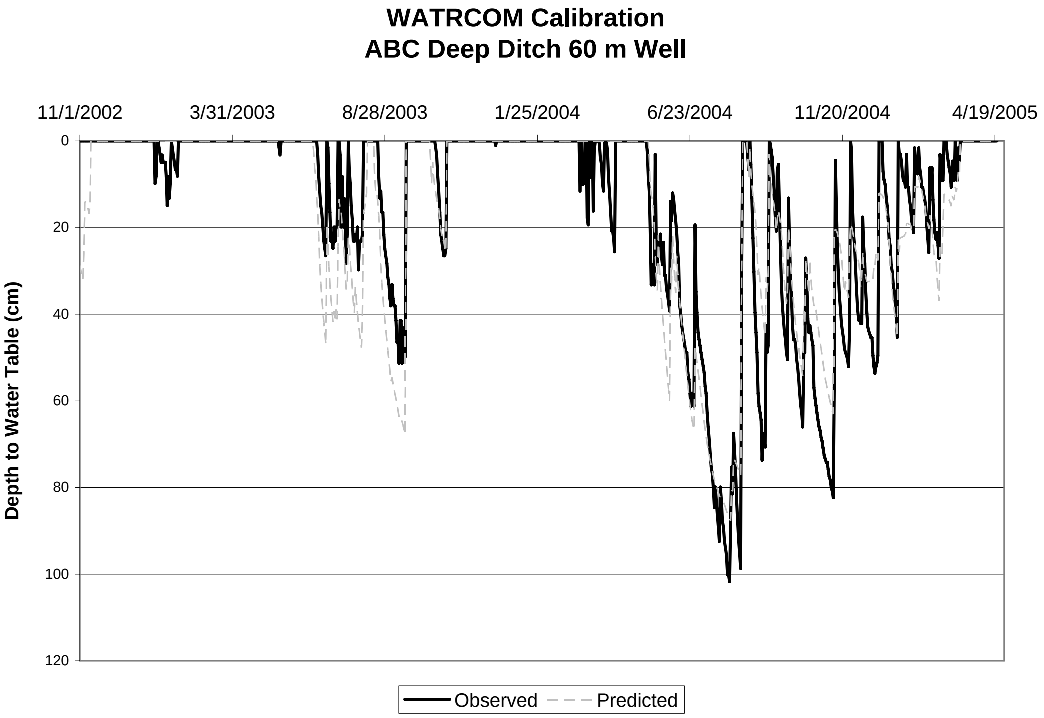

Figure 37. Water table plot for WATRCOM calibration at ABC deep ditch 60 m well

WATRCOM Long term Simulation Results

Long-term simulations were performed for each well on each transect for a 54-year period from 1951 to 2004. As in the DRAINMOD simulations, the objective was to determine whether the wetland hydrologic criterion was satisfied over the long-term. The hydrologic criterion assumed a threshold duration based on 5% of the growing season. This means that a site that would barely satisfy the wetland hydrologic criterion in 50% of the years over a 54-year period would have the water table within 30 cm of the surface for a continuous period equal or greater than 5% of the growing season (12 days at Mildred Woods, 13 days at the ABC site). For WATRCOM, it was possible to make this determination for every node and thereby determine, at least approximately, the distance from the ditch where the criterion is satisfied in exactly one-half of the years. Results of the long-term simulations for each well are listed in Table 11.

Table 11. WATRCOM long term simulation results**.**

Summary of long term simulations

Mildred Woods

Distance of well from ditch	Number of years out of 54 meeting criterion
7.5 m	0
15 m	0
30 m	0
37.5 m[1]	11
45 m	41
60 m	45
90 m	53

ABC Shallow Ditch

Distance of well from ditch	Number of years out of 54 meeting criterion
3.75 m	9
7.5 m	23
11.25 m	34
15 m	34
22.5 m	39
30 m	40

ABC Deep Ditch

Distance of well from ditch	Number of years out of 54 meeting criterion
7.5 m	0
15 m	15
22.5 m	32
30 m	34
45 m	39
60 m	40

1. No physical well located at this distance from ditch. 37.5 m represented by WATRCOM simulated node.

Based on these results, the lateral effect of the drainage ditches appears to be between 37.5 and 45 meters for Mildred Woods, between 7.5 and 11.25 meters for the ABC shallow ditch, and between 15 and 22.5 meters for the ABC deep ditch.

WATRCOM Limitations

WATRCOM, like DRAINMOD, is a FORTRAN language software application. Unlike DRAINMOD, no front-end software has been developed for WATRCOM. Inputs are entered into text files with specific format. Albeit a minor inconvenience, entering data in text files does have associated problems. The author found that if the character spacing did not match spacing in the FORTRAN code, errors in the simulation or inaccurate simulations would occur.

Another issue with the WATRCOM model is the two dimensional aspect of the system design. Like DRAINMOD, the variation in the topography of the site in areas to the left and the right of the transect were not modeled. Therefore, subsurface lateral flows from directions perpendicular to the transect were not predicted. As discussed earlier, lateral flows can impact ET and predicted water table fluctuations.

Summary

The Mildred Woods, ABC shallow ditch, and ABC deep ditch were modeled using the two-dimensional water management models DRAINMOD and WATRCOM. The DRAINMOD model was originally designed to predict the water table fluctuations at the point midway between a system of parallel drains. The WATRCOM model was designed to predict the response to the water table due to the influence of multiple drains, including a single drain. Both models use inputs of soil properties, weather, drain system design, and surface depressional storage. They differ in their method of calculating movement of water in the saturated zone. DRAINMOD utilizes the Hooghoudt and Kirkham equations and WATRCOM the Boussinesq equation.

The Mildred Woods site was calibrated for the period of January 2002 to December 2004 (August 2003 for the three wells nearest the ditch). Except for WATRCOM results for the well nearest the ditch, coefficients of efficiency, E, were in the satisfactory or good range for each well for both models. The highest reported E values were obtained with DRAINMOD for the wells located 30 and 45 meters from the ditch. Long-term simulations, (1951 – 2004), were performed with each model for all transect wells. The objective was to determine the number of years the wetland hydrologic criterion was satisfied for each well, and, in the case of WATRCOM, for nodes between the wells. Results indicate that the expected lateral effect of the ditch was between 30 and 45 m. WATRCOM predicted the criterion would be satisfied in 11 of 54 years at the node 37.5 m from the ditch versus 41 of 54 years at the well 45 m from the ditch. Linear interpolation indicates a lateral effect of 39 m using DRAINMOD and 42 m using WATRCOM. These results compare closely to the lateral effect of 41 meters determined directly from observed as discussed at the end of Chapter 2.

The ABC shallow ditch was calibrated for the period of January 2002 to December 2004. All values for E were within the satisfactory or good range. The 3.75 meter well calibrated with the WATRCOM produced the lowest coefficient of efficiency value, 0.47. This trend was noted with all three transects. In order for WATRCOM to successfully predict the overall water table fluctuations along the transect, conditions at the wells nearest the ditch were predicted to be substantially wetter than conditions observed in the field. Long term simulations, (1951 – 2004), predicted the lateral effect to be less than 3.75 meters using DRAINMOD and between 7.5 and 11.25 meters using WATRCOM. The models differed significantly in their efficiencies, as noted by the coefficient of efficiency, at the 3.75 m well (0.76 for DRAINMOD and 0.47 for WATRCOM).

The ABC site deep ditch was calibrated for the period of November 2002 to May 2005. DRAINMOD calibrations for this site produced the lowest overall efficiency values. The highest calculated coefficient of efficiency was 0.68 for the 15 and 45 m wells. WATRCOM better predicted the observed water table fluctuations on this site. Results for 7.5 m from the ditch were poor (E = 0.05). Long-term simulations, (1951 – 2004), predicted the lateral effect to be between 15 and 22.5 meters for both the DRAINMOD and WATRCOM models.

CHAPTER 4: TESTING THE APPROXIMATE METHOD

Introduction

Theory

The approximate method developed by Skaggs et al. (2005) (and referred to as the Skaggs Method by the NC DOT[1] may be used to predict the lateral effect of a drainage ditch on adjacent wetland hydrology. As previously defined, the lateral effect of a ditch or subsurface drain may be defined as the width of a strip of land adjacent to the ditch in which the hydrology has been changed such that it will no longer meet the wetland hydrologic criterion as defined in the 87 Manual (USACOE , 1987). Skaggs et al. (2005) determined that, for poorly drained soils in North Carolina, sites that barely satisfied the wetland hydrologic criterion had characteristic water table draw down rates that depended on local weather conditions and surface depressional storage, but were relatively independent of soil type. The characteristic draw down rates can be quantified as the threshold time, T_{25}, required for the water table to be lowered by drainage from the surface to a depth of 25 cm. Example results are shown in Figure 1 for five soils in New Hanover County, NC. Long-term (50 year) simulations were conducted for a wide rang of ditch spacings for each soil. The threshold spacing, that spacing that resulted in conditions midway between the drains barely satisfying the wetland hydrologic criterion, was determined for each of the five soils. Results in Figure 1 were calculated for the threshold drain spacing for each soil. They indicate that sites barely satisfying the wetland hydrologic criterion in New Hanover County have characteristic draw down

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[1] http://www.ncdot.org/doh/operations/dp%5Fchief%5Feng/roadside/fieldops/downloads/

rates of 25 cm in 6.4 days. That is, the T_{25} value for a ditch depth of 120 cm and surface depressional storage of 2.5 cm, is 6.4 days for New Hanover County.

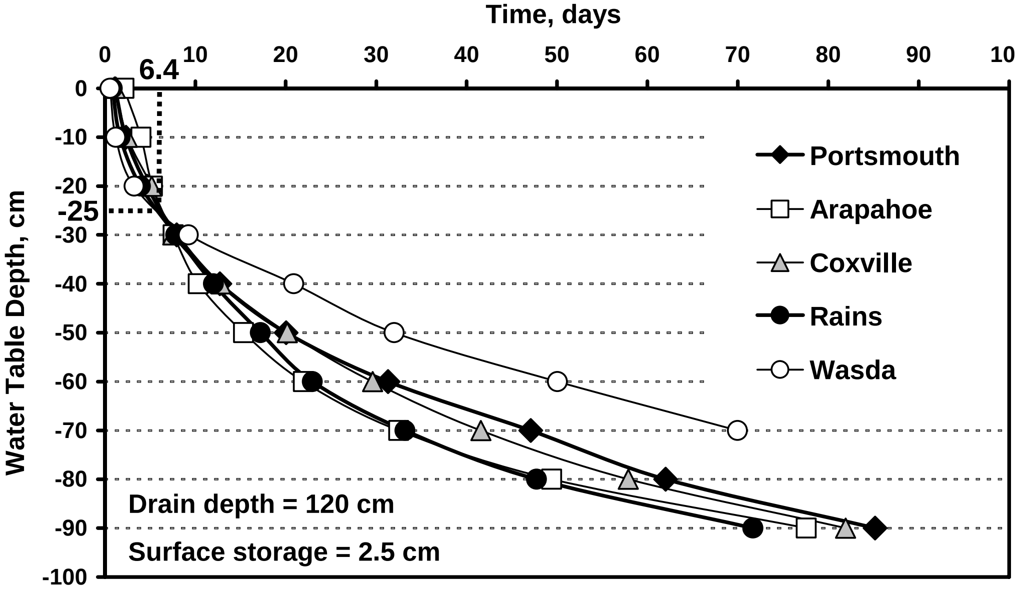

Figure 1. Predicted midpoint water table drawdown for threshold ditch spacings of 5 North Carolina soils. Results are for a ditch depth of 120 cm and surface storage of S = 2.5 cm. Time for water table drawdown of 25 cm (T_{25}) is approximately 6.4 days for all soils (after Skaggs et al., 2005).

The approximate method estimates the lateral effect of a ditch as the distance from the ditch where the water table drawdown, from an initially saturated profile (water table coincident with the surface) is 25 cm in a time of T_{25}. This distance may be calculated with numerical solutions to the Boussinesq equation presented by Skaggs (1976). These solutions are plotted in nondimensional form in Figure 2.

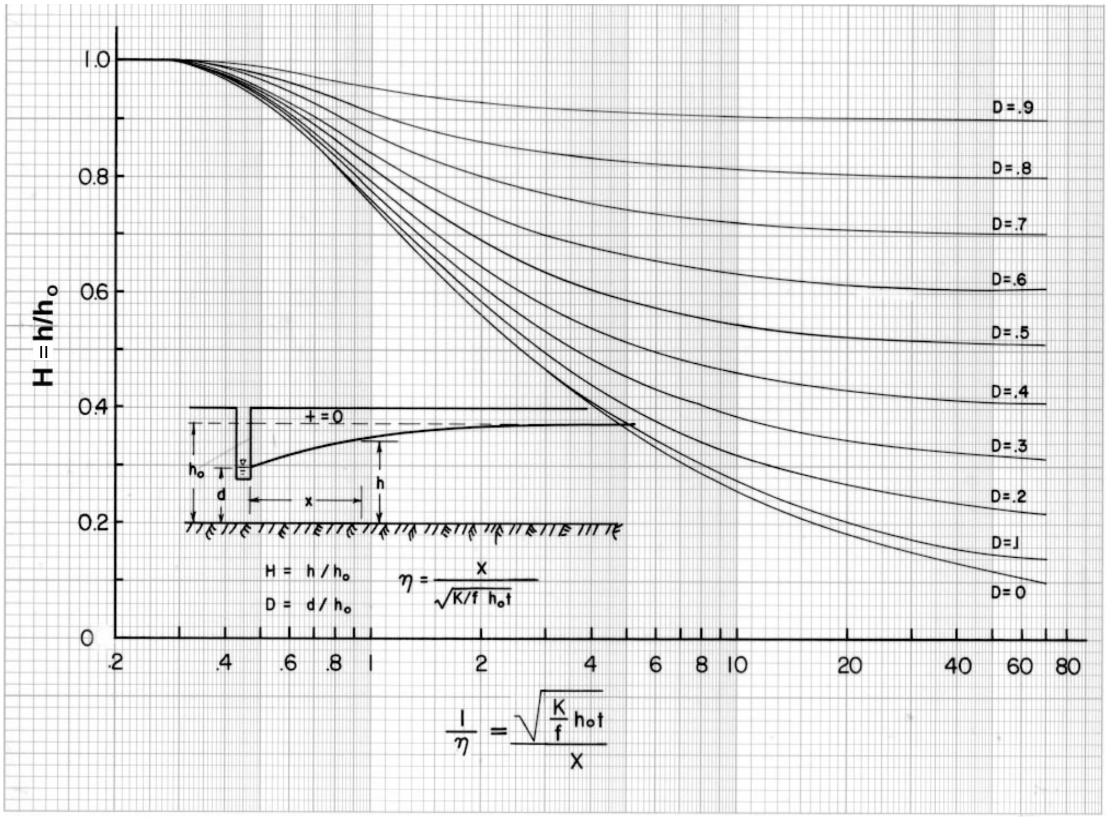

Figure 2. Nondimensional solutions to the Boussinesq equation for water table drawdown due to drainage to a single ditch (after Skaggs, 1976).

An explanation of the variables involved in using the numerical solution follows:

x = distance from the ditch,

t = time, days

H = h/h_o, where h is the water table elevation above the impermeable layer at time t and h_o, is that elevation at t=0,

D = d/h_o, where d is the elevation of the water level in the ditch above the impermeable layer,

K = effective hydraulic conductivity of the profile extending from the ground to the impermeable layer,

f = drainable porosity,

ή = nondimensional parameter.

For a given application we need to find x where $h = h_o - 25$ (25 cm of drawdown) at $t=T_{25}$. The terms h_o and d are known, so it is a simple matter to determine H and D and find the corresponding value of 1/ ή from Figure 2. Then the lateral effect, x, can be solved as,

$$x = \frac{\sqrt{[\frac{K}{f}] * h_o * t}}{\frac{1}{\eta}} \qquad [1]$$

By substituting $t=T_{25}$ the lateral effect can be determined in terms of known values of K, f and h_o. In other words, if one knows the soil and site parameters and the characteristic T_{25} value, the lateral effect can be calculated from the solutions plotted in Figure 2. A complete list of T_{25} values determined for all 100 North Carolina counties is given in Appendix 3.

Input Parameters

Required input parameters for the approximate method of calculating the lateral effect include the following:

Location – county of roadside ditch

Ditch depth

Surface storage conditions

Effective hydraulic conductivity – for profile extending from soil surface to impermeable layer

Drainable porosity – for top 30 cm

Depth to impermeable layer

T_{25} value – from table based on location, ditch depth, surface storage

Boussinesq solution – from nondimensional solution plot.

Example

An example of using the approximate method to calculate the lateral effect is presented here. The lateral effect at the Mildred Woods site will be calculated for this example. The Mildred Woods input parameters are listed in Table 1.

Table 1. Approximate method inputs for Mildred Woods site.

Parameter	
Location	Edgecombe Co.
Ditch depth	1.20 m
Surface storage	5.0 cm
K_{eff}	0.94 m/hr
Drainable porosity, f	0.035
Depth to impermeable layer	4.8 m

As shown in Appendix 3., a 1.2 m deep ditch and 5.0 cm surface storage located in Edgecombe Co. has a T_{25} value of **5.6 days**.

Two values are required to obtain the Boussinesq solution, H and D. H can be viewed as the nondimensional water table depth and D the nondimensional ditch water elevation. For this example H and D are,

$$H = \frac{4.8 - 0.25}{4.8} = 0.95 \qquad [2]$$

$$D = \frac{4.8 - 1.2}{4.8} = 0.75 \qquad [3]$$

From Figure 2 with these values of H and D, the value for 1/ ή is approximately **0.63**. Applying equation {1} the predicted lateral effect of the drainage ditch considered is,

$$x = \frac{\sqrt{[(0.94m/hr)*(24hr/day)/0.035]*4.8m*5.6days}}{0.63} = \boldsymbol{43m} \qquad [4]$$

The user may note that ET is not directly considered in these calculations. However its effect is accounted for in that ET is addressed in the long term DRAINMOD simulations used to determine the T_{25} values.

Results

Calculations of Lateral Effect Method for Field Sites

The approximate method for calculating the lateral effect was applied to each of the three field transects. A summary of the input parameters are listed in Table 2. These parameters were based on calibrated inputs to the WATRCOM model.

Table 2. Inputs and results for calculating lateral effect of drainage ditch on field sites by approximate method.

	Mildred Woods	**ABC Shallow Ditch**	**ABC Deep Ditch**
Location	Edgecombe Co	Beaufort Co.	Beaufort Co
Ditch depth, m	1.2	0.9	1.2
Surface storage, cm	5.0	10.0	2.5
$K_{eff,}$, m/day	0.94	0.10	0.10
Drainable porosity	0.035	0.06	0.06
Depth to impermeable layer, m	4.8	6.0	6.0
T_{25}, days	5.6	2.63	7.6
H	0.95	0.96	0.96
D	0.75	0.85	0.80
1/ή (from Figure 2)	0.63	0.72	0.62
Lateral Effect (m)	**43**	**7**	**14**

A summary of the predicted lateral effects for the methods listed in this report is given in Table 3. The lateral effects for the DRAINMOD and WATRCOM models in Table 3 represent linear interpolations based on the long-term simulations results.

Table 3. Summary of lateral effect predicted or calculated for all methods presented.

	Mildred Woods	**ABC Shallow Ditch**	**ABC Deep Ditch**
Method		Lateral Effect (m)	
Field Results	41	<3.75	12
DRAINMOD	38.6	<3.75	18.0
WATRCOM	41.5	8.9	20.3
Approximate Method	42.6	7.2	14.1

Discussion

The approximate method closely predicted the Mildred Woods and ABC deep ditch lateral effect when compared to field results. It also closely predicted the Mildred Woods and the ABC site shallow ditch lateral effect compared to the WATRCOM simulations. The method predicted a smaller lateral effect for the ABC site deep ditch than that predicted by DRAINMOD and WATRCOM simulations. The method over predicted the effect for the ABC site shallow ditch compared to the field results and the DRAINMOD simulations.

The lateral effect results for the field, DRAINMOD, WATRCOM, and the approximate methods were within 4 m of each other for the Mildred Woods ditch. The ratio between the largest and the smallest predicted distance was 1.10. The largest ratio for the ABC deep ditch was 1.70. It was not possible to calculate a ratio for the ABC shallow ditch, but as listed in Table 3 the difference is at least 2.40 and probably greater.

The ABC site shallow ditch resides in a tight clay layer. Observed water table fluctuations close to the ditch indicate very slow drainage and high head loss in the vicinity of the ditch. The tight soil around the ditch could reduce water movement in the higher conductivity layer under the clay layer. In essence, the effective transmissivity, defined as the thickness of the profile multiplied by the effective conductivity, is likely lower than used in the equation to calculate the lateral effect in Table 2. Lowering the transmissivity will lower the lateral effect predicted using the approximate method. In Equation [1], the transmissivity is represented by the product of K and h_o. Any reduction in the transmissivity, and therefore a reduction in the product, will reduce the value of x calculated. For example, setting the depth of the impermeable layer to be equivalent to the depth of the ditch and adjusting the effective conductivity results in a predicted lateral effect of 5 m for the shallow ditch. Although still an over prediction, it is closer to the field result. Additional research is needed to determine how the method should be modified for shallow ditches confined in a low conductivity layer.

The predicted lateral effects for the ABC deep ditch were 18.0 m using DRAINMOD and 20.3 using WATRCOM. Modeling efficiencies, E, for the 15 and 22.5 m wells were 0.68 and 0.64 for DRAINMOD and 0.91 and 0.58 for WATRCOM. Calibration efficiencies were slightly better at the 22.5 m well from DRAINMOD compared to WATRCOM. It is possible the lateral effect predicted using the WATRCOM model is an over-prediction. Discounting the results of the predicted lateral effect using the WATRCOM model would reduce the percent difference between the smallest and largest predicted lateral effect to a value of 1.50, and it would reduce the difference in the range of values from 8.3 to 6 m. As noted in Chapter 3, there were discrepancies with water table data for the ABC deep ditch during the early part of 2002. The predicted lateral effect for 2002 based on field data was <7.5 m. The values for 2003 and 2004 were 15 and 14 m, respectively. It is possible that the field results for 2002 are incorrect and lean more towards an under-prediction of the lateral effect. An under-prediction for 2002 would skew the overall average predicted lateral effect towards a lower value. Therefore, it is possible that the true lateral effect based on field results is closer to the value predicted using the approximate method.

Lateral Effect Method Limitations

The approximate method was developed for relatively flat sites with soils having slow drainage rates. The dominant source of water is precipitation and the method should not be applied to sites where flooding due to upstream conditions is a primary cause of wetland hydrologic status. More research is needed to determine how the method can be adjusted for cases where there are high head losses near the drain, such as the ABC shallow ditch case.

Summary

The approximate method provides a theoretically sound approach to calculating the lateral effect of a drainage ditch on adjacent wetland hydrology. The method uses inputs of ditch depth, depth to impermeable layer, effective hydraulic conductivity, drainable porosity, T_{25}, and the nondimensional solution to the Boussinesq equation to calculate the lateral effect. T_{25} times, based on the drawdown time of several soils at threshold drain spacings, have been determined for all 100 counties in the state of North Carolina. Once soil properties and site parameters are known, published numerical solutions to the Boussinesq equation (plotted in non-dimensional form) may be used to calculate the lateral effect.

The lateral effect was calculated for the three study transects. The method predicted a lateral effect of 42.6, 7.2, and 14.1 m for Mildred Woods, ABC shallow ditch, and the ABC deep ditch, respectively. Compared to field results for Mildred Woods (41 m) and the deep ditch (12 m), the method performed well. It over predicted the lateral effect but by only 4% for Mildred Woods and 17% for the ABC deep ditch. The lateral effect predicted by the method for the shallow ditch at the ABC site was at least two times that measured in the field. In this case, the ditch was located in a tight clay layer which substantially reduced the effective transmissivity of the profile and the lateral effect of the ditch on the hydrology adjacent wetlands. Additional research is needed to determine how the method should be modified for such situations.

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APPENDICES

APPENDIX 1 : DRAINMOD SOIL FILES

Mildred Woods

```
MILDRED
 921
  .4700000       .0
  .4580000      -4.0
  .4430000     -14.0
  .4340000     -29.0
  .4250000     -54.0
  .4070000    -104.0
  .3800000    -204.0
  .3560000    -404.0
  .0100000  -15000.0
     .0000     .0000     .2000
    3.0000     .1200     .2000
    6.0000     .2400     .2000
    9.0000     .3600     .1000
   12.0000     .4800     .0800
   15.0000     .6000     .0700
   20.0000     .8000     .0600
   25.0000    1.0000     .0500
   30.0000    1.2000     .0500
   35.0000    1.4000     .0150
   40.0000    1.6000     .0150
   45.0000    1.8000     .0100
   60.0000    2.4750     .0050
   75.0000    3.5000     .0010
   90.0000    6.0000     .0010
  100.0000    7.0000     .0010
  120.0000    9.5000     .0010
  150.0000   10.5000     .0005
  200.0000   20.0000     .0000
  500.0000   45.0000     .0000
 1000.0000  100.0000     .0000
10
      .00       .00       .60
    10.00       .03       .60
    20.00       .05       .60
    40.00       .06       .60
    60.00       .08       .60
    80.00       .09       .60
   100.00       .10       .60
   150.00       .74       .60
   200.00       .74       .60
  1000.00       .74       .60
```

ABC Shallow Ditch

```
SHALLOW
 820
  .3950000       .0
  .3890000     -4.0
  .3800000    -14.0
  .3200000    -34.0
  .3170000    -64.0
  .3140000   -104.0
  .2920000   -204.0
  .0100000 -15000.0
     .0000     .0000     .1000
    3.0000     .3000     .0800
    6.0000     .6000     .0800
    9.0000     .9000     .0800
   12.0000    1.2000     .0800
   15.0000    1.5000     .0474
   20.0000    2.0000     .0201
   25.0000    2.4000     .0130
   30.0000    2.8000     .0105
   35.0000    3.1500     .0084
   40.0000    3.5000     .0067
   45.0000    3.8500     .0052
   60.0000    4.9000     .0025
   75.0000    5.9500     .0013
   90.0000    7.0000     .0003
  120.0000    9.1000     .0000
  150.0000   12.8800     .0000
  200.0000   19.9300     .0000
  500.0000   67.0300     .0000
 1000.0000  100.0000     .0000
10
      .00       .00       .60
    10.00       .07       .60
    20.00       .19       .60
    40.00       .40       .60
    60.00       .40       .60
    80.00       .40       .60
   100.00       .40       .60
   150.00      2.19       .60
   200.00      2.19       .60
  1000.00      2.19       .60
```

ABC Deep Ditch

```
DEEP
```

```
820
 .3950000       .0
 .3890000      -4.0
 .3800000     -14.0
 .3200000     -34.0
 .3170000     -64.0
 .3140000    -104.0
 .2920000    -204.0
 .0100000  -15000.0
    .0000     .0000     .1000
   3.0000     .3000     .0010
   6.0000     .6000     .0010
   9.0000     .9000     .0010
  12.0000    1.2000     .0010
  15.0000    1.5000     .0010
  20.0000    2.0000     .0010
  25.0000    2.4000     .0010
  30.0000    2.8000     .0010
  35.0000    3.1500     .0010
  40.0000    3.5000     .0010
  45.0000    3.8500     .0010
  60.0000    4.9000     .0010
  75.0000    5.9500     .0010
  90.0000    7.0000     .0003
 120.0000    9.1000     .0000
 150.0000   12.8800     .0000
 200.0000   19.9300     .0000
 500.0000   67.0300     .0000
1000.0000  100.0000     .0000
10
      .00       .00       .60
    10.00       .07       .60
    20.00       .19       .60
    40.00       .40       .60
    60.00       .40       .60
    80.00       .40       .60
   100.00       .40       .60
   150.00      2.19       .60
   200.00      2.19       .60
  1000.00      2.19       .60
```

APPENDIX 2 : WATRCOM INPUT FILES

Mildred Woods

GEN file – general inputs

```
Testing Version 4.25, WATRCOM-2D
 0 0 1 0 1 1 1 1                idaily,isat,iredp,iptype,isatst,idbal,iweir, idmwea
 1   0   0.1E-06      1.0       iod,irf,eps,alpha
17 16   1   0 1983          nnodes, nelements, npres, nfarm, yr
    366.0       1.0       0.0       3.0 0       2.0       1.0
 7
   1  2  3 5 7 9 13
   1  1 0.0000
 1
 5
17
  3.33 3.33 3.40 3.33 3.27 3.31 3.36 3.32 3.28 3.29
  3.29 3.30 3.30 3.30 3.30 3.30 3.30        WTE
17
  4.63 4.63 4.80 4.70 4.67 4.59 4.51 4.52 4.53 4.51
  4.48 4.46 4.43 4.43 4.40 4.40 4.43
  0
  0
```

FEM file – finite element grid inputs

```
121.92 7.62
```

BDY file – boundary conditions versus time

```
  1.000  3.88 3.88
  61.000  3.88 3.88
  91.000  3.88 3.88
  99.000  3.88 3.88
 190.000  3.88 3.88
 195.000  3.88 3.88
 231.000  3.88 3.88
 367.000  3.88 3.88
   1.000  3.88 3.88  s2
   61.000  3.88 3.88
  91.000  3.88 3.88
  99.000  3.88 3.88
 190.000  3.88 3.88
 195.000  3.88 3.88
 231.000  3.88 3.88
```

```
 367.000  3.88 3.88
```

SAT file – saturated soil input data

```
1
 2  0.0 200
1.4    .3    4.8       1.2
19
  0       0.000    0.03     0.005    0.06     0.013    0.09     0.017
0.12      0.022    0.15     0.026    0.2      0.029    0.25     0.032
0.3       0.035    0.35     0.035    0.4      0.032    0.45     0.028
0.6       0.028    0.75     0.035    0.9      0.045    1.2      0.057
1.5       0.068    2        0.078    4.8      0.099
```

UNS file – unsaturated inputs

```
1 2
1 9 0 0 0
480       0.1
0         0.470
4         0.458
14        0.443
29        0.434
54        0.425
104       0.407
204       0.380
404       0.356
15000     0.010
19
0         0.5000
3         0.3224
6         0.1083
9         0.0700
12        0.0700
15        0.0600
20        0.0500
25        0.0400
30        0.0300
35        0.0200
40        0.0100
45        0.0050
60        0.0050
75        0.0050
90        0.0025
120       0.0005
150       0.0000
200       0.0000
480       0.0000
10
0         0.0      0
0.03      0.6      10
0.05      0.6      20
```

```
0.06       0.6       40
0.08       0.6       60
0.09       0.6       80
0.10       0.6       100
0.74       0.6       150
0.74       0.6       200
0.74       0.6       1000
 17       no of surface storage nodes (1 use one for area)
 1.25 1.25 1.25 5.0 5.0 5.0 5.0 1.0 1.0 2.0 2.0 2.0 2.0 20.0 45.0 45.0 45.0   surfacestorage in cm
 0   no lateral drainage
  0.400  manning's roughness between poor grass and ave. grass (0.2-0.4) for forest conditions
******* encUN15.DATA   2.0 2.5 2.5 2.5 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 20.0 45.0 45.0 45.0
```

CRO file – crop inputs

```
1  1
 15 1 1.0 366.0
  0.0         3.0
   30.0         3.0
   60.0         3.0
   90.0         3.0
  100.0         3.0
  118.0         3.0
  131.0         5.0
  145.0         25.0
  165.0         25.0
  198.0         25.0
  235.0         25.0
  253.0         10.0
  292.0         10.0
  336.0          3.0
  366.0          3.0
7  100.0 0.71       no., wmax,wlsp  CROP TYPE 1, CORN - roe's new values FOR WET
   0.0  0.20
  30.0  0.22    --> wet stress
  50.0  0.31
  70.0  0.19
  90.0  0.08
 110.0  0.02
 131.0  0.00
 8 100.0 1.22
  42.5  0.50
  62.5  1.00
  67.5  1.75
  82.5  2.00    --> DRY STRESS
 107.5  1.30
 112.5  1.20
 117.5  1.00
 131.0  0.50
 0
```

STI file – storage input parameters

```
  1   1
 3.88
 15 0.50   1
  1   2   3   4   5   6   7   8   9  10
 11  12  13  14  15
  1
  1   1
  1       PUMPING INFO
365.0 365.0 0.00
  1   1
0   ***> IWEIR
1.0 0.0 3.88 0.5 50
1.0 0.0 3.88 0.5 50
0   ***> IRESER
1.0 0.0 2.00 1.0 200.0
1 4.0  ***> IRESIN, RESFAC
```

ABC Shallow Ditch

GEN file – general inputs

```
Testing Version 4.25, WATRCOM-2D
 0 0 1 0 1 1 1 1                  idaily,isat,iredp,iptype,isatst,idbal,iweir, idmwea
 1   0   0.1E-06       1.0       iod,irf,eps,alpha
17 16   1   0 1983           nnodes, nelements, npres, nfarm, yr
    366.0       1.0       0.0       3.0 0       2.0       1.0
 7
  1  2  3 4 5 7 9
  1  1 0.0000
 1
 5
17
 5.97 5.97 6.00 5.96 5.96 5.93 5.90 5.88 5.87 5.87
 5.87 5.87 5.87 5.87 5.87 5.87 5.87       WTE
17
 6.00 5.90 6.00 5.96 5.96 5.93 5.90 5.88 5.87 5.87
 5.87 5.87 5.87 5.87 5.87 5.87 5.87
 0
 0
```

FEM file – finite element grid inputs

```
60.96 3.81
```

BDY file – boundary conditions versus time

```
    1.000 5.40 5.40
  61.000  5.40 5.40
  91.000  5.40 5.40
 231.000  5.40 5.40
 367.000  5.40 5.40
   1.000  5.40 5.40  s2
   61.000  5.40 5.40
  91.000  5.40 5.40
 231.000  5.40 5.40
 367.000  5.40 5.40
```

SAT file – saturated soil input data

```
1
 4  0.0 200.0
 0.20 0.50   0.45 0.25  1.45    0.08   6.0   0.08
15
0.0         0.000     0.15       0.200     0.2         0.200     0.25       0.060
0.3         0.060     0.35       0.070     0.4         0.070     0.45       0.070
0.6         0.070     0.75       0.070     0.9         0.070     1.2        0.070
1.5         0.126     2          0.141     6.0         0.157
```

UNS file – unsaturated inputs

```
1 20
1 8 0 0 0
600      0.200
0        0.395
3        0.389
14       0.380
34       0.320
64       0.317
104      0.314
204      0.292
15000    0.010
19
0        0.5000
3        0.3000
6        0.3000
9        0.3000
12       0.1126
15       0.0474
20       0.0201
25       0.0130
30       0.0105
35       0.0084
40       0.0067
45       0.0052
60       0.0025
75       0.0013
90       0.0000
120      0.0000
150      0.0000
200      0.0000
600      0.0000
10
0        0.6      0
0.07     0.6      10
0.19     0.6      20
0.40     0.6      40
0.40     0.6      60
0.40     0.6      80
0.40     0.6      100
2.19     0.6      150
2.19     0.6      200
2.19     0.6      1000
 17     no of surface storage nodes (1 use one for area)
  5.0 20.0 9.0 3.0 3.0 3.0 6.0 9.0 9.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0   surface storage in cm
 0   no lateral drainage
  0.300  manning's roughness between poor grass and ave. grass (0.2-0.4) for forest conditions
******* encUN15.DATA   10.0 10.0 5.0 5.0 3.0 5.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0
```

CRO file – crop inputs

```
1  1
 9 1 100.0 200.0
   0.0         12.0
  30.0         12.0
  60.0         12.0
  90.0         12.0
 100.0         12.0
 150.0         15.0
 292.0         15.0
 336.0         12.0
 366.0         12.0
7  100.0 0.71       no., wmax,wlsp  CROP TYPE 1, CORN - roe's new values FOR WET
  0.0  0.20
 30.0  0.22    --> wet stress
 50.0  0.31
 70.0  0.19
 90.0  0.08
110.0  0.02
131.0  0.00
 8 100.0 1.22
 42.5  0.50
 62.5  1.00
 67.5  1.75
 82.5  2.00    --> DRY STRESS
107.5  1.30
112.5  1.20
117.5  1.00
131.0  0.50
0
```

STI file – storage input parameters

```
  1   1
 5.20
 13 0.50   1
  1   2   3   4   5   6   7   8   9  10
 11  12  13
  1
  1   1
  1      PUMPING INFO
 365.0 365.0 0.00
  1   1
 0   ***> IWEIR
 1.0 0.0 5.20 0.5 100.0
 1.0 0.0 5.20 0.5 100.0
 0   ***> IRESER
 1.0 0.0 2.00 1.0 200.0
 1 4.0  ***> IRESIN, RESFAC
```

ABC Deep Ditch

GEN file – general inputs

```
Testing Version 4.25, WATRCOM-2D
 0 0 1 0 1 1 1 1                idaily,isat,iredp,iptype,isatst,idbal,iweir, idmwea
 1   0   0.1E-06      1.0       iod,irf,eps,alpha
17 16   1   0 1983          nnodes, nelements, npres, nfarm, yr
     366.0      1.0      0.0      3.0 0      2.0      1.0
 7
  1  2  3 4 5 7 9
  1  1 0.0000
 1
 5
 17
  4.78 5.93 6.00 5.89 5.82 5.78 5.74 5.76 5.77 5.77
  5.77 5.77 5.77 5.77 5.77 5.77 5.77       WTE
 17
  5.93 5.93 6.00 5.89 5.82 5.78 5.74 5.74 5.74 5.74
  5.74 5.74 5.74 5.74 5.77 5.77 5.77
 0
 0
```

FEM file – finite element grid inputs

```
121.92 7.62
```

BDY file – boundary conditions versus time

```
    1.000 4.83 4.83
  61.000  4.83 4.83
  91.000  4.83 4.83
 231.000  4.83 4.83
 367.000 4.83 4.83
   1.000  4.83 4.83  s2
  61.000  4.83 4.83
  91.000  4.83 4.83
 231.000  4.83 4.83
 367.000 4.83 4.83
```

SAT file – saturated soil input data

```
1
 4  0.0 200.0
 0.30 2.0   0.45 0.5  1.45    0.08   6.0   0.08
15
0.0        0.000     0.15       0.200     0.2        0.200     0.25       0.060
0.3        0.060     0.35       0.070     0.4        0.070     0.45       0.070
0.6        0.070     0.75       0.070     0.9        0.070     1.2        0.070
1.5        0.126     2          0.141     6.0        0.157
```

UNS file – unsaturated inputs

```
1 20
1 8 0 0 0
600     0.200
0       0.395
3       0.389
14      0.380
34      0.320
64      0.317
104     0.314
204     0.292
15000   0.010
19
0       0.5000
3       0.3000
6       0.3000
9       0.3000
12      0.1126
15      0.0474
20      0.0201
25      0.0130
30      0.0105
35      0.0084
40      0.0067
45      0.0052
60      0.0025
75      0.0013
90      0.0000
120     0.0000
150     0.0000
200     0.0000
600     0.0000
10
0       0.6     0
0.07    0.6     10
0.19    0.6     20
0.40    0.6     40
0.40    0.6     60
0.40    0.6     80
0.40    0.6     100
2.19    0.6     150
2.19    0.6     200
2.19    0.6     1000
 17     no of surface storage nodes (1 use one for area)
0.1 0.1 0.1 0.1 0.1 10.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 surface storage in cm
 0   no lateral drainage
  0.300  manning's roughness between poor grass and ave. grass (0.2-0.4) for forest conditions
******* encUN15.DATA    6.0 6.5 6.5 6.5 5.0 5.0 5.0 5.0 10.0 30.0 30.0 30.0 30.0 30.0 45.0 45.0 45.0
```

CRO file – crop inputs

```
1  1
 8 1 60.0 101.0
   0.0         12.0
  30.0         12.0
  60.0         12.0
  90.0         12.0
 100.0        20.0
 292.0        20.0
 336.0        12.0
 366.0        12.0
7  100.0 0.71       no., wmax,wlsp  CROP TYPE 1, CORN - roe's new values FOR WET
  0.0  0.20
  30.0  0.22    --> wet stress
  50.0  0.31
  70.0  0.19
  90.0  0.08
 110.0  0.02
 131.0  0.00
 8 100.0 1.22
  42.5  0.50
  62.5  1.00
  67.5  1.75
  82.5  2.00    --> DRY STRESS
 107.5  1.30
 112.5  1.20
 117.5  1.00
 131.0  0.50
0
```

STI file – storage input parameters

```
    1   1
  4.83
  15 0.50   1
  1   2  3  4  5   6  7  8  9  10  11  12  13  14  15
  1
  1   1
  1      PUMPING INFO
 365.0 365.0 0.00
  1   1
 0   ***> IWEIR
 1.0 0.0 4.83 0.5 10.0
 1.0 0.0 4.83 0.5 10.0
 0   ***> IRESER
 1.0 0.0 2.00 1.0 200.0
 1 4.0  ***> IRESIN, RESFAC
```

APPENDIX 3 : T_{25} VALUES FOR ALL NORTH CAROLINA COUNTIES

Table 1. Summary of T_{25} values (in days) for all North Carolina counties for surface depressional storage of 1 inch (2.5 cm).

Depth of water in pit below surface	1 ft	2 ft	3 ft	4 ft	5 ft	6 ft
Alamance	9.4	9.0	9.7	10.7	11.8	12.6
Alexander	5.0	5.6	6.3	7.0	7.5	8.0
Alleghany	5.4	5.7	6.7	7.2	7.7	8.2
Anson	8.6	8.5	9.1	9.9	10.4	10.9
Ashe	2.5	2.9	3.3	4.0	4.8	5.2
Avery	2.3	3.0	3.7	4.4	5.2	5.6
Bertie	10.3	8.7	9.3	10.7	11.9	13.1
Beaufort	6.6	6.2	7.0	7.6	8.1	8.7
Bladen	11.8	10.3	10.5	10.9	11.3	12.4
Brunswick	4.2	4.6	5.1	5.4	5.8	5.9
Buncombe	4.0	4.0	4.1	5.1	5.4	6.2
Burke	4.7	5.6	6.4	6.8	7.3	7.6
Cabarrus	6.5	6.7	7.2	7.6	8.0	8.4
Caldwell	4.8	5.1	5.7	5.9	6.1	6.6
Camden	6.5	6.0	6.7	7.4	8.1	8.8
Carteret	4.8	5.0	5.4	5.9	6.3	6.6
Caswell	9.2	8.2	8.9	9.3	10.5	10.8
Catawba	5.0	5.6	6.3	7.0	7.5	8.0
Chatham	5.6	5.4	6.2	6.9	7.6	8.6
Cherokee	3.3	4.0	4.5	5.0	5.4	5.7
Chowan	7.9	7.1	8.1	8.6	9.2	9.7
Clay	2.4	2.8	3.3	3.5	3.9	4.2
Cleveland	5.3	5.2	5.7	6.3	6.7	6.8
Columbus	9.7	9.2	10.2	11.0	11.6	12.2
Craven	5.1	5.2	6.0	6.9	7.5	8.1
Cumberland	6.3	6.3	7.4	8.6	9.1	9.7
Currituck	6.5	6.0	6.7	7.4	8.1	8.8
Dare	5.4	5.7	6.2	6.9	7.3	7.6
Davidson	7.8	8.6	9.4	10.3	10.4	10.8
Davie	7.6	6.9	8.5	10.2	11.1	11.7
Duplin	6.1	5.5	6.4	7.1	7.8	8.6
Durham	7.0	7.1	7.6	8.1	8.8	9.8
Edgecombe	10.7	9.5	10.2	11.0	11.8	12.4
Forsyth	7.0	7.1	7.6	8.7	9.6	10.3
Franklin	12.4	10.5	11.9	13.1	14.8	16.1
Gaston	7.5	7.0	7.6	8.1	8.7	9.0

Gates	7.3	6.2	7.3	8.2	9.0	9.5
Graham	4.0	4.8	5.6	6.1	6.7	7.2
Granville	12.0	9.7	10.9	11.4	12.2	12.7
Greene	10.5	8.6	9.4	10.9	11.7	12.6
Guilford	5.5	6.2	6.9	7.6	8.1	8.8
Halifax	8.3	7.9	8.7	9.9	10.9	11.3
Harnett	10.5	8.9	9.6	11.1	12.2	13.0
Haywood	7.4	10.4	12.1	13.5	15.9	16.5
Henderson	3.2	3.3	4.2	4.4	4.9	5.1
Hertford	7.3	6.2	7.3	8.2	9.0	9.5
Hoke	6.3	6.3	7.4	8.6	9.1	9.7
Hyde	7.8	7.2	7.6	7.8	8.7	8.9
Iredell	5.0	5.6	6.3	7.0	7.5	8.0
Jackson	6.2	6.4	7.4	8.9	11.4	12.7
Johnston	11.2	9.8	10.8	12.2	10.3	13.6
Jones	7.7	6.2	6.6	7.6	7.9	9.0
Lee	11.9	9.5	10.2	10.9	12.5	13.8
Lenoir	9.8	8.4	9.1	10.4	11.2	12.1
Lincoln	6.0	5.7	6.3	7.0	7.2	7.4
Macon	2.4	2.8	3.3	3.5	3.9	4.2
Madison	4.0	4.0	4.1	5.1	5.4	6.2
Martin	7.0	6.2	6.9	7.8	8.2	8.8
McDowell	7.3	7.1	7.9	8.9	9.5	10.1
Mecklenburg	6.6	6.6	7.5	8.3	8.6	9.0
Mitchell	2.1	2.9	3.4	4.0	4.2	4.7
Montgomery	7.3	7.2	8.5	10.4	11.1	11.6
Moore	9.7	8.1	8.5	9.8	10.4	10.7
Nash	10.0	9.3	10.4	11.1	11.7	12.2
New Hanover	4.5	5.5	5.9	6.3	6.6	6.9
Northampton	11.8	8.6	9.5	11.0	12.1	12.9
Onslow	6.8	6.2	7.4	8.8	9.2	9.5
Orange	10.2	8.2	8.9	10.0	10.6	11.6
Pamlico	5.1	5.7	6.1	7.0	7.5	8.0
Pasquotank	6.5	6.0	6.7	7.4	8.1	8.8
Pender	6.5	6.2	7.2	8.2	8.8	9.3
Perquimans	9.0	8.9	9.9	10.3	10.7	11.3
Person	8.0	7.4	8.3	9.3	10.0	11.4
Pitt	10.5	8.6	9.4	10.9	11.7	12.6
Polk	3.2	3.7	4.0	4.2	4.5	4.7
Randolph	8.3	7.6	8.6	9.5	10.8	9.3
Richmond	8.8	8.6	10.3	11.5	12.3	12.8
Robeson	10.4	9.1	9.6	10.9	11.6	12.7
Rockingham	8.9	6.6	7.6	8.3	8.7	9.0
Rowan	7.1	7.1	7.6	8.2	9.1	9.7
Rutherford	6.3	6.0	6.6	7.6	8.0	8.4

Sampson	7.4	6.6	7.4	7.6	8.1	8.4
Scotland	10.7	10.9	11.9	12.7	15.0	15.7
Stanly	4.9	5.5	6.6	7.6	8.3	8.4
Stokes	4.2	4.9	5.4	6.8	7.9	8.7
Surry	6.2	6.0	6.7	7.3	7.8	8.1
Swain	3.2	4.2	5.0	5.9	6.2	6.4
Transylvania	2.2	2.6	3	3.3	3.6	3.9
Tyrrell	9.1	7.9	8.1	8.9	9.6	10.2
Union	8.3	8.5	10.5	11.4	12.3	12.8
Vance	6.8	6.7	7.6	8.4	9.1	9.5
Wake	9.6	7.7	8.4	9.6	10.3	10.7
Warren	8.8	7.6	9.1	9.5	10.0	10.6
Washington	9.1	7.9	8.1	8.9	9.6	10.2
Watauga	3.0	3.7	4.3	4.7	5.5	5.6
Wayne	14.0	11.1	11.4	12.3	12.9	13.4
Wilkes	4.5	4.3	5.4	6.7	7.5	7.7
Wilson	11.0	11.2	11.4	12.0	12.0	12.8
Yadkin	7.6	6.9	8.5	10.2	11.1	11.7
Yancey	2.1	2.9	3.4	4.0	4.2	4.7

Table 2. Summary of T_{25} values (in days) for all North Carolina counties for surface depressional storage of 2 inches (5.0 cm).

Depth of water in pit below surface	1 ft	2 ft	3 ft	4 ft	5 ft	6 ft
Alamance	5.3	4.6	5.3	5.8	6.6	7.0
Alexander	3.4	3.5	3.8	4.1	4.3	4.5
Alleghany	3.5	3.5	3.8	4.2	4.6	4.9
Anson	5.4	4.6	4.7	5.1	5.7	6.0
Ashe	1.7	1.9	2.3	3.0	3.5	2.6
Avery	1.7	2.2	2.7	3.4	4.1	4.5
Bertie	4.5	4.1	5.0	5.4	6.0	6.3
Beaufort	3.9	3.7	4.1	4.6	4.9	5.2
Bladen	5.6	4.8	5.3	5.9	6.4	6.7
Brunswick	2.8	3.0	3.2	3.5	3.6	3.8
Buncombe	2.7	2.8	3.3	3.6	3.8	4.0
Burke	3.2	3.3	3.6	3.9	4.0	4.5
Cabarrus	4.5	3.9	4.2	4.7	5.0	5.4
Caldwell	3.0	2.9	3.1	3.6	4.0	4.1
Camden	3.7	3.8	4.2	4.5	4.8	5.1
Carteret	3.3	3.2	3.6	3.9	4.0	4.2
Caswell	4.9	4.5	5.0	5.3	5.9	6.3
Catawba	3.4	3.5	3.8	4.1	4.3	4.5

Chatham	3.4	3.6	3.9	4.5	5.0	5.5
Cherokee	2.2	2.5	3.1	3.6	4.0	4.2
Chowan	4.4	4.0	4.1	4.4	4.8	5.0
Clay	1.5	1.7	2.0	2.3	2.5	2.7
Cleveland	3.3	3.2	3.3	3.7	4.4	4.9
Columbus	4.9	4.6	5.0	5.5	5.8	6.3
Craven	3.1	3.2	3.8	4.4	4.9	5.3
Cumberland	4.9	4.6	5.1	5.5	5.8	6.0
Currituck	3.7	3.8	4.2	4.5	4.8	5.1
Dare	3.3	3.2	3.6	4.0	4.2	4.4
Davidson	5.4	4.8	5.1	5.6	5.9	6.5
Davie	5.2	4.4	5.2	6.1	6.3	6.9
Duplin	3.6	3.4	4.2	4.8	5.3	5.6
Durham	4.1	4.0	4.2	4.9	5.5	5.8
Edgecombe	5.5	4.7	5.3	5.6	6.1	6.3
Forsyth	4.5	4.1	4.8	5.4	5.6	6.0
Franklin	5.9	5.5	5.7	6.0	6.5	7.0
Gaston	3.9	3.7	4.2	4.9	5.1	5.7
Gates	3.7	3.7	4.3	4.7	5.3	5.7
Graham	3.0	3.1	3.7	4.1	4.6	5.0
Granville	6.0	4.6	5.0	5.7	6.5	6.8
Greene	4.7	4.0	4.5	4.9	5.6	6.0
Guilford	3.4	3.9	4.3	4.9	5.6	6.1
Halifax	4.8	4.6	5.1	5.6	5.9	6.2
Harnett	5.6	4.7	5.1	5.5	6.0	6.5
Haywood	4.0	5.7	6.8	7.4	7.7	8.3
Henderson	2.2	2.4	2.5	2.8	3.2	3.4
Hertford	3.7	3.7	4.3	4.7	5.3	5.7
Hoke	4.9	4.6	5.1	5.5	5.8	6.0
Hyde	3.6	3.6	4.0	4.4	4.7	5.1
Iredell	3.4	3.5	3.8	4.1	4.3	4.5
Jackson	4.1	4.2	5.0	6.1	6.6	7.3
Johnston	6.3	5.2	5.9	6.6	7.1	7.4
Jones	4.6	4.9	4.2	4.6	5.5	5.5[1]
Lee	4.5	4.0	4.6	5.1	5.5	6.2
Lenoir	4.9	4.4	5.1	5.5	5.9	6.2
Lincoln	3.4	3.4	4.0	4.4	4.6	4.7
Macon	1.5	1.7	2.0	2.3	2.5	2.7
Madison	2.7	2.8	3.3	3.6	3.8	4.0
Martin	4.3	3.8	4.1	4.6	5.1	5.4
McDowell	4.0	4.1	4.4	4.9	5.2	5.5
Mecklenburg	5.1	4.6	5.2	5.6	6.3	6.5
Mitchell	1.6	2.0	2.4	2.7	3.0	3.3
Montgomery	4.6	4.8	4.8	5.2	5.5	6.0
Moore	4.5	4.0	4.3	4.8	5.2	5.6

Nash	5.7	5.1	5.7	6.2	6.4	6.6
New Hanover	2.9	3.2	3.4	3.7	3.9	4.1
Northampton	6.1	4.7	5.4	6.1	6.7	7.0
Onslow	3.4	3.2	3.7	4.1	4.3	4.5
Orange	4.2	4.1	4.6	5.5	6.3	6.6
Pamlico	3.3	3.2	3.8	4.2	4.5	4.8
Pasquotank	3.7	3.8	4.2	4.5	4.8	5.1
Pender	3.6	3.5	3.9	4.5	4.9	5.2
Perquimans	5.2	4.1	4.7	5.1	5.6	6.3
Person	4.8	4.6	4.9	5.6	5.9	6.6
Pitt	4.7	4.0	4.5	4.9	5.6	6.0
Polk	2.4	2.4	2.5	2.6	2.8	3.0
Randolph	4.9	4.3	4.9	5.2	6.1	6.7
Richmond	5.3	4.6	5.0	5.6	6.2	6.7
Robeson	5.0	4.7	5.4	6.1	6.6	7.2
Rockingham	3.8	3.8	4.1	4.5	4.8	5.5
Rowan	4.7	4.6	5.5	5.8	6.6	7.1
Rutherford	3.4	3.2	3.8	4.2	4.6	4.9
Sampson	4.7	4.2	4.6	5.0	5.3	5.7
Scotland	6.2	5.1	5.4	5.9	6.4	6.8
Stanly	3.5	3.4	3.7	3.9	4.3	4.8
Stokes	3.1	3.2	3.7	4.2	4.6	5.0
Surry	3.8	3.9	4.2	4.6	5.3	5.9
Swain	2.9	3.0	3.6	3.9	4.4	4.7
Transylvania	1.5	1.9	2.1	2.4	2.9	3.1
Tyrrell	4.0	4.0	4.4	4.7	5.1	5.3
Union	5.4	4.9	5.2	5.9	6.6	7.3
Vance	4.2	3.8	4.2	4.8	5.3	5.5
Wake	4.6	4.3	4.7	5.1	5.5	5.9
Warren	4.5	4.2	4.5	4.8	5.6	6.0
Washington	4.0	4.0	4.4	4.7	5.1	5.3
Watauga	2.1	2.4	2.8	3.2	3.5	3.7
Wayne	6.2	5.3	5.7	6.4	6.9	7.3
Wilkes	3.0	3.0	3.7	4.2	4.5	4.8
Wilson	6.4	6.2	6.7	7.1	7.4	7.9
Yadkin	5.2	4.4	5.2	6.1	6.3	6.9
Yancey	1.6	2.0	2.4	2.7	3.0	3.3

1. Values for the 5 and 6 ft depths are equal.