Abstract

WRIGHT, JASON DEE. The Evaluation and Modeling of the Effects of Surface Treatments on the Hydrology of a Restored Wetland in the Coastal Plain of North Carolina. (Under the direction of Dr. Robert O. Evans).

Wetlands can be valuable for removing sediment and pollutants from drainage waters. Many wetlands are being restored through state and federal incentive programs, however more research is needed to develop and document the success of restoration practices. Wetland hydrology is critical in the success of wetland restoration. This study was conducted to determine the effects of surface treatments on the hydrology of a 100 ha prior converted wetland in coastal North Carolina that was restored in March of 2003.

A depressional non-riverine bottomland hardwood wetland was also evaluated to serve as a reference for comparison of the hydrologic conditions in the restored wetland. A natural stream in the reference wetland served as the drainage outlet. Water table monitoring wells were installed along three different transects across the reference.

Approximately 60 ha of the prior converted crop land was restored using three types of surface treatments; plug and plant, crown removal, and microtopography. In each of the treatments the ditches were plugged and wetland vegetation was planted. Plug and plant left the ground surface as it was during agricultural production, crown removal leveled the approximately 20 cm of crown in order to reduce runoff, and microtopography was added to provide storage and slow runoff. The three surface treatments were replicated in three blocks**,** approximately 20 ha each. Each of the 6.5 ha plots were separated by berms to allow measurement of surface runoff.

Water table monitoring wells were installed in a single transect across each treatment. Water control structures with weirs were used to control outlet stage and outflow from each treatment. Continuous water level recorders were installed in each well and at the outlets.

The water table depth in the treatments was analyzed using eight criteria to characterize the hydrology of the site. The criteria were the 1) number of times that jurisdictional wetland criteria was met; 2) the range of the water table fluctuation; 3) the number of days that the water table was at or above the surface during the study period and 4) the growing season; 5) the number of days that the water table was within 30 cm of the surface during the study period and 6) the growing season; 7) SEW_{30} for the study period and 8) the growing season. SEW_{30} is a measure of the duration and frequency that the water table is above a threshold depth.

The average water table in the crown removal treatment was deeper than in the plug and plant and the microtopography treatment across all three blocks. The water table was also closer to the surface in the microtopography treatment than in the plug and plant treatment. Outflows from the crown removal treatment were less than from the microtopography and plug and plant treatments. A ditch plug near the outlet of plot 9 (Block 3) failed which likely affected the hydrology of this plot. When the criteria were applied to only block 1 and block 2, the crown removal treatment was wetter (water table closer to the surface) than the microtopography treatment and the plug and plant treatment. These latter results showed that crown removal was the most effective practice to maintain the water table within 30 cm, or closer to the surface, compared to adding microtopography or just plug and plant.

DRAINMOD was calibrated using the 20 months of water table data and used to simulate the hydrology of each plot in blocks 1 and 2. Long term simulation results were similar to the observed results. The simulated water table was at the surface for more days in the crown removal treatment than in the reference or the microtopography and the plug and

plant treatments. The water table was within 30 cm of the surface for more days and the SEW_{30} was greater in the crown removal treatment indicating that it was wetter. DRAINMOD was also used to model the expected conditions in the wetland once mature wetland vegetation was established. Minimal jurisdictional wetland criteria (water table within 30 cm of the surface for 5% of the growing season) was satisfied for more than 41 out of 50 years in the treatments and 46 out of 50 years in the center of the reference. The restored surface treatments were saturated continuously above 30 cm for 12.5% or more of the growing season in 17 to 22 years out of 50 compared to 24 out of 50 for the center of the reference. Both the reference and the restored treatments satisfied the drier range of the jurisdictional criteria but neither satisfied the wet end of the range. Finally, outflow was simulated for a wetland with mature vegetation and compared to conventional row crop conditions. Each of the restored treatments showed an approximate 30% reduction in flow compared to conventionally drained row crops.

The Evaluation and Modeling of the Effects of Surface Treatments on the Hydrology of a Restored Wetland in the Coastal Plain of North Carolina

by

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BIOGRAPHY

Jason Wright was born in Raleigh, North Carolina on October 17th, 1979. He spent his first 10 years living in Garner, North Carolina with his mother, father, and eventually, younger sister. In 1990 the family moved to Goodyear, Arizona where they lived for 3 years. During this time the family was active in the Boy Scouts of America where Jason earned his Eagle Scout award. In 1993 the family returned to Garner, North Carolina and Jason began high school at W.G. Enloe High School from where he graduated in 1998.

Jason then attended North Carolina State University in the Fall of 1998. He eventually received his undergraduate degree in Environmental Engineering. During the course of his study he began to develop an interest in other types of Environmental study, specifically restoration. This led him to an internship with the Ecosystem Enhancement Program (formerly know as the Wetland Restoration Program) where his interest in restoration grew. Jason then continued his education by pursuing a Masters in Biological and Agricultural Engineering at North Carolina State University. He will take a position as a Research Engineer with the department upon graduation.

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Chapter 1 Evaluation of the Immediate and Long Term Effects of Surface Treatments on the Hydrology of a Restored Wetland in the Coastal Plain of North Carolina

Introduction

Agriculture is important to the economy of many Atlantic Coast and Gulf coast states, including North Carolina. Nearly 20 million acres of poorly drained soils in the Atlantic coast and Gulf coast areas have been drained to make them suitable for agriculture (Evans et al., 1992). In North Carolina, more than 40% of the land in crop production requires drainage (Thomas et al., 1995). Agricultural drainage has often been blamed for the degradation of water quality in watersheds containing or adjacent to areas that are artificially drained. A study by Gilliam and Skaggs (1986) determined that clearing, draining, and developing poorly drained areas increased the peakrunoff rates to three times that of undeveloped areas, which can increase sediment and phosphorus exports. A similar study by Skaggs et al. (1980) showed that artificial drainage can increase sediment loads 1.6 to 10 times depending on land use after drainage. Gilliam and Skaggs (1986) showed NO_3-N losses were 7-10 times greater in drained areas than in undeveloped areas. The U.S. EPA (1983) estimated that agriculture was responsible for 60% of the nitrogen discharges and 27% of the phosphorus discharges to the Chesapeake Bay. The impacts of agriculture on water quality can be reduced by restoring drained areas to wetlands. Restoring prior converted sites can limit impacts to the surrounding watershed by limiting drainage from the site and improving water quality.

The functional value of wetlands and their value to the ecosystems and watersheds where they are located has been well documented. They serve to store rainfall, reduce peak runoff during storms, and provide habitat for a diverse variety of plant and animal species.

Wetlands also improve water quality, reduce the effects of erosion by stabilizing soils, and dampening the effects of wave action in shoreline areas, and help sustain surrounding aquatic environments (Dennison et al., 1993, Mitsch and Gosselink, 1986). A riverine wetland study in Illinois showed a reduction in sediment and phosphorus loads by 88% and 60% respectively from water drained from agricultural and rural watersheds through wetlands (Kadlec and Hey, 1994). Another study in Maryland observed 59% removal of phosphorus in the first year, though there was no significant removal the second year (Jordan et al., 2003). Wetlands can be particularly effective in the processes of nitrification and denitrification (DeLaune et al., 2001; Kadlec and Hey, 1994). A study in Maryland showed 38% removal of total nitrogen in its first year (Jordan et al., 2003). Burchell (2003) showed that the increased organic matter in wetland substrates can increase nitrate nitrogen removal efficiency most likely through increased carbon availability for the process of denitrification. Undrained hydric soils are ideal for the process of denitrification, and are attributed to the high rates of nitrate nitrogen removal found in wetlands (Gilliam, 1994).

Wetlands have been altered and drained at an alarming rate. It has been estimated that 47 percent of the 89 million ha (221 million acres) of wetlands in the United States were converted or destroyed by the 1980's (Dahl, 1990). There was another net loss of 260,700 ha (644,000 acres) of wetlands in the United States between 1986 and 1997 despite increased legislation and restoration efforts. Ninety eight percent of the wetlands that were impacted or drained between 1986 and 1997 were freshwater wetlands (Dahl, 2000).

Large wetland losses have also been documented in North Carolina. Approximately 95% of North Carolina's 2.4 million ha of wetlands are in coastal plain counties (Wilson, 1962) and approximately 50% of the original wetlands have been altered in some way

(Cashin et al., 1992). Much of the wetland areas have been altered and drained in order to convert them to usable and productive farmland (Table 1.1). Alteration of wetlands has shifted to commercial and residential development in the Southeastern United States but a large portion is still the result of agriculture (Table 1.2) (NRCS, 2000).

Restoration of converted wetlands require a reversal of the practices employed in draining farmland. Lilly (1981) described the practices that were often used to convert wetlands to agricultural land such as an enhanced drainage network of parallel field ditches and collector canals and the installation of subsurface drainage in dark surface mineral soils and deep organic soils. Timber was harvested followed by stump removal, windrowing, and burning of woody vegetation. There were various degrees of land surface grading and shaping, including crowning, that removed the natural microtopography that provided

Table 1.1 Causes of wetlands alteration on the North Carolina costal plain: 1950's–1980's (Cashin et al., 1992)

Type of Development	Percent of Total Alteration
Forestry	52.8%
Agriculture	42.2%
Urban	2.2%
Military	0.8%
Other	2.0%

Table 1.2 Causes of Wetland Losses 1992-1997

Type of Development	Percent of Total Alteration
Development	48.9%
Agriculture	26.4%
Silviculture	11.9%

topographic and hydrologic variability common in natural wetlands. Tweedy (2001) concluded that simply plugging the ditches of prior converted wetlands will not restore the hydrologic variability that existed prior to conversion. Prior converted wetlands are defined by the 1985 Farm Bill (Swampbuster) as a wetland that was drained, filled, leveled or otherwise altered that no longer has wetland hydrology and has produced a commodity crop during at least one year before December 23, 1985.

The Wetland Reserve Program (WRP) was introduced by the United States Department of Agriculture's (USDA) Food, Agriculture, Conservation and Trade Act in 1985. WRP is a voluntary cost share program designed to restore prior converted wetlands to their original wetland state. Under the program, farmers who enroll their land for a permanent easement are compensated for the land by receiving cost share benefits for installation of practices needed for wetland restoration. Only "farmed wetlands" or "prior converted wetlands" are eligible for the program. As of 2001, 434,732 ha (1,074,245 acres) of wetlands have been restored through WRP and 7,918ha (19,567 acres) of these wetlands are located in North Carolina (NRCS 2002). While strong efforts are being made by the WRP and other conservation groups to restore converted wetlands, better guidelines are needed for the best practice of restoring wetland hydrology (Tweedy et al., 2001).

Wetlands are generally defined by three main criteria: (1) Hydric soils, (2) presence of wetland vegetation, and (3) wetland hydrology characterized by frequently recurrent sustained saturation of the soil (Cowardin et al., 1979). Many researchers believe that hydrology is the most important factor in restoring a wetland. Mitsch and Gosselink (1986) state that "Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes." Gosselink and Turner

(1978) state that hydrology has an effect on vegetative composition, structure, and diversity. Hydrology can influence wetland productivity, control organic accumulation and transport, and drive nutrient cycling. Research by Sharitz et al., (1990) showed that the hydrologic regime strongly affects the regeneration of wetland vegetative communities. LaBaugh (1986), Novitzki (1989), Sharitz et al. (1990), Wetzel (1993) and Hunt et al. (1999) all report that wetland hydrology is the most influencing factor in wetland development, structure, function, and persistence.

While wetland hydrology is generally considered the most important component in terms of wetland restoration success it is also the least understood (WRP, 1997) and the most difficult to achieve (Holman et al., 1993). Partial failures in meeting the criteria for wetland restoration have been documented for different types of wetlands (NRC, 2002; Pfeifer et al., 1995; Kusler et al., 1990). Wetland hydrology, and subsequently wetland restoration success, is most often quantified in terms of jurisdictional criteria established by the U.S. Army Crops of Engineers (1987). It is assumed and generally accepted that this criterion will result in anaerobic conditions developing within the root zone and will give wetlands their unique character and function. If this jurisdictional criterion was the only hydrologic criterion of importance, all wetlands could be hydrologically quantified as being equal which is clearly not the case. Wetland hydrology is both temporally and spatially variable from one wetland type to another and often within the same wetland type or same wetland from year to year. Some restoration sites have not satisfied wetland jurisdictional criteria because they did not have adequate wetness. However, many restorations have been unsuccessful because they were too wet as a result of the emphasis on guaranteeing minimum jurisdictional criteria during a relatively short monitoring period (3 out of 5 years) (NRCS, 2002).

Clark and Benforado (1981) defined hydrologic criterion for wetlands to include a water table within 30 cm of the soil surface for at least one continuous period of 5 to 12.5% of the growing season in 50% of the years. The growing season is defined as the first average frost free day in the spring until the last average frost free day in the fall for a particular location. They concluded that root zone saturation for less than this duration of time would not develop anaerobic conditions leading to hydric soil formation and subsequently, the site should be considered upland. They also concluded, and it is generally accepted, that when the root zone is saturated for more than 12.5% of the growing season, the site is very likely to have the characteristics of a wetland. When the water table is within 30 cm of the surface for more than 5%, but less than 12.5% of the growing season, it is not certain that the site will be a wetland. However, for regulatory purposes, the U.S. Army Corps of Engineers has assumed that wetland conditions exist whenever the water table is within 30 cm of the surface for more then 5% of the growing season.

To exhibit wetland hydrology, a site must be saturated long enough to form anaerobic conditions that lead to hydric soil formation. The amount of time required for anaerobic conditions to develop depends on many factors including soil temperature, duration, frequency, and depth of saturation, organic matter content, and microbial activity. Depending on the mix of these factors, the time required to develop anaerobic conditions may vary from a few days in warm conditions to several weeks during colder conditions (Richardson and Vepraskas, 2001). Anaerobic conditions will not form unless there is microbial activity in the soil. It has been assumed that microbial activity ceases at soil temperatures below about 5 degrees C (Pickering and Veneman, 1984). Microbial activity in the soil has been assumed to be correlated to the growing season of plants.

Regulatory criterion assume that anaerobic conditions only form during the growing season. Several studies, however, have shown that microbial activity can be found in some soils under certain land uses year round. Burdt (2003) found that the biological growing season for native plants and microbes should include the entire year in forested areas, one week shorter in early-successional fields, and two weeks shorter in active cropland. Megoniagle et al. (1996) found that there was microbial activity in the soil year round in a wetland in the southeast United States. Seybold et al. (2002) stated that there was year round biological activity in a wetland in Virginia justifying monitoring the water table year round as well as during the growing season. Smith (1998) concluded biological activity occurred year round in two soils in eastern North Carolina.

Past restoration projects have often over compensated in their design for the uncertainty about the 5% to 12.5% of the growing season range used to describe wetland hydrology. For example, restoration designs have often been based on the 12.5% criterion to ensure that wetland hydrology conditions develop. This has resulted in many restoration sites being too wet and ultimately leading to large expanses of open water (NRC, 2002). While jurisdictional criterion as established by the U.S. Army Corps of Engineers is an important measure of wetland hydrology, there are other measures equally important to the establishment and maintenance of a particular wetland type. For example, non-riverine wetlands are not wet all the time (Tweedy and Evans, 2001; Skaggs et al., 1995; Skaggs et al., 1994). The sequence of wet and dry cycling may be just as important for some wetland functions as satisfying the minimum jurisdictional wetness criterion. In addition to minimum jurisdictional criterion, other criterion that may be of importance in describing overall wetland hydrology include: seasonal and annual range in water table depth, time and duration

that the water table is at the surface, and duration and frequency that the water table is below 30 cm.

Zedler (2003) stressed the importance of understanding the interaction of the processes and functions that occur in wetlands, and recommended that more studies be performed in order to better understand the established functional ability of restored and constructed wetlands with respect to hydrology in order to set appropriate criteria. Hydrologic regime in natural wetlands is a function of the topography of the area and the annual rainfall pattern (Gunderson et al., 1988).

Sun et al. (2002) compared the hydrology of three forested watersheds and also concluded that topography is an important factor in wetland hydrology. They concluded that flat or depressional topography can reduce the magnitude of storm peak flow and volume in most conditions but that the effect of topography diminishes under extremely wet conditions. Under wet conditions the water table will be held higher regardless of surface roughness, making it difficult to determine any differences in water table depth.

Tweedy (1998) analyzed the effect of topography on two prior converted wetlands in Beaufort and Craven Counties, North Carolina. In one treatment, the ditches were plugged and the surface was not altered maintaining the smooth surface. In the second treatment the ditches were plugged and the land surface was roughed providing microtopography for the purpose of enhancing surface ponding as found in natural wetlands. The rough treatment resulted in more variable soil moisture in the surface layer during dryer periods. It also delayed runoff during storm events resulting in an overall decrease in outflow and prolonged outflow periods. Research such as this prompted the National Research Council to recommend that hydrologic variability be introduced into the design and construction of

restored and constructed wetlands with variability in the microtopography of the site (National Research Council, 2001). Zedler (2000) recommended that future restoration projects be designed to determine the effects of topographic heterogeneity.

Analyzing long term wetland hydrology will also help to better understand the hydrologic variability found in wetlands. Skaggs et al. (1995) analyzed 40 years of data at a site in Wilmington, NC and determined that wetlands must be monitored for many years before it can be determined if the site meets the criteria for wetland hydrology. They concluded that decisions about the status of a wetland based on short-term water table data could result in significant error. Long term monitoring requires long periods of time and resources that may not always be available. Consequently, a more practical approach to determine the long term effects of restoration is to simulate hydrologic conditions using hydrologic models such as DRAINMOD, calibrated with short term data.

DRAINMOD was developed to simulate drainage and changes in the water table at sites with poorly drained soils and shallow water tables drained with a series of parallel drainage ditches or subsurface drains (Skaggs et al., 1999). The model was tested and evaluated for the accuracy of simulated water table and drainage conditions at a variety of sites. Skaggs, (1982) tested the model using 5 years of field data from three locations in the North Carolina Coastal Plain each with field scale drainage systems. The predicted water table depths were in excellent agreement with the measured water table depths leading to the conclusion that DRAINMOD was a reliable tool for predicting the effect of drainage systems on water table depth. Youssef, et al. (2003) evaluated DRAINMOD 5.1 using 6 years of data from an artificially drained site in the coastal plain of North Carolina. They found the simulated water table and flow to be in good agreement with the measured data at the site.

The model has also been tested in Georgia (Shirmohammadi et al., 1991), Virginia (McMahon et al., 1988), Louisiana (Fouss et al., 1989; Fouss et al., 1987), Ohio (Desmond et al., 1996; Nolte et al., 1983; Skaggs et al., 1981), Illinois (Kurien et al., 1997; Mostaghimi et al., 1985), and Iowa (Sanoja et al., 1990). International evaluation of DRAINMOD has been conducted in Canada (Shukla et al., 1994; Madramootoo 1990), Mexico (Quej and Palacios-Valez, 1996), Italy (Borin et al., 1999; Bixio and Bortolini, 1997), Australia (Cox et al., 1994), and Turkey (Cizikel et al., 2004).

The hydrologic response of a watershed was accurately simulated by coupling DRAINMOD with Arcview GIS technology in a study by Northcott et al. (2002). Amatya and Skaggs (2001), using 10 years of data, determined that DRAINMOD was a reliable tool for assessing the hydrologic changes resulting from silvicultural and water management treatments in pine stands. Amatya et al. (2003) used a large ditch spacing with small drain depths to model the drainage rate and water table depth in two naturally drained forested watersheds, without the pattern drainage typically found in prior converted wetlands, in Florida and South Carolina. They found satisfactory results from the watershed in South Carolina with minimal calibration and obtained better results from the Florida watershed using a higher degree of calibration. He et al. (2002) determined that DRAINMOD was able to accurately simulate the water table levels in landscapes that do not have a network of parallel drains. Tweedy (1998) also determined that DRAIMOD was accurate in modeling water table hydrology in a restored wetland with varying degrees of surface treatments.

DRAINMOD has also been used in several studies when multiple years of water table data were not available and long term effects are required. Tweedy (1998) determined the long term effect of surface treatments on wetland hydrology using DRAINMOD simulations.

DRAINMOD has also been used to simulate the hydrology of pocosin wetland areas in North Carolina. Skaggs et al. (1991) used DRAINMOD to simulate the hydrology of drained and undrained pocosins near Wilmington, NC. Chescheir et al. (2004) used DRAINMOD to simulate the hydrology and nitrate nitrogen loadings from two watershed in the Coastal Plain of North Carolina. Skaggs and Chescheir (2002) used DRAINMOD to determine the minimum or threshold drainage intensity that would result in failure of a wetland site to satisfy the wetland hydrologic criteria. Skaggs et al. (1994) performed simulations with DRAINMOD to compare the hydrologic criteria of several sites that met various degrees of wetland hydrology.

The research conducted for this thesis was designed to advance the development of criteria that can be applied to evaluate the restoration success of prior converted wetlands. A restored wetland was monitored at a prior converted farm in Carteret County, North Carolina. The restored wetland consisted of three surface treatments designed to restore varying surface conditions in a randomized block design, using three blocks, each with one of the surface treatments, separated by berms. The surface treatments consisted of 1) plugging the field ditches and planting wetland vegetation, 2) adding microtopography by roughing the surface and planting wetland vegetation, and 3) removing the crown and planting wetland vegetation. Instruments were installed in transects across each treatment to monitor water table depth and water control structures were installed to control and monitor outflow.

The observed water table depths were then used to calibrate DRAINMOD. The predicted results were compared to the observed results to verify the accuracy of the model. DRAINMOD was then used to simulate the conditions expected after the vegetation matured

using the surface treatments with 50 years of weather data. The treatments were then compared to determine treatment effects in the mature wetland.

The observed data collected in 2003 and 2004 as well as the modeling results are presented in the following chapters. Chapter II describes the construction of the site and site instrumentation. Results of the developed criteria and the evaluation of the effects of the surface treatments using observed data are also presented in Chapter II. The results of the DRAINMOD simulations are presented in Chapter III along with the long term effects of the surface treatments.

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Chapter 2 Evaluation of the Effects of Surface Treatments on the Hydrology of a Restored Wetland in the Coastal Plain of North Carolina

Jason D. Wright and Robert O. Evans

Abstract

Wetlands are valuable in the process of removing sediment and pollutants from drainage waters. Wetlands are often restored in prior converted wetland sites, however more research is needed into successful restoration practices. Wetland hydrology is critical in the success of wetland restoration. This study was conducted to determine the effects of surface treatments on the hydrology of a prior converted wetland in coastal North Carolina. One hundred ha of prior converted wetlands were restored in March of 2003. Approximately 60 ha was restored using three types of surface treatments. The ditches were plugged and wetland vegetation was planted in each treatment. The surface treatments investigated were plug and plant, crown removal, and microtopography. The surface was left as it was during agricultural production in the 1) plug and plant treatment, the approximately 20 cm of crown was removed in order to reduce runoff in the 2) crown removal treatment, and 3) microtopography was added to provide storage and slow runoff. The three surface treatments were replicated in three plots, approximately 6.5 ha each, separated by berms. The water table was monitored with water table monitoring wells installed in a transect across the treatments. Water control structures with weirs were used to control outlet stage and monitor outflow.

A depressional non-riverine bottomland hardwood wetland was selected as a reference to serve as a comparison with the conditions in the restored wetland. Natural drainage in the reference remains intact. Water table monitoring wells were installed in three

different transects across the reference.Conditions in the restored wetland were compared to the reference area to determine if the restoration successfully restored wetland hydrology to the degree found in the reference.

Water table depths in the treatments were analyzed using eight criteria to characterize the hydrology of the site. The criteria were 1) the number of times that jurisdictional wetland criteria was met, 2) the range of the water table fluctuation, 3) the number of days that the water table was at or above the surface during the study period and 4) the growing season, 5) the number of days that the water table was within 30 cm of the surface during the study period and the 6) growing season, and 7) SEW_{30} for the study period and 8) the growing season. SEW_{30} is a measure of the duration and frequency that the water table is above a threshold depth.

Considering the water table depths across all three blocks, the plug and plant treatment was wetter than the crown removal and the microtopography treatments. The water table was also closer to the surface, on average, in the microtopography treatment than in the crown removal treatment. Outflows from the crown removal treatment were lower than the microtopography and plug and plant treatments. When the 8 criteria listed above were applied in analysis of block 1 and block 2 the crown removal treatment was wetter than the microtopography treatment and the plug and plant treatment. Theses data were also scrutinized because of differences in the elevations of some of the monitoring wells in block 3, which contained one replicate of each of the treatments. These latter results showed that crown removal was the more effective treatment to maintain the water table within 30 cm and at the surface compared to adding microtopography or just plugging the ditches and planting vegetation.

Introduction

The functional value of wetlands and their role in the ecosystems and watersheds where they are located has been well documented. They serve to store rainfall, reduce peak runoff during storms, and provide habitat for a diverse variety of plant and animal species. Wetlands also improve water quality, reduce the effects of erosion by stabilizing soils, dampen the effects of wave action in shoreline areas, and provide nutrients to surrounding aquatic environments (Dennison et al., 1993, Mitsch and Gosselink, 1986). A riverine wetland study in Illinois showed a reduction in sediment and phosphorus loads by 88% and 60% respectively from water drained from agricultural and rural watersheds through wetlands (Kadlec and Hey, 1994). Another study in Maryland observed 59% removal of phosphorus in the first year, though there was no significant removal the second year (Jordan et al., 2003). Wetlands can be particularly effective in the processes of nitrification and denitrification (DeLaune et al., 2001; Kadlec and Hey, 1994). A study in Maryland showed 38% removal of total nitrogen in its first year (Jordan et al., 2003). Burchell (2003) showed that the increased organic matter in wetland substrates can increase nitrate nitrogen removal efficiency most likely through increased carbon availability for the process of denitrification. Undrained hydric soils are ideal for the process of denitrification, and are attributed to the high rates of nitrate nitrogen removal found in wetlands (Gilliam, 1994).

Large wetland losses have also been documented in North Carolina. Approximately 95% of North Carolina's 2.4 million ha of wetlands are in coastal plain counties (Wilson, 1962) and approximately 50% of the original wetlands have been altered in some way (Cashin et al., 1992). Much of the wetland areas have been altered and drained in order to convert them to usable and productive farmland (Table 2.1). Alteration of wetlands has

Table 2.1 Causes of wetlands alteration on the North Carolina costal plain: 1950's–1980's (Cashin et al., 1992)

Type of Development	Percent of Total Alteration
Forestry	52.8%
Agriculture	42.2%
Urban	2.2%
Military	0.8%
Other	2.0%

shifted to commercial and residential development in the Southeastern United States but a large portion is still the result of agriculture (Table 2.2) (NRCS, 2000).

The Wetland Reserve Program (WRP) was introduced by the United States Department of Agriculture's (USDA) Food, Agriculture, Conservation and Trade Act in 1985. WRP is a voluntary cost share program designed to restore prior converted wetlands to their original wetland state. Under the program, farmers who enroll their land for a permanent easement are compensated for the land by receiving cost share benefits for installation of practices needed for wetland restoration. Only "farmed wetlands" or "prior converted wetlands" are eligible for the program. As of 2001, 434,732 ha (1,074,245 acres) of wetlands have been restored through WRP and 7,918ha (19,567 acres) of these wetlands are located in North Carolina (NRCS 2002). While strong efforts are being made by the

Table 2.2 Causes of Wetland Losses 1992-1997

Type of Development	Percent of Total Alteration
Development	48.9%
Agriculture	26.4%
Silviculture	11.9%

WRP and other conservation groups to restore converted wetlands, better guidelines are needed for the best practice of restoring wetland hydrology (Tweedy et al., 2001).

Wetlands are generally defined by three main criteria: (1) Hydric soils, (2) Presence of wetland vegetation, and (3) wetland hydrology characterized by frequently recurrent sustained saturation of the soil (Cowardin et al., 1979). Many researchers believe that hydrology is the most important factor in restoring a wetland. Mitsch and Gosselink (1986) state that "Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes." Gosselink and Turner (1978) state that hydrology has an effect on vegetative composition, structure, and diversity. Hydrology can influence wetland productivity, control organic accumulation and transport, and drive nutrient cycling. Research by Sharitz et al. (1990) showed that the hydrologic regime strongly affects the regeneration of wetland vegetative communities. LaBaugh (1986), Novitzki (1989), Sharitz et al. (1990), Wetzel (1993) and Hunt et al. (1999) all report that wetland hydrology is the most influencing factor in wetland development, structure, function, and persistence.

While wetland hydrology is generally considered the most important component in terms of wetland restoration success it is also the least understood (WRP, 1997) and the most difficult to achieve (Holman et al., 1993). Partial failures in meeting the criteria for wetland restoration have been documented for different types of wetlands (NRC, 2002; Pfeifer et al., 1995; Kusler et al., 1990). Wetland hydrology, and subsequently wetland restoration success, is most often quantified in terms of jurisdictional criteria established by the U.S. Army Crops of Engineers (1987). It is assumed and generally accepted that this criterion will result in anaerobic conditions developing within the root zone and will give wetlands their

unique character and function. If this jurisdictional criterion was the only hydrologic criterion of importance, all wetlands could be hydrologically quantified as being equal which is clearly not the case. Wetland hydrology is both temporally and spatially variable from one wetland type to another and often within the same wetland type or same wetland from year to year. Some restoration sites have not satisfied wetland jurisdictional criteria because they did not have adequate wetness. However, many restorations have been unsuccessful because they were too wet as a result of the emphasis on guaranteeing minimum jurisdictional criteria during a relatively short monitoring period (3 out of 5 years) (NRCS, 2002).

Clark and Benforado (1981) defined hydrologic criterion for wetlands to include a water table within 30 cm of the soil surface for at least one continuous period of 5 to 12.5% of the growing season in 50% of the years. The growing season is defined as the first average frost free day in the spring until the last average frost free day in the fall for a particular location. They concluded that root zone saturation for less than this duration of time would not develop anaerobic conditions leading to hydric soil formation and subsequently, the site should be considered upland. They also concluded, and it is generally accepted, that when the root zone is saturated for more than 12.5% of the growing season, the site is very likely have the characteristics of a wetland. When the water table is within 30 cm of the surface for more than 5%, but less than 12.5% of the growing season, it is not certain that the site will be a wetland. However, for regulatory purposes, the U.S. Army Corps of Engineers has assumed that wetland conditions exist whenever the water table is within 30 cm of the surface for more then 5% of the growing season.

To exhibit wetland hydrology, a site must be saturated long enough to form anaerobic conditions that lead to hydric soil formation. The amount of time required for anaerobic

conditions to develop depends on many factors including soil temperature, duration, frequency, and depth of saturation, organic matter content, and microbial activity. Depending on the mix of these factors, the time required to develop anaerobic conditions may vary from a few days in warm conditions to several weeks during colder conditions (Richardson and Vepraskas, 2001). Anaerobic conditions will not form unless there is microbial activity in the soil. It has been assumed that microbial activity ceases at soil temperatures below about 5 degrees C (Pickering and Veneman, 1984). Microbial activity in the soil has been assumed to be correlated to the growing season of plants.

Regulatory criterion assumed that anaerobic conditions only form during the growing season. Several studies, however, have shown that microbial activity can be found in some soils under certain land uses year round. Burdt (2003) found that the biological growing season for native plants and microbes should include the entire year in forested areas, one week shorter in early-successional fields, and two weeks shorter in active cropland. Megoniagle et al. (1996) found that there was microbial activity in the soil year round in a wetland in the southeast United States. Seybold et al. (2002) stated that there was year round biological activity in a wetland in Virginia justifying monitoring the water table year round as well as during the growing season. Smith (1998) concluded biological activity occurred year round in two soils in eastern North Carolina.

Past restoration projects have often over compensated in their design for the uncertainty about the 5% to 12.5% of the growing season range used to describe wetland hydrology. For example, restoration designs have often been based on the 12.5% criterion to ensure that wetland hydrology conditions develop. This has resulted in many restoration sites being too wet and ultimately leading to large expanses of open water (NRC, 2002).

While jurisdictional criterion as established by the U.S. Army Corps of Engineers is an important measure of wetland hydrology, there are other measures equally important to the establishment and maintenance of a particular wetland type. For example, non-riverine wetlands are not wet all the time (Tweedy and Evans, 2001; Skaggs et al., 1995; Skaggs et al., 1994). The sequence of wet and dry cycling may be just as important for some wetland functions as satisfying the minimum jurisdictional wetness criterion. In addition to minimum jurisdictional criterion, other criterion that may be of importance in describing overall wetland hydrology include: seasonal and annual range in water table depth, time and duration that the water table is at the surface, and duration and frequency that the water table is below 30 cm.

Zedler (2003) stressed the importance of understanding the interaction of the processes and functions that occur in wetlands, and recommended that more studies be performed in order to better understand the established functional ability of restored and constructed wetlands with respect to hydrology in order to set appropriate criteria. Hydrologic regime in natural wetlands is a function of the topography of the area and the annual rainfall pattern (Gunderson et al., 1988).

Sun et al. (2002) compared the hydrology of three forested watersheds and also concluded that topography is an important factor in wetland hydrology. They concluded that flat or depressional topography can reduce the magnitude of storm peak flow and volume in most conditions but that the effect of topography diminishes under extremely wet conditions. Under wet conditions the water table will be held higher regardless of surface roughness, making it difficult to determine any differences in water table depth.

Tweedy (1998) analyzed the effect of topography on two prior converted wetlands in Beaufort and Craven Counties, North Carolina. In one treatment, the ditches were plugged and the surface was not altered maintaining the smooth surface and the crown. In the second treatment the ditches were plugged and the land surface was roughed providing microtopography for the purpose of enhancing surface ponding as found in natural wetlands. The rough treatment resulted in more variable soil moisture in the surface layer during dryer periods. It also delayed runoff during storm events resulting in an overall decrease in outflow and prolonged outflow periods. Research such as this prompted the National Research Council to recommend that hydrologic variability be introduced into the design and construction of restored and constructed wetlands with variability in the microtopography of the site (National Research Council, 2001). Zedler (2000) recommended that future restoration projects be designed to determine the effects of topographic heterogeneity.

To achieve wetland hydrology in prior converted wetlands, at a minimum, the ditches that were installed for agricultural drainage must be plugged in the converted areas in order to reduce drainage from the site. Removing the crown and adding microtopography may improve the chances of meeting wetland hydrology requirements although it can be costly. Studies have suggested that these restoration techniques may increase storm water storage, prolong surface moisture during dry periods, and provide a more diverse habitat. However, there is currently a lack of data to support a particular treatment practice for restoring wetland hydrology. Research on the specific effects of microtopography will help determine the most efficient and cost effective alternative to sustain hydrology in restored wetlands.

Objectives

Recent studies have increased our understanding of the importance of hydrology in wetlands restoration. However, more studies are needed to better define wetland hydrology beyond mere jurisdictional criterion. Criterion are needed to quantify the full range of hydrologic variability that exists in natural wetlands and to define which should be incorporated into restored wetlands. The effects of microtopography on wetland hydrology should also be examined further. A better understanding of the effects of microtopography will help determine the most efficient and cost effective alternative to establish hydrology in restored wetlands.

The overall objective of this study was to develop several hydrologic criterion for a reference, non-riverine wetland and to apply those criterion to evaluate the influence of three techniques for establishing surface topography on wetland hydrology. Specific objective were:

1) Monitor and evaluate the hydrology of a reference wetland based on continuous water table measurements.

2) Use the monitored data to define a number of hydrologic criterion to more fully describe the hydrology of the reference wetland beyond jurisdictional criterion.

3) Monitor and evaluate the hydrologic effect of three surface microtopography treatments in terms of the criterion identified in 2.

Materials and Methods

Site Description

This field study was conducted on North River Farms which is a prior converted (PC) site located in Carteret County near the town of Beaufort in the White Oak River Basin

(Figure 2.1). The first recorded efforts to drain the area around and adjacent to North River Farms was in 1855 when a canal was dug from the headwaters of Wards Creek into the area known as Open Grounds Swamp. The headwaters of Wards Creek were channelized and the canal was dug in an effort to drain an area of one square mile of Open Grounds Swamp. In 1856, Edmund Ruffin described the effort by saying that "… A ditch 10 feet wide and about 4 feet deep was brought up from Ward's Creek to the higher part of the savanna and then a mile square ditched around by ditches approximately 5 feet wide and 3 feet deep. Through the middle of this square the large ditch passed and into which the smaller surrounding ditches emptied…"(Lilly 1980). This canal drained south through an area of North River Farms. Sometime around 1917 Open Grounds Swamp was transferred to the University of

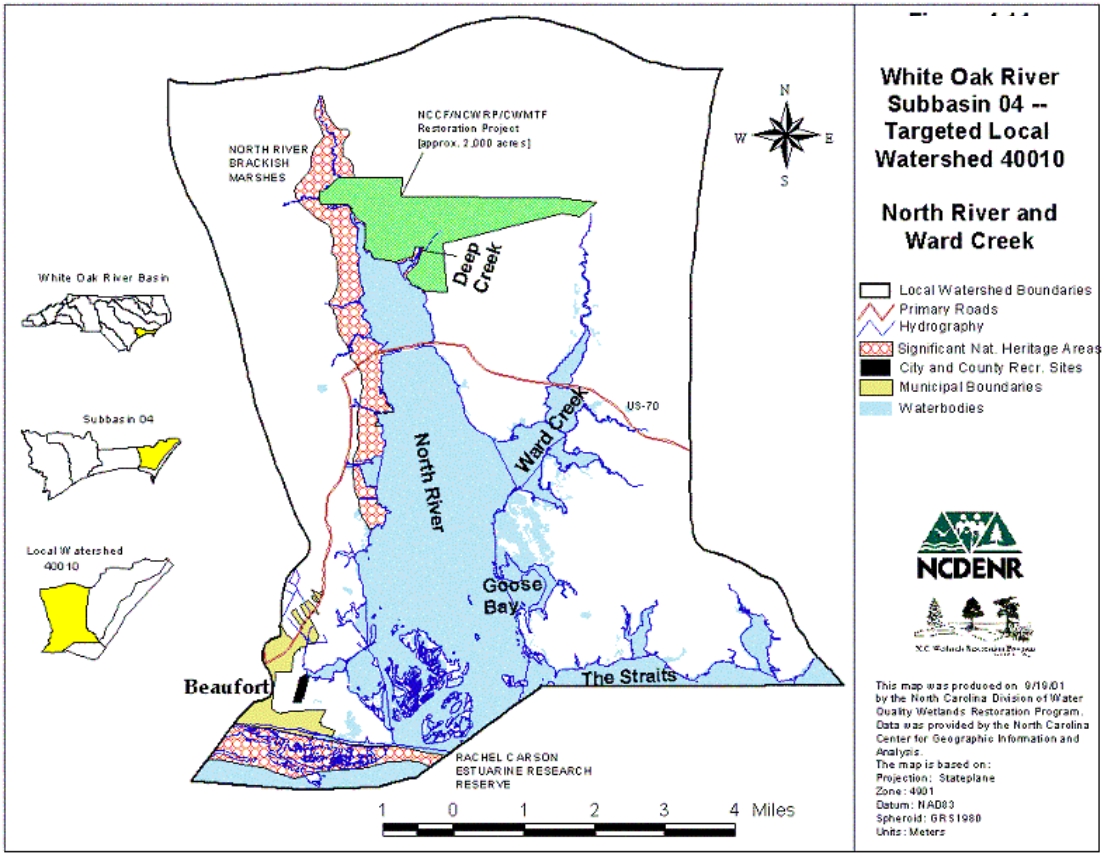

Figure 2.1 Location and Drainage From North River Farms Project

Chicago, who also made an attempt to drain the area. Canals and lateral ditches were dug that were designed to carry ¾ of an inch of water per 24 hour period. In 1923 drainage districts were organized in the area and some of the first agricultural operations were established (Journal of the Washington Academy of Sciences, 1929). Agricultural operations continued in the area of Open Ground Swamp. North River Farms was cleared and drained and the current level of agricultural operation was established at the site sometime around 1980.

Drainage occurs from Open Grounds Farm and North River Farms through the head waters of North River and Deep Creek as indicated Figure 2.1. The site was drained to provide conditions conducive for agriculture using a network of parallel field ditches and main collector canals along the perimeter. Field ditches were spaced 100 m apart and were approximately 1 m deep. The fields were crowned approximately 20 cm between the ditches to facilitate surface drainage.

North River Farms was purchased by the North Carolina Costal Federation in 2002 for the purpose of restoration through a grant from the North Carolina Clean Water Management Trust Fund. The North Carolina Ecosystem Enhancement Program (formerly known as the NC Wetland Restoration Program) was chosen to oversee the restoration efforts and contracted North Carolina State University to provide design, construction oversight, and post construction monitoring for the first two phases of restoration. The project consisted of wetland restoration and creation designed to retain a portion of the agricultural runoff from an approximately 3500 ha drainage area. Phase 1 involved 100 ha of non-riverine or precipitation flat wetland restoration and phase 2 incorporated 117 ha of riverine or floodplain wetland adjacent to phase 1 (Figure 2.2).

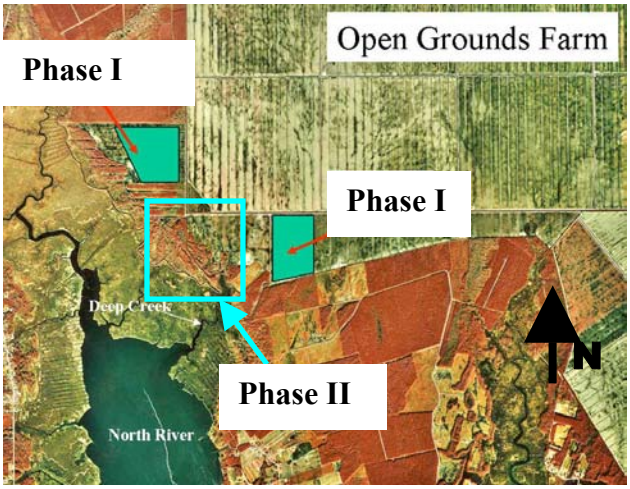

Figure 2.2 Location of Phase I and Phase II

Reference Wetland

A non-riverine bottomland hardwood wetland, representative of the conditions desired at the restored site, was chosen as a reference wetland. Natural drainage in the reference remained intact and served as a natural drainage outlet for the wetland flowing south towards Wards Creek. The reference site was instrumented to monitor water table depth with INFINITY continuous water table monitors (Infinities USA Inc., Daytona Beach, FL). Three transects with three water table monitoring wells each (REF01-REF09) were installed in the reference (Figure 2.3). Stream stage was also monitored at two locations, REFS1 and REFS2. Figure 2.4 shows the location of the reference wetland in relation to the restored experimental treatment areas.

The land surface in the reference was depressional with drier conditions along the east and west edges of the wetland. The center of the reference was the flood plain around the channel, with drainage occurring from the edge of the reference.

The monitoring wells were divided for analysis into the wetter wells found in the center of the wetland, referred to as center, and the drier wells along the edge, referred to as

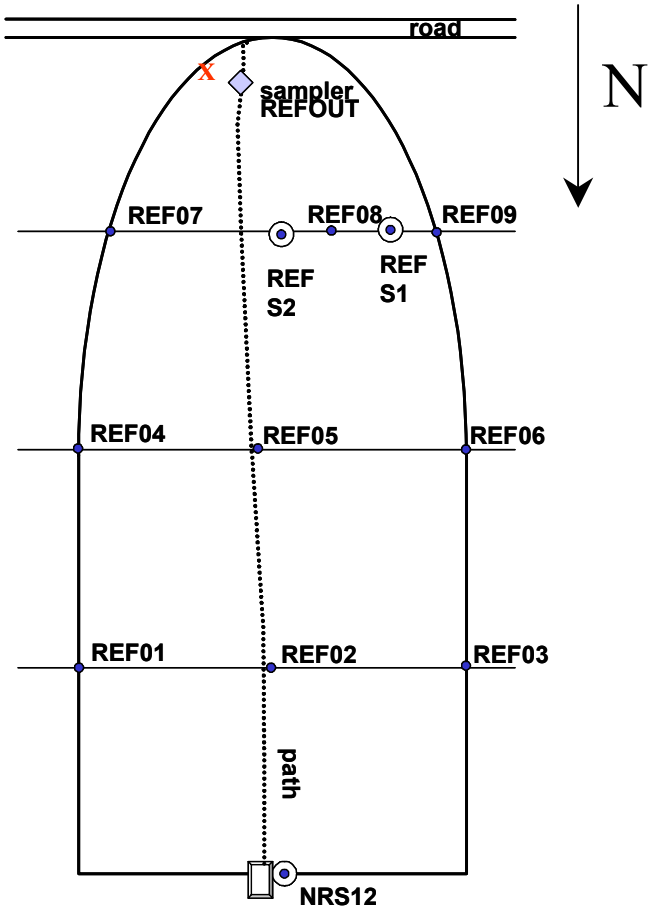

Figure 2.3 Reference Wetland

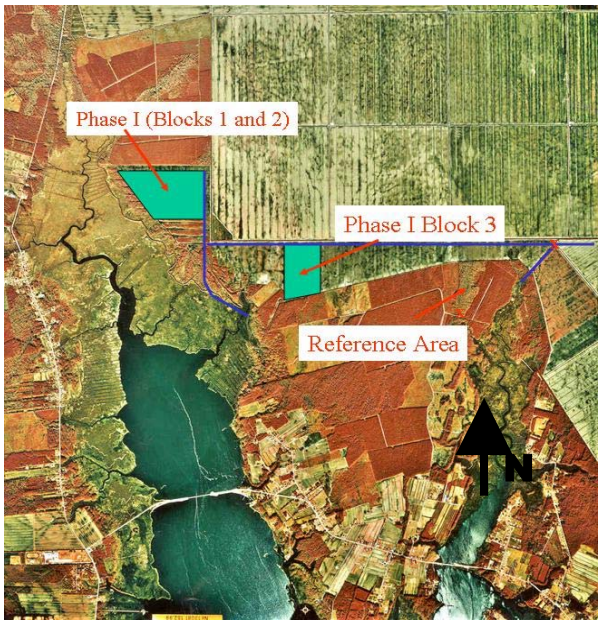

Figure 2.4 Reference Wetland Location

edge. The wells that had wetter conditions were REF02, REF05 and REF08 and the drier wells were REF01, REF03, REF04, REF06, REF07, and REF09.

The wells in the middle transect (REF 04-REF06) are an example of the surface conditions found in the reference wetland that influence the hydrology reflected in the water table measurements (Figure 2.5). The ground elevation was higher at well REF 04 and sloped down to the center of the reference wetland at REF 05. REF 06 was located in the transition between the low area of the reference wetland and the higher area around the edge. Natural drainage occurred from REF 04 and REF 06 to REF 05. The water table in the reference was at the same elevation across the transects while the ground surface was sloped resulting in apparent differences in the water table depth at each measurement location. The reference was drained by small channels that flowed south toward the outlet. While drainage did not occur directly from the area on REF06 to REF 05, the higher areas drained south eventually draining into the center of the reference wetland.

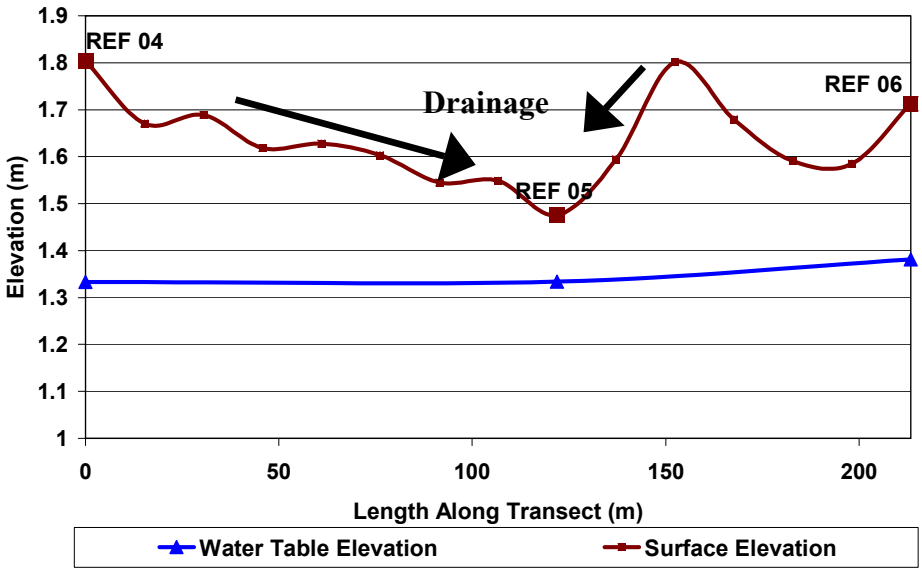

Figure 2.5 Land and Water Table Elevation in the Reference Wetland for 1 Day

Some of the water table recorders installed in the reference wells were not long enough to record the entire range of the water table fluctuation during extremely dry conditions. This was not a problem in 2003, a wet year, however, some of the wells "bottomed out" in 2004, a drier year. DRAINMOD (Skaggs, 1978) was used to estimate the water table depth during these brief periods in 2004 when the water table dropped below the level of the recording device. For a thorough discussion of DRAINMOD and the calibration procedures see chapter 3. Data simulated by DRAINMOD was substituted for the deeper water table depths that were not accurately recorded by the monitoring wells in order to establish the full range of water table fluctuation in the reference. The hydrologic conditions in the reference were compared to the conditions at the restored site as an indication of hydrologic restoration success.

Phase I Restoration

Restoration of phase 1 was completed in March of 2003. Nine treatment plots, approximately 6.5 ha each, were established within the 100 ha of the restored non-riverine forested wetland. The surface treatments involved three microtopographical treatments with three replications resulting in a randomized block design (Figure 2.6). The three topographic treatments aimed to restore wetland hydrology and consisted of: 1) plugging the field ditches and planting wetland tree species, 2) plugging the field ditches, removing the existing crown, and planting, 3) plugging the ditches, contouring the surface to create microtopography, and planting. The first treatment will be referred to as the P/P treatment, the second treatment will be referred to as the CR,P/P treatment, and the third

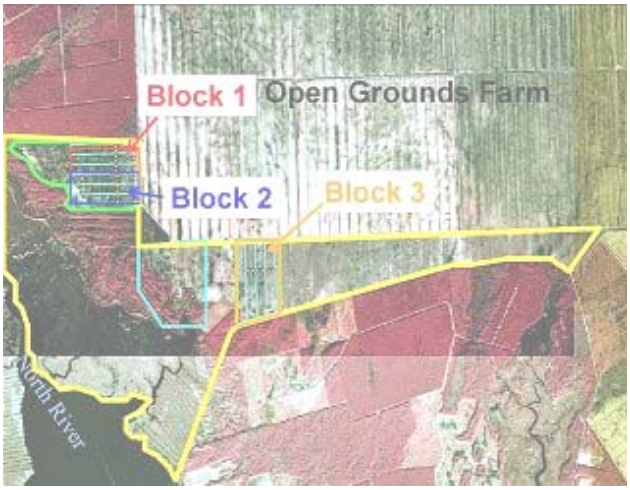

Figure 2.6 Replications and Drainage

treatment will be referred to as the C,P/P treatment. The treatments in blocks one and two are shown in Figure 2.7 and the treatments in block 3 are in Figure 2.8.

Soils

According to the Carteret County Soil Survey (USDA, 1978), much of the restoration area consisted of Deloss soil but there were small patches of Wasda, Arapahoe, and Leon (Figure 2.9). The Deloss (fine-loamy, mixed, thermic Typic Umbraquults) fine sandy loam soil series is described as very poorly drained soil found on low marine and stream terraces. It is subject to rare flooding but ponding can occur in depressions for brief to long periods and the seasonal water high water table is at or near the surface. The Deloss consists of black fine sandy loam in the first 40 cm followed by a gray sandy to sandy clay loam to approximately 100 cm.

A small portion of the P/P treatment area in Block 1 consists of the Wasda (fine-loamy, mixed, acid, thermic Histic Humaquepts) soil series. The Wasda series is described

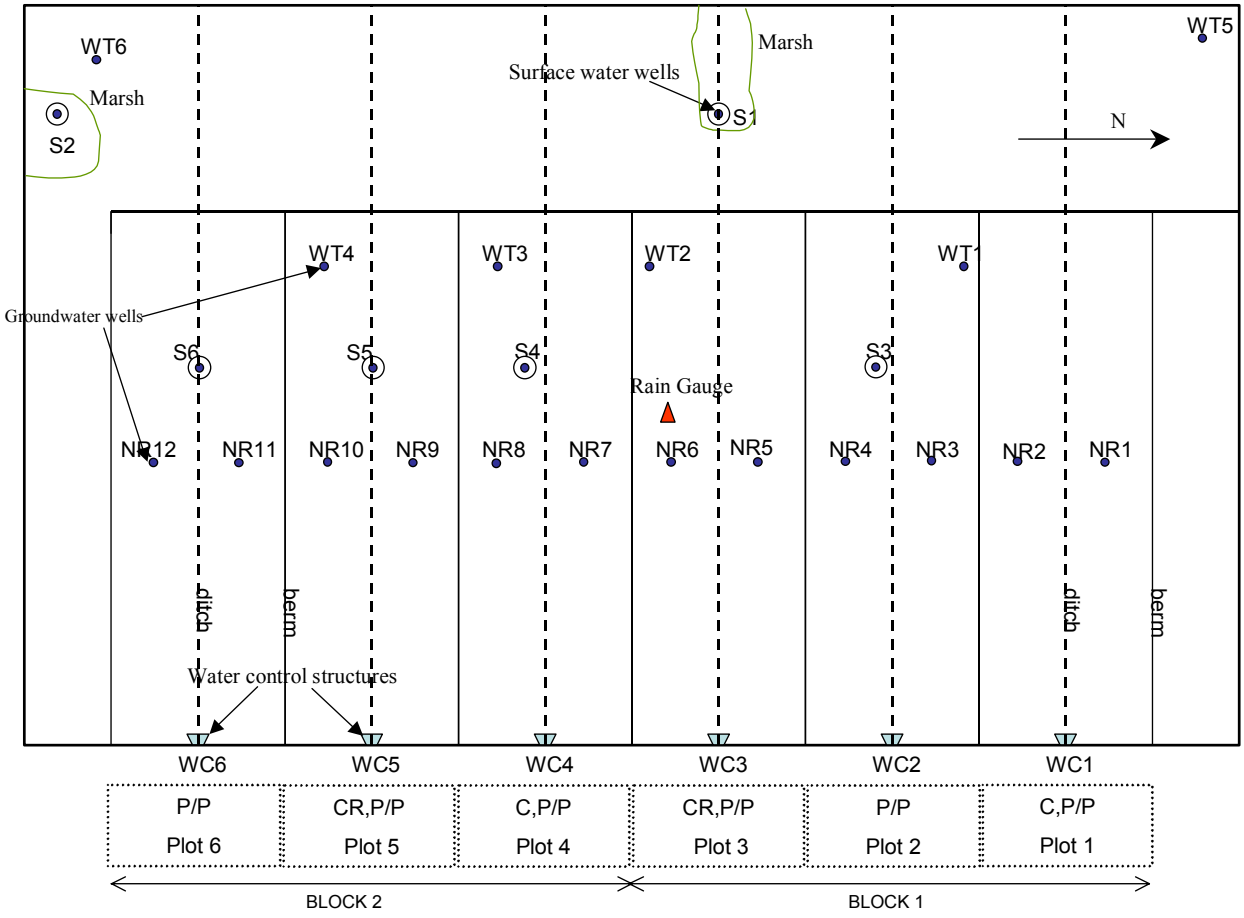

Figure 2.7 Treatments in Block 1 and Block 2

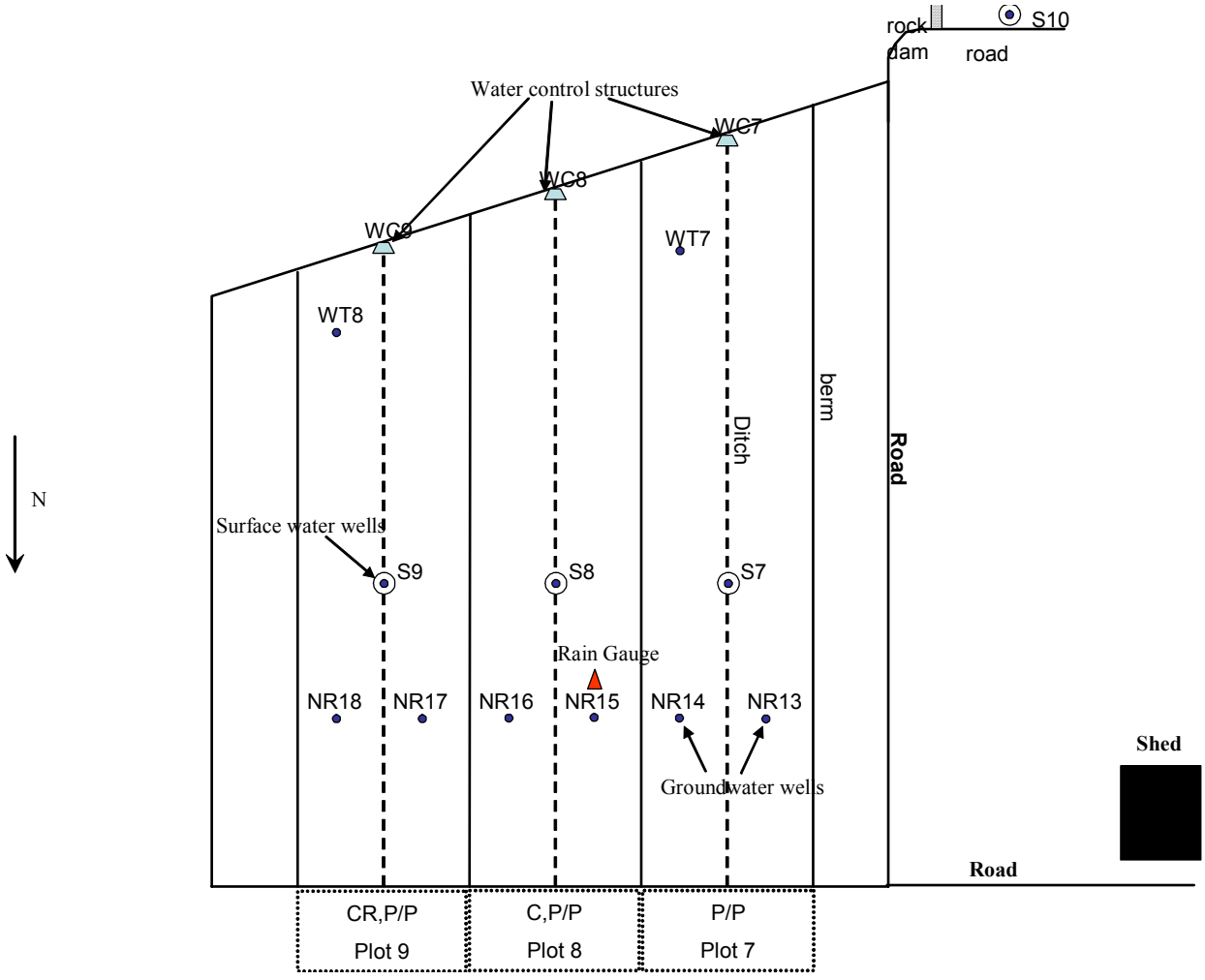

Figure 2.8 Block 3 Treatments

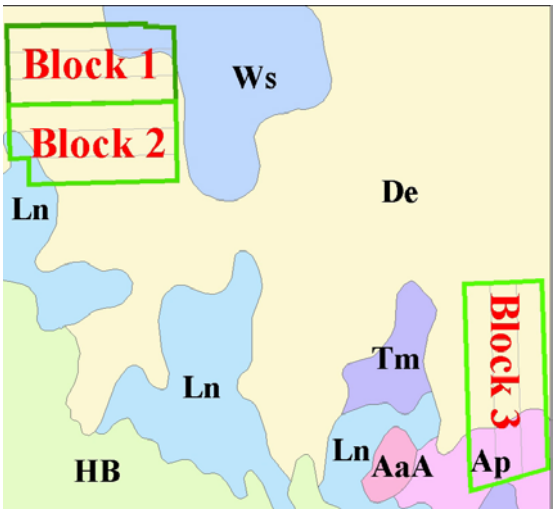

Figure 2.9 Soil Series in the Treatments

as level and very poorly drained with a seasonal high water table at or near the surface. It is typically found on broad flats and in depressions on low marine terraces. Typically there is black muck in approximately the first 80 cm followed by a very dark grayish brown loam below that. The subsoil is dark grayish brown clay loam to a depth of approximately 115 cm. The underlying material to approximately 200 cm is gray sand.

A small corner of block 2 consists of the Leon (sandy, siliceous, thermic Aeric Haplaquods) soil series. It is described as being nearly level to gently sloping and poorly drained with the seasonal high water table commonly within 30 cm of the surface from November to April. It is typically found on low ridges and flats and in depressions on uplands, low marine terraces, and islands. Typically there is a very dark gray sand in the surface layer approximately 15 cm thick and gray sand to a depth of approximately 60 cm. The subsoil is black, weakly cemented and brittle sand to a depth of approximately 150 cm and the underlying material is gray sand to a depth of approximately 200 cm.

Block 3 also contains a section of the Arapahoe (coarse-loamy, mixed, nonacid, thermic Typic Humaquepts) soil series. It is described as being nearly level and very poorly

drained typically found on broad flats and in depressions on low marine and marine terraces. The seasonal high water table is found at or near the surface and water frequently ponds in depressions. Typically there is fine sandy loam to approximately 90 cm followed by loamy sand and sand to approximately 180 cm. (USDA, 1978)

Restoration Procedures

Plug and Plant (P/P)

The ditches were plugged to reduce surface and subsurface drainage. Successionial vegetation on the ditch bank was scraped off along the area to be plugged. Approximately 15 cm of topsoil of varying width alongside the ditch was scraped back and stockpiled and the underlying mineral material was used for the earthen ditch plug. The depth of cut was determined such that it included a mixture of lower topsoil (15-30 cm) and underlying mineral soil (30-60 cm) for the plug. The plug material was compacted by several passes with heavy equipment during placement. The plug was crowned to an elevation at least 15 cm above the existing bank elevation and tapered back at least 1.5 m into the field on each side of the existing ditch bank. Final grading of the borrow areas resulted in irregular depressions. Figure 2.10 shows the installation of a ditch plug.

Figure 2.10 Installation of a Ditch Plug

Crown Removal (CR,P/P)

The objective of removing the crown was to eliminate smooth topography and artificial surface drainage, to create microtopography with small mounds or depressions, and encourage surface ponding. Ditches were plugged as described earlier. The field crown was reduced by scraping and removing 10 cm of topsoil from the two center quartiles of the field and redistributing the soil into the two quartiles alongside the ditch on each side of the field. The finished surface was irregular with small ridges, depressions, and potholes of varying size, up to 15 meters in diameter, and varying depth or height of 0 to 15 cm. The crown removal concept is illustrated schematically in Figure 2.11 and Figure 2.12 shows the implementation at North River.

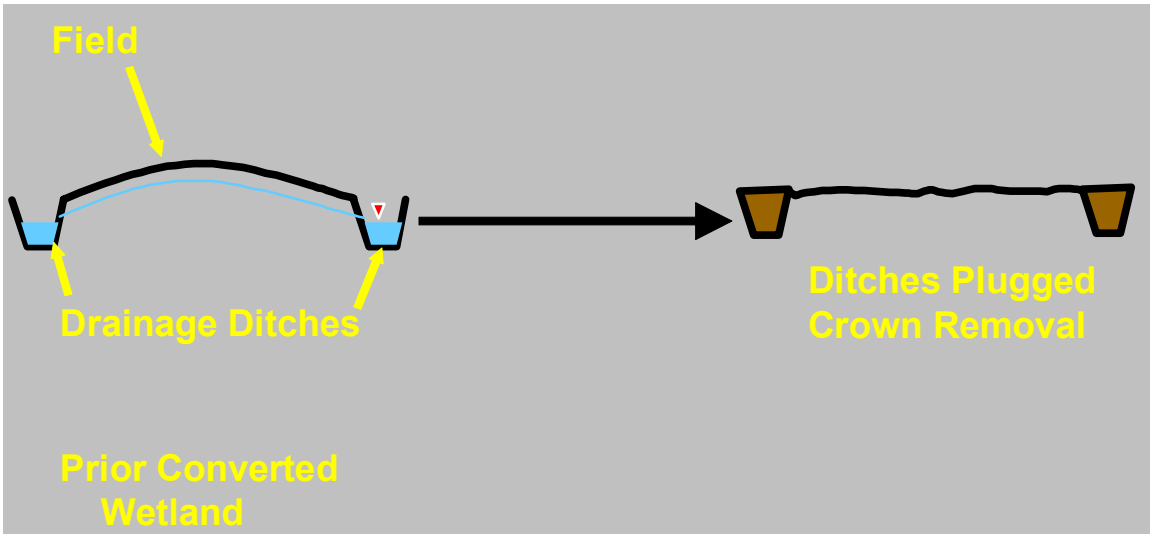

Figure 2.11 Crown Removal Implementaion

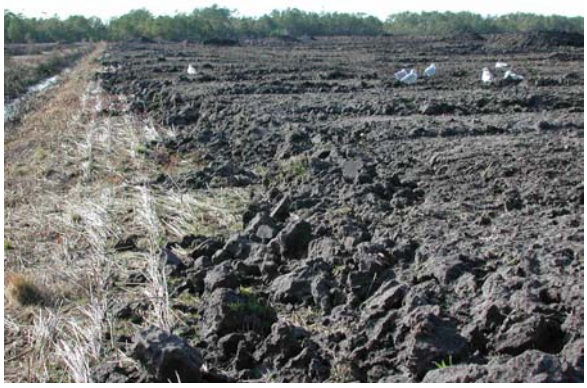

Figure 2.12 Crown Removal

Contour (C,P/P)

A method of surface contouring was introduced in order to create random, natural microtopography that provides elevation heterogeneity, hydrologic variability, and microhabitats in a mature forest. Normal agricultural tillage operations aim to smooth and level the field, contouring was introduced to have the exact opposite effect. Equipment was used to create micro lows and highs of varying depths or heights up to +/- 15 cm. Approximately 25% of the treatment area was tilled with the remaining 75 % left at existing grade. The tillage pattern was irregular and random resulting in isolated small depressions

and ridges or mounds that trapped surface water and led to irregular depths of surface ponding. Tillage equipment was engaged and disengaged frequently so as not to create contiguous flow paths.

Figure 2.13 illustrates surface roughness, Figure 2.14 shows typical equipment and Figure 2.15 shows contouring at North River.

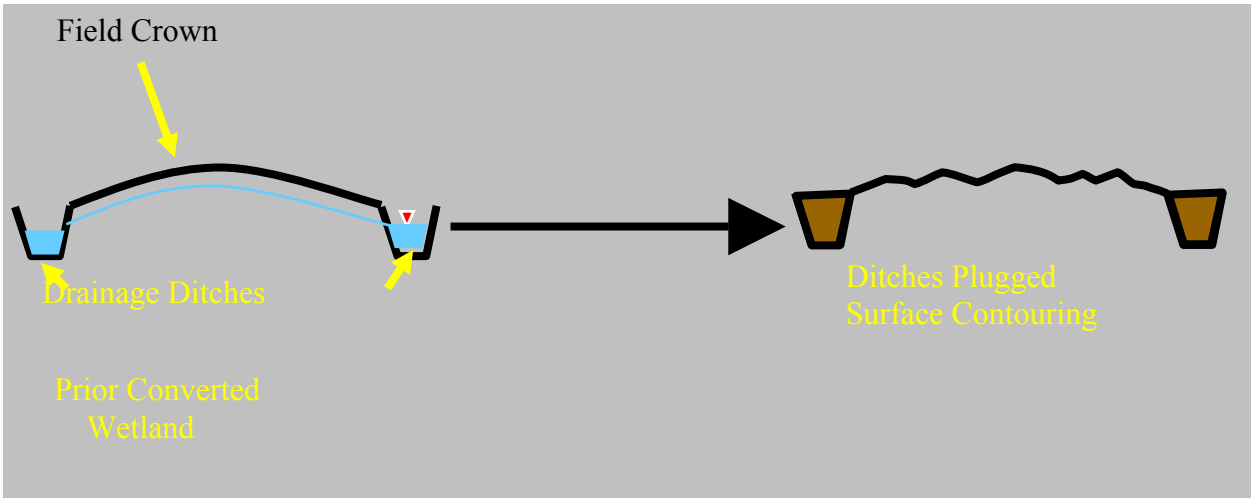

Figure 2.13 Surface Contouring Concept

Figure 2.14 Small farm implement used to create rough microtopograhy

Figure 2.15 Surface Contouring at North River

Simulated Tree Falls

Simulated tree falls were constructed to provide more diversity to the constructed wetland. Simulated tree falls were designed to simulate the abrupt pits and mounds that are formed in natural hardwood forests. When trees are blown over, depressions are left in the ground where the soil was pulled up by the root ball. When the roots decay the mound of soil that was pulled up by the root ball remains. Tree falls leave low areas that collect water and higher areas that remain dry. These areas are designed to provide habitat for species that prefer both the saturated areas of the pit and the dryer area of the mound. Simulated tree falls were established in each treatment at the rate of 10-15 per hectare. They were formed by scraping back the topsoil in an approximately four meter by four meter area and depositing it in a mound next to the depression. The depth of cut varied from 15 cm to 30 cm in order to simulate the root ball depth of a mature hardwood tree. Simulated tree falls at North River are shown in Figure 2.16.

Figure 2.16 Simulated Tree Fall

Surface Depressions

Excavated areas, or surface depressions, were also incorporated into each treatment. These areas were designed to provide shallow water habitat for waterfowl and aquatic species. The excavated depressions simulated areas in natural wetlands caused by wildfire and the burning of organic topsoil. The depressions were excavated along the existing ditches with the ditch as the approximate centerline of the depression. The depressions varied in width from 8 m to 23 m and were roughly 60 m long. They were from 15 cm to 30 cm deep with side slopes of 5H:1V along the transition from ground surface to surface depression. Figure 2.17 shows an aerial view of surface depressions and simulated tree falls.

Berm Construction

Earthen berms were constructed around each of the treatment areas to provide surface delineation of each research plot and to ensure that outflow from the wetland would occur at a single point in order that flow may be monitored. Lateral berms were constructed between treatments in the center of each field. A shallow trench 30 cm deep and approximately 2 m wide was excavated in the center of the field. The top 15-20 cm of topsoil along the side

Figure 2.17 Surface Depressions and Simulated Tree Falls

trench was scraped back to expose mineral subsoil in a 2.5 to 3 meter swath. The exposed subsoil material was removed, mounded, and compacted in the shallow trench to form the 2 meter wide berm 30 cm higher than the midfield crown. Topsoil material was irregularlyredistributed to create micro depressions and mounds in the borrow areas. Berms were also installed perpendicular to the existing field ditches at the boundaries of the treatment areas. Figure 2.18 illustrates the procedure for creating berms.

Water Control Structures

Water control structures were installed in the field ditches at the outflow end of each field (the east end of blocks 1 and 2 and the south end of block 3) in order to control the wetland water depth and outflow from the wetlands. The control structures consist of flashboard risers that can be adjusted to control the water level and a weir cut into the flashboard riser to monitor the outflow. Figure 2.19 illustrates a typical water control structure in a field ditch installed near the existing road.

Figure 2.18 Berm Construction

Figure 2.19 Water Control Structure Installation

Vegetation

Trees were planted at the completion of construction. There were 89,000 seedlings of various wetland species planted. The number of each species and the spacing in each soil type are shown in Table 2.3. The spacing varied by soil type and ranged from 3 meters by 3 meters to 3.7 meters by 3.7 meters.

Table 2.3 Species Planted

Planting Area Soil Type Soil Drainage Class Plant Spacing	Tree Species		Wetland Plant Indicator Status	Acres	Number of Individuals
	Common Name	Scientific Name			
DELOSS - WET Deloss fine sandy loam Very Poorly Drained 3.4 x 3.4 meters	Atlantic white cedar	*Chamecyparis thyoides*	OBL	93	14,760
	water tupelo	*Nyssa aquatica*	FAC		365
	baldcypress	*Taxodium distichum*	OBL		12,200
	overcup oak	*Quercus lyrata*	OBL		6,600
	carolina ash	*Fraxinus caroliniana*	OBL		1,200
DELOSS - DRY Deloss fine sandy loam and other fine sandy loams Very Poorly Drained 3.7 x 3.7 meters	black gum	*Nyssa sylvatica*	FAC	125	869
	water oak	*Quercus nigra*	FAC		18,500
	laurel oak	*Quercus laurifolia*	FACW		10,000
	green ash	*Fraxinus pennsylvanica*	FACW		10,300
WASDA Wasda muck Very Poorly Drained 3 x 3 meters	Atlantic white cedar	*Chamecyparis thyoides*	OBL	12	5,236
LEON Leon sand Poorly Drained 3 x 3 meters	longleaf pine	*Pinus palustris*	FACU+	21	9,250

Restoration was completed at the site in March of 2003. Figure 2.20 is an aerial view of blocks 1 and 2 looking west to east and shows the completed restoration soon after a prolonged wet period.

Figure 2.20 Treatments

Installation of Monitoring Equipment

Water Table Monitoring

Water table depth was monitored using 10 cm schedule 40 PVC pipe installed approximately 2 m into the ground. Holes 1.25 cm in diameter were drilled along the length of the pipe and the pipe was covered with a drain sock to prevent the wells from filling with silt. Water table elevations were recorded continuously with INFINITY water table monitors (Infinities USA Inc., Daytona Beach, FL). Two water table monitoring wells were installed in each plot of the three blocks allowing six replications of the water table data for each treatment type. Figure 2.21 shows the transect in blocks 1 and 2 and Figure 2.22 shows the position of the water table wells in the treatments.

Figure 2.21 Transect

Figure 2.22 Position of the Water Table Well in the Treatments

The infinity data loggers measured the depth of water above the sensor located at or near the bottom of the well. Calibration was needed to convert the infinity readings to water table depths. To convert the infinity readings, the height of the well above the surface was determined (Table 2.4). The infinities were calibrated by measuring the distance to the water table from the top of the well and adding that value to the logger reading. Subtracting the height of the well above the ground (A) from the sum of the water table below the top of the

Table 2.4 Average Ground Surface Elevation and Well Heights

Well	Average Ground Elevation (m)	Well Height Above Ground(m)
NR 1	1.46	0.98
NR 2	1.63	0.94
NR 3	1.44	0.98
NR 4	1.54	0.96
NR 5	1.44	1.04
NR 6	1.42	1.1
NR 7	1.45	0.88
NR 8	1.29	0.81
NR 9	1.27	0.87
NR 10	1.28	0.71
NR 11	1.28	0.91
NR 12	1.24	0.96
NR13	2.35	1.10
NR14	2.09	1.08
NR15	2.32	1.03
NR16	2.20	1.02
NR17	2.46	1.03
NR18	2.47	1.27

well and the infinity reading (B) gave the depth of the sensor below the ground (C). Subtracting the infinity reading from the depth of the sensor below the ground gave the depth of the water table below the ground surface at the well. Figure 2.23 illustrates the calibration procedure.

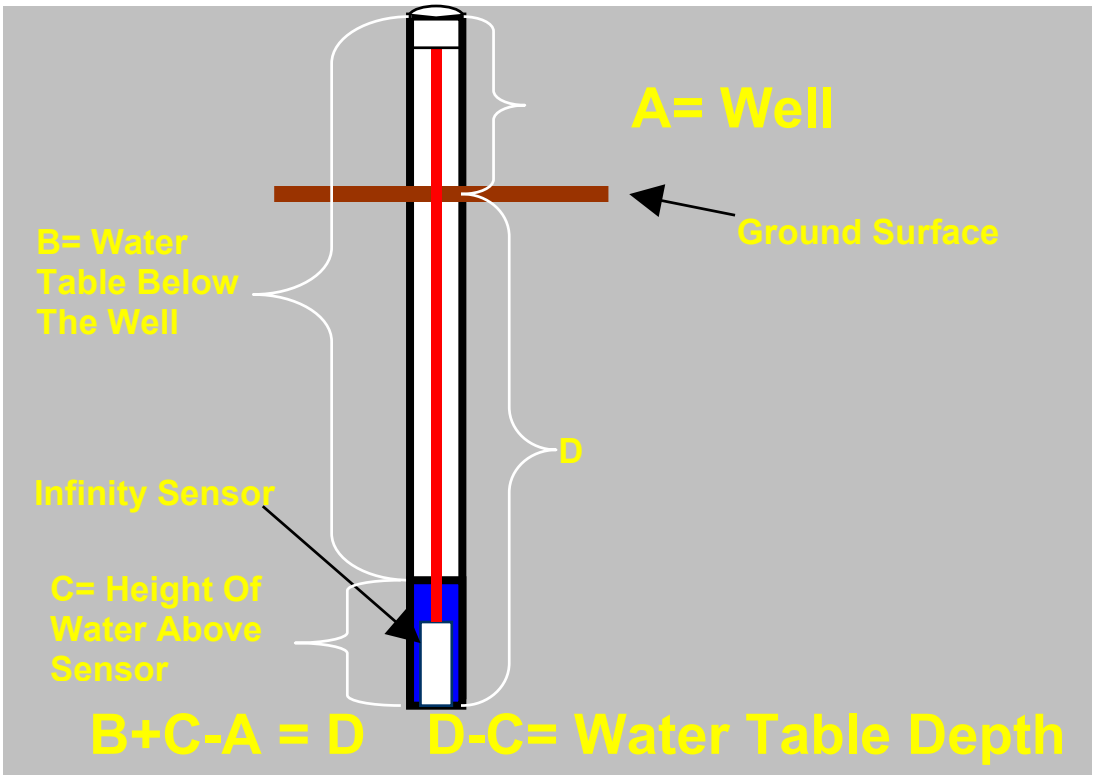

Figure 2.23 Infinity Calibration

Water table data was recorded hourly. The loggers were downloaded with a Hewlett Packard 48G model calculator with custom software provided by the INFINITY USA. Hourly readings from each well were averaged to determine the daily average water table depth at each well. The daily averages from both of the wells in each plot were averaged to determine the daily average water table depth for each treatment.

Flow

Water control structures were installed in the ditches at the outlet of each treatment. Flash board risers with 30^{o} v-notch weirs 20 cm in height were placed in each of the control structures (Figure 2.24). The invert of each weir was set close to the ground surface

Figure 2.24 Weir at the Control Structure

elevation. Table 2.5 shows the elevation of each weir invert and the distance of the invert below the average ground elevation at each water table well.

Table 2.5 Depth of Weir Inverts Below the Ground Surface

Treatment	Water Control Structure	Invert Elevation (m)	Well	Average Ground Surface Elevation	Depth Of Invert Below Ground Surface (m)
C,P/P	WCS1	1.22	NR 1	1.46	0.24
			NR 2	1.63	0.4
P/P	WCS2	1.23	NR 3	1.44	0.21
			NR 4	1.54	0.31
CR,P/P	WCS3	1.21	NR 5	1.44	0.23
			NR 6	1.42	0.21
C,P/P	WCS4	1.01	NR 7	1.45	0.44
			NR 8	1.29	0.29
CR,P/P	WCS5	0.98	NR 9	1.27	0.3
			NR 10	1.28	0.3
P/P	WCS6	0.98	NR 11	1.28	0.29
			NR 12	1.24	0.25
P/P	WCS7	2.00	NR 13	2.35	0.35
			NR 14	2.09	0.09
C,P/P	WCS8	2.02	NR 15	2.32	0.30
			NR 16	2.20	0.19
CR,P/P	WCS9	1.97	NR 17	2.46	0.49
			NR 18	2.47	0.51

Flow from each plot was monitored by recording the depth of flow through each weir every twenty minutes. Ten centimeter diameter polyvinyl chloride (PVC) observation wells were installed with INFINITY water level monitors (Infinites USA Inc., Daytona Beach, FL) at each of the water control structures to record the depth of flow over the weir. In December of 2003 the INFINITY water level monitors were replaced with pulley-tape potentiometer recorders consisting of a float, counterweight, potentiometer, and a two channel 12-bit Sargent data logger (SGT Engineering, Champaign, Illinois) (Figure 2.25). The infinities were replaced because the pulley tape system with the sargent data loggers were more precise and less expensive. The Sargent logged the counts from the potentiometer and a best fit linear regression equation was used to convert the counts to a depth above the invert of the weir. The equation that was used to calculate the flow over a v-notch weir is presented in Equation 2.1.

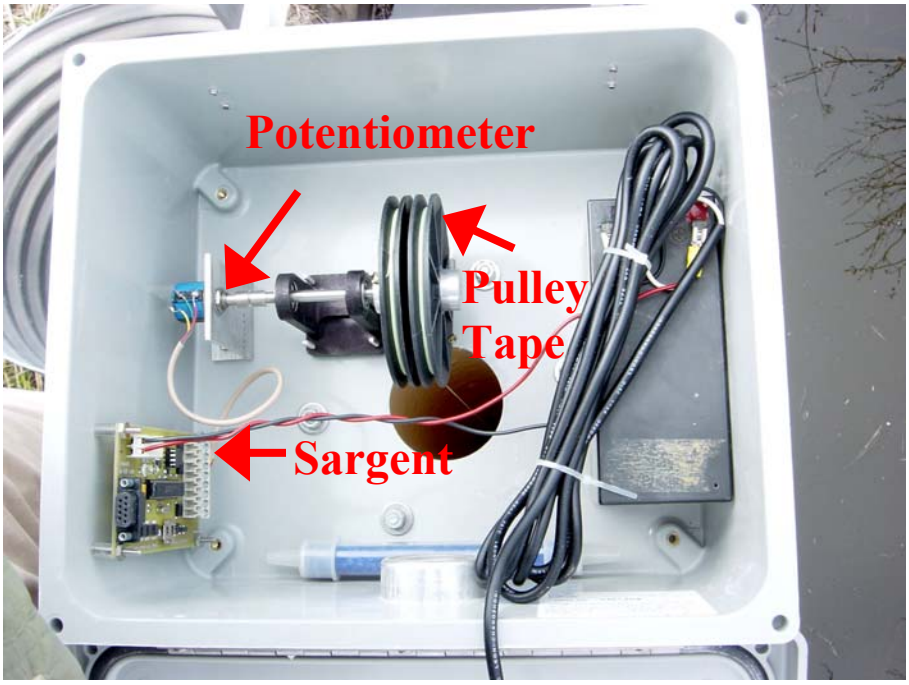

Figure 2.25 Sargent Pulley Tape System

Equation 2.1 Flow Through a V-Notch Weir

$$Q = \frac{8}{15} C_d \tan\frac{\theta}{2} \sqrt{2g}\, H^{5/2}$$

Q = Flow (cfs)
C_d = Discharge Coefficient = 0.589
θ = Weir Angle (degrees)
g = gravitation coefficient
h = head (ft)
(Daugherty et al., 1985)

When the depth of water above the weir invert exceeded the depth of the weir, orifice flow develops. Orifice flow through a 30^o v-notch orifice was computed using Equation 2.2.

Equation 2.2 Orifice Flow

$$Q = C_d\, A_o \sqrt{2g(h - h_o)}$$

Q = Flow (cfs)
C_d=Discharge Coefficient=0.589
A_o=Orifice Area (ft^2)
g = gravitation coefficient
h = elevation of water above centerline (ft)
h_o=elevation of orifice centerline (ft)
(Bedient and Huber, 1992)

Once h was equal to the distance from the invert of the weir to the base of the board above the weir then flow was calculated using Equation 2.2, otherwise flow was calculated using Equation 2.1. The infinities were downloaded as in the transects. The sargent data loggers were downloaded using ZTerm (coolstuff.com) on a handheld pc with the Windows Mobile 2003 operating system. The flow data was summed to a daily value for further analysis.

Rainfall Data

Rainfall data was collected at three locations at the North River site. The data was collected using Davis Rain Collector tipping bucket recorders with a 0.01 inch capacity

bucket (Davis Instruments, Hayward CA, Model 7852). The rainfall was logged using HOBO® data loggers (Onset Computer Corporation), and the data was collected using the HOBO® Shuttle data logger (Onset Computer Corporation, Part H09-003-08). There was also a backup manual gauge located near each tipping bucket. Figure 2.26 shows the rain gauges.

Statistical Analysis

SAS statistical analysis software was used to analyze the data from the treatments. The water table and flow data was analyzed using an ANOVA procedure and the Tukey method to adjust for multiple comparisons (SAS Institute, 1985). The model statement included the block, treatment, year, and a block*treatment interaction term. Because of the few number of data points, and the resulting small degree of freedom, a large difference was required before a result could be determined statistically different.

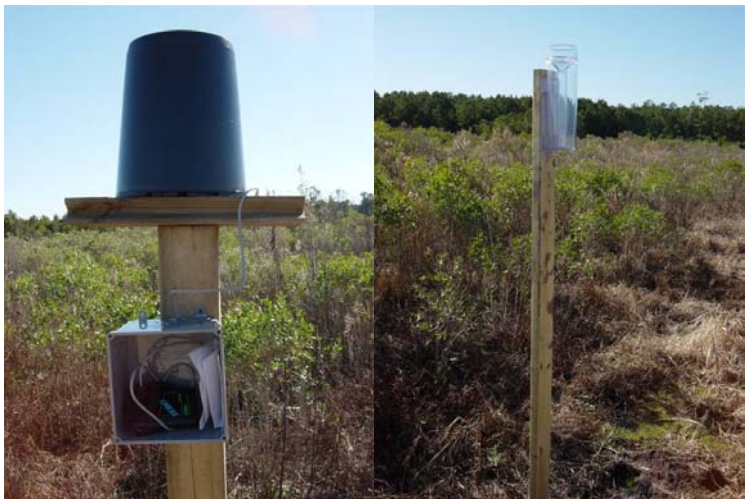

Figure 2.26 Rain Guages

Results and Discussion

Precipitation

Rainfall for 2003 and 2004 was recorded at the site and missing data were estimated with data collected at Beaufort Smith Air Field in Beaufort. The long term average was recorded in Morehead City by the State Climate office of North Carolina. There were several hurricanes and many major storms that produced large amounts of precipitation. Hurricane Isabel in 2003 and Hurricane Alex in 2004 both passed near the site. There were 209 cm of rainfall recorded in 2003 and 129 cm of rainfall recorded in 2004. The long term average rainfall at the site is 148 cm. Rainfall was 61 cm above average in 2003 and 19 cm below average in 2004. Monthly rainfall and cumulative rainfall for 2003 and 2004 along with the long term monthly average and cumulative rainfall are shown in Figure 2.27.

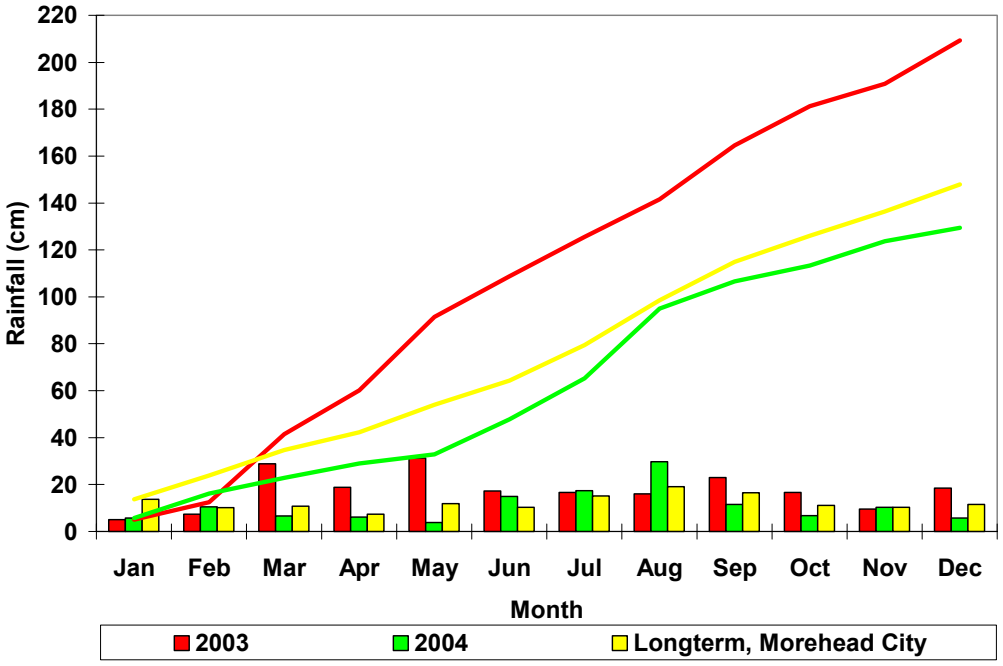

Figure 2.27 2003 and 2004 Precipitation Compared to Long Term Precipitation

Criteria For Evaluating Wetland Hydrology

The water table data will be evaluated in terms of several criteria for evaluating wetland hydrology. The reference and restored wetlands hydrology are evaluated in terms of jurisdictional wetland hydrologic criteria; that is maintaining the water table depth within 30 cm of the surface continuously for 5% or more of the growing season. The frequency that wetlands satisfy jurisdictional criteria does not necessarily describe the hydrology or relative wetness of a site, therefore several other hydrologic criteria were also evaluated. The second criteria involved a comparison of the range that the water table fluctuated. In order to describe, quantify, and compare the hydrology of the wetlands, it is important to look at the entire range of the water table as well as the proximity to the surface. Another criteria involved determining the frequency and duration that the water table was at or above the surface for the study period and the growing season. The number of days that the water table was within 30 cm of the surface for the study period and the growing season was also evaluated. The frequency and duration that the water table was within 30 cm of the surface for was determined by measuring the SEW_{30}. The evaluation criteria are summarized in Table 2.6.

The sum of excess water, SEW, is a measurement of the amount of time the water table is above a threshold depth. SEW considers both water table position and duration and thus has units of cm-days. To coincide with jurisdictional criteria, 30 cm was considered the critical threshold depth. Thus, any time that the water table was within 30 cm of the surface, a SEW_{30} value was computed. SEW_{30} for each day was determined by subtracting the average daily water table depth from the threshold depth of 30 cm. That value was then multiplied by a duration of 1 day as shown in Equation 2.3.

Table 2.6 Evaluation Criteria

Criteria 1	**Number of times Jurisdictional Hydrologic Criteria was met.**
Criteria 2	**Range of Water Table Fluctuation**
Criteria 3	**Number of Days during the Study Period That the Water Table was at or Above the Surface**
Criteria 4	**Number of Days during the Growing Season That the Water Table was at or Above the Surface**
Criteria 5	**Number of Days during the Study Period that the Water Table was within 30 cm of the Surface**
Criteria 6	**Number of Days during the Growing Season that the Water Table was within 30 cm of the Surface**
Criteria 7	**SEW_{30} For the Study Period**
Criteria 8	**SEW_{30} For the Growing Season**

Equation 2.3 SEW_{30}

$$SEW_{30} = \sum_{i=1}^{n} (30 - x_i)$$

SEW_{30}= Sum of Excess Water above 30 cm (cm-days)
x_i= Daily Average Water Table Depth (cm)

If the water table was deeper than 30 cm, the SEW_{30} for that day would be 0 cm-days. In the example shown in Figure 2.28 the water table in REF 08 was 15.75 cm on July 14th, 13.77 cm on July 15th, and 14.74 cm on July 16th. The SEW_{30} for the period of July 14th to July 16th REF 08 would be calculated as follows:

$$30 - 15.75 = 14.25$$
$$30 - 13.77 = 16.23$$
$$\underline{30 - 14.74 = 15.26}$$
$$SEW_{30} = 45.74$$

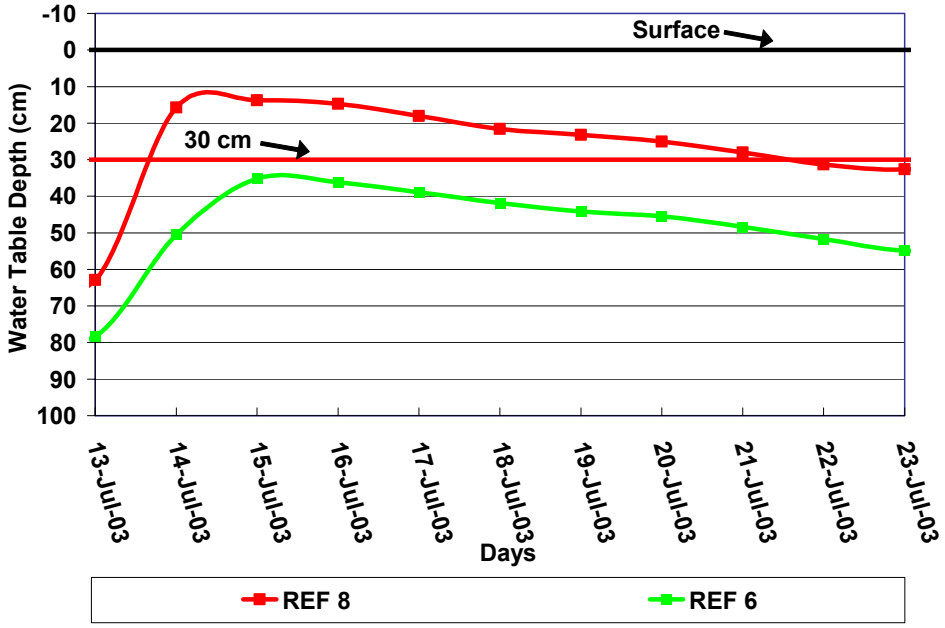

Figure 2.28 Example of SEW_{30}

SEW_{30} for July 14th to July 16th would be 45.74 cm-days. The SEW_{30} for REF 08 for the period shown in Figure 2.28 was 79.92 cm-days. The SEW_{30} for well REF 06 would be 0 cm-days because the water table was not within 30 cm of the surface. A study by Sieben (1964) indicated that SEW_{30} values greater than 200 cm days caused a decrease in the yield of cereal crops providing an estimate of the maximum SEW_{30} for typical agricultural conditions. Higher values would be expected in wetlands

According to the Carteret County Soil Survey, the growing season in Carteret County is from March 20th to November 19th, or 245 days. The monitoring period considered in this study began April 30th 2003 and ended December 8th 2004. The total study period was 589 days and the growing season from the 2 year field study was 449 days. The total number of monitoring days during the study period in 2003 was 246 with 204 days in the growing season. There were 343 monitoring days in the study period in 2004 and a complete growing season of245 days. Because the study period did not include two complete years and only a

portion of the growing season in 2003, the percentage of the year and the growing season for criteria 3, 4, and 5 were also included in the analysis.

Evaluation Of Hydrology Criteria For The Reference

The water table depth in each of the wells in the reference wetland is shown in Figure 2.29. The water table was closer to the surface (wetter) in the center wells REF 2, REF 5 and REF 8, and the water table levels in the wells along the edge, REF 3, REF 4, REF 6, REF 7, and REF 9, were the furthest from the surface (driest). The average of the wells in two relative positions, the center and the edge of the reference are shown in Figure 2.30.

The evaluation criteria from Table 2.6 were computed for each well in the reference. The results of the criteria from each well were then averaged for each of the areas in the reference, 3 wells for the center and 5 wells for the edge. For a brief period in 2004, the water table dropped below the instrument depth in some wells. For this period, May 22,

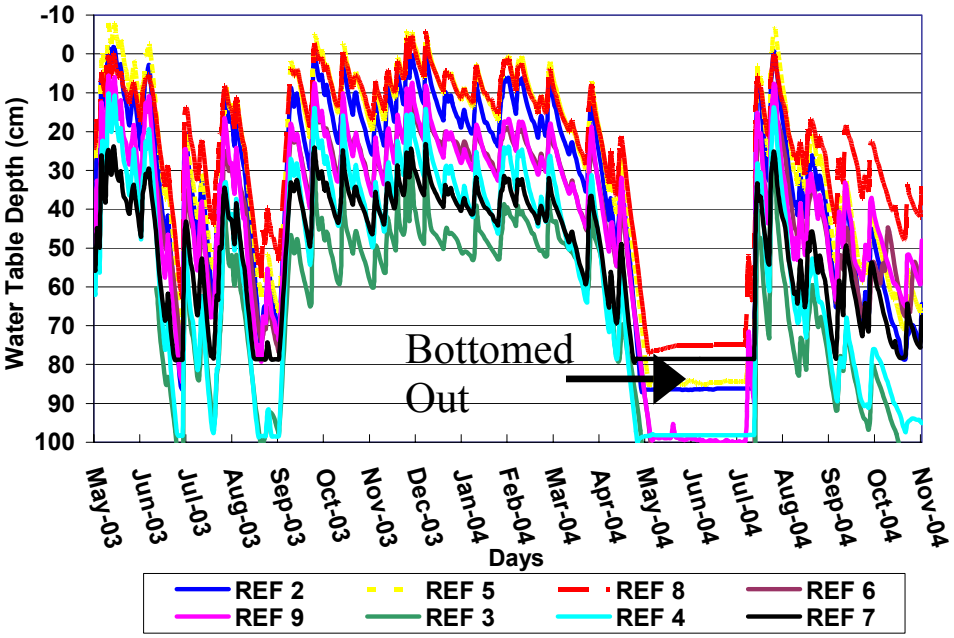

Figure 2.29 Reference Water Table Wells

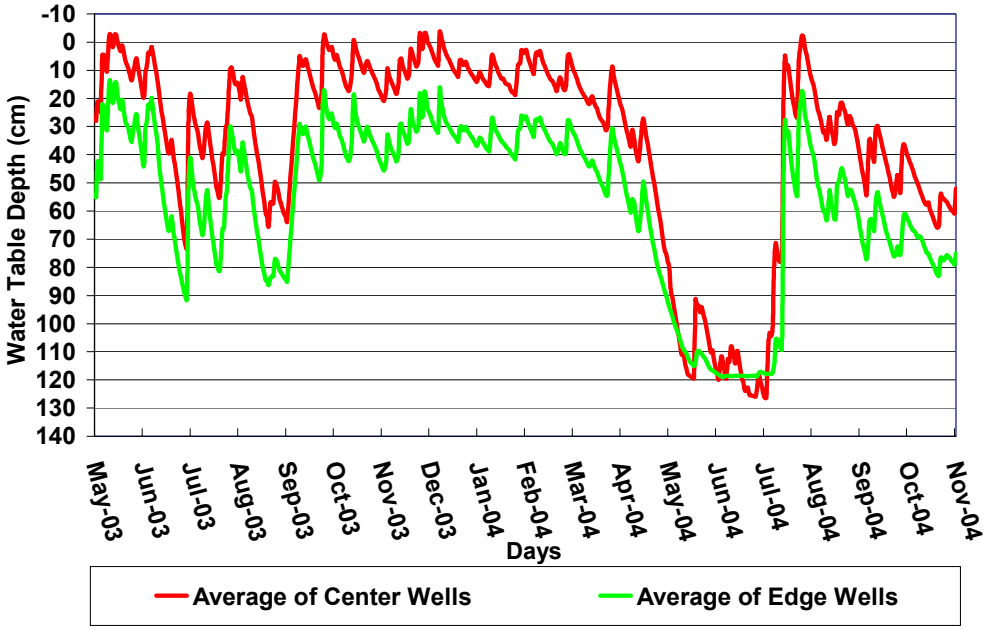

Figure 2.30 Center and Edge of the Reference Wetland

2004 to July 28, 2004, DRAINMOD was used to estimate water table values when the wells "bottomed out".

Criteria 1 (Jurisdictional Criteria)

The center of the reference satisfied jurisdictional criteria more times than the edge wells (Figure 2.31). However, both of the reference areas met jurisdictional wetland hydrologic criterion based on the observed data. The water table was within 30 cm of the surface for 5.7% of the growing season in 2003, one out of two years, enough to satisfy jurisdictional criteria, in the edge of the reference wetland. The water table was within 30 cm of the surface in the center of the reference for 7% to 23.2% of the growing season in 2003 and 5% to 10.6% of the growing season in 2004. The wide variation in the number of times jurisdictional criteria were satisfied in the center and edge of the reference wetland illustrated the wide variation of hydrologic conditions that was found in the reference wetland.

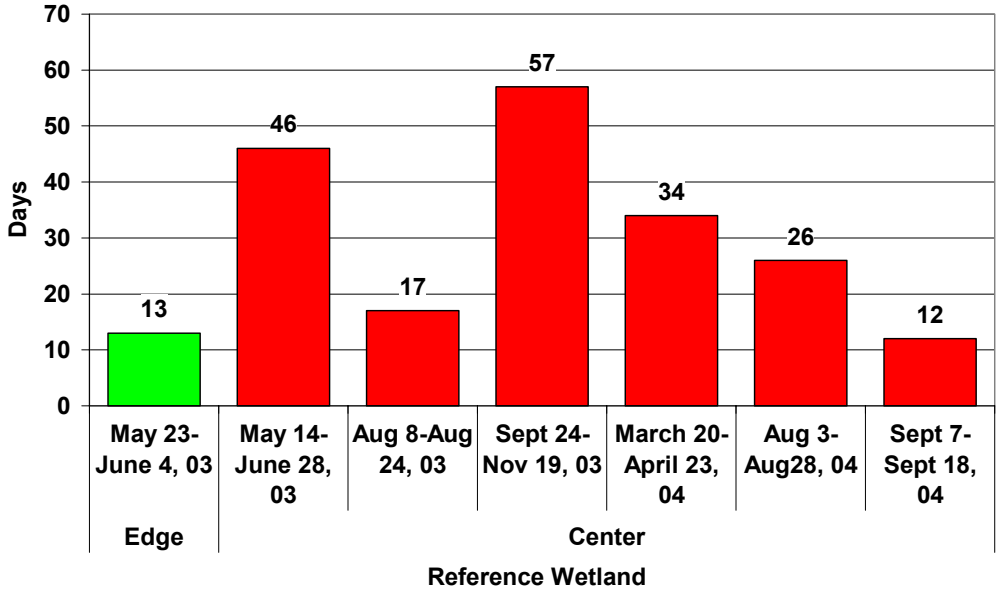

Figure 2.31 Periods Which Minimum Jurisdiction Hydrologic Criteria was met in the Reference Wetland

All areas of the reference wetland met jurisdictional criteria, however, the number of times that jurisdictional criteria were met does not fully describe the range of hydrologic conditions in the reference. There are several other hydrologic criteria that may provide a better description of the relative wetness of the reference wetland.

Criteria 2 (Range in Water Table Depth)

The water table in the center of the reference wetland had a smaller range of fluctuation than the water table around the edge of the reference wetland (Table 2.7). The water table was above the surface (ponded conditions) in the center of the reference and

Table 2.7 Range of Water Table Depth in the Reference

	2003			2004		
	Max	Min	Range	Max	Min	Range
Edge	91.6	15.	76.6(a)	152.4	17.3	135.1 (b)
Center	73.4	-5	78.3(a)	121.3	-2.3	123.6(b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

never reached the surface at the edge of the reference wetland, however the water table was not at or above the surface for long periods in the center of the reference. The water table fluctuated well below 30 cm from the surface in both areas. The difference in the range of the water table depth was not significantly different in the edge and the center of the reference wetland. There was a significant difference between years indicating that the significantly more rainfall in 2003 showed a smaller range in the water table depth.

Criteria 3 and 4 (Water Table at the Surface)

The water table was at the surface for a greater number of days and a greater percentage of the study period and the growing season in the center than the edge of the reference wetland, though there was no significant difference (Table 2.8). There was no significant difference in the number of days that the water table was at or above the surface in 2003 and 2004 despite the differences in rainfall. Most importantly, the natural wetlands were seldom saturated to the surface.

Table 2.8 Number of days and the Percentage of the Study Period and the Growing Season that the Water Table was at or Above the Surface in the Reference

		2003	2004	Total
Criteria 3	Reference Edge	0 (0%)	0 (0%)	0 (0%) (a)
	Reference Center	16 (7%)	2 (1%)	18 (3%) (a)
		2003	2004	Total
Criteria 4	Reference Edge	0 (0%)	0 (0%)	0 (0%) (a)
	Reference Center	9 (4%)	2 (1%)	11 (2%) (a)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Criteria 5 and 6 (Water Table within 30 cm of the Surface)

The water table was within 30 cm of the surface during the study period and the growing season for significantly more days and a greater percentage of the study period in the center of the reference wetland than at the edge (Table 2.9). The difference in the number of days that the water table was within 30 cm of the surface indicated the wide variability in the water table and relative wetness that can be found in natural non-riverine bottomland wetlands. The water table in the edge of the wetland was near the surface although not at the surface as shown in criteria 3 and criteria 4. Because of the landscape position of the areas of the reference wetland discussed previously, the water table must rise close to the surface in the center of the reference before the water table will be within 30 cm of the surface at the edge of the wetland. It is important to consider the number of days that the water table was at or above the surface in conjunction with the number of days that the water table was within 30 cm of the surface.

There was no significant difference between 2003 and 2004 for criteria 5 but there was a significant difference between years for criteria 6. This was because the full year was not considered in 2003 where most of the year was included for 2004 giving a longer monitoring period in 2004. Criteria 6 showed a significant difference between years because

Table 2.9 Number of Days and the Percentage of the Study Period and Growing Season that the Water Table was Within 30 cm of the Surface in the Reference Wetland

		2003	2004	Total
Criteria 5	Reference Edge	65 (31%)	47 (14%)	112 (21%) (a)
	Reference Center	169 (75%)	159 (49%)	328 (59%) (b)
		2003	2004	Total
Criteria 6	Reference Edge	41 (24%)	13 (5%)	54 (13%) (a)
	Reference Center	127 (69%)	80 (33%)	207 (48%) (b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

2003 included a nearly complete growing season making the periods similar between the two years.

Criteria 7 and 8 (SEW_{30})

SEW_{30} is a good measure of relative wetness because it integrates both position of the water table and duration that the water table is above a critical depth. The SEW_{30} was higher in the center of the reference wetland than at the edge of the reference wetland for the study period and the growing season, though there was no significant differences reported (Table 2.10). There is quite a large difference in the SEW_{30} in the center and edge of the reference. The reason that no significant difference was found may be because the sampling size was small providing few degrees of freedom. The differences in the SEW_{30} can also be explained by the differences in landscape position. The water table would also be closer to the surface more often in the center of the reference wetland because of the lower ground surface elevation.

Each of the eight criteria described the position of the water table in the soil profile and provide comparison of the hydrology and relative wetness of the wetland. The number of days that the water table was at or above the surface described the extreme wet conditions expected in a wetland. The number of days that the water table was within 30 cm of the

Table 2.10 SEW_{30} For the Study Period and Growing Season in the Reference

		2003	2004	Total
Criteria 7	Edge	511	286	224 (a)
	Center	3308	2402	5710 (a)
		2003	2004	Total
Criteria 8	Edge	310	88	139 (a)
	Center	2312	867	3179 (a)

surface described the maximum depth of the water table for jurisdictional purposes and the SEW_{30} was an indication of the duration that the water table was within 30 cm of the surface. For each criterion the water table was closer to the surface more frequently in the center of the reference. The proximity of the water table to the surface at each location in the reference was correlated due to the relationship between the water table along the transect as previously described. There was little fluctuation in the water table elevation, therefore, as the water table came closer to the surface in the center it also rose closer at the edge. The difference in the number of days at a given depth could be attributed to the differences in elevation.

The conditions in the reference should be considered when restoring wetlands. It is important to consider the correlation between the number of days that the water table was within 30 cm of the surface and the number of days that the water table was at or above the surface. The water table must be within 30 cm of the surface to satisfy jurisdictional criteria and to develop wetland hydrologic conditions but the water table should not be at the surface for extended periods. The patterns found in the reference wetland should be used as a guide for comparison to restored wetlands and will be compared to the criterion results from the treatment plots.

Statistics

During preliminary analysis of the eight criteria for the three experimental surface treatments, there appeared to be a difference between results from block 3 and the other two blocks. Therefore, a statistical analysis, using blocks as the main factor, was performed on the criteria (Table 2.11). The eight evaluation criteria were applied to each well in the

Table 2.11 Evaluation Criteria Results With Significant Differences

	C,P/P			CR,P/P			P/P		
	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
Criteria 1	4a	4a	4a	5a	4a	2a	4a	3a	2a
Criteria 2	116a	111a	112a	111a	112a	119a	119a	96a	111a
Criteria 3	8a	7a	15a	20a	68a	6a	14a	26a	101a
Criteria 4	7a	5a	9a	14a	38a	6a	10a	17a	69a
Criteria 5	170ab	172ab	179ab	185b	192b	81a	160ab	141ab	189b
Criteria 6	104a	104a	112a	117a	124a	52a	97a	85a	126a
Criteria 7	2691ab	3271ab	3522ab	3806ab	4787ab	969a	2874ab	2554ab	5503b
Criteria 8	1642a	1852a	2001a	2282a	2864a	693a	1710a	1464a	3673a

Comparisons can only be made by criteria row
Values followed by the same letter (horizontally) are not significantly different (α=0.05)

treatments. The results of the evaluation criteria at each of the two wells in each treatment were then averaged to determine the result for the treatment effect for each block. There were differences observed between treatments and blocks in criteria 5 and criteria 7. Results from Criteria 5 indicated that the water table depth in each of the treatments was similar except for the CR,P/P treatment in block 3. The CR,P/P treatment in block 3 was significantly different from the CR,P/P treatment in block 1 and block 2 and the P/P treatment in block 3, but not significantly different from the other treatments. Criteria 7 showed a difference in the CR,P/P treatment and the P/P treatment in block 3.

The statistical results can be explained by the observed physical differences in the blocks. The absolute ground surface elevations in block 3 were approximately 0.75 m to 1 m higher than the ground surface in blocks 1 and 2. Though the weirs were set at the same elevation relative to average ground in each of the blocks, the ground elevations vary in block 3 around the wells. The ground elevation was lower around well NR 14 (block 3) causing the P/P treatment to collect surface water and causing the water table to be naturally closer to the surface. The ground surface around wells NR 17 and NR 18 was higher causing the water table to naturally be further from the surface giving the impression that the CR,P/P

treatment was drier. The transect was installed while crops were in the field, therefore, some of the wells were unintentionally installed in depressions or on mounds.

There were also factors in the construction of block 1 and block 2 that could have influenced the results, specifically in the water table depths. The average ground elevation of the site naturally increases from south to north or from well NR12 in block 2 to NR1 in block 1, meaning that the average ground elevation at well NR1 was about 0.2 m higher than at NR12. Despite the fact that the weirs were installed at approximately the same elevation for each block there were differences in elevation that could have caused differences in the water table depth. Each of the wells were installed at nearly the same height above the ground in each treatment, however, the ground elevation around well NR2 was 10 to 20 cm higher than around the rest of the wells. This resulted in the weir for NR2 being 10 to 20 cm lower compared to the ground surface than NR1, in the same treatment. In effect, this causes NR2 to appear a little drier than the other wells in the same treatment. The same effect occurred at well NR7 causing it to appear drier. Wells NR2 and NR7 were both in the C,P/P treatment which may explain why there was no significant difference between the C,P/P and the P/P treatments in block 1 and 2.

Block 1 and block 2 were located next to each other in a similar landscape position. Because of the elevation and location differences between the blocks, block 1 and block 2 showed treatments effects that differed from block 3. Therefore a separate analysis of block 1 and block 2 are included in the results and discussion.

Evaluation of Hydrologic Criteria For the Restoration Treatments (Includes all three Blocks)

Criteria 1 (Jurisdictional Criteria)

Each period that the water table was within 30 cm of the surface for a consecutive period of at least 5% of the growing season, 12 days, is shown in Figure 2.32. The jurisdictional criteria was met for more than 5% of the growing season consecutively 4 times in 2003 and 3 times in 2004 in the C,P/P treatment. The jurisdictional criteria was met for more than 5% of the growing season consecutively 5 times in 2003 and 2 times in 2004 in the CR,P/P treatment. The jurisdictional criteria was met for more than 5% of the growing season consecutively 5 times in 2003 and 2 times in 2004 in the P/P treatment. Jurisdictional criteria were satisfied for more than 5% of the growing season 1 time in 2003 and not at all in 2004 in the edge of the reference wetland. The criteria was satisfied for more than 5% of the growing season 3 times in 2003 and 3 times in 2004 in the center of the reference wetland.

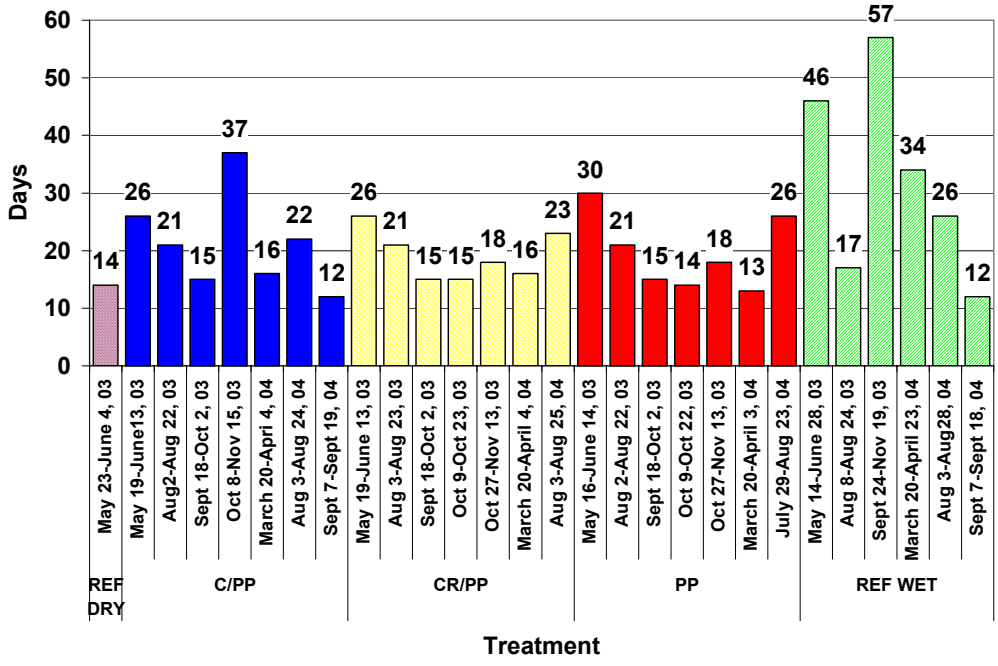

Figure 2.32 Number of Times Jurisdictional Wetland Hydrology Criteria was Met

The jurisdictional wetland hydrology criteria was met for more than 12% of the growing season, 30 days, once in 2003 but not in 2004 in the C,P/P treatment, was not met in the CR,P/P treatment in 2003 or 2004, and once in 2003 in the P/P treatment. The criteria was satisfied for more than 12% of the growing season twice in 2003 and once in 2004 in the center of the reference wetland and was not satisfied in the edge of the reference.

Based on the jurisdictional criteria, the C,P/P treatment maintained the water table within 30 cm of the surface for one additional period than the CR,P/P treatment and the P/P treatment that occurred September 7th to the 19th. Maintaining the water table within 30 cm of the surface is critical in the formation of anaerobic and hydric soil development. Wetland hydrology criteria was met more frequently and for longer periods in the treatments than in the edge of the reference wetland indicating that the treatments were restored to conditions that were wetter than the conditions found in the edge of the reference. The C,P/P treatment and the P/P treatment exceeded a period of continuous days where the water table was within 30 cm of the surface for more than 12.5% of the growing season and the CR,P/P treatment did not. This was also an indication that the water table in the C,P/P and the P/P treatments was within 30 cm of the surface for longer periods than in the CR,P/P treatment.

While jurisdictional criteria is the standard for determining the status of a wetland, it does not provide an adequate description of the full range of hydrologic conditions. There are several other criteria that should be examined to determine the relative wetness of a wetland.

Criteria 2 (Range of Water Table Depth)

The water table fluctuated less in magnitude but more frequent in all the treatments and the reference in 2003 when there was greater rainfall. The range and variability in water table depth was similar to the reference in all of the treatments (Table 2.12).

Criteria 3 (Days at the Surface for the Study Period)

The water table was at the surface for more days (Figure 2.33) and for a greater percentage of the study period in the P/P treatment than in the C,P/P and the CR,P/P treatments (Table 2.13) although the difference was not significant.

Table 2.12 Range of Water Table Fluctuation in the Treatments and the Reference

	2003			2004		
	Max	Min	Range	Max	Min	Range
Reference Edge	91.6	15	76.6(a)	152.4	17.3	135(a)
C,P/P	87.1	-6.5	93.6(a)	129.7	-3.0	132.8(a)
CR,P/P	90.6	-10.7	101.3(a)	122.5	-3.7	126.2(a)
P/P	81.2	-9.1	90.3(a)	116.3	-10.9	127.2(a)
Reference Center	73.4	-5.0	78.3(a)	121.3	-2.3	123.6(a)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

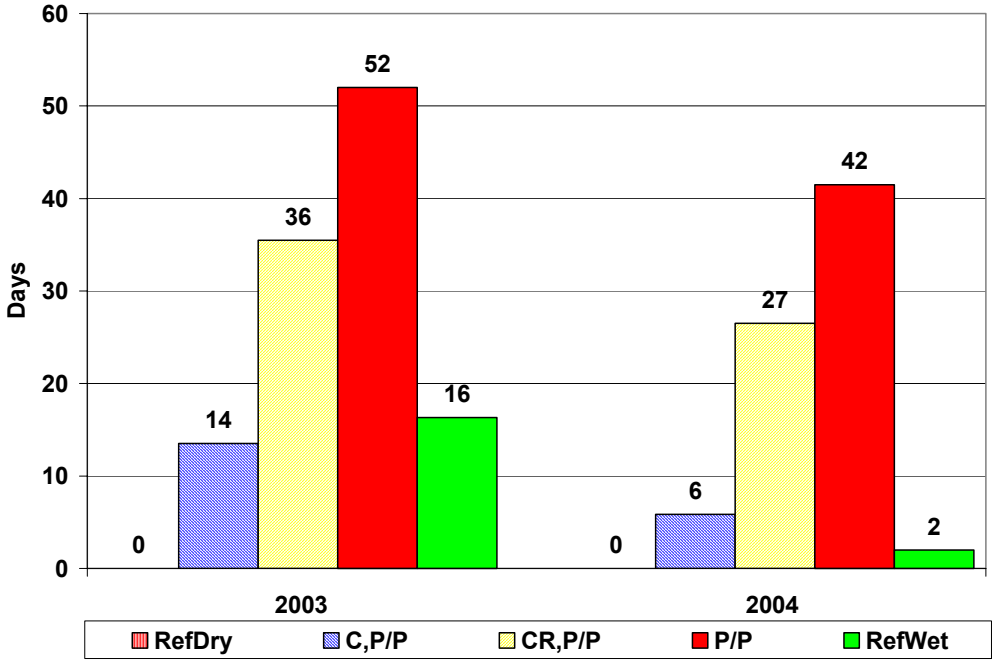

Figure 2.33 Number of Days the Water Table was at or Above the Surface

Table 2.13 Percentage of the Study Period that the Water Table was at or Above the Surface

	2003	2004	Total
Reference Edge	0%	0%	0%(a)
C,P/P	5%	2%	3%(a)
CR,P/P	14%	8%	11%(a)
P/P	21%	12%	16%(a)
Reference Center	7%	1%	3%(a)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Comparing the treatments to the reference for criteria 3 indicated that the water table was not at the surface for significantly more days in the treatments than in the reference. This is important when establishing a wetland as a balance in the duration of ponding must be met. Anaerobic conditions will develop more quickly when the water table is near the surface, however, it may be difficult for vegetation to establish if the area is inundated for long periods of time.

Criteria 4 (Days at the Surface for the Growing Season)

During the growing season, the water table was at or above the surface for more days, and a greater percentage of the growing season in the P/P treatment in both years followed by the CR,P/P and the C,P/P treatments, though the difference was not significant (Figure 2.34 and Table 2.14). There was no significant difference in the number of days that the water table was at the surface during the growing season in the center or the edge of the reference and the treatments. Even though the water table was at the surface for more days in the treatments than in the reference, they were statistically restored to similar surface wetness conditions.

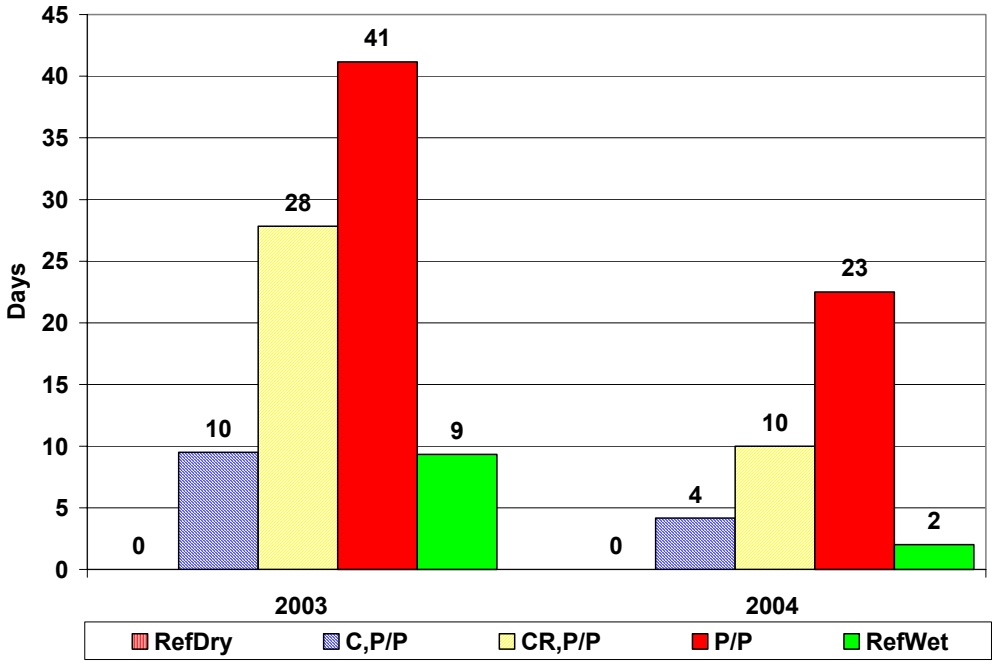

Figure 2.34 Number of Days the Water Table was at or Above the Surface During the Growing Season

Table 2.14 Percentage of the Growing Season that the Water Table was at or Above the Surface

	2003	2004	Total
Reference Edge	0%	0%	0%(a)
C,P/P	5%	2%	3%(a)
CR,P/P	14%	4%	8%(a)
P/P	20%	9%	14%(a)
Reference Center	4%	1%	2%(a)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Criteria 5 (Days Within 30 cm of the Surface During the Study Period)

The water table was within 30 cm of the surface for a similar number of days and percentage of the study period in each of the three treatments and the center of the reference (Figure 2.35 and Table 2.15).

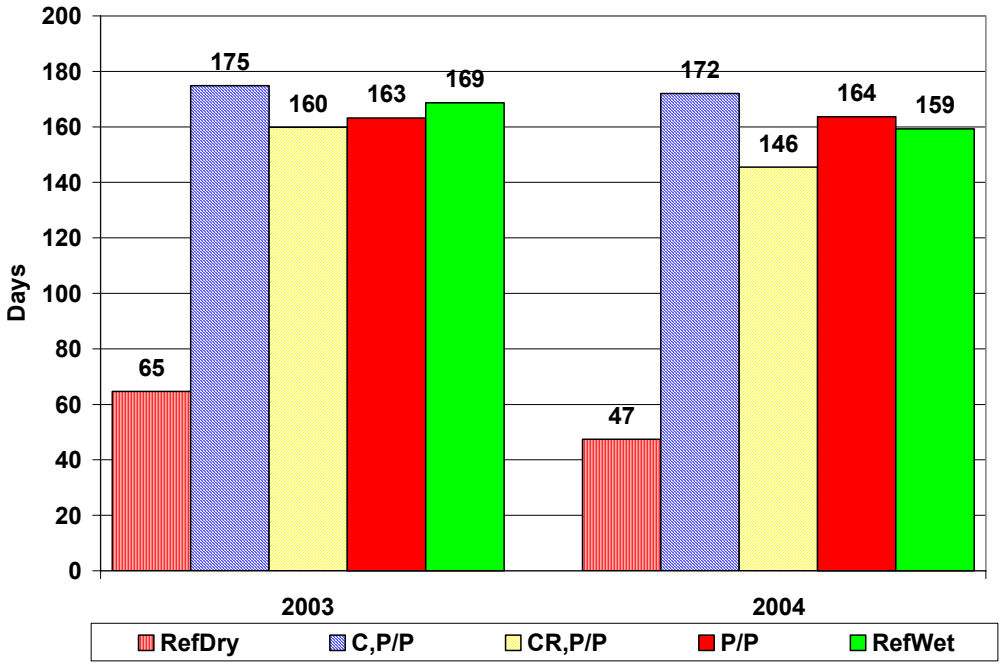

Figure 2.35 Number of Days the Water Table was Within 30 cm of the Surface

Table 2.15 Percentage of the Study Period that the Water Table was Within 30 cm of the Surface

	2003	2004	Total
Reference Edge	31%	14%	21%(a)
C,P/P	71%	50%	59%(b)
CR,P/P	65%	42%	52%(b)
P/P	66%	48%	55%(b)
Reference Center	75%	49%	59%(b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

The edge of the reference had significantly fewer periods with the water table within 30 cm of the surface than the treatments. The water table was within 30 cm of the surface for more days in the C,P/P treatment than the other treatments throughout the study period, however the difference was not significant.

Criteria 6 (Days Within 30 cm of the Surface During the Growing Season)

The water table was within 30 cm of the surface for a few more days and a greater percentage of the growing season in the C,P/P treatment in 2003, however no significant difference was observed (Figure 2.36 and Table 2.16). The number of days that the water table was within 30 cm in the center of the reference was similar to the number of days in the treatments but significantly less in the edge of the reference indicating that the treatments were restored to conditions within the range of variability of the reference.

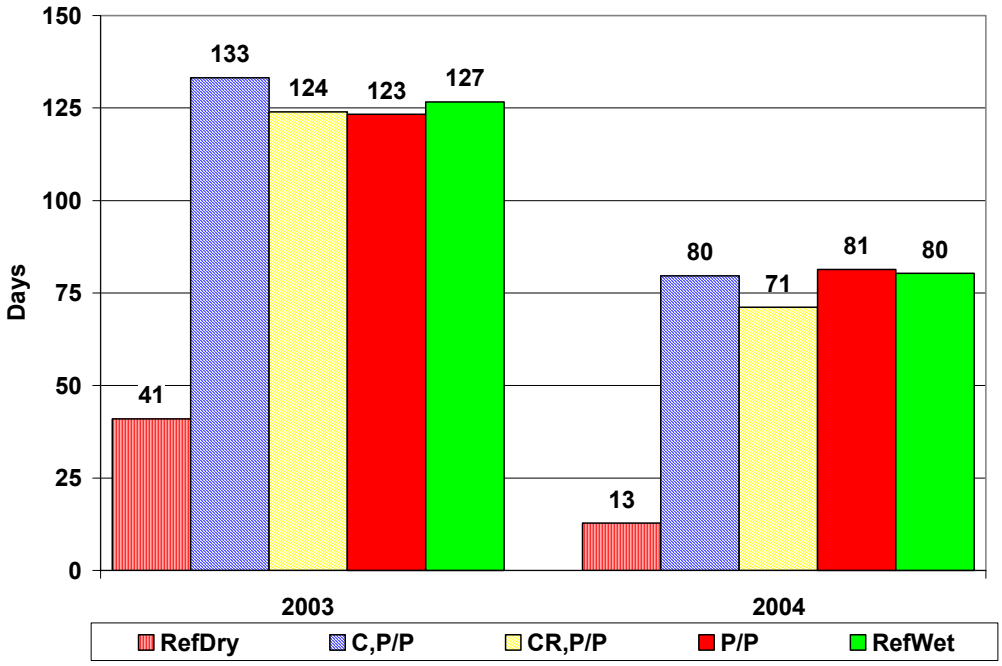

Figure 2.36 Number of Days the Water Table was Within 30 cm of the Surface During the Growing Season

Table 2.16 Percentage of the Growing Season that the Water Table was Within 30 cm of the Surface

	2003	2004	Total
Reference Edge	24%	5%	13%(a)
C,P/P	65%	33%	47%(b)
CR,P/P	61%	29%	43%(b)
P/P	60%	33%	46%(b)
Reference Center	69%	33%	48%(b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Criteria 7 (SEW_{30} for the Study Period)

The SEW_{30} was greater in the P/P treatment than in the other treatments, though not statistically different (Figure 2.37). The SEW_{30} was significantly higher in the treatments than in the edge of the reference. The SEW_{30} was higher in the treatments than in the center of the reference, but was not statistically significant. The SEW_{30} was greater in

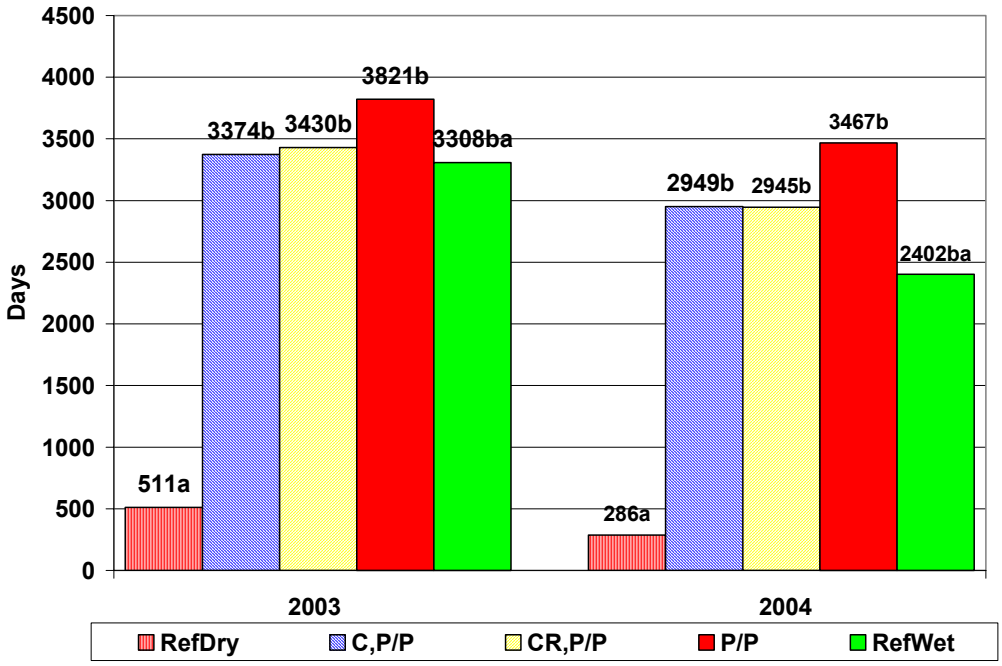

Figure 2.37 SEW_{30} For the Study Period

2003 than in 2004 indicating the variability between the years. Based on the SEW_{30} value sited by Sieben (1964) of 200 cm-days, the SEW_{30} was significantly greater in each of the treatments and the center of the reference wetland than in typical agricultural conditions.

Criteria 8 (SEW_{30} for the Growing Season)

The SEW_{30} was higher in the P/P treatment followed by the CR,P/P and the C,P/P treatments, though the differences were not significant (Figure 2.38). The SEW_{30} of the treatments was greater than the center and the edge of the reference, although in was only statistically greater than the edge of the reference. The SEW_{30} was significantly greater than the SEW_{30} value

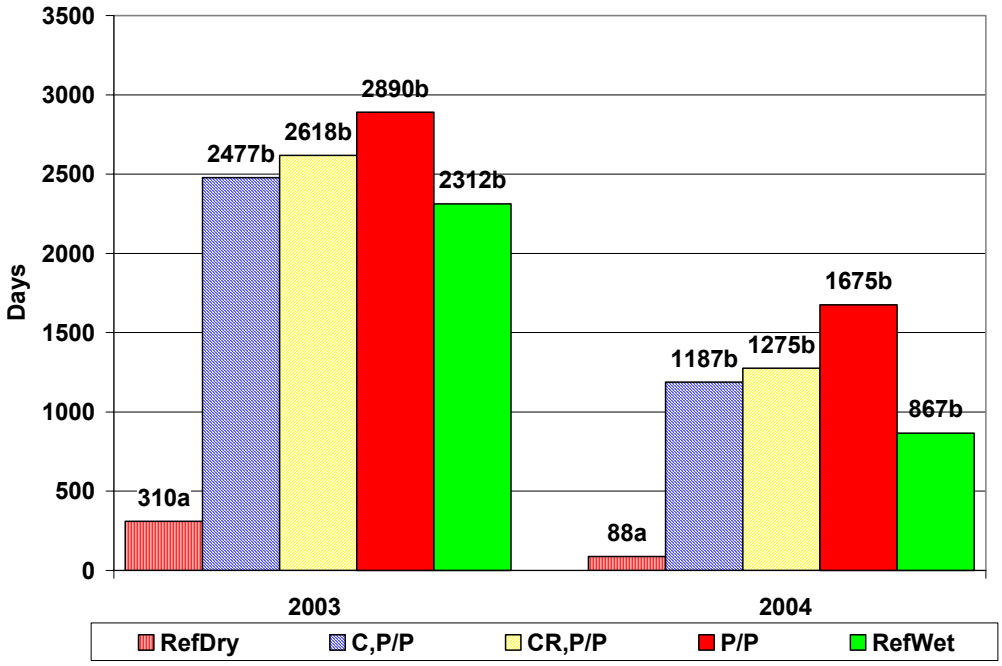

Figure 2.38 SEW_{30} For the Growing Season

sited by Sieben (1964) of 200 cm-days in each of the treatments and the center of the reference wetland indicating that typical agricultural crops would not be able to survive as a result of the relative wetness.

Each of the criteria described a different aspect of the water table position in the soil profile. Based on the criteria, the treatment areas and the reference satisfied the jurisdictional criteria, however, the water table was at the surface for a small portion of the time. The treatments exhibited the range of the water table that can be found in natural wetlands. The P/P treatment appeared to be wetter than the CR,P/P and the C,P/P treatments when all of the blocks were considered, however, there was no significant difference. The number of days that the water table is at the surface should be considered in conjunction with the number of days that the water table is within 30 cm of the surface to ensure that the proper range of the water table is established.

Evaluation of Hydrologic Criteria for the Restoration (Block 1 and Block 2):

Statistical analysis revealed apparent differences between some of the treatments in block 3 and those treatments in block 1 and 2. Therefore, the hydrologic criteria were also evaluated for just blocks 1 and 2. These results are presented below.

Criteria 1 (Block 1 and Block 2, Jurisdictional Criteria)

Each period that the water table was within 30 cm of the surface for a consecutive period of at least 5% of the growing season, 12 days, is shown in Figure 2.39. The jurisdictional criteria was met for periods longer than 5% of the growing season 5 times in 2003 and 2 times in 2004 in the C,P/P treatment, 5 times in 2003 and 4 times in 2004 in the CR,P/P treatment, and 5 times in 2003 and 1 time in 2004 in the P/P treatment.

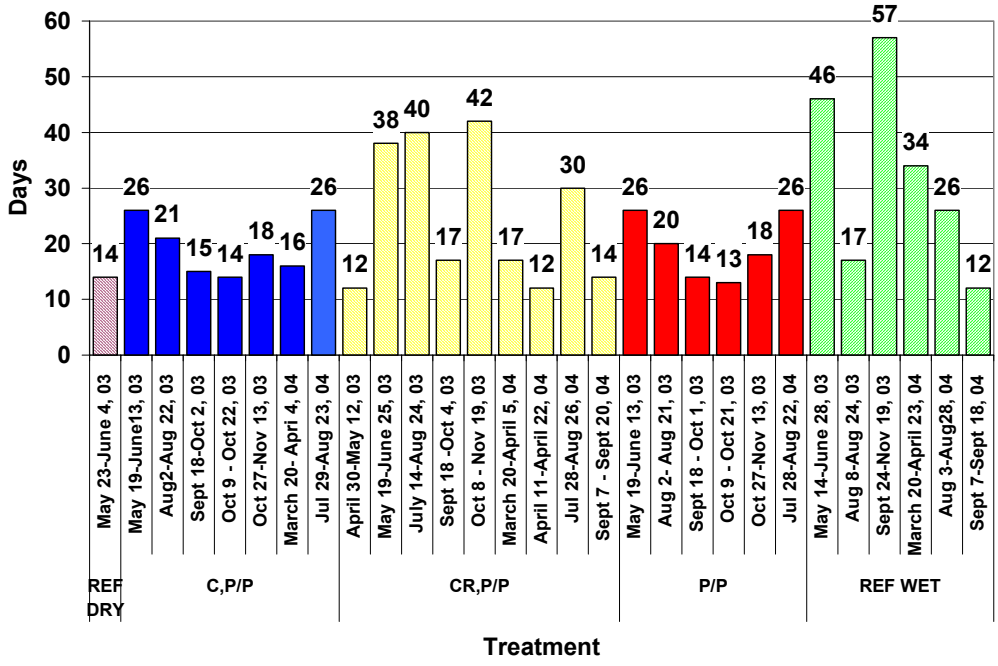

Figure 2.39 Number of Times Jurisdictional Wetland Hydrology Criteria was Met

Jurisdictional wetland hydrology criteria was not met for periods longer than 12.5% of the growing season, 30 days, in the C,P/P treatment or the P/P treatment. The water table was within 30 cm of the surface for a continuous period of greater than 30 days 3 times in 2003 and 1 time in 2004 in the CR,P/P treatment. The criteria was satisfied for more than 12% of the growing season twice in 2003 and once in 2004 in the center of the reference wetland.

Jurisdictional criteria was met more often in the treatments than in the center of the reference wetland but on several occasions the water table was within 30 cm of the surface in the reference for longer periods than in the treatments. The CR,P/P treatment met the jurisdictional criteria for the period of April 11 to April 22, exactly 12 days, and the other treatments did not. When all three of the blocks were considered the water table was within 30 cm of the surface for one extra period in the C,P/P treatment.

Criteria 2 (Block 1 and Block 2, Range of Water Table Depth)

The range of the water table depths in each treatment were not significantly different and were similar to the range in the reference (Table 2.17). The water table ranged from

Table 2.17 Range of Water Table Depth Fluctuation

	2003			2004		
	Max	Min	Range	Max	Min	Range
Reference Edge	91.6	15	76.6(a)	152.4	17.3	135(a)
C,P/P	**89.3**	**-6.1**	**95.5(a)**	**129.2**	**-2.8**	**132.0(a)**
CR,P/P	**84.0**	**-14.8**	**98.8(a)**	**115.8**	**-8.2**	**124.0(a)**
P/P	**84.1**	**-8.0**	**92.1(a)**	**115.4**	**-7.9**	**123.3(a)**
Reference Center	**73.4**	**-5.0**	**78.3(a)**	**121.3**	**-2.3**	**123.6(a)**

Values followed by the same letter (vertically) are not significantly different (α=0.05)

above the surface to more than 80 cm below the surface in 2003 and 115 cm below the surface in 2004. The fluctuations in the water table depth illustrated the variability that can occur in the hydrology of wetlands.

Criteria 3 (Block 1 and Block 2, Days at the Surface During the Study Period)

The water table was at or above the surface for more days and for a greater percentage of the study period in the CR,P/P treatment than in the other treatments or the center of the reference wetland (Figure 2.40 and Table 2.18), however, the difference was not significant. The water table was at the surface for significantly more days in the treatments and center of the reference wetland than in the edge of the reference wetland. This indicated that the treatments were restored to similar hydrologic conditions as the center of the reference wetland.

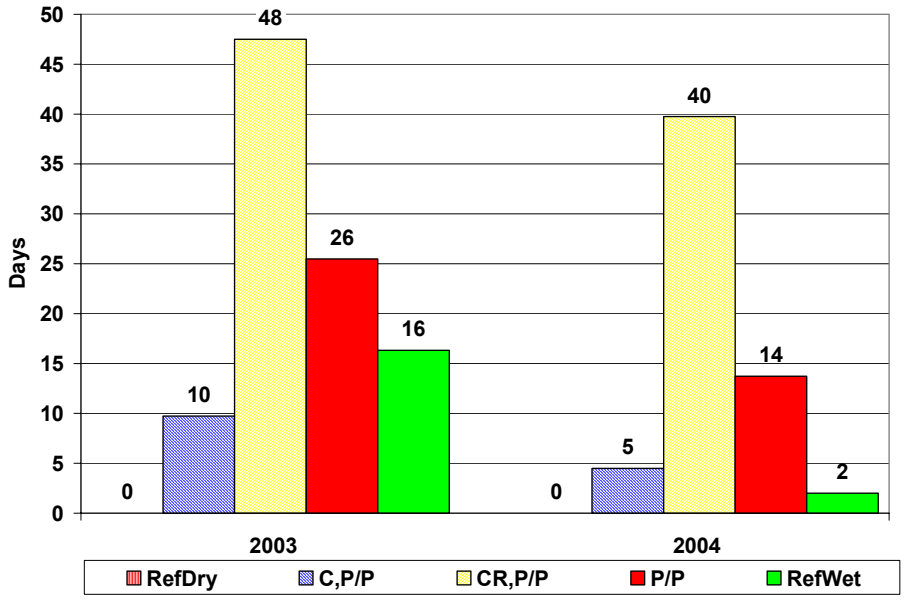

Figure 2.40 Number of Days the Water Table was at or Above the Surface

Table 2.18 Percentage of the Study Period that the Water Table was at or Above the Surface

	2003	2004	Total
Reference Edge	0%	0%	0%(a)
C,P/P	4%	1%	2%(b)
CR,P/P	19%	12%	10%(b)
P/P	10%	4%	7%(b)
Reference Center	7%	1%	3%(b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Criteria 4 (Block 1 and Block 2, Days at the Surface for the Growing Season)

The water table was at or above the surface for significantly more days and a greater percentage of the growing season in the CR,P/P treatments than in the edge of the reference wetland (Figure 2.41 and Table 2.19). There was no significant difference between the

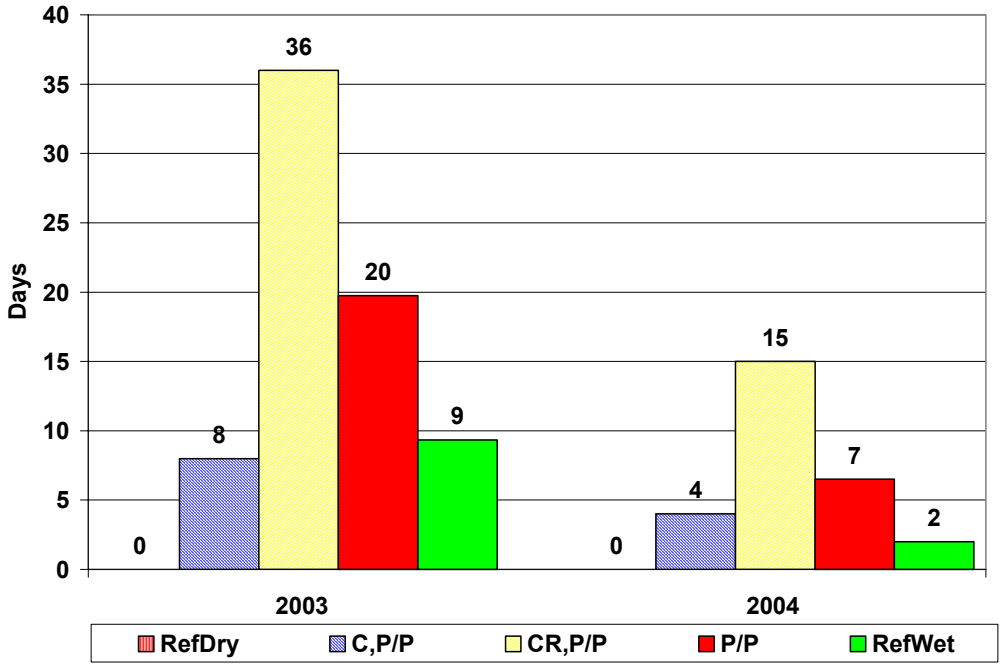

Figure 2.41 Days the Water Table was at or Above the Surface During the Growing Season in Block 1 and 2

Table 2.19 Percentage of the Growing Season that the Water Table was at Or Above the Surface

	2003	2004	Total
Reference Edge	0%	0%	0%(a)
C,P/P	4%	2%	3%(a)(b)
CR,P/P	18%	6%	10%(b)
P/P	10%	3%	6%(a)(b)
Reference Center	4%	1%	2%(a)(b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

treatments and the center of the reference. The results were the same as when all of the blocks were considered except that the water table was at the surface for more days in the CR,P/P treatment. It is important that the water table be near the surface, but the root zone should not be saturated indefinitely. The periods of wet and dry are needed so that vegetation may establish and for wetland functions such as denitrification. A balance must be met to form bottomland hardwood wetlands similar to the reference wetland.

Criteria 5 (Block 1 and Block 2, Water Table within 30 cm of the Surface for the Study Period)

The number of days and the percentage of the study period that the water table was within 30 cm of the surface was similar in the treatments and in the reference wetland (Figure 2.42 and Table 2.20). The water table was within 30 cm of the surface in the CR,P/P treatment for more days than the other treatments throughout the study period, followed by the C,P/P treatment and the P/P treatment, however the differences were not significant.

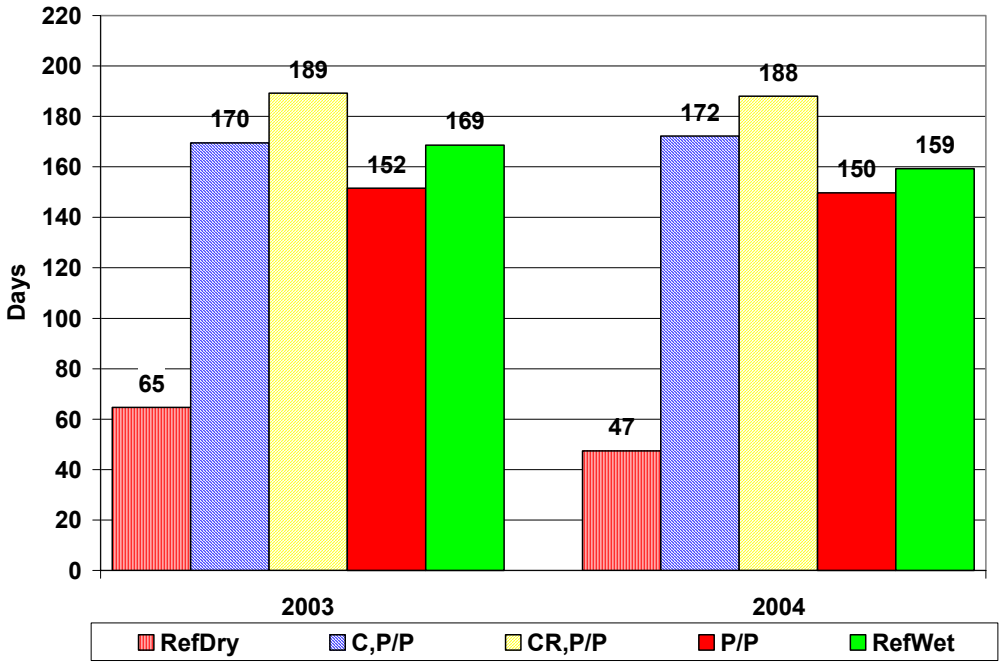

Figure 2.42 Number of Days The Water Table was Within 30 cm of the Surface for the Study Period

Table 2.20 Percentage of the Study Period That the Water Table was Within 30 cm of the Surface

	2003	2004	Total
Reference Edge	31%	14%	21%(a)
C,P/P	69%	50%	58%(b)
CR,P/P	77%	55%	62%(b)
P/P	62%	44%	51%(b)
Reference Center	75%	49%	59%(b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Criteria 6 (Block 1 and Block 2, Water Table Within 30 cm of the Surface for the Growing Season)

The water table was within 30 cm of the surface for a similar number of days and percentage of the growing season in the treatments and in the center of the reference, however, the center of the reference and the treatments were significantly wetter than the edge of the reference (Figure 2.43 and Table 2.21). The water table was within 30 cm of the

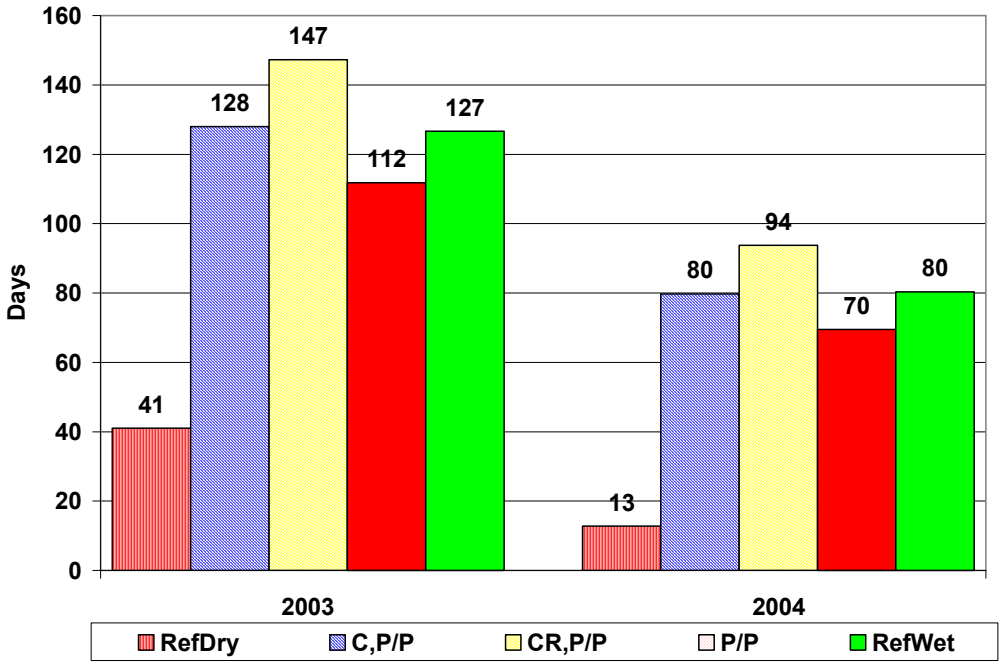

Figure 2.43 Number of Days the Water Table was Within 30 cm of the Surface During the Growing Season

Table 2.21 Percentage of the Growing Season that the Water Table was Within 30 cm of the Surface

	2003	2004	Total
Reference Edge	24%	5%	13% (a)
C,P/P	63%	33%	46%(b)
CR,P/P	72%	38%	55%(b)
P/P	55%	28%	40%(b)
Reference Center	69%	33%	48% (b)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

surface for the greatest number of days in the CR,P/P treatment followed by the C,P/P and the P/P treatments, though the difference was not significant. Significant differences were observed between years.

Criteria 7 (Block 1 and Block 2, SEW_{30} for the Study Period)

The greatest difference between the blocks was observed in the SEW_{30} for the study period. The SEW_{30} was significantly higher in the CR,P/P treatment than in the edge of the reference wetland and the P/P treatment (Figure 2.44). The SEW_{30} indicated that the water table was within 30 cm of the surface for a greater duration in the CR,P/P treatment than in the P/P treatment. The SEW_{30} was higher in the CR,P/P treatment than the C,P/P treatment, though the difference was not significant. The SEW_{30} was higher in the center of the reference than the P/P treatment and the C,P/P treatment in 2003 and greater in the C,P/P treatment and the P/P treatment in 2004. This indicated that there was not much difference in the P/P and the C,P/P treatments and the reference. The difference in the SEW_{30} in 2003 and in 2004 illustrated the variability between years. Sieben (1964) reported a maximum SEW_{30} of 200 cm–days for the maximum yield of cereal crops. This is an indication that the site was much wetter than conditions in a typical agricultural field.

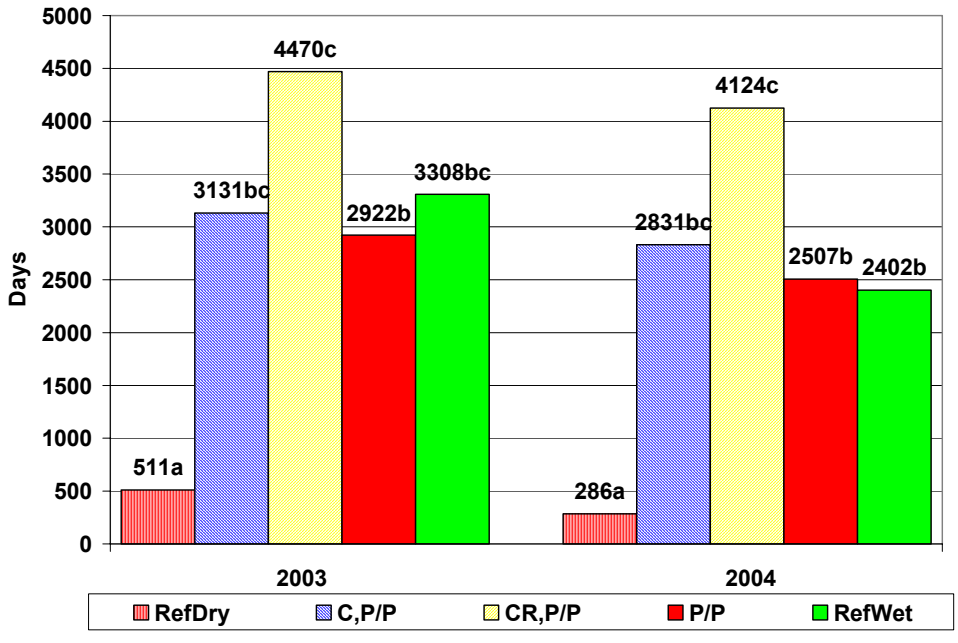

Figure 2.44 SEW_{30} For the Study Period

Criteria 8 (Block 1 and Block 2, SEW_{30} for the Growing Season)

The SEW_{30} in the treatment areas were not significantly different during the growing season than the center of the reference (Figure 2.45). The SEW_{30} was greater in the C,P/P treatment than in the P/P treatment though the difference was not significant. The difference in the SEW_{30} between years showed the variability of the years during the growing season. The SEW_{30} was much higher than the threshold value of 200 cm days reported by Sieben (1964) for the maximum yield of cereal crops. This is an indication that the site was much wetter than conditions in a typical agricultural field.

Each of the criteria described a different level of the water table in the soil profile. The water table was within 30 cm of the surface for enough time to meet jurisdictional criteria. The treatments were saturated to the surface for a small portion of the

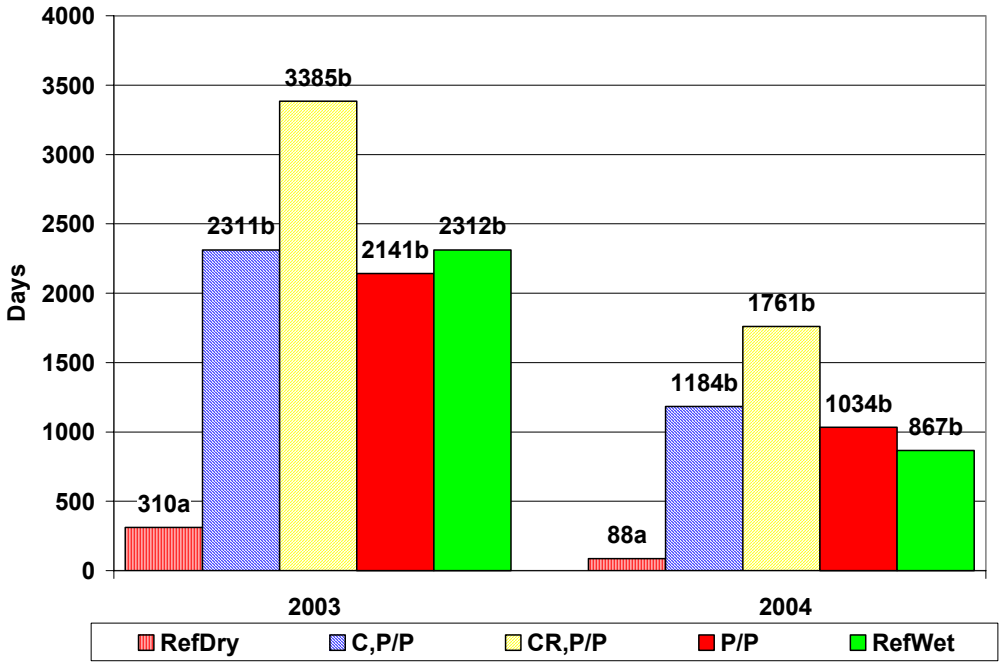

Figure 2.45 SEW_{30} For the Growing Season

study period and the growing season compared to the number of days that the water table was within 30 cm of the surface. The water table was at the surface and within 30 cm of the surface for more days and the SEW30 was higher indicating that the CR,P/P treatment was the wetter of the treatments, however, the difference between the treatments was not significant.

Flow

Flow data was recorded every twenty minutes with 30^{o} v-notch weirs installed at the outlets of each treatment. The data was summed to a daily value by plot and then averaged by treatment for comparison. Flow was not recorded from the reference. There were 27 storms that produced flow from the treatments, 15 storms during 2003 and 12 storms in 2004.

Flow data from each outlet was summed for the duration of each storm and averaged by treatment for statistical analysis. Because flow is strongly correlated to storm intensity and duration, auto correlation in the data was high, therefore, the natural log of the sum of each storm was used to normally distribute the data for the statistical analysis.

The flow data from the treatments was analyzed using an ANOVA procedure with treatment, block, and storm as factors. The resulting analysis from all of the blocks is shown in Table 2.22 and the resulting p-values are presented in Table 2.23. There was no

Table 2.22 Mean Storm Flow by Treatments in All Three Blocks

Treatment	Mean Flow (per Storm) (cm)
C,P/P	3.80 (a)
CR,P/P	2.50 (b)
P/P	3.47 (a)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Table 2.23 Resulting P-Values From the LSM Analysis, Mean flow per Storm

	Crown Removal	Contour	Plug and Plant
Crown Removal	0	0.02	0.001
Contour	0.02	0	0.58
Plug and Plant	0.001	0.58	0

difference in flow between the C,P/P and the P/P treatments. There was a difference in flow between the CR,P/P treatment and the C,P/P and P/P treatments.

There was more rainfall in 2003 than in 2004 which resulted in greater cumulative flow in 2003 (Figure 2.46). The greatest flow occurred from the C,P/P and the P/P treatments. The flow from the CR,P/P treatment was 21 cm less than the flow from the P/P treatment yet the water table was at the surface 16 days more than in the P/P treatment in 2003. The flow from the CR,P/P treatment was 5 cm less and the water table was at the surface for 15 days more than in the P/P treatment in 2004. Less water flowed from the

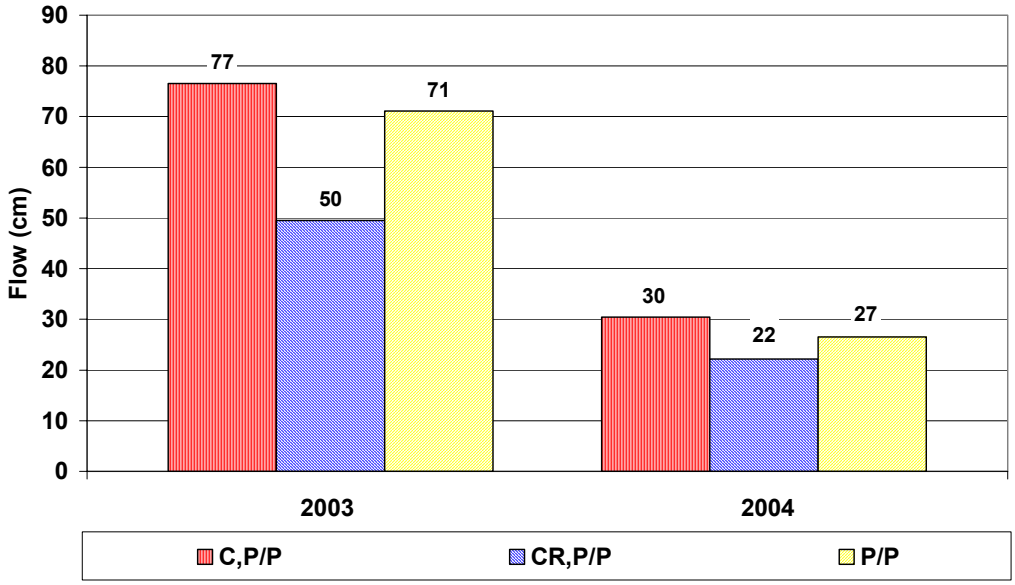

Figure 2.46 Comparison of Cumulative Flow By Treatment

CR,P/P treatment because of the greater storage provided by removing the crown. Leveling the field provided more area for water to be stored. When the water rose to the surface in the P/P and the C,P/P treatments runoff occured from the area between the well at the quarter point in the field and the ditch because the ditch was at a lower elevation than the well. When the crown was removed the well was at the same elevation as the edge of the ditch allowing for more soil storage and consequently less runoff.

The flow hydrographs for each storm are shown in Figure 2.47. The flow for shorter periods are presented so that the trends described in the cumulative flow section are more apparent. The flow for the CR,P/P treatment was generally less than the flows for the C,P/P and P/P treatments during storms that caused greater flow (Figure 2.48). During storms that caused less flow from the treatments, the C,P/P treatment flows were lower than the P/P treatment flows (Figure 2.49).

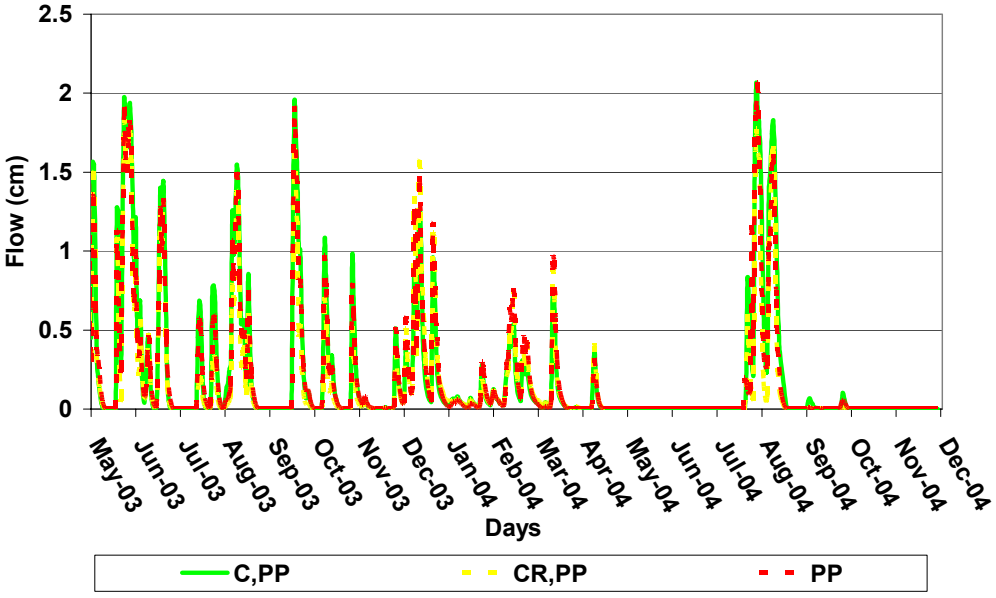

Figure 2.47 Comparison of Flow By Treatment for the Study Period

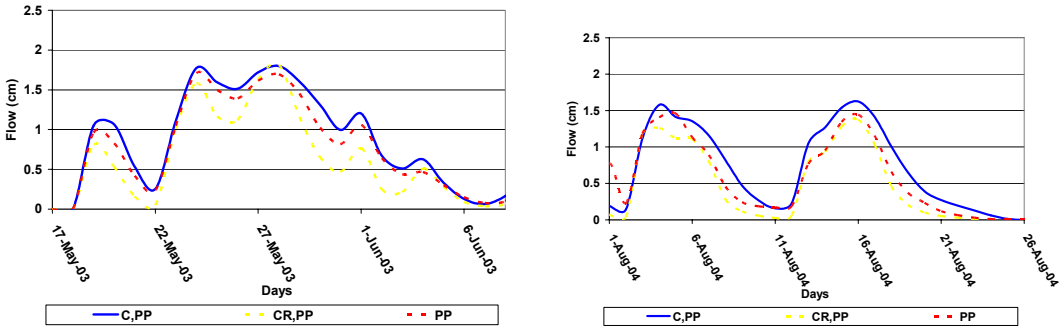

Figure 2.48 Period of Higher Intensity Storms

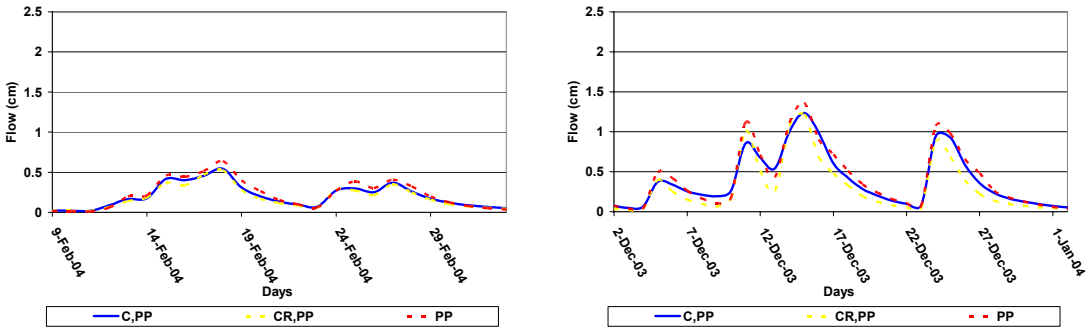

Figure 2.49 Period of Lower Intensity Storms

An example of the correlation between the peak in flow and the depth of the water table is shown in Figure 2.50. The flow from the site is clearly correlated with the water table depth. The closer the water table was to the surface the greater the flow. Flow occured from the treatments once the water table reached the depth of the weir invert. Subsurface flow to the ditches caused flow even when the water table was not above the surface.

The difference in the amount of cumulative rainfall versus cumulative outflow indicated that the amount of rainfall that was temporarily stored in the treatments was greater in the CR,P/P treatment than the P/P and the C,P/P treatments (Figure 2.51). Leveling the

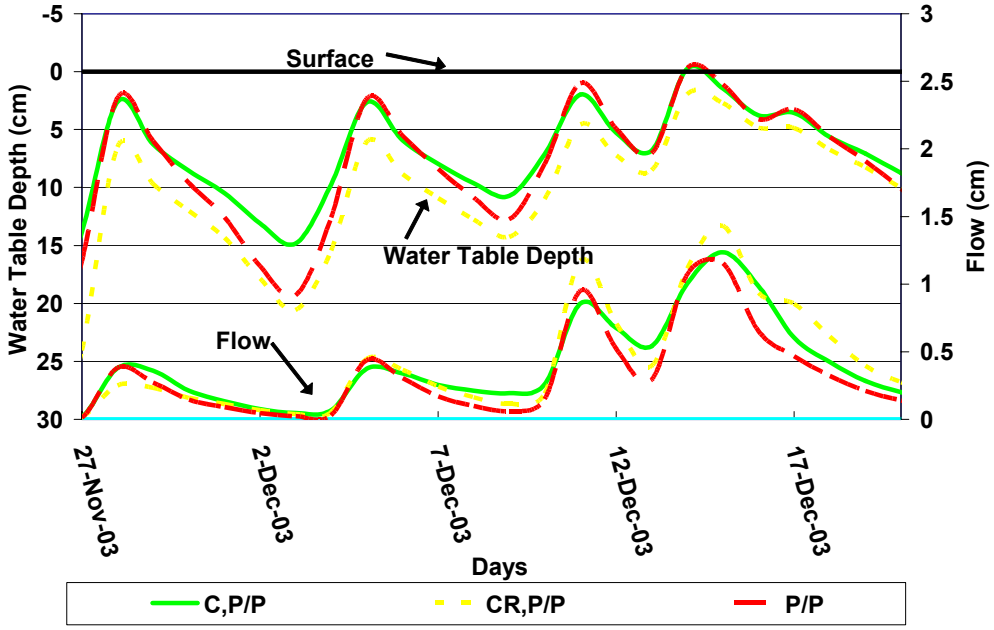

Figure 2.50 Flow Correlated to Water Table Depth

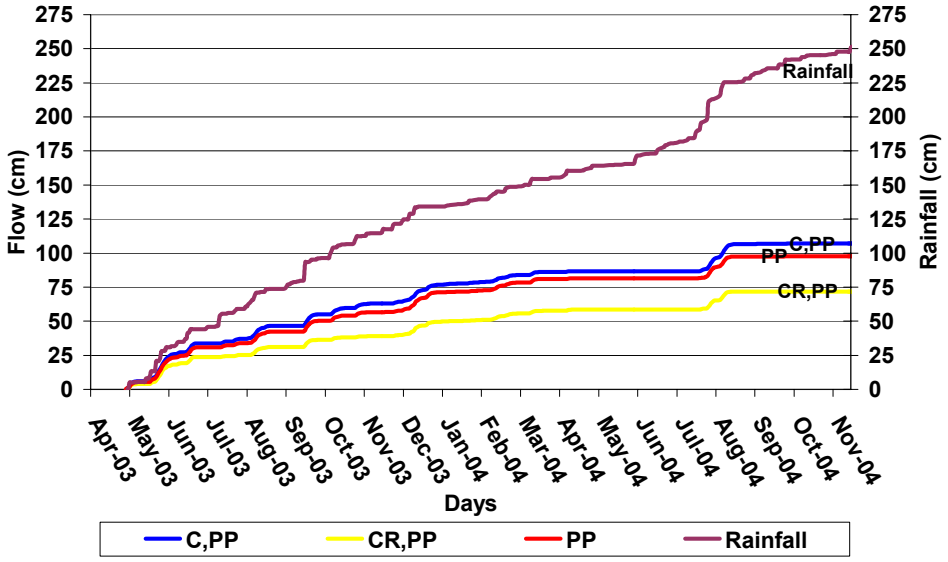

Figure 2.51 Comparison of Rainfall and Flow For the Study Period

crown provided more short term soil storage, as previously discussed, in the CR,P/P treatment ultimately allowing for greater evapotranspiration.

Flow (Block 1 and Block 2)

The Anova analysis was also performed on the flow data from the treatments in block 1 and block 2. The results are shown in Table 2.24 and the corresponding p-values are presented in Table 2.25. There was no statistical difference in flow from any of the treatments in block 1 and block 2.

Outflow appeared to be correlated to the frequency and duration that the water table was near the surface when only block 1 and block 2 were analyzed. The flow from the C,P/P treatment was 5 cm greater than the flow from the P/P treatment and the water table was at the surface 16 days more in the P/P treatment than in the C,P/P treatment in 2003. The flow from the C,P/P treatment was higher than the flow from the P/P treatment by 3 cm in 2004 and the water table was at the surface 9 days more in the P/P than in the C,P/P treatment.

Hydrographs for blocks 1 and 2 are shown in Figure 2.52. The flow from the

Table 2.24 Mean Storm Flow by Treatment in Blocks 1 and 2

Treatment	Mean Flow (per Storm) (cm)
C,P/P	4.18 (a)
CR,P/P	3.25 (a)
P/P	3.92 (a)

Values followed by the same letter (vertically) are not significantly different (α=0.05)

Table 2.25 Resulting P-Values From the LSM Analysis, Mean flow per Storm

	Crown Removal	Contour	Plug and Plant
Crown Removal	0	0.32	0.06
Contour	0.32	0	0.63
Plug and Plant	0.06	0.63	0

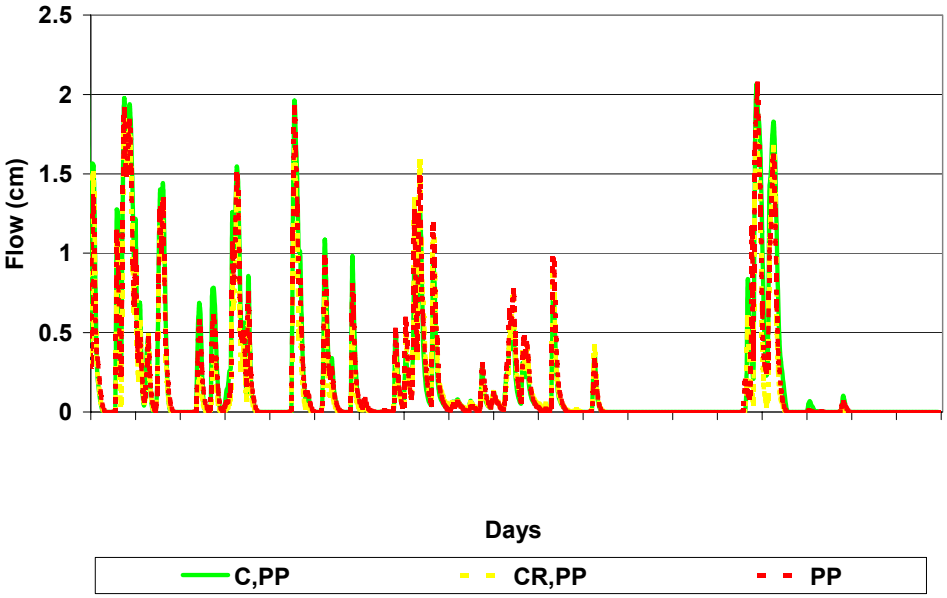

Figure 2.52 Comparison of Flow By Treatment for the Study Period in Block 1 and Block 2

treatments was similar so it was difficult to compare the flow from the treatments over the entire study period. Therefore, the study period was broken up into shorter periods to compare outflow from individual storms making it easier to evaluate and see the effects of the treatments. The trends described in the cumulative flow can be seen in the comparison of the hydrographs of shorter duration. An example of a storm producing greater flow from the C,P/P treatment than the CR,P/P treatment and the P/P treatment flows is shown in Figure 2.53. On average, the flow from the CR,P/P treatment was the lowest and the flow from the C,P/P was the highest, however, during storms that produced small flow the C,P/P treatment flow was lower than the P/P and the CR,P/P treatments (Figure 2.54).

The occasions when the C,P/P treatment peak flows were higher than the P/P treatment flows during storms of less intensity, typically occurred after periods of higher intensity storms when the ground was saturated allowing the water to pond to depths where runoff occurred faster. An example of the correlation between the peak in flow and the depth

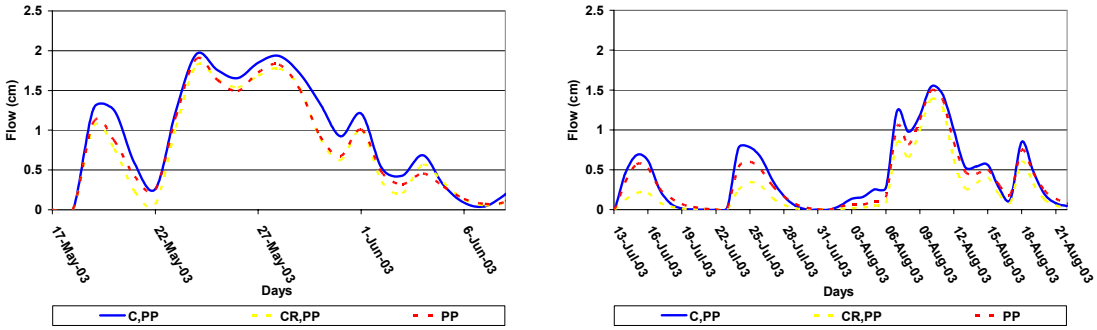

Figure 2.53 Period of Higher Intensity Storms in Block 1 and Block 2

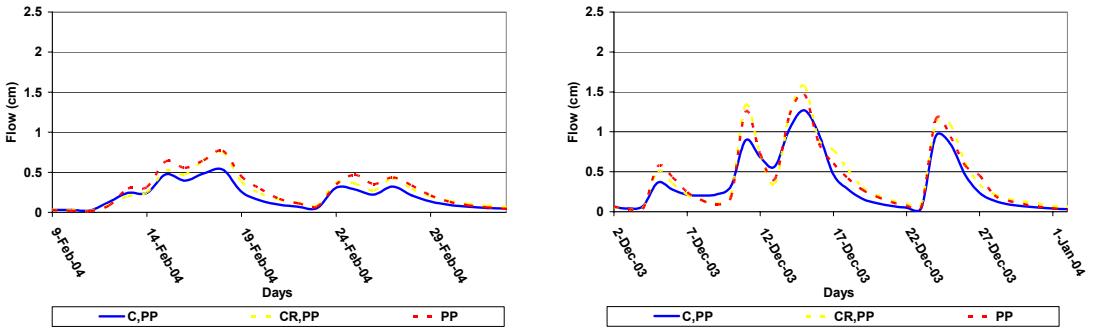

Figure 2.54 Period of Lower Intensity Storms in Block 1 and Block 2

of the water table is show in Figure 2.55. This shows that an increase in flow was correlated to a rise in the water table depth.

The difference in cumulative rainfall versus cumulative flow (Figure 2.56) indicated that each of the treatments temporarily stored a large amount of rainfall. The difference in flow and rainfall could also have been correlated to a greater evapotranspiration from the CR,P/P treatment than the C,P/P and the P/P treatments due to greater soil storage resulting in less outflow.

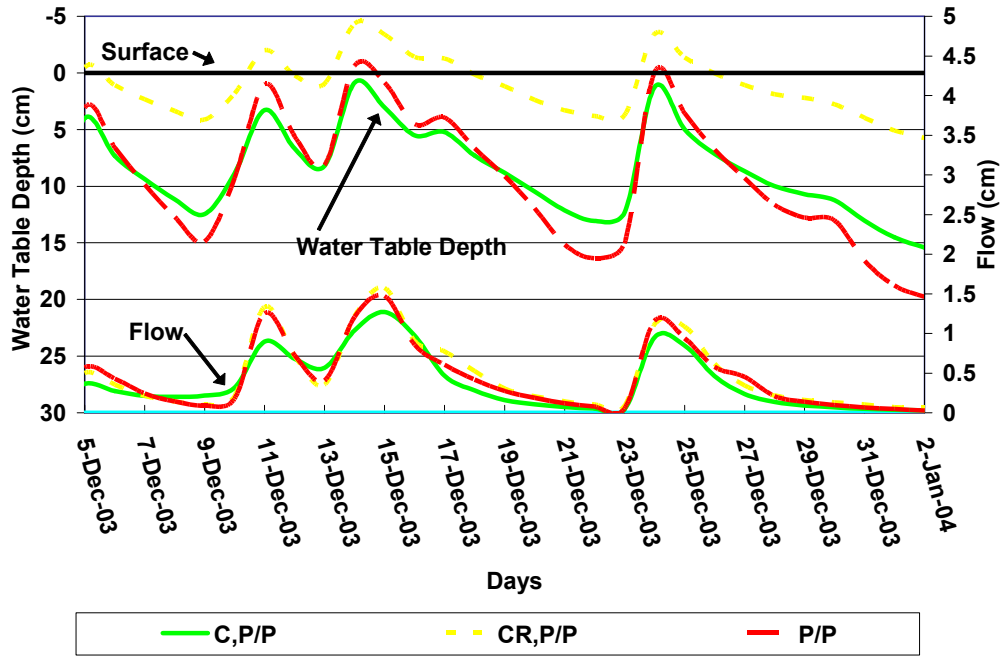

Figure 2.55 Flow Correlated to Water Table Depth in Block 1 and Block 2

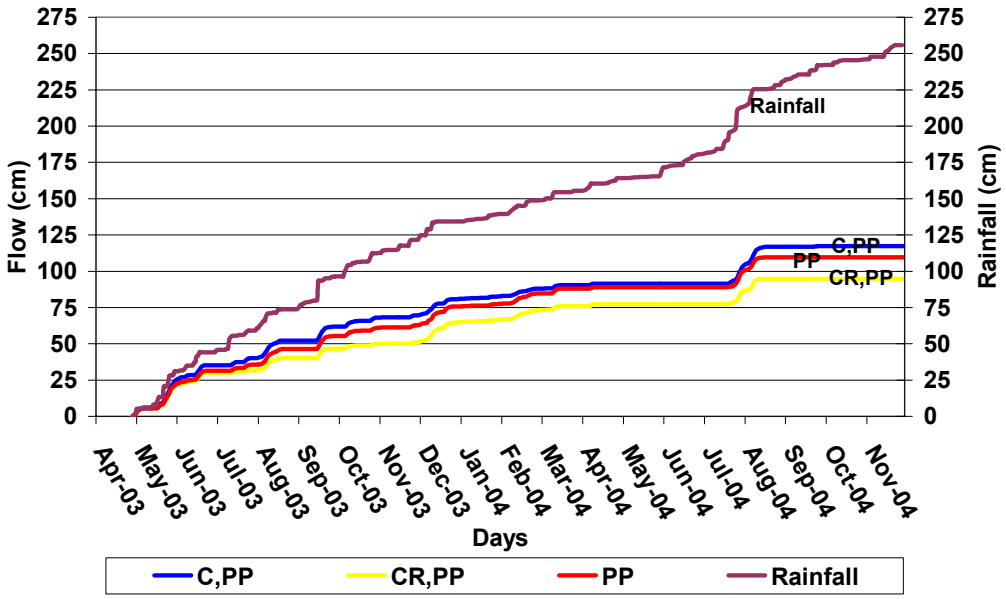

Figure 2.56 Comparison of Rainfall and Flow For the Study Period in Block 1 and Block 2

Methods of Determining Jurisdictional Criteria Compliance

There are several approaches to determine if water table data satisfies jurisdictional criteria. A daily average of the water table was used in the previous section to determine if the wetland jurisdictional criteria was met but, there are several other approaches to analyzing the frequency that the water table is within 30 cm of the surface. The wetland jurisdictional criteria can also be evaluated by analyzing the water table on an hourly basis, by taking manual water table depth measurements during daily site visits at the same time each day, and taking less frequent water measurements such as weekly site visits. The frequency of measurement could have an influence on the determination of a sites ability to meet the jurisdictional criteria for wetland hydrology. For example, using the hourly measurement, the water table must be within 30 cm of the surface for each hour of the day for that day to be counted for wetland jurisdiction. If continuous water table monitoring equipment is not available the water table might be estimated from daily manual water table measurements. If the resources were not available to visit the site daily then the water table may be measured less frequently, such as weekly. Using the weekly method the water table must be within 30 cm of the surface for 3 consecutive measurements for the site to meet wetland jurisdictional criteria.

C,P/P

The number of consecutive days that the water table was within 30 cm of the surface was a day or two less when examined with the hourly method, however, the jurisdictional criteria was satisfied the same number of times in the C,P/P treatment (Figure 2.57). The number of consecutive days was the same for both the daily average and the once daily

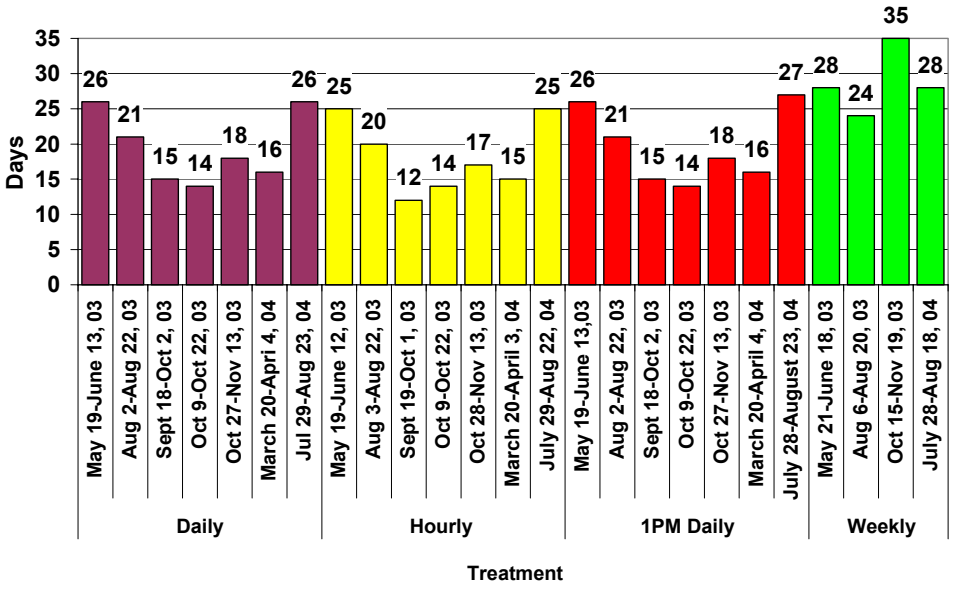

Figure 2.57 Consecutive Days in the C,P/P Treatment

manual methods. There were not as many periods that the site met jurisdictional criteria when the once weekly method was used, however, the periods when the water table was within 30 cm of the surface were longer. The periods were longer because the time that the water table may have dropped below 30 for an hour or a day were not captured in the weekly measurement, it only considered the value at one time during the week.

CR,P/P

The wetland met the jurisdictional criteria for one period more using the daily average versus the once daily method in the CR,P/P treatment (Figure 2.58). The number of consecutive days that the water table was within 30 cm of the surface was more when the daily average and the once daily manual methods were used compared to the hourly method. The water table was within 30 cm of the surface for more than 12% of the growing season when the daily average and the once daily manual methods were used but not when the hourly method was used. The water table may fluctuate below 30 cm from the surface for a

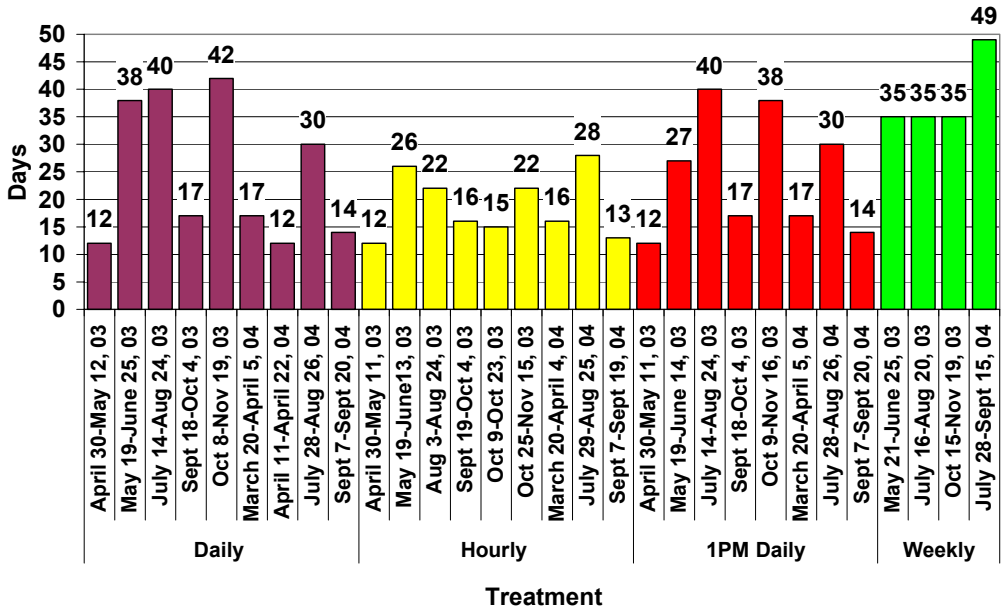

Figure 2.58 Consecutive Days in the CR,P/P Treatment

few hours each day that would not be captured using the daily average or once daily method. For example, the water table was within 30 cm of the surface for the period of October 8th to November 19th, 42 days, using the daily average method and from October 9th to November 19th, 41 days, using the once daily method. Using the hourly method the water table was within 30 cm of the surface for the periods of October 9th to October 23rd, 15 days, and October 25th to November 15th, 22 days. The water table fell below 30 cm at some point on October 24th and rose to within 30 cm of the surface before October 25th (Figure 2.59). The water table fluctuation was not apparent when using the daily average or the once daily method.

The different methods did not cause a difference in the jurisdictional status of the wetland in this situation, however, use of the hourly method could have resulted in a different conclusion in borderline situations. Jurisdictional criteria was met fewer times using the once weekly method than with the average daily, hourly, and once daily methods.

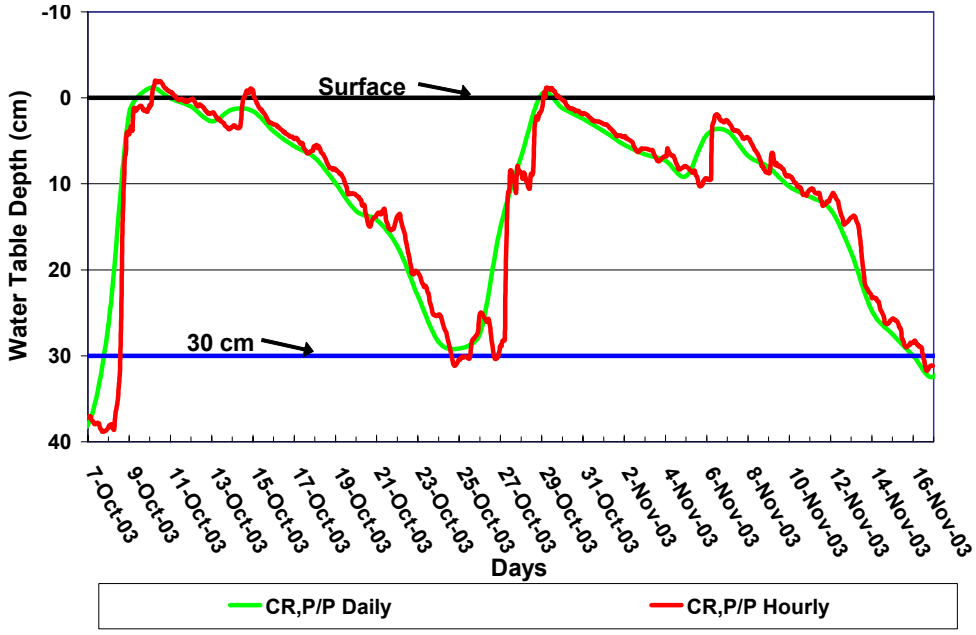

Figure 2.59 Comparison of Daily and Hourly Methods in the CR,P/P Treatment

P/P

The number of consecutive days that the water table was within 30 cm of the surface was similar when computed with the average daily and the once daily manual method and a day or two less when computed by the hourly method in the P/P treatment (Figure 2.60). The weekly method did not meet jurisdictional criteria for two periods where the criteria was met using the daily average, hourly, and the once daily methods. The P/P method shows that the method used to determine jurisdictional status made no difference in the status of the wetland.

The jurisdictional status of the wetland was not affected by the method used to determine the number of consecutive days that the water table was within 30 cm of the surface. The method that was used to determine jurisdictional wetland status may have been critical if the site had been marginal, as discussed previously. The smaller the measurement interval the more descriptive the data will be regarding the hydrology of an area. The hourly

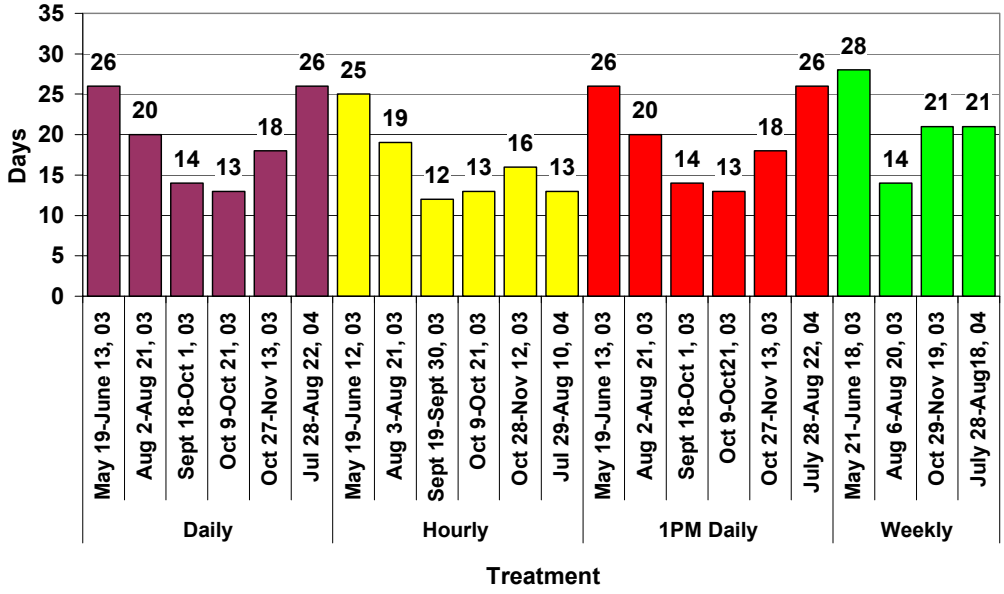

Figure 2.60 Consecutive Days in the P/P Treatment

method should be used to best determine the jurisdictional status of a site. The probability of making an error using the weekly, the daily and the daily average method is greater, especially when a site is marginal.

The effects of the surface treatments might also be evaluated by the different methods used to determine the number of days that the water table was within 30 cm of the surface. Each of the methods showed that the water table was within 30 cm of the surface for more days in the CR,P/P treatment. The greatest difference in the methods was evident in the CR,P/P treatment in which results from the hourly method indicated that the water table was within 30 cm of the surface for fewer consecutive days than either the average daily or the once daily methods. When the average daily method was used, the water table was within 30 cm of the surface for more days in the CR,P/P treatment than in the C,P/P and the P/P treatments indicating that the water table was within 30 cm of the surface for more than half of the day for some days in the CR,P/P treatment and was not in the C,P/P or the P/P

treatments. This indicated that the water table was within 30 cm of the surface for a few hours longer in the CR,P/P treatment than in the C,P/P and the P/P treatments. The difference in results reported by the hourly method and the average daily and once daily methods were an indication that the water table was within 30 cm of the surface for a longer duration in the CR,P/P treatment than the C,P/P and the P/P treatments.

Conclusions

There was no significant treatment differences in number of days that the water table was within 30 cm of the surface, the SEW_{30}, or jurisdictional criteria. When the effects of the treatments in block 1 and block 2 were considered, the results were somewhat different. The water table was at the surface for more days, was within 30 cm of the surface for more days, and the SEW_{30} was greater in the CR,P/P treatment. The SEW_{30} in the CR,P/P treatment was significantly greater than in the P/P treatment indicating that the CR,P/P treatment was wetter than the C,P/P and the P/P treatments. There was no significant difference in the C,P/P treatment and the P/P treatment.

The flow from the CR,P/P treatment was significantly less when all of the blocks were considered but not when only block 1 and block 2 were considered. The CR,P/P treatment was the most effective at reducing outflow.

Crown removal was the single most effective method to improve conditions for wetland hydrology. Adding microtopography had no effect on the hydrologic indicators evaluated without removing the crown. For sites that do not meet wetland criteria, removing the crown and then adding microtopography may create conditions more conducive to meeting the wetland hydrology criteria.

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Chapter 3 Evaluation and Modeling of the Effects of Surface Treatments Using DRAINMOD

Jason D. Wright and Robert O. Evans

Abstract

Wetlands are valuable in the process of removing sediment and pollutants from drainage waters. Wetlands are often restored in prior converted cropland, however more research is needed to enhance restoration success. Wetland hydrology is critical in the success of wetland restoration. This study was conducted to determine the effects of surface treatments on the hydrology of a prior converted wetland in coastal North Carolina. A depressional non-riverine bottomland hardwood wetland was selected as a reference to serve as a comparison for the conditions in the restored wetland. Water table monitoring wells were along transects across the reference and the restored treatments and monitored for 20 months.

Hydrologic results based on monitoring are difficult to interpret and often inconclusive because of short term variability in rainfall. As a result, simulation models such as DRAINMOD are sometimes used to extend monitoring data to establish trands based on long term climate records. DRAINMOD was calibrated using the 20 months of water table data to simulate the hydrology of the reference and restoration treatments. Long term simulation results were similar to the observed results. The water table was at the surface for more days in the crown removal (CR,P/P) treatment than in the reference and the microtopography (C,P/P) and the plug and plant (P/P) treatments. The water table was within 30 cm of the surface for more days and the SEW_{30} was greater in the CR,P/P treatment indicating that it was wetter. DRAINMOD was also used to model the conditions

in the wetland once wetland vegetation matured. The treatments satisfied minimal jurisdictional wetland criteria, 5% of the growing season, for approximately 40 out of 50 years. The streatments satisfied jurisdictional criteria for more than 12% of the growing season for approximately 15 out of 50 years. Outflow was simulated for a mature wetland and conventional row crop conditions at the site. Each of the treatments showed an approximate 30% reduction in flow.

Introduction

The value of wetlands to the ecosystems and watersheds where they are located have been well documented. They serve to store rainfall, reduce flood stage during storms, and provide habitat for a diverse variety of plant and animal species. Wetland areas also improve water quality, reduce the effects of erosion by stabilizing soils and dampening the effects of wave action in shoreline areas, and provide nutrients to surrounding aquatic environments (Dennison et al., 1993, Mitsch and Gosselink, 1986).

Wetlands have been destroyed and drained at an alarming rate. It has been estimated that 47 percent of the 89 million ha (221 million acres) of wetlands in the United States were converted or destroyed by the 1980's (Dahl, 1990). There was another net loss of 260,700 ha (644,000 acres) of wetlands in the United States between 1986 and 1997 despite increased regulation and restoration efforts. Ninety eight percent of the wetlands that were impacted or drained between 1986 and 1997 were freshwater wetlands (Dahl, 2000).

The Wetland Reserve Program (WRP) was introduced by the United States Department of Agriculture's (USDA) Food, Agriculture, Conservation and Trade Act in 1985. WRP is a voluntary cost share program designed to restore prior converted cropland back to their original wetland state. While strong efforts are being made by the WRP and other conservation groups to restore converted wetlands, better guidelines are needed for the best practice of restoring wetland hydrology (Tweedy et al., 2001).

Three criteria must be met for an area to be considered a wetland: (1) Hydric soils, (2) Presence of wetland vegetation, and (3) and wetland hydrology characterized by frequently recurring and sustained saturation of the soil (Cowardin et al., 1979). Mitsch and Gosselink (1986) state that "Hydrology is probably the single most important determinate for the

establishment and maintenance of specific types of wetlands and wetland processes." Hunt et al. (1999), Sharitz et al. (1990), Novitzki (1989),and LaBaugh (1986) aalso report that wetland hydrology is the most influencing factor in wetland development, structure, function, and persistence. Wetland hydrology is considered the most important component in terms of restoration success but also the most difficult to deal with in restoring prior converted wetlands (Holman et al., 1995) and the least understood and measured (WRP, 1997).

Partial failures in meeting the criteria for wetland restoration have been documented for different types of wetlands (Pfeifer et al., 1995 and Kusler et al., 1990). Many restoration sites do not meet wetland criteria because they do not have wetland hydrology. Part of the reason that some restored wetlands did not meet wetland hydrology was because the monitoring period was not sufficient. Skaggs et al. (1995) analyzed 40 years of data at a site in Wilmington, NC and determined that wetlands must be monitored for many years before it can be concluded if the site meets the criteria for wetland hydrology especially if the site marginally satisfied hydrologic criteria. They concluded that decisions about the status of a wetland based on short-term water table data could result in significant error. Long term monitoring requires long periods of time and resources that may not always be available. Consequently, a more practical approach to determine the long term effects of restoration is to simulate hydrologic conditions using hydrologic models such as DRAINMOD.

DRAINMOD was developed to simulate hydrology and changes in the water table in poorly drained soils and shallow water tables drained by a series of parallel drainage ditches or subsurface drains (Skaggs et al., 1999). The model has been tested and evaluated for simulating water table and drainage conditions at a variety of sites. Skaggs, (1982) tested the model using 5 years of field data from three locations in the North Carolina Coastal Plain

each with field scale drainage systems. The predicted water table depths were in excellent agreement with the measured water table depths leading to the conclusion that DRAINMOD was a reliable tool for predicting the effect of drainage systems on water table depth. Youssef, et al. (2003) evaluated DRAINMOD 5.1 using 6 years of data from an artificially drained site in the coastal plain of North Carolina. They found the simulated water table and flow to be in good agreement with the measured data at the site. The model has also been tested in Georgia (Shirmohammadi et al., 1991), Virginia (McMahon et al., 1988), Louisiana (Fouss et al., 1989; Fouss et al., 1987), Ohio (Desmond et al., 1996; Nolte et al., 1983; Skaggs et al., 1981), Illinois (Kurien et al., 1997; Mostaghimi et al., 1985), and Iowa (Sanoja et al., 1990). International evaluation of DRAINMOD has been conducted in Canada (Shukla et al., 1994; Madramootoo 1990), Mexico (Quej and Palacios-Valez, 1996), Italy (Borin et al., 1999; Bixio and Bortolini, 1997), Australia (Cox et al., 1994), and Turkey (Cizikel et al., 2004).

Amatya and Skaggs (2001), using 10 years of data, determined that DRAINMOD was a reliable tool for assessing the hydrologic changes resulting from silvicultural and water management treatments in pine stands. Amatya et al. (2003) used a large ditch spacing with small drain depths to model the drainage rate and water table depth in two naturally drained forested watersheds that did not have a network of parallel drains, in Florida and South Carolina. They found satisfactory results from the watershed in South Carolina with minimal calibration and obtained better results from the Florida watershed using a higher degree of calibration. He et al. (2002) determined that DRAINMOD was able to accurately simulate the water table levels in landscapes that do not have pattern drainage. Tweedy (1998) also

determined that DRAIMOD was accurate in modeling water table hydrology in a restored wetland with varying degrees of surface treatments.

DRAINMOD has also been used in several studies when multiple years of water table data were not available to establish long term effects. Tweedy (1998) determined the long term effect of surface treatments on wetland hydrology using DRAINMOD simulations. DRAINMOD was used to simulate the hydrology of pocosin wetland areas in North Carolina. Skaggs et al. (1991) used DRAINMOD to simulate the hydrology of drained and undrained pocosins near Wilmington, NC. Chescheir et al. (2004) used DRAINMOD to simulate the hydrology from two watershed in the Coastal Plain of North Carolina. Skaggs and Chescheir (2002) used DRAINMOD to determine the minimum or threshold drainage intensity that would result in failure of a wetland site to satisfy the wetland hydrologic criteria. Skaggs et al. (1994) performed simulations with DRAINMOD to compare the hydrologic criteria of several sites that met various degrees of wetland hydrology.

Objectives

The reference wetland and the restored wetland were monitored for 246 days in 2003, 204 days during the growing season, and 343 days in 2004 including a full growing season. The data collected during the study period was used to calibrate the model and then establish long term effects of the treatments.

The objectives of this chapter were:

1) To use the observed water table data to calibrate the hydrologic model DRAINMOD and apply the calibrated DRAINMOD to establish the full range of the hydrologic variability of the reference wetland in terms of the criterion identified in chapter 1.

2) Use the calibrated DRAINMOD and the criterion defined in chapter 1 to evalutate the effects of the surface microtopography treatments on long term restored hydrology.

Material and Methods

Site Description

Reference

A depressional bottom land hardwood wetland, was chosen as a reference wetland near the site of the restoration. The natural drainage channel in the reference was intact and served as a natural drainage outlet for the wetland flowing south towards Wards Creek. The hydrologic conditions in the reference were compared to the conditions at the restored site as an indication of hydrologic restoration success. The reference site was instrumented to monitor water table depth in the same manner previously described in Chapter 2. Three transects with three water table monitoring wells (REF01-REF09) were installed in the reference as shown in Figure 3.1

The land surface in the reference was depressional with drier conditions around the edge of the wetland. The monitoring wells were divided for analysis into the wetter wells found in the center of the wetland and the drier wells found around the edge. The wells that had wetter conditions were REF02, REF05 and REF08, and the wells that had drier conditions were wells REF03, REF04, REF 06, REF07, and REF09.

Restoration Treatments

North River Farms is a prior converted site located in Carteret County near the town of Beaufort in the White Oak river basin. The land was purchased and a 1618 ha refuge was established by the North Carolina Costal Federation in 2002 through grants from the North Carolina Clean Water Management Trust Fund. Current drainage occurs from the area to the

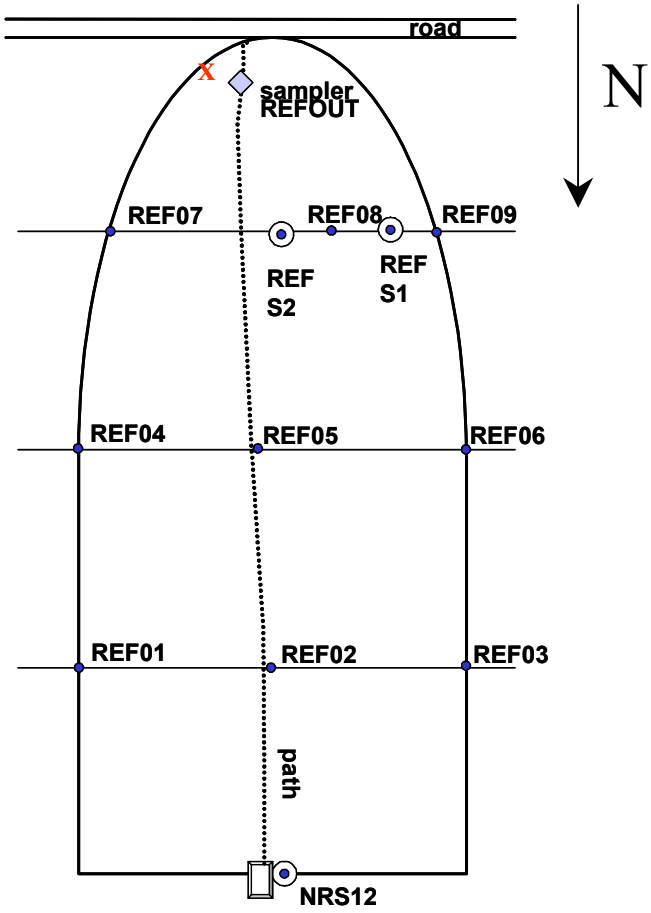

Figure 3.1 Reference Transects

head waters of North River and to Deep Creek as show in Figure 3.2. The site was drained around 1980 to provide conditions conducive for agriculture with a network of parallel field ditches along with main collector canals along the perimeter. Ditches were spaced 100 m apart and were approximately 1 m deep. The fields were crowned approximately 20 cm between the ditches to facilitate surface drainage.

The study area involved 100 ha of nonriverine or precipitation flat wetland restoration with approximately 60 ha within the 100 ha of the non-riverine forested wetland that were divided into different surface treatments and separated by berms. The surface treatments involved three microtopographical treatments with two replications resulting in a randomized

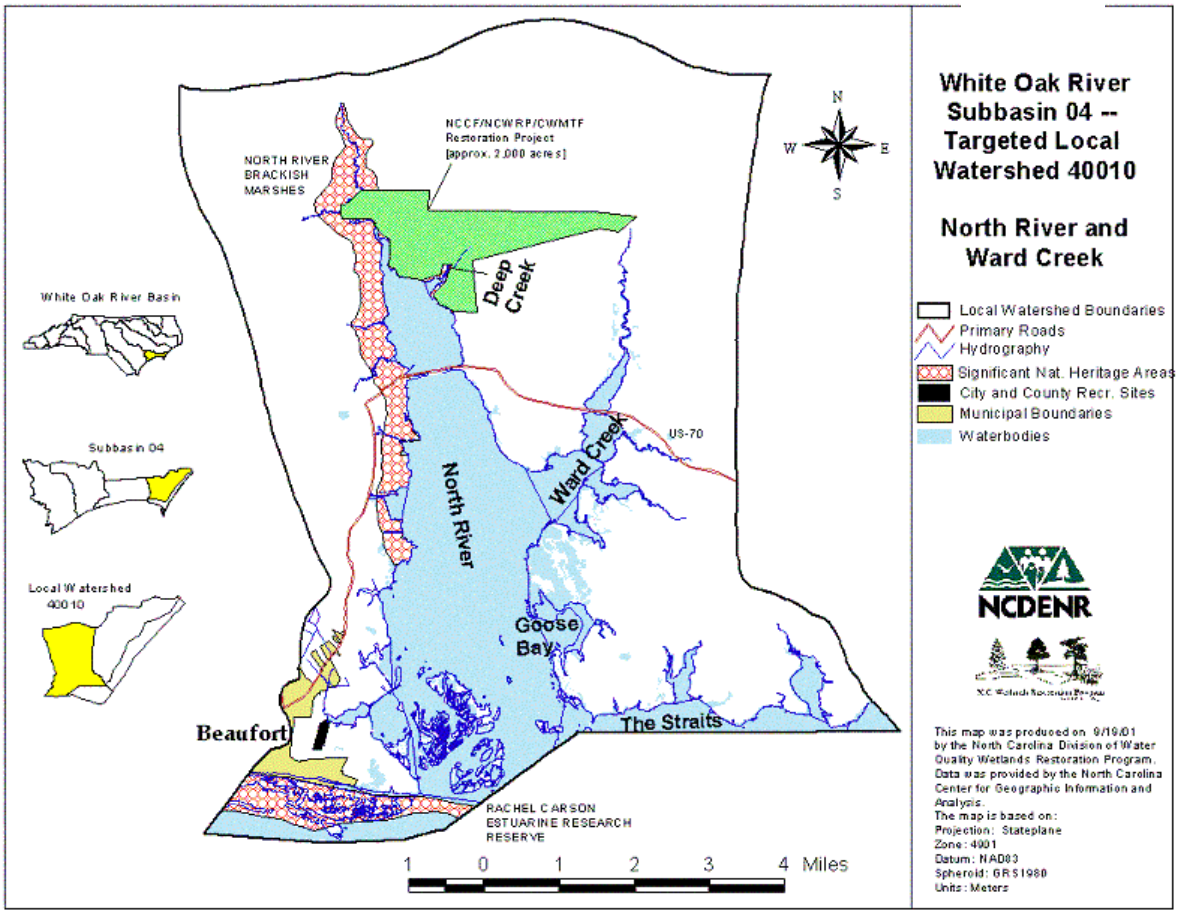

Figure 3.2 Location and Drainage From North River Farms Project

block design. The treatments were plug and plant, surface contouring, and crown removal. The plug and plant treatment involved plugging the ditches and planting wetland vegetation. The surface contouring treatment involved roughing the surface to provide added surface storage and planting wetland vegetation. The crown removal plug and plant treatment leveled the crown to reduce surface runoff and wetland vegetation was planted. The contour plug and plant treatment will be referred to as C,P/P, the crown removal plug and plant treatment as CR,P/P, and the plug and plant treatment as P/P. The treatment replicates are shown in Figure 3.3.

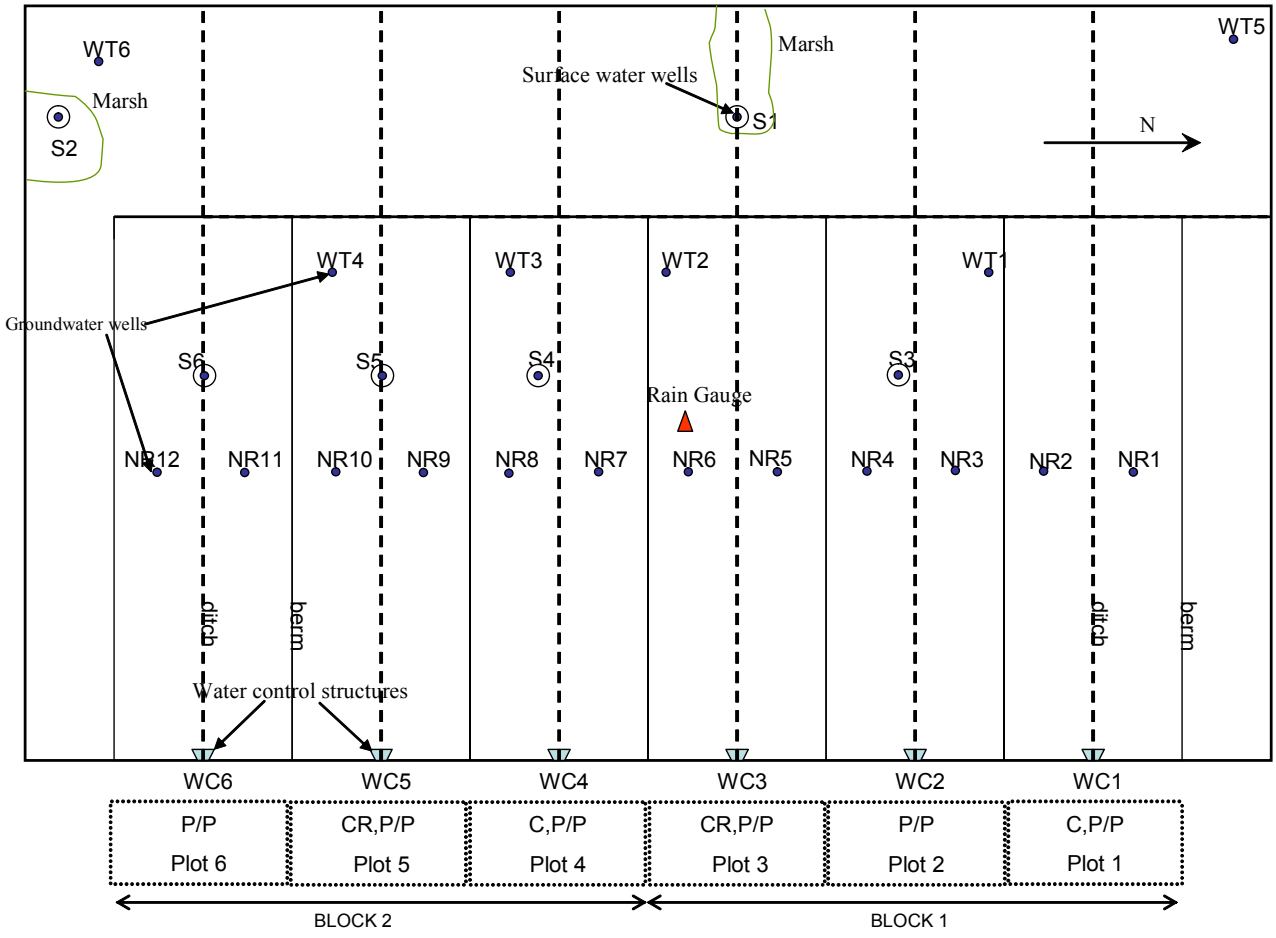

Figure 3.2 Treatments in Block 1 and Block 2

Water table elevations were monitored hourly with infinity continuous water table recorders (Infinities USA Inc., Daytona Beach, FL) in transects across the treatments. There were two water table monitoring wells located in each of the three treatments allowing six replications of the data. Berms were constructed around each of the treatments to prevent surface runoff to adjacent treatments and to force outflow to one location for monitoring. The flow was monitored using 30^{o} v-notch weirs with water table monitoring equipment used to determine the height of flow over the weir. A detailed description of the site preparation, treatments, and monitoring procedures was presented in chapter 2.

Model Description

DRAINMOD was developed to simulate the hydrology in poorly drained soils utilizing a series of parallel drainage ditches or subsurface drains (Skaggs et al., 1999). The model computes a water balance for a cross section midway between the drains from the soil surface to the impermeable layer. The water table depth midway between the drains is calculated on an hourly and daily basis based on the water balance illustrated in Figure 3.4. The inputs required are: soil properties including saturated hydraulic conductivity and the soil water characteristic of the soil layers, crop parameters, weather data including precipitation, maximum and minimum daily temperature, drainage system parameters such as drain depth, drain spacing, effective radius of the drain, and surface storage, and the timing and intensity of irrigation. The water balance calculated midway between the drains for any time increment, Δt, is computed using Equation 3.1.

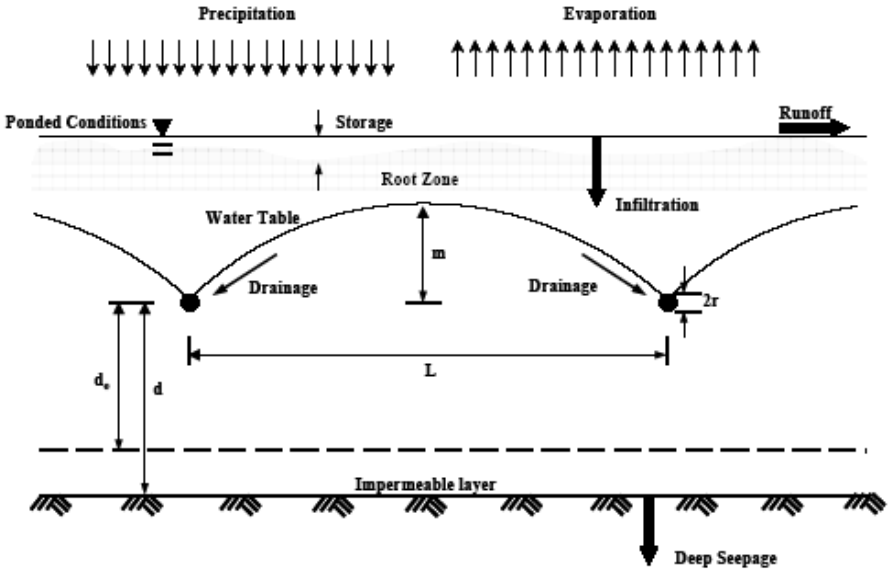

Figure 3.4 Illustration of DRAINMOD Inputs and Processes (Burchell, 2003)

Equation 3.1 Water Balance Midway Between Drains (Skaggs, 1999)

$$\Delta Va = D + ET + DS - I$$

ΔVa= Change in water free pore space (cm)
D = Drainage from the Section (cm)
ET = Evapotranspiration (cm)
DS = Deep Seepage from the Section (cm)
I = Infiltration into the Section (cm)

The water balance at the soil surface is calculated using Equation 3.2.

Equation 3.2 Water Balance at the Soil Surface (Skaggs, 1999)

$$P = I + \Delta S + RO$$

P = Precipitation (cm)
I = Infiltration in the Section (cm)
ΔS = Change in Volume of Water Stored in Surface Depressions (cm)
RO = Surface Runoff from the Section (cm)

The drainage rate, under most conditions, is calculated using the steady-state Hooghoudt equation based on the Dupuit-Forchheimer assumptions with a correction for

convergence near the drains when the water table is below the soil surface. The water table is assumed to be elliptical and the notation is used as shown in Figure 3.4. The Hooghoudt equation is presented in Equation 3.3.

Equation 3.3 Hooghoudt Equation For Drainage

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

q = Drainage Flux (cm/hr)
d_e = Equivalent Depth From the Drain to the Impermeable Layer (cm)
m = Distance From the Drain to the Water Table at the Midpoint Between Drains (cm)
K = Effective Lateral Hydraulic Conductivity (cm/hr)
L = Drain Spacing (cm)

The equivalent depth to the impermeable layer is required to correct for convergence head loss as the water moves towards the drain. DRAINMOD calculates d_e using the actual depth to the impermeable layer, the spacing between drains, and the equivalent radius of the drains. When the water table rises to the surface, the water table is no longer elliptical and the water begins to pond at the surface. The Hooghoudt equation does not consider the high gradients and vertical movement of water to drains directly above the drain during ponded conditions. Under these conditions, drainage is calculated with an equation by Kirkham (1957).

DRAINMOD was modified by Skaggs et al. (1991) for the use of determining wetland hydrology. A counter was added to determine the number of consecutive days that the water table was within a determined distance from the surface during a user specified time period. DRAINMOD determines the number of times during a year and the number of years that the criteria are met.

Model Inputs

Climatic Data: Weather inputs into DRAINMOD are the hourly rainfall and the maximum and minimum daily temperatures. Precipitation data was collected at three locations on North River Farms using Davis Rain Collector tipping bucket recorders with a 0.01 inch capacity bucket (Davis Instruments, Hayward CA, Model 7852). The rainfall was logged using HOBO® data loggers (Onset Computer Corporation), and the data was collected using the HOBO® Shuttle data logger (Onset Computer Corporation, Part H09-003-08). The maximum and minimum daily temperatures were collected approximately 16 km from North River Farms at Beaufort Smith field by the State Climate Office of North Carolina.

Potential evapotranspiration is calculated in DRAINMOD using the Thornthwaite (1948) method with the previously mentioned weather parameters. The Thorntwaite method is a practical method to calculate PET because it requires input parameters that are readily available for many locations. Because of the few number of input parameters there may be error in the method for some locations, therefore, geographically specific correction factors can be input into the model to correct the PET. Correction factors for the Carteret County area that were used in the simulation for North River were obtained from a study performed by Amatya (1995) and are presented in Table 3.1. PET is calculated hourly with PET equal to zero for any hour that rainfall occurs. The ET is set equal to PET as long as the ET is not limited by soil water conditions.

Soil Data: Soil parameters required in DRAINMOD are the soil water characteristic and the saturated hydraulic conductivity in each layer of the soil profile. Skaggs and Tabrizi (1986) determined that the soil properties can vary widely depending on location even within the same soil series. In an evaluation of DRAINMOD using different sources of soil input

Table 3.1 Estimated Monthly Correction Factors for the Thornthwaite Equation

Month	Correction Factor
January	1.94
February	2.32
March	2.09
April	1.73
May	1.23
June	1.02
July	0.89
August	0.84
September	0.95
October	1.07
November	1.23
December	1.38

data in the Veneto region of NE Italy, Borin et al. (1999) determined that DRAINMOD accurately simulated water table depth using literature estimates for many soils input data. A sensitivity analysis by Haan and Skaggs (2003) to determine the effect of parameter uncertainty determined that simulation results from DRAINMOD were not sensitive to errors in vertical hydraulic conductivity. In this study, saturated vertical hydraulic conductivity values were estimated from the Carteret County Soil Survey.

The root systems of woody vegetation found in the reference wetland can form macropores in the upper layers of the soil causing the hydraulic conductivity to be much higher in the surface layers. The hydraulic conductivity in a natural wetland was documented by Chescheir et al. (1995) and Amatya et al. (1995) to range from 43 to 156 cm/hr in the top 30 to 60 cm of the soil profile. These values were utilized near the surface.

The volume drained to water table depth relationship determines the drainable porosity of the soil. Drainable porosity is the change in the volume drained over the change

in water table depth. The porosity effects how quickly the water table will respond to water being added or removed. If the porosity is high then there is a large pore volume and the changes in water table depth will be small as water is added or removed. If the porosity is low then there is a small pore volume and the water table will fluctuate rapidly.

Upward flux is a measure of how easily or difficult water is moved through the soil by evapotranspiration. The ET is set equal to PET as long as the PET is greater than upward flux. If PET is greater than upward flux then ET is equal to PET and a dry zone will form. When the dry zone exceeds the depth of the root zone then ET becomes equal to upward flux. The upward flux and the volume drained relationships were estimated in a study by Skaggs and Evans (1989) at Open Grounds farm in a similar soil series from the observed soil water characteristics.

Crop Parameters: Rooting depths in DRAINMOD are the depth that the majority of the root mass is found. Late successional wetland vegetation, hardwoods, were planted at the site, however, early successional wetland vegetation dominated the treatments during the monitoring period. The early successional vegetation was annual, therefore rooting depths were varied according to the stage of growth in the treatment areas. Growth began during the beginning of the growing season with an increase in rooting depth to a maximum in the summer, then reduced as the above ground biomass began to die in the fall, similar to an agricultural crop such as corn. The rooting depths for corn were used as an estimate for early successional vegetation root depth and adjusted, through calibration, to best fit the water table data in the treatment areas.

Rooting depths have been reported by Skaggs et al. (1991), and Skaggs et al. (1994) to be between 40 and 60 cm in natural wetland systems. A root depth of 40 cm was used to

model the conditions in the center of the reference. In dry conditions, vegetation may extend its roots deeper into the soil in an attempt to find water. Therefore when conditions are dryer, such as in the edge of the reference, rooting depths may be deeper. A root depth of 60 cm was used in the simulation of the edge of the reference.

Drainage System Parameters: Input parameters are required in DRAINMOD that describe the subsurface drainage system, surface conditions, and the depth to the impermeable layer. The inputs include drain depth and spacing, effective radius of the drains, distance to the impermeable layer, drainage coefficient, bottom width of the ditch, maximum surface storage, and Kirkham's depth. The input parameters were measured or estimated based on prior knowledge of drainage systems. The ditch depth and spacing was measured in the field. The ditch spacing for the center of the reference wetland was approximated from field observations and determined from calibration in the edge of the reference wetland. The effective radius of the drains, the bottom width of the ditch, and the ditch side slope were estimated based on the dimensions of typical drainage systems. The depth to the impermeable layer was based on field borings and known values for the area from the Carteret County Soil Survey.

The drainage coefficient represents the maximum capacity of the drainage system in a 24 hour period. In this study the flow from each treatment was limited by the size of the weir in the control structure. The drainage coefficient was set as the maximum amount of drainage observed from the site during the monitoring period. Drainage in the reference was limited only by the drainage parameters, therefore the drainage coefficient was set high to not restrict the drainage capacity.

Maximum surface storage is the depth that water must pond before surface runoff occurs. Kirkham's depth, referred to as STORRO in DRAINMOD, is the depth that water must pond before flow will occur across the surface to the drains. Kirkham's depth can also be considered as the percentage of depressions that must be filled before surface drainage will occur. Maximum surface storage values were set high to model the effect of the berms. The berms caused flow that ordinarily would have been surface runoff to be simulated as subsurface drainage. The berms prevented surface runoff from the site except through the weir outlet. Surface flow occurred from within the treatments to the ditch once water ponded in the field reached a depth equal to Kirkham's depth. Surface storage has been estimated by Skaggs et al. (1994) to range from 1.5 to 5 cm in native forests with hydric soils in the Coastal Plain of North Carolina.

Controlled drainage managed the water level in the ditches, therefore DRAINMOD simulations were run in the controlled drainage mode. Weir elevations in the model were set at the average of the distance between the surface around the two wells in each treatment and the invert of the weir. The weir depths were adjusted through calibration within the range of values observed between the two wells in each treatment because the effective weir depth might be closer to one well or another depending on the proximity of the well to the outlet.

Model Calibration

The model was calibrated by systematically altering estimated inputs to fit the simulated water tables to the observed water tables. The model was calibrated for each block because of differences in the characteristics of the soils and the surface conditions. The inputs previously described were input into DRAINMOD and run to simulate the water table

depth. Some input parameters had similar effects on simulated water tables. The best combination of input values was determined to provide the best fit to the observed data.

The calibration process was begun by fitting the simulated water table to the observed water table near the surface. The water table was adjusted closer to the surface by increasing the STORRO value. Increasing STORRO reduced surface drainage as more water was stored before surface drainage occurred. Likewise, reducing STORRO allowed more surface drainage and thereby lowered the water table more quickly. Increasing the hydraulic conductivity in the upper layer also resulted in faster drainage from the surface and lowered the water table. The depth of the layers was determined by examining the soil profile at the site or estimated by the area Soil Survey. The STORRO and hydraulic conductivity in the upper layer was adjusted until the simulated water table reached the surface the same number of times as the observed water table.

The drainable porosity was then adjusted to match the pattern of rising and falling water tables in the upper layer. Decreasing the drainable porosity caused the water table to fluctuate more rapidly as a smaller change in the water content resulted in a greater incremental change in the water table.

The horizontal hydraulic conductivity, drainable porosity, root depth, and upward flux were next altered to fit the simulated and observed water table at lower depths in the profile. Increasing the hydraulic conductivity and decreasing drainable porosity allowed for greater fluctuation in the water table. Once the pattern was matched the water table was brought closer to the surface by decreasing the root depth or drawn deeper by increasing the root depth. The water table was also adjusted by changing the upward flux. Increasing the

upward flux at lower depths caused the water table to drop farther from the surface. The range of the inputs were all within a reasonable limit of known values for similar soils.

The two wells from each treatment were averaged to establish the observed water table depth for each treatment in each block. The water table depth from each treatment block combination was then compared with the water table predicted from the calibrated model. The fit of the model to the observed data was determined using the average absolute deviation computed in Equation 3.4 as well as the average daily difference shown in Equation 3.5.

Equation 3.4 Average Absolute Deviation

$$\alpha = \frac{\sum_{i=1}^{n} \left| Y_o - Y_p \right|}{n}$$

α = average absolute deviation (AAD) (cm)
Y_o = observed water table depth (cm)
Y_p = predicted water table depth (cm)
n = number of observations

Equation 3.5 Average Daily Difference

$$\alpha = \frac{\sum_{i=1}^{n} \left(Y_o - Y_p \right)}{n}$$

α = average daily difference (ADD) (cm)
Y_o = observed water table depth (cm)
Y_p = predicted water table depth (cm)
n = number of observations

These methods were used as described by Amatya (2001). The observed water table depth was subtracted from the simulated water table depth. The average of the absolute value of the difference was calculated for the study period to determine the average absolute

difference and the average of the difference was calculated to determine the average daily difference.

Treatment Effects

Once the model was calibrated, the criteria established in the previous chapter were applied to the water table predicted by DRAINMOD. The results of the criteria from the predicted water table was compared to the results of the observed water table to determine if the simulated water table provided a similar result to the observed data.

Long Term Simulations

Fifty years of weather data collected at Morehead City by the State Climate Office of North Carolina was used to simulate long term drainage and water table depths in each of the treatments. The crop inputs were adjusted to simulate conditions as wetland vegetation matured. Simulations were also performed to model expected agricultural conditions existing prior to restoration. The reference was simulated as a mature hardwood forest. The wetland hydrology option of DRAINMOD was used to determine the number of years out of fifty that wetland hydrology was met for 5% and 12.5% of the growing season. Long term yearly average flow from the treatments was simulated by DRAINMOD and was used to determine the reduction in flow due to the restoration compared to agricultural conditions.

Statistical Analysis

The criteria were analyzed using the GLM procedure in SAS with the Tukey method to adjust for multiple comparisons. Using the Tukey method allows for each of the treatments to be compared simultaneously (SAS Institute, 1985). The long term simulations

were analyzed for each treatment and the reference using the long term data with treatment and year as the main factors.

Results and Discussion

Model Calibration

The values for the measured DRAINMOD inputs that were used in the simulation of the restoration areas are presented in Table 3.2. Each of the measured inputs used to calibrate the model for the reference are shown in Table 3.3.

Table 3.2 Restoration Drainage System and Site Inputs For DRAINMOD

Depth from soil surface to bottom of the ditch	90	cm
Spacing between drains	100	m
Effective radius of drains	40	cm
Actual distance from surface to impermeable layer	300	cm
Drainage coefficient	2.25	cm/day
Maximum surface storage	50	cm
Bottom width of the ditch	60	cm
Ditch side slope (H:V)	0.5	

Table 3.3 Reference Drainage System and Site Parameters for DRAINMOD

	REFDRY	REFWET	
Depth from soil surface to bottom of the ditch	45	30	cm
Spacing between drains	30	100	m
Effective radius of drains	14	14	cm
Actual distance from surface to impermeable layer	300	300	cm
Drainage coefficient	40	40	cm
Maximum surface storage	3	4	cm

The model was calibrated with inputs for six plots, block 1 and block 2, considered in this part of the study and the reference wetland. Inputs to the model for calibrating the treatments are show in Table 3.4 and in Table 3.5 for the reference.

Considerable landforming was done in the CR,P/P treatment which would have caused variation in the Kirkham's depth. The surface of the ground was at different elevations in some of the treatments causing variation in distance from the ground surface to the invert of the weir and weir depth inputs.

An example of the best fit, lowest AAD, of the simulated to observed water table is shown in Figure 3.5 and an example of the worst fit, highest AAD, is shown in Figure 3.6. The best fit was in the P/P treatment in block 1 in 2003. The predicted water table follows

Table 3.4 Restoration Inputs Determined by Calibration for DRAINMOD

	Kirkham's Depth (cm)	Weir Setting	K (cm/day)		
			0-15	15-115	115-300
P/PB1	0.8	24	30	15	5
P/PB2	0.8	30	30	15	5
C,P/PB1	1.25	32	30	15	5
C,P/PB2	1.5	30	30	15	5
CR,P/PB1	2	22	30	15	5
CR,P/PB2	4	30	30	15	5

Table 3.5 Reference Inputs Determined by Calibration for DRAINMOD

	Kirkham's Depth (cm)	Weir Setting	K (cm/day)		
			0-20	20-115	115-300
REF Center	1.5	0	150	80	5
REF Edge	2	0	150	80	5

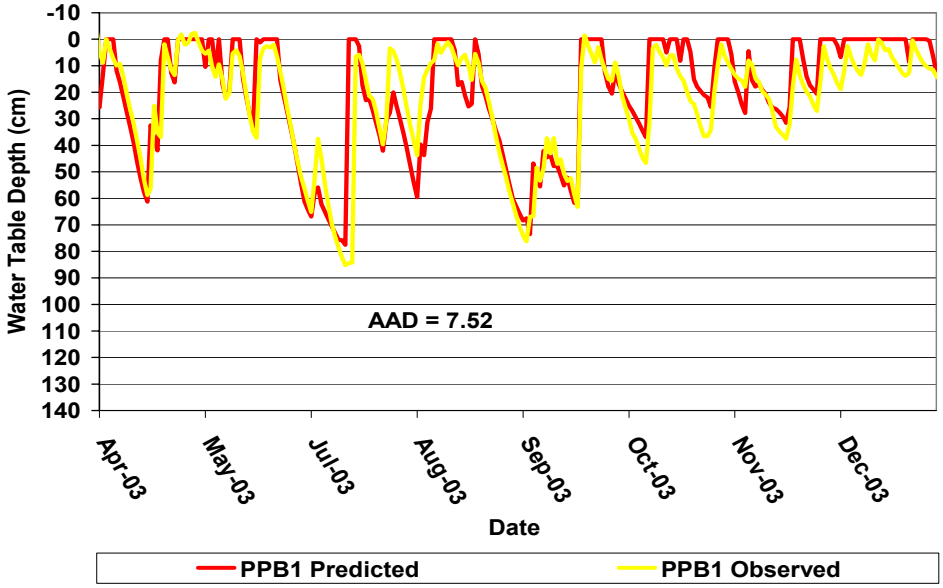

Figure 3.5 Comparison of Observed and Simulated Water Table Best Fit (lowest AAD) for Block 1 P/P

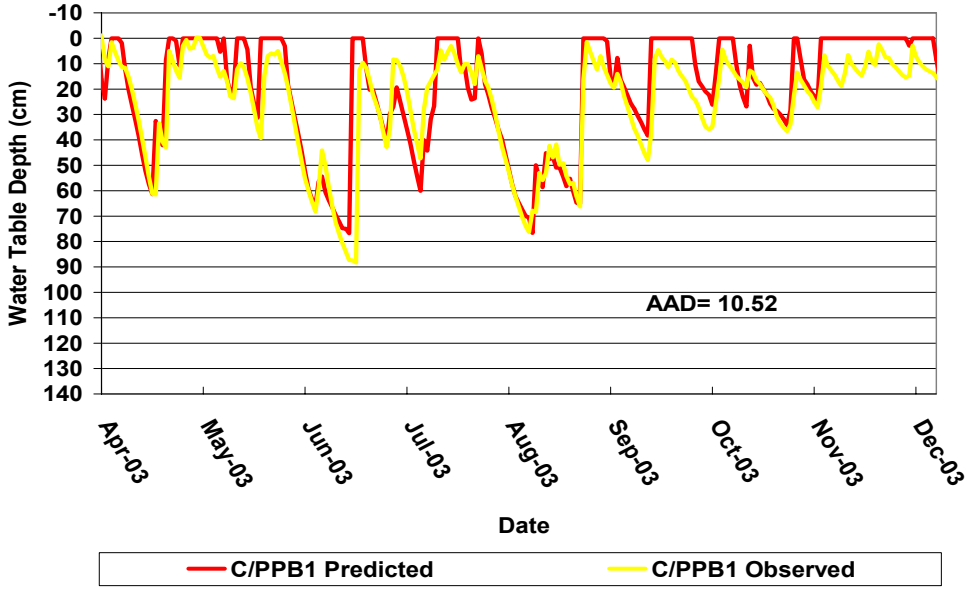

Figure 3.6 Comparison of Observed and Simulated Water Table Worst Fit (highest AAD) for Block 1 C,P/P

the same pattern as the observed water table with some deviation lower in the soil profile around October of 2003. The simulated water table tends to be closer to the surface than the observed with longer periods of surface ponding. The AAD was the highest in the C,P/P

treatment in block 1 in 2004. The predicted water table was closer to the surface and remained there longer than the observed water table. This was most likely caused by the STORRO values being higher than observed in the field.

The main source of deviation was between March and May in 2004. The same trend was observed in all of the predicted water tables as in the C,P/P treatment in block 1 where the predicted water table was further from the surface than the observed. This was most likely a result of the evapotrainspiration being higher than observed or there was more rainfall at the site than was recorded.

An example of the fit in the center the reference is shown in Figure 3.7 and an example of the fit in the drier edge of the reference is shown in Figure 3.8. The predicted water table was close to the observed in the spring and winter, but was closer to the surface in late summer than the observed. This could have been caused by the simulated evapotranspiration being to low or possibly the drainable porosity in the lower layers was higher than in the field. The period when the wells "bottomed out", from May 23 to July 27 2004, was not considered in the AAD.

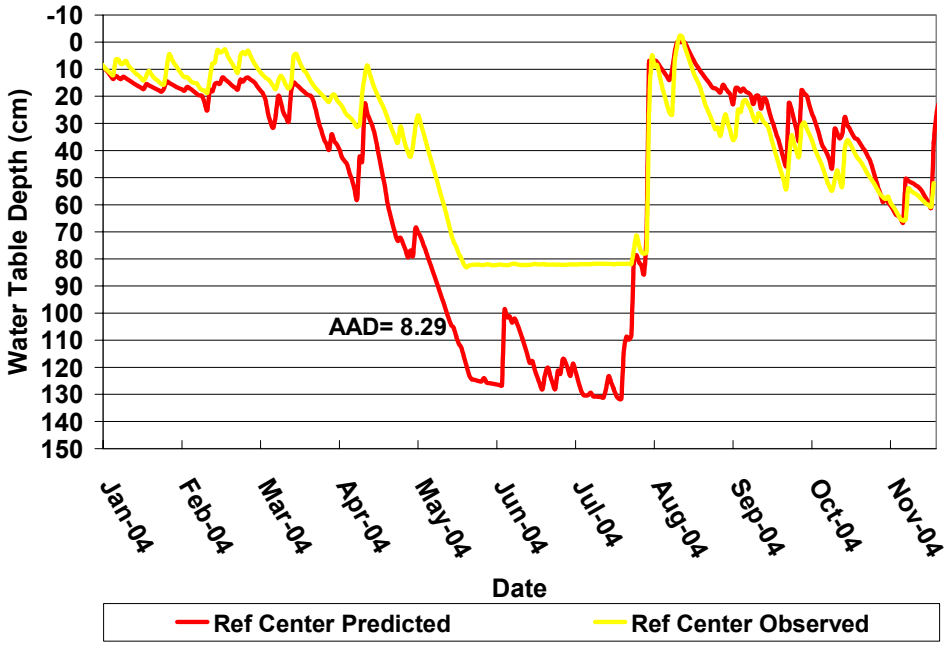

Figure 3.7 Comparison of Observed to Predicted Water Table in the Center of the Reference in 2003

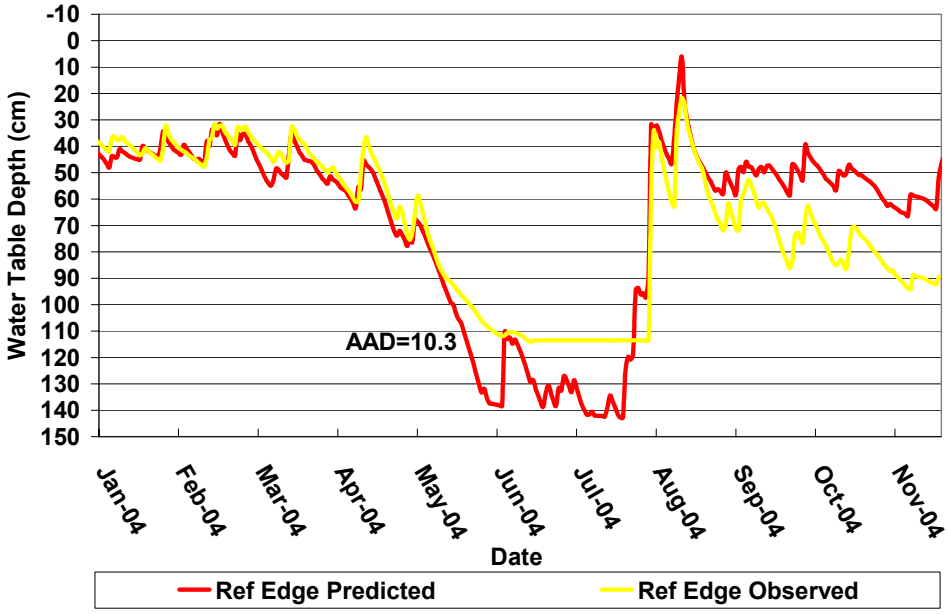

Figure 3.8 Comparison of Observed to Predicted Water Table in the Edge of the Reference

The average daily difference and average absolute deviation were within the ranges obtained by Tweedy (1998) and Burchell (2003) indicating that the predicted water tables

were found to reasonably correspond with the observed water table depths (Table 3.6). The average daily difference ranged from –5.81 to 7.21 and the average absolute deviation ranged

Table 3.6 Comparison of Modeled Water Tables and Observed

Treatment	Average Daily Difference (cm)	Average Absolute Deviation (cm)
	2003	
P/PB1	2.34	7.52
P/PB2	1.88	9.99
C,P/PB1	5.20	8.30
C,P/PB2	4.56	7.90
CR,P/PB1	3.87	7.94
CR,P/PB2	4.76	8.06
Ref Center	4.45	8.29
Ref Edge	7.21	10.30
	2004	
P/PB1	-2.16	8.78
P/PB2	-1.81	8.26
C,P/PB1	-4.36	10.52
C,P/PB2	-5.81	10.28
CR,P/PB1	-3.16	10.29
CR,P/PB2	-2.71	9.02
Ref Center	-5.47	11.76
Ref Edge	6.75	11.30
	Study Period	
P/PB1	-0.25	8.25
P/PB2	-0.24	8.99
C,P/PB1	-0.31	9.58
C,P/PB2	-1.42	9.27
CR,P/PB1	-0.18	9.29
CR,P/PB2	0.45	8.61
Ref Center	-0.89	10.15
Ref Edge	6.96	10.84

from 7.9 to 11.76. Annual rainfall in 2003 was 61 cm above average and 2004 was 19 cm below average. Positive values for the average daily difference indicate that the predicted water table was closer to the surface than the observed and negative values indicated that the observed water table was closer to the surface. The simulated water table depths were generally closer to the surface than the observed depths in 2003 and further from the surface than the observed depths in 2004. DRAINMOD simulations tended to be more accurate when the water table was closer to the surface. This is because there is an inherent correction that occurs each time the water table rises to the surface. Observed and simulated water tables may deviate as the water table recedes, but a large rainfall will cause both the observed and simulated water tables to rise to the surface resetting them such that they are equal to each other, hence an inherent correction factor. Because 2003 was a wetter year than 2004 the water table reached the surface more often resulting in more frequent realignments between the observed and predicted.

The method for determining the number of consecutive days that the water table was within 30 cm of the surface was described in the previous chapter. DRAINMOD was used to simulate the number of consecutive days that the water table was above 30 cm during the growing season. The number of consecutive days simulated by DRAINMOD was similar to the number of consecutive days observed in 2003 (Table 3.7). The number of consecutive days that the water table was within a threshold depth, such as within 30 cm, of the surface can be sensitive to minor changes in the water table depth around the threshold value. It is possible for there to be a difference in the number of consecutive days above a threshold depth yet not be much different in the water table depth. A minor drop in the water table depth below the threshold causes the count of the number of consecutive days to restart

Table 3.7 Number of Consecutive Days in 2003 with the Water Table Within 30 cm of the Surface

	Number of Consecutive Days	
Treatments	DRAINMOD	Observed
PPB1	40	51
PPB2	39	52
C/PPB1	39	50
C/PPB2	43	50
CR/PPB1	63	52
CR/PPB2	63	54
Ref Center	63	57
Ref Edge	3	13

which can cause a large difference in the number of consecutive days. For example, as seen in Figure 3.9, even though the simulated and observed water tables are relatively close in pattern, the observed water table dropped below 30 cm three times during the period from

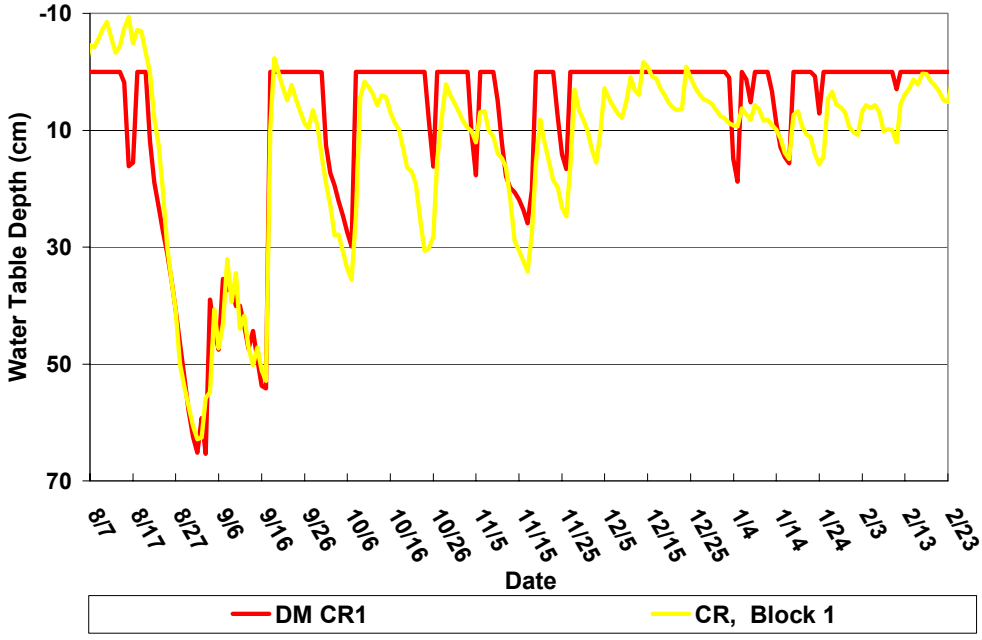

Figure 3.9 Example of the Number of Consecutive Days

October 1st to November 20th while the simulated water table remained just above the 30 cm threshold. As a result, the observed data resulted in three separate periods with the water table above 30 cm from September 15th to November 20th whereas the predicted water table showed this as one long continuous period.

The amount of flow simulated by DRAINMOD was also compared to the amount of flow measured at the site (Table 3.8). The observed flow from the wetland was calculated by

Table 3.8 Simulated and Observed Flow at the Site

Treatments	Flow (cm)	
	DRAINMOD	Observed
	2003	
P/PB1	73.46	74.51
P/PB2	73.44	76.82
C,P/PB1	73.64	85.80
C,P/PB2	73.64	75.64
CR,P/PB1	73.65	56.39
CR,P/PB2	73.73	77.91
	2004	
P/PB1	30.36	33.30
P/PB2	34.37	34.76
C,P/PB1	30.79	30.56
C,P/PB2	30.58	42.31
CR,P/PB1	30.11	24.37
CR,P/PB2	37.46	35.98
	Study Period	
P/PB1	103.82	107.81
P/PB2	107.81	111.58
C,P/PB1	104.43	116.36
C,P/PB2	104.22	117.95
CR,P/PB1	103.76	80.77
CR,P/PB2	111.19	113.89

measuring the flow through a weir and converting it to a depth over the entire area inside of. the berm for each treatment. Flow was not recorded from the reference wetland, therefore the calibration could not be compared for the accuracy in the simulated flows. When calculating flow, DRAINMOD assumes a one dimensional area, therefore the site parameters are the same across the entire plot. In reality, conditions can vary widely over the plot area. There were surface depressions, simulated tree falls, and varying soil properties that could affect the amount of flow from the treatment causing discrepancies between the observed flow and the flow simulated in DRAINMOD. An example of the simulated and the observed flow from May 1st to September 30th, 2003 in the C,P/P block 2 treatment is shown in Figure 3.10. The simulated peak flows were mostly higher than the measured peak flows. Several periods of flow were missed in the simulated data. This could have been caused by the same reasons that caused the predicted water table to be deeper in the profile than the observed, evapotranspiration rates were to high or a period of rainfall was not properly recorded.

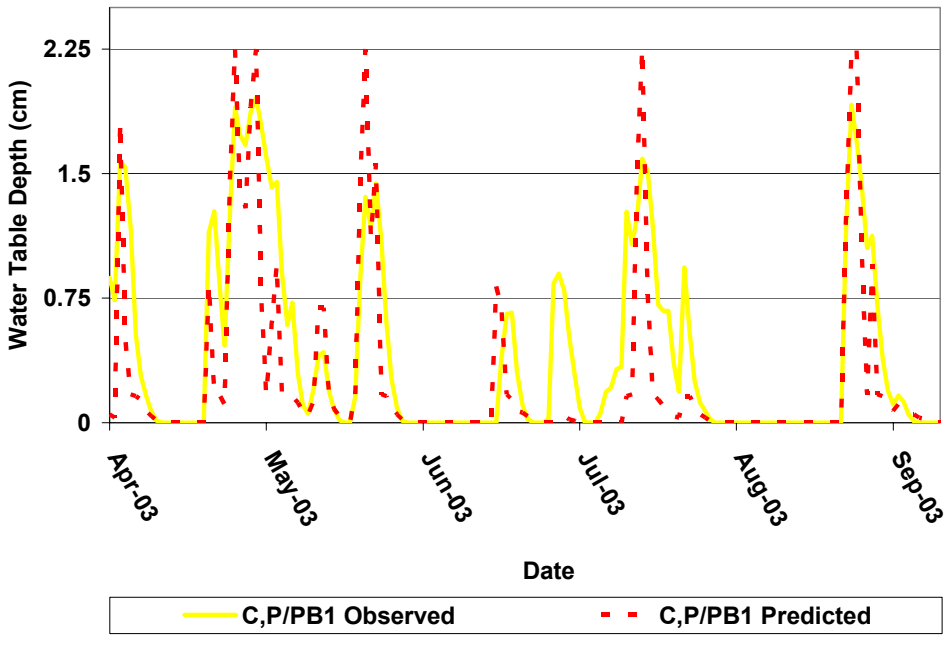

Figure 3.10 Example of the Predicted and Observed Flow From Block 1 C,P/P

Criteria For Comparison

The water table data is discussed in terms of several criteria for evaluating wetland hydrology. The water table is analyzed in terms of jurisdictional wetland hydrologic criteria; that is maintaining the water table depth within 30 cm of the surface continuously for 5% of the growing season. Determining the number of times that the wetlands met jurisdictional criteria does not completely describe the hydrology or relative wetness of a site, therefore several other criteria were used to evaluate the site in addition to the jurisdictional criteria. The second criteria involved a comparison of the range that the water table fluctuated. In order to describe, quantify, and compare the hydrology, it is important to look at the entire range of the water table as well as the proximity to the surface. Another criteria involved determining the frequency and duration that the water table was at or above the surface for the study period and the growing season. The number of days that the water table was within 30 cm of the surface for the study period and the growing season was also evaluated.

The sum excess water, SEW, is a measurement of the amount of time the water table is above a threshold depth. SEW considers both water table position, duration, and frequency and thus has units of cm-days. In this study, 30 cm was taken as the critical threshold depth. Thus, any time that the water table was within 30 cm of the surface a SEW_{30} value was computed, by Equation 3.6

Equation 3.6 SEW_{30}

$$SEW_{30} = \sum_{i=1}^{n} (30 - x_i)$$

SEW_{30}= Sum of Excess Water above 30 cm (cm-days)
x_i= Daily Average Water Table Depth (cm)

If the water table was deeper than 30 cm, the SEW_{30} for that day would be 0 cm-days. In the example shown in Figure 3.11 the water table in REF 08 was 15.75 cm on July 14th, 13.77 cm on July 15th, and 14.74 cm on July 16th. The SEW_{30} for the period of July 14th to July 16th at REF 08 would be calculated as follows:

$$30 - 15.75 = 14.25$$
$$30 - 13.77 = 16.23$$
$$\underline{30 - 14.74 = 15.26}$$
$$SEW_{30} = 45.74$$

SEW_{30} for July 14th to July 16th would be 45.74 cm-days. The SEW_{30} for REF 08 for the period shown in Figure 3.11 was 79.92 cm-days. The SEW_{30} for well REF 06 would be 0 cm-days because the water table was not within 30 cm of the surface. A study by Sieben (1964) indicated that SEW_{30} values greater than 200 cm days caused a decrease in the yield of cereal crops providing an estimate of the maximum SEW_{30} for typical agricultural conditions. All evaluation criteria are summarized in Table 3.9.

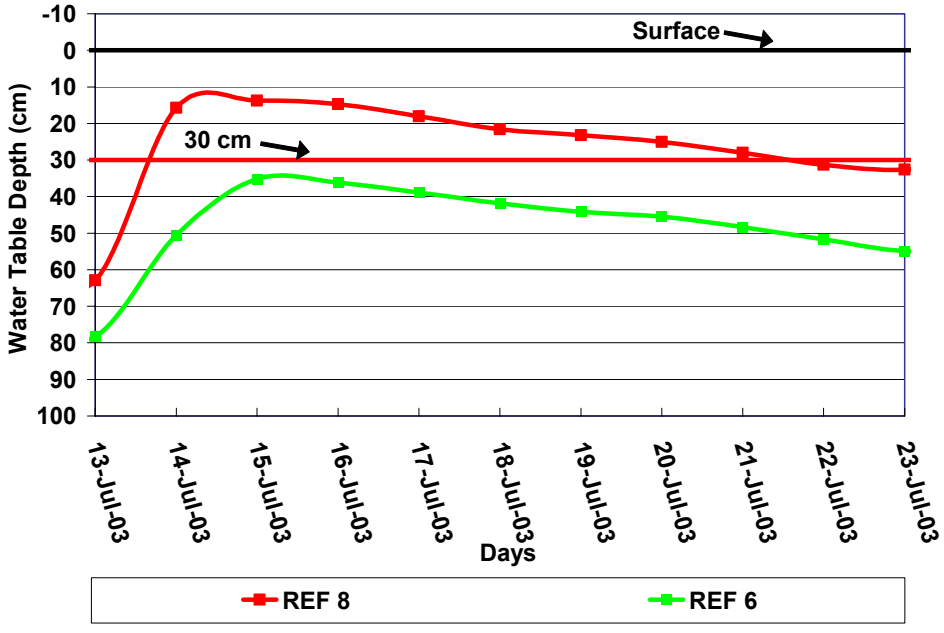

Figure 3.11 Example of SEW_{30}

Table 3.9 Evaluation Criteria

Criteria 1	**Range of Water Table Fluctuation**
Criteria 2	**Number of Days during the Study Period That the Water Table was at or Above the Surface**
Criteria 3	**Number of Days during the Growing Season That the Water Table was at or Above the Surface**
Criteria 4	**Number of Days during the Study Period that the Water Table was within 30 cm of the Surface**
Criteria 5	**Number of Days during the Growing Season that the Water Table was within 30 cm of the Surface**
Criteria 6	**SEW_{30} For the Study Period**
Criteria 7	**SEW_{30} For the Growing Season**
Criteria 8	**Number of times Jurisdictional Hydrologic Criteria was met.**

Comparison of the Observed and Simulated Criteria

The results of all the criteria, except for criteria 1, were applied to the predicted water table and then compared to the criteria applied to the observed water table presented in chapter 2 using the ANOVA procedure in SAS (Table 3.10).

There was no significant difference between the observed and the predicted water table depth in comparing the fluctuation of the water table depth, criteria 2, in each block of the treatments. There was a significant difference in the number of days that the water table was at the surface between the observed and predicted water table depths in the C,P/P block 1 treatment and the CR,P/P treatments. This may have been because the STORRO values used in the simulations could have been higher than the actual values.

There was no significant difference in the number of days that the water table was at the surface during the growing season. The number of days that the observed and predicted water table was within 30 cm of the surface for the study period and the growing season

Table 3.10 Comparison of the Predicted and Observed Results

		C,P/P B1	C,P/P B2	CR,P/P B1	CR,P/P B2	P/P B1	P/P B2	Ref Center	Ref Edge
Criteria 2	Predicted	95a	95a	93a	79a	96a	77a	94a	114a
	Observed	116a	111a	111a	111a	119a	96a	101a	106a
Criteria 3	Predicted	74a	86a	110a	144a	67a	63a	5a	1a
	Observed	8a	7b	20b	68b	14a	26a	9a	0a
Criteria 4	Predicted	39a	47a	60a	86a	34a	33a	5a	1a
	Observed	7a	5a	14a	38a	10a	17a	6a	0a
Criteria 5	Predicted	146a	155a	179a	181a	147a	145a	175a	17a
	Observed	170a	172a	185a	192a	160a	141a	164a	56a
Criteria 6	Predicted	86a	93a	115a	117a	87a	85a	115a	12a
	Observed	104a	104a	117a	124a	97a	85a	104a	27a
Criteria 7	Predicted	3054a	3330a	4012a	4786a	2986a	2781a	2821a	127a
	Observed	2691a	3271a	3806a	4787a	2874a	2555a	2855a	399a
Criteria 8	Predicted	1679a	1848a	2311a	2937a	1574a	1484a	1901a	106a
	Observed	1642a	1852a	2282a	2864a	1710a	1465a	1589a	199a

Values followed by the same letter (vertically, within Criteria) are not significantly different (α=0.05)

showed no significant difference in the predicted and observed values. This was an indication that the soil and drainage properties below the surface were properly calibrated.

The SEW_{30} for the observed and predicted water table during the study period and the growing season were not significantly different. This indicated that the duration that the water table was within 30 cm of the surface was similar for the observed and the predicted water tables. Because SEW_{30} considers both water table position and duration, it is considered the best indication of wetness

DRAINMOD accurately predicted the water table for each criteria, except for the number of days that the water table was at the surface for the study period. The model adequately predicted the range of the water table, the water table within 30 cm of the surface and the days at the surface during the growing season. These results demonstrate that the model is a good tool for predicting the long term water table and hydrologic condition.

Long Term Simulations

It is important to compare the differences in the treatments based on long term conditions so that variation caused by extreme rainfall conditions is minimized. The differences in treatments should be more apparent when many years of data are considered. Because 2003 was a wet year, subtle differences between treatments may have been masked in the observed values by the unusual wettness. Long term simulations were used to compare the eight hydrologic criteria from the previous sections. The criteria were computed for each year and the average of the results from all years are presented to determine the treatment effects.

Criteria 1

DRAINMOD was used to predict the number of times per year and the number of years out of fifty that jurisdictional wetland hydrology criteria was met. The water table was within 30 cm for at least one period of 12 consecutive days or more in 41 out of 50 years in the C,P/P treatment in block 1 (Figure 3.12). The results for all of the treatments can be found in Appendix B. Table 3.11 shows the number of years where the water table was within 30 cm of the surface for at least one consecutive period of at least 5% and 12% of the growing season, 12 and 30 days respectively, in the reference and in the treatments. The treatments met wetland hydrology for more than 41 out of 50 years on average for 5% of the growing season and the center of the reference for 46 out of 50 years. The treatments and the center of the reference wetland, were jurisdicational.

Wetland hydrology was satisfied for at least 12.5% of the growing season for 17 or more out of 50 years in the treatment areas and 24 years out of 50 in the center of

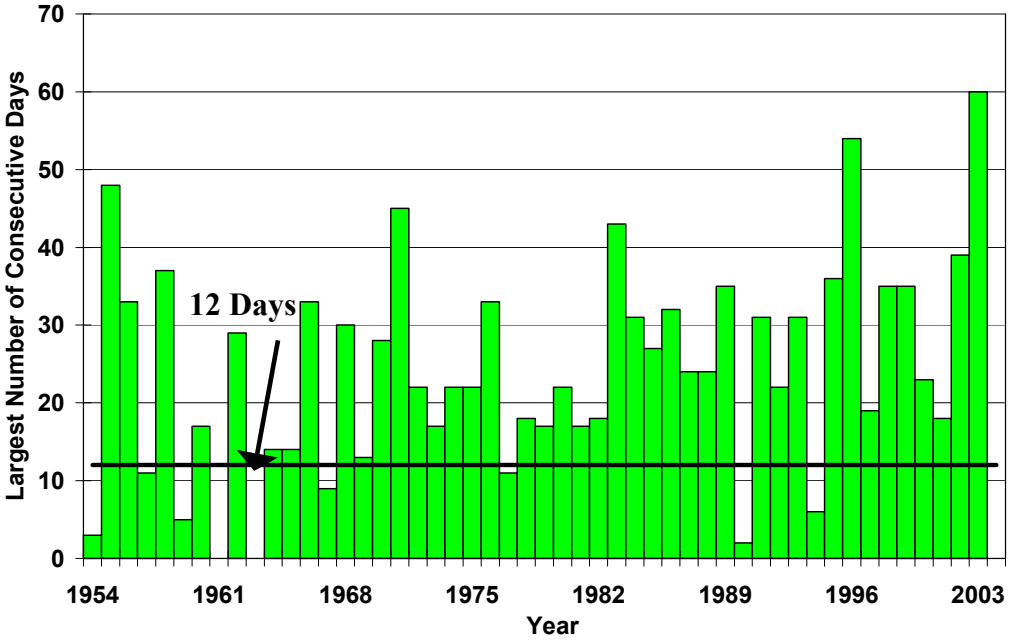

Figure 3.12 Greatest Number of Consecutive Days Each Year in the C,P/P Block 1 Treatment

Table 3.11 Number of Years out of Fifty Reporting Wetland Hydrology

	Number of Years Wetland Hydrology Satisfied	
Treatments	**5%=12 Days**	**12% = 30 days**
P/PB1	**41**	**18**
P/PB2	**41**	**17**
C,P/PB1	**41**	**19**
C,P/PB2	**42**	**20**
CR,P/PB1	**46**	**22**
CR,P/PB2	**45**	**22**
Ref Center	**46**	**24**
Ref Edge	**0**	**0**

the reference. The CR,P/P met the wetland hydrology criteria for more years than the C,P/P treatment and the P/P treatment, and was more like the center of the reference wetland.

While jurisdicational critieria is the standard for determining the wetland status of a site, it does not fully describe the hydrology of a wetland. Further criteria are needed to adequately describe the hydrologic conditions of a wetland.

Criteria 2

To compare the differences in water table depth extremes, the average annual minimum and the average annual maximum water table depth over the fifty years is shown in Table 3.12. There was no significant difference in the range of the water table depth when the long term average was considered. This indicated the variability in the water table depth was restored in each treatment to the same extent that was found in the reference.

Criteria 3

The results of criteria 3 will not be discussed because the conditions in the surface of the treatments for the study period were not adequately simulated by the model.

Criteria 4

The water table was at the surface during the growing season for significantly more days in the CR,P/P treatment than the other treatments and the reference wetland (Figure 3.13) because the STORRO values were significantly higher. The water table was at the surface for significantly more days in the C,P/P treatments than in the P/P treatments. The water table at the edge and the center of the reference wetland was at the surface for significantly less days that in the treatments.

Table 3.12 Range in Water Table Depth Over 50 Years

	REF Edge	C,P/P	CR,P/P	P/P	REF Center
Minimum	7a	1a	1a	1a	1a
Maximum	130a	123a	121a	121a	117a

Values followed by the same letter (horizontally) are not significantly different (α=0.1)

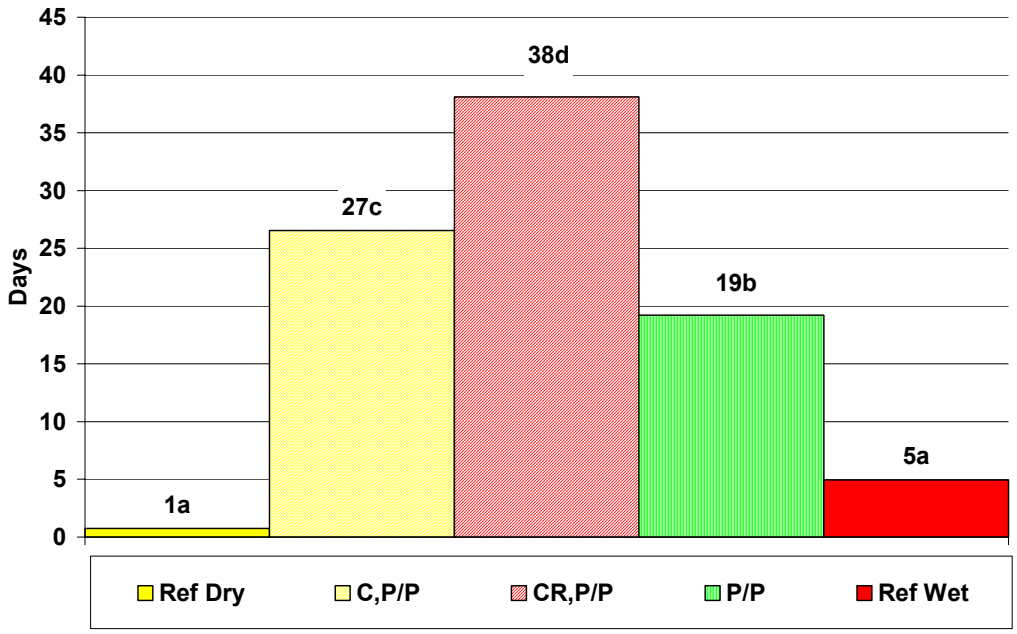

Figure 3.13 Number of Days that the Water Table was at the Surface During the Growing Season

Criteria 5

The water table was within 30 cm of the surface for significantly more days during the study period in the CR,P/P treatment than in the C,P/P and P/P treatments (Figure 3.14). This indicated that the CR,P/P treatment was significantly wetter than the C,P/P and the P/P treatments. The P/P treatment was not significantly different from the C,P/P treatment. The water table was within 30 cm of the surface for significantly more days in the center of the reference wetland and significantly less days in the edge of the reference wetland than in the treatments. This indicated that the conditions in the treatment were within the range of the conditions in the reference.

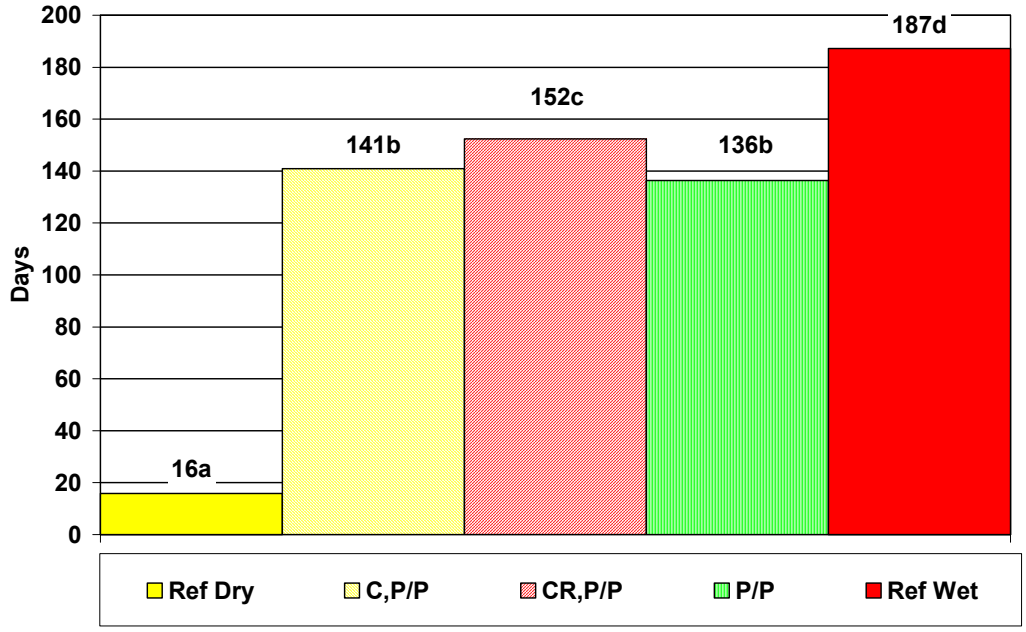

Figure 3.14 Number of Days the Water Table was within 30 cm of the Surface

Criteria 6

The water table was within 30 cm of the surface for significantly more days during the growing season in the CR,P/P treatments than in the C,P/P and the P/P treatments (Figure 3.15). There was no significant difference between the C,P/P treatment and the P/P treatment. The number of days that the water table was within 30 cm of the surface was significantly greater in the center of the reference and significantly less in the edge of the reference than in the treatments.

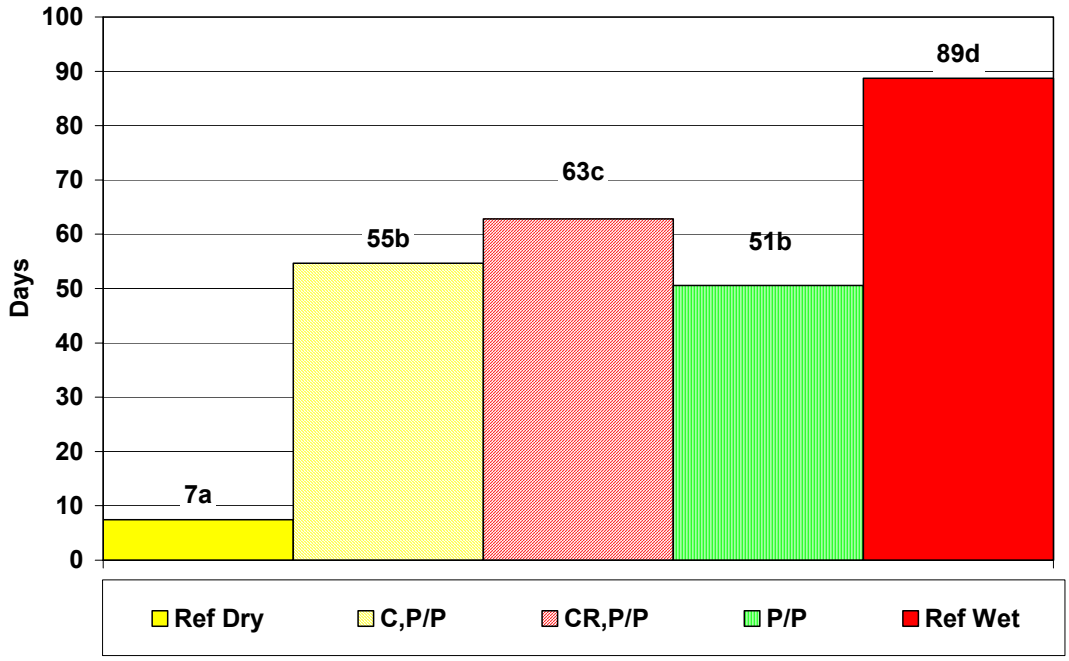

Figure 3.15 The Average Number of Days the Water Table was Within 30 cm of the Surface During the Growing Season

Criteria 7

The SEW_{30} was significantly greater during the study period in the CR,P/P treatments than in the C,P/P and the P/P treatments (Figure 3.16). The SEW_{30} was significantly greater in the C,P/P treatment than in the P/P treatment. The SEW_{30} was also significantly greater than 200cm-days, the value reported by Sieben (1964) as the threshold value for reduction in yield of cereal crops, in the treatments and the center of the reference.

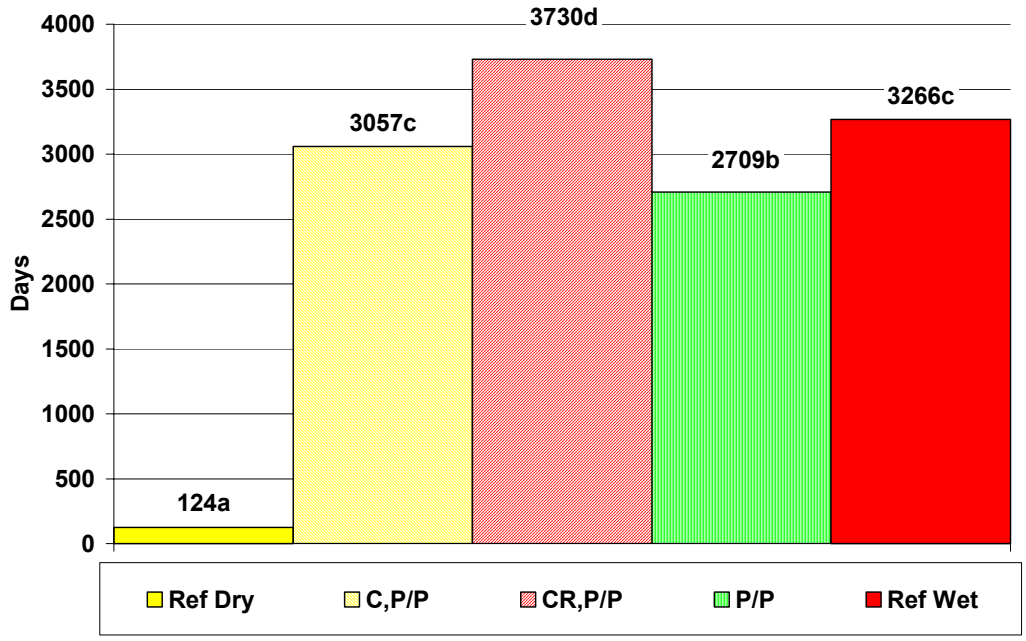

Figure 3.16 Average SEW_{30} By Year For the Study Period

Criteria 8

The growing season SEW_{30} in the CR,P/P treatments was significantly greater than the SEW_{30} in the C,P/P and the P/P treatments, Figure 3.17. The growing season SEW_{30} in the C,P/P treatment was significantly greater than the SEW_{30} in the P/P treatment. The CR,P/P treatment and the center of the reference wetland was wetter than the C,P/P and P/P treatments and the edge of the reference wetland.

Each of the criteria described the water table with respect to the position in the soil profile and are important in describing the hydrology of a wetland. Each of the treatments and the reference wetland met the criteria for jurisdictional wetland hydrology.

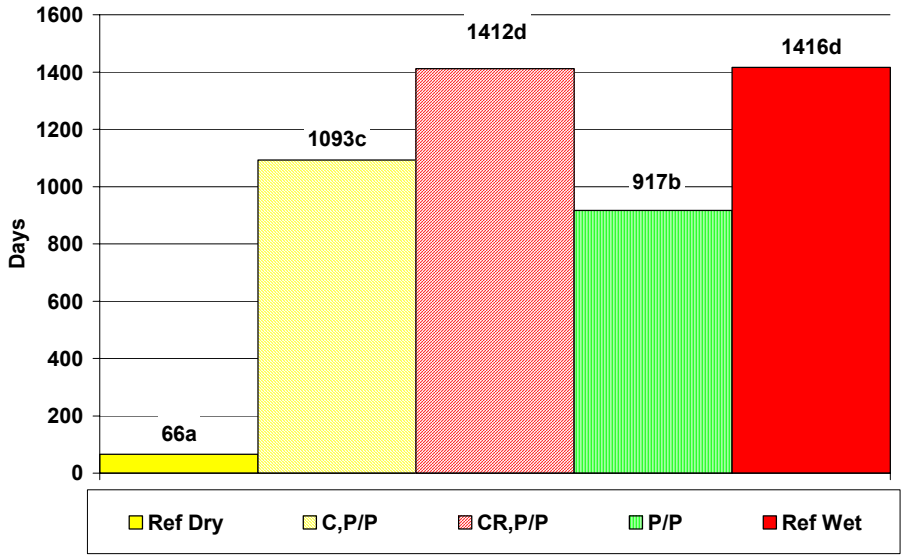

Figure 3.17 Average SEW_{30} for the Growing Season

The criteria indicated that the water table was within 30 cm of the surface but neither the treatments or the reference were continuously inundated. It is important to consider the number of days that the water table was at the surface along with the jurisdictional criteria, the number of days that the water table was within 30 cm of the surface, in order to provide the proper balance of wetting and drying found in natural wetlands. Monitoring the number of days the water table is at the surface would prevent restoration projects from being to wet.

Reduction in Outflow

Long term simulations were used to determine the average yearly flow from the restored wetlands. Conventional row crop conditions were simulated by lowering the weir elevations to the bottom of the ditches in the P/P treatment simulations. These conditions were simulated to determine baseline conditions prior to restoration. Simulated outflow from the mature wetland was at least 29% less that the outflow from the same fields in agricultural production (Table 3.13).

Table 3.13 Reduction in Flow From Mature Wetland to Conventional Row Crop

	Outflow (cm)		
Treatments	Mature Wetland	Conventional Row Crop	Reduction
PPB1	38.7	54.4	29%
PPB2	39.8	53.9	26%
C/PPB1	38.2	54.4	30%
C/PPB2	38.4	53.9	29%
CR/PPB1	29.0	54.4	47%
CR/PPB2	34.0	53.9	37%

Conclusions

DRAINMOD was found to adequately simulate the conditions in the treatments and the restoration with good agreement between the predicted and observed water table depths. The criteria for the range in water table depth, the number of days that the water table was within 30 cm of the surface, and the SEW_{30} were not significantly different for the observed and predicted water table. The predicted water table was sensitive to the level of surface microtopography indicating that surface treatments can have an influence on wetland hydrology.

Each of the treatment areas and the center of the reference wetland were wetlands based on the jurisdictional criteria. Each of the treatments and the center of the reference wetland had at least one period where the water table was within 30 cm of the surface for a period of at least 12 consecutive days (5% of the growing season) in more than half of the years. The CR,P/P treatment and the reference were not significantly different in the number of times that the jurisdictional criteria were met.

When the simulated results from fifty years of data were evaluated, the differences in the treatments were significant. The CR,P/P treatment was significantly wetter, with the

water table at the surface and within 30 cm of the surface for more days and had a greater SEW_{30}, than the C,P/P and the P/P treatments during the long term analysis. The water table was at the surface for significantly more days and there was a greater SEW_{30} in the C,P/P treatment than in the P/P treatment indicating that the C,P/P treatment was wetter. For the long term average, the CR,P/P treatment was more effective to maintain the water table closer to the surface than the C,P/P and the P/P treatments. The water table was closer to the surface in the C,P/P treatment than in the P/P treatment.

This research has shown that DRAINMOD is an effective tool for evaluating the long term hydrology of a prior converted wetland. DRAINMOD could be used in future projects to determine the surface conditions that will most effectively restore wetland hydrology. Models could determine the level of landforming that would create the ideal conditions most conducive for natural wetland functions.

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Appendix A: Water Table Wells And Flow From the Treatments

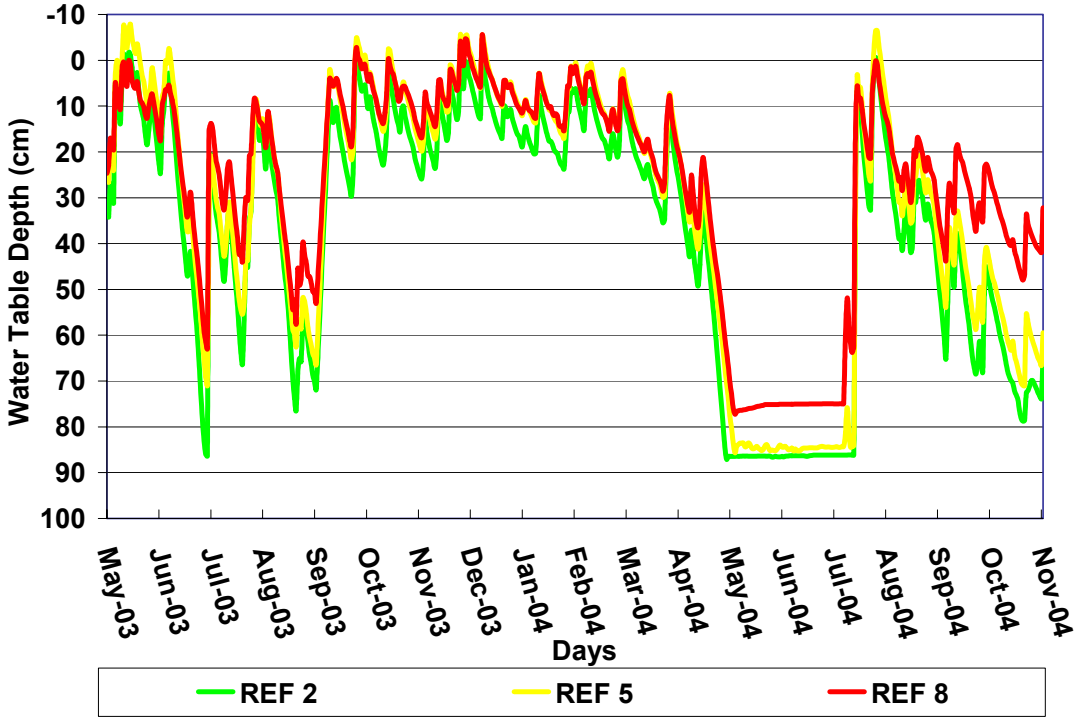


Figure A.1 Water Table Wells In the Wet Area of the Reference

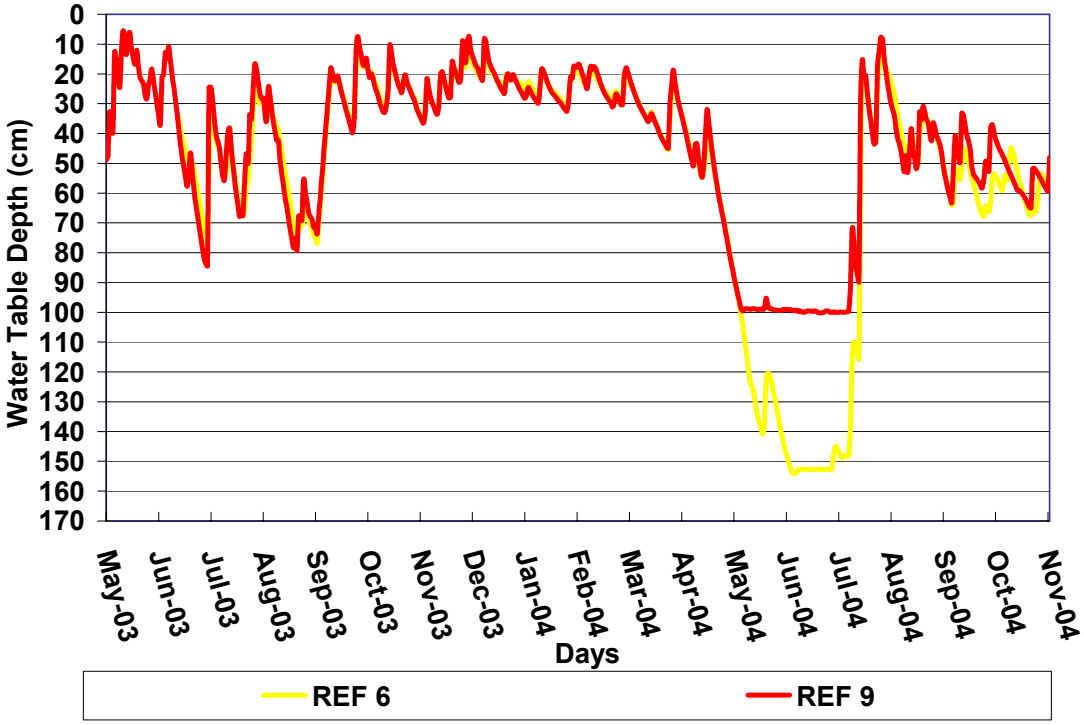


Figure A.2 Water Table Wells in the Intermediate Area of the Reference

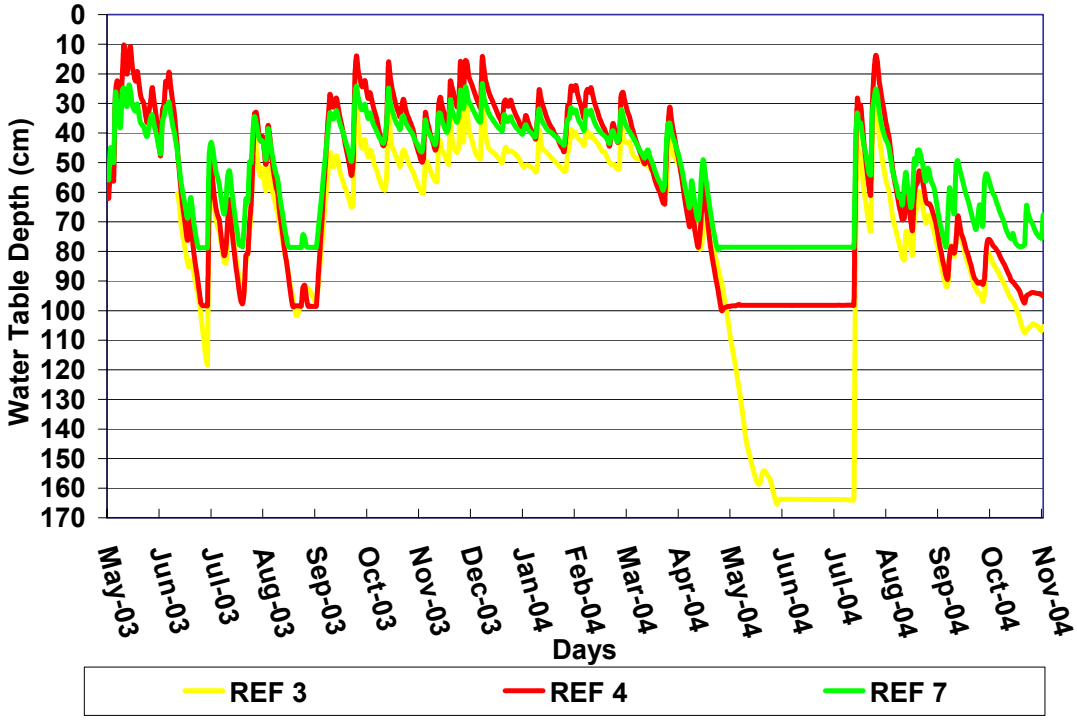


Figure A.3 Water Table Wells in the Wet Area of the Reference

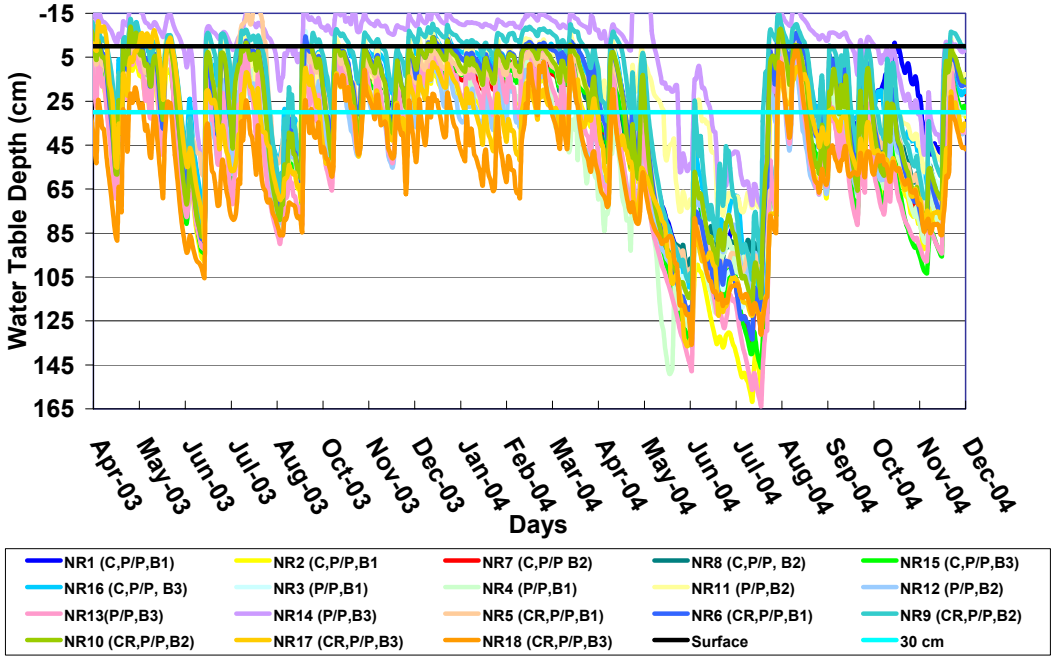


Figure A.4 Water Table Wells In the Treatments

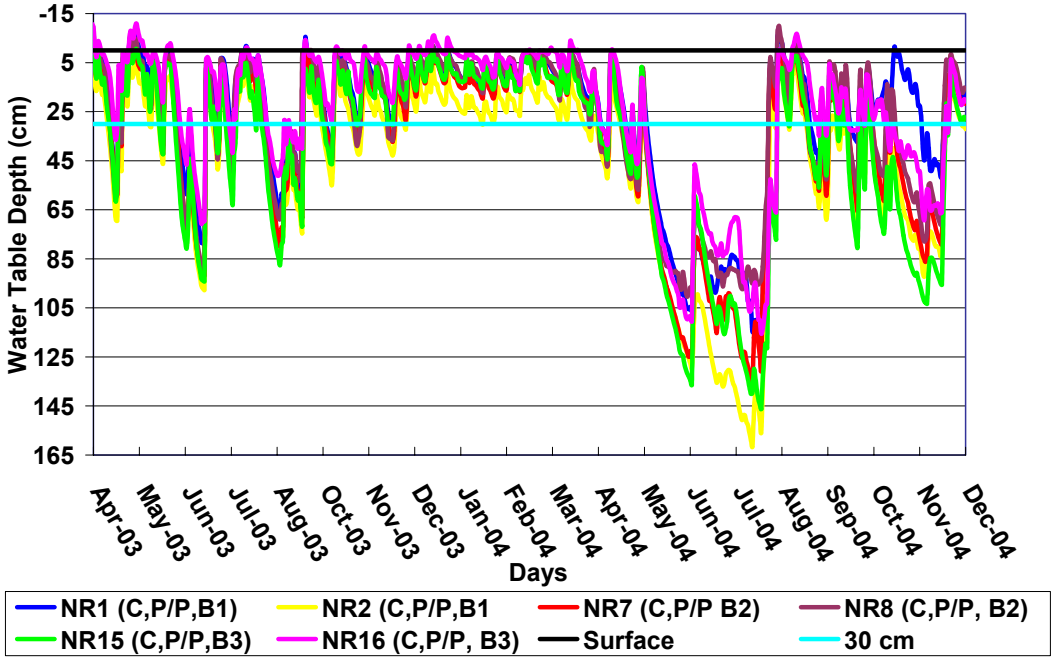


Figure A.5 Water Table Wells in the C,P/P Treatment

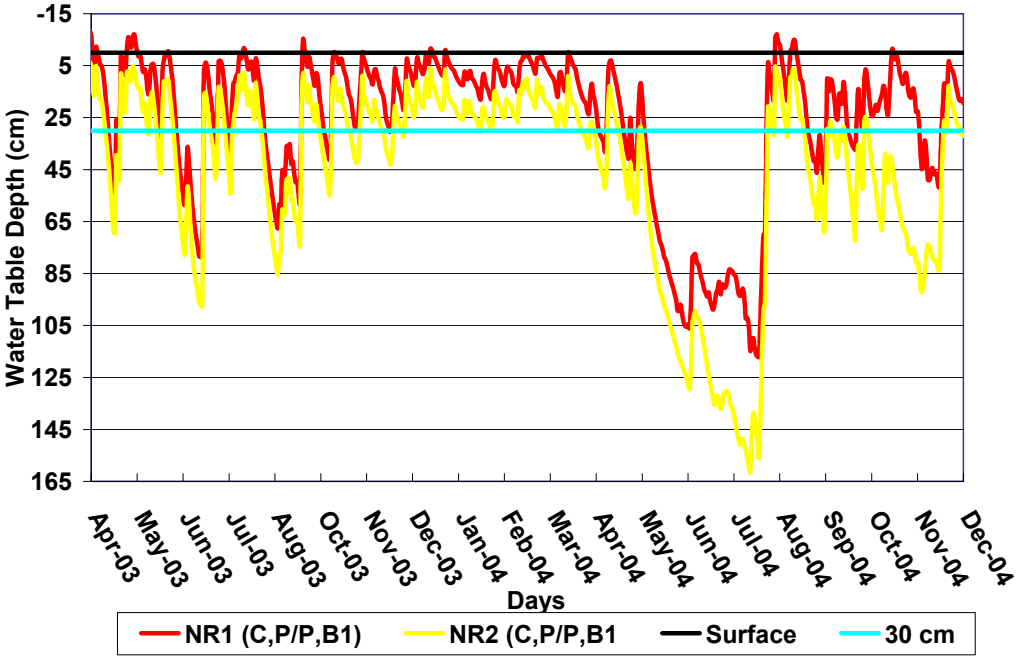


Figure A.6 Water Table Wells in the C,P/P Treatment in Block 1

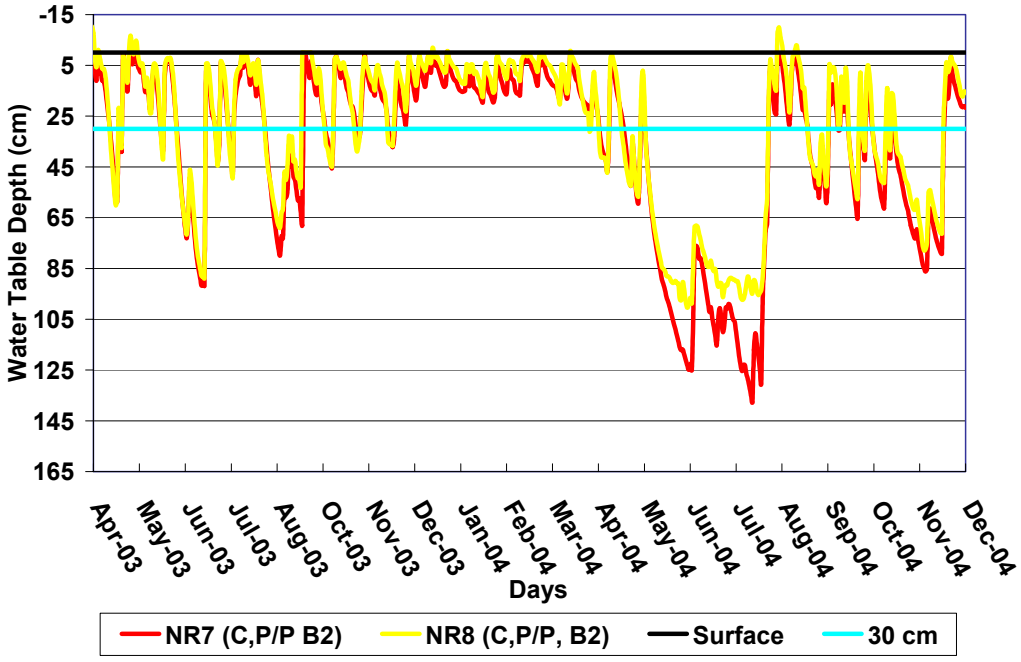
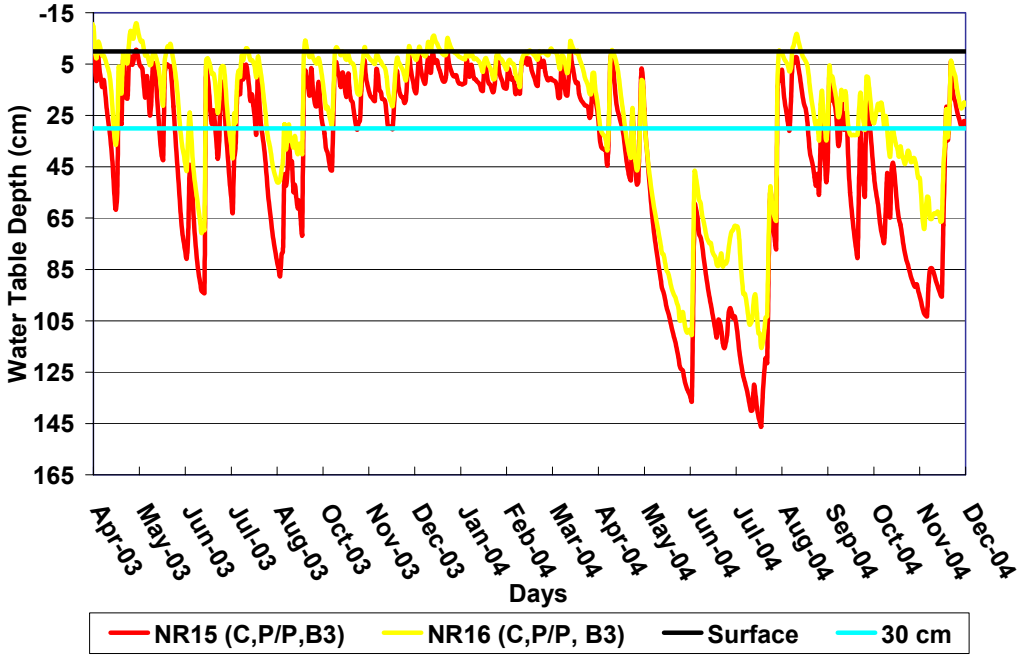


Figure A.7 Water Table Wells in the C,P/P Treatment in Block 2



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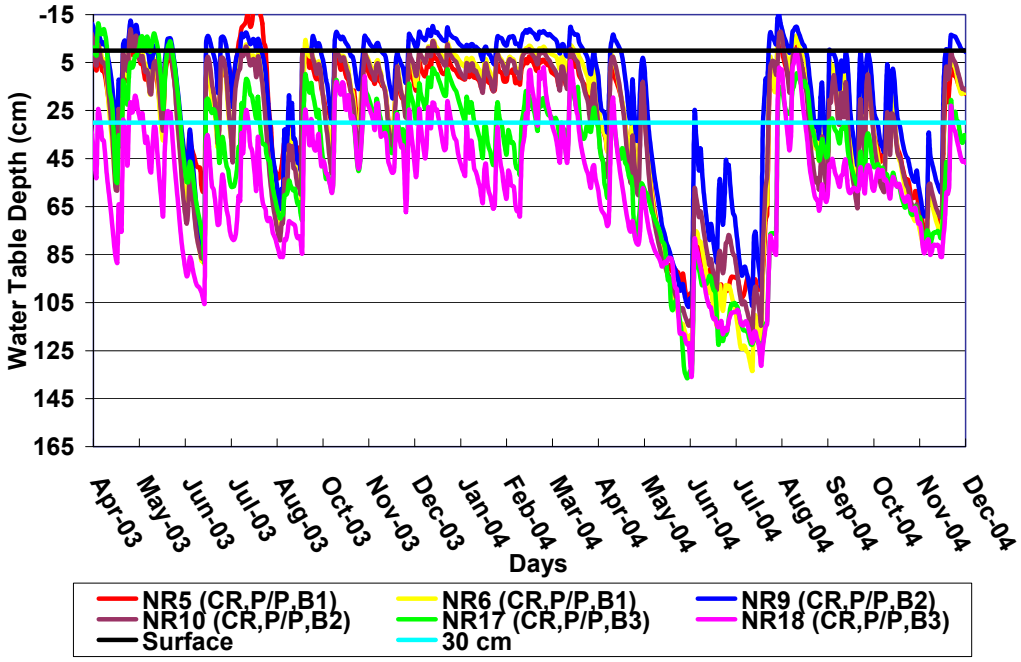


Figure A.9 Water Table Wells in the CR,P/P Treatment

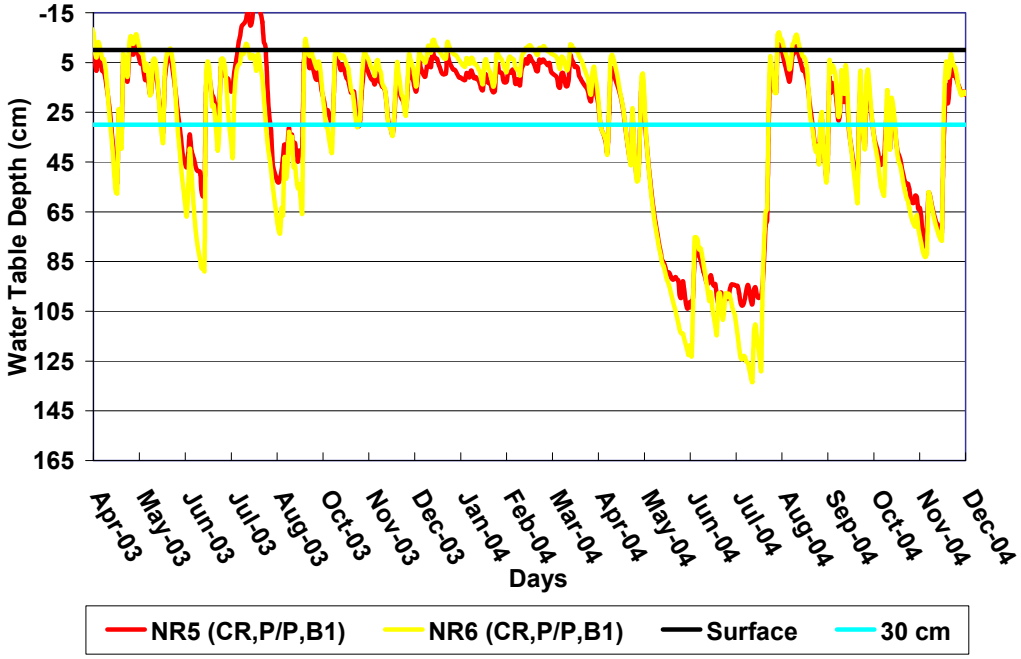
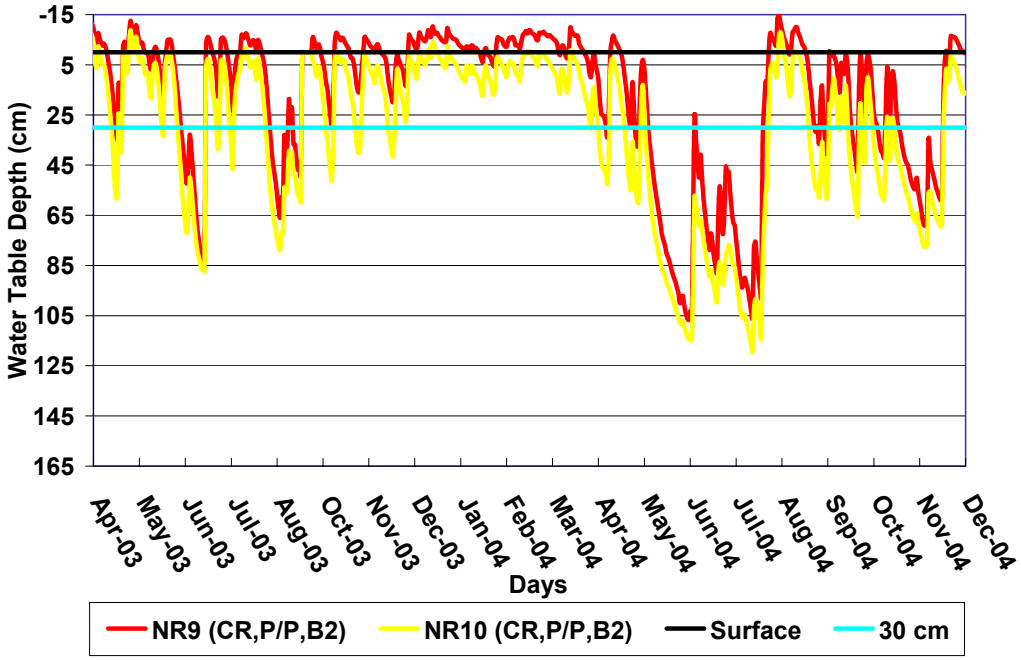


Figure A.10 Water Table Wells in the CR,P/P Treatment in Block 1



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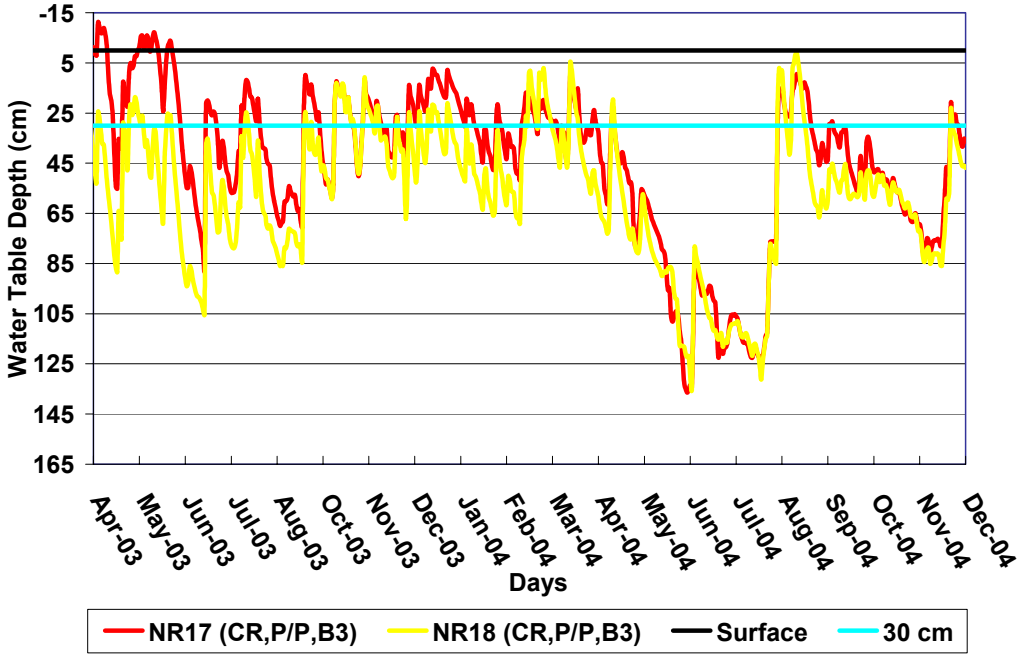

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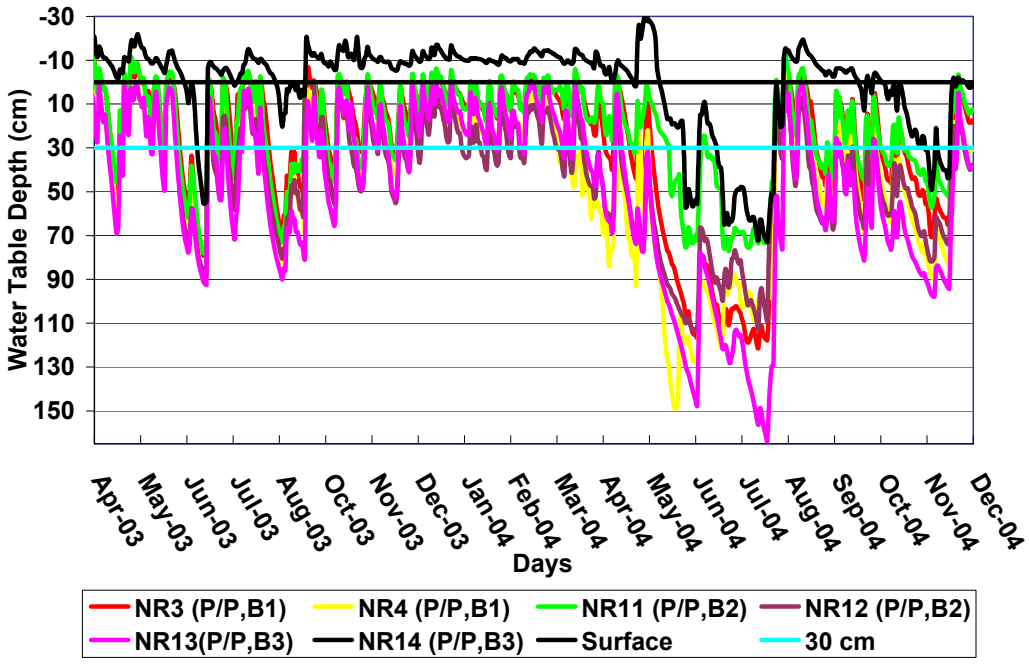


Figure A.13 Water Table Wells in the P/P Treatment

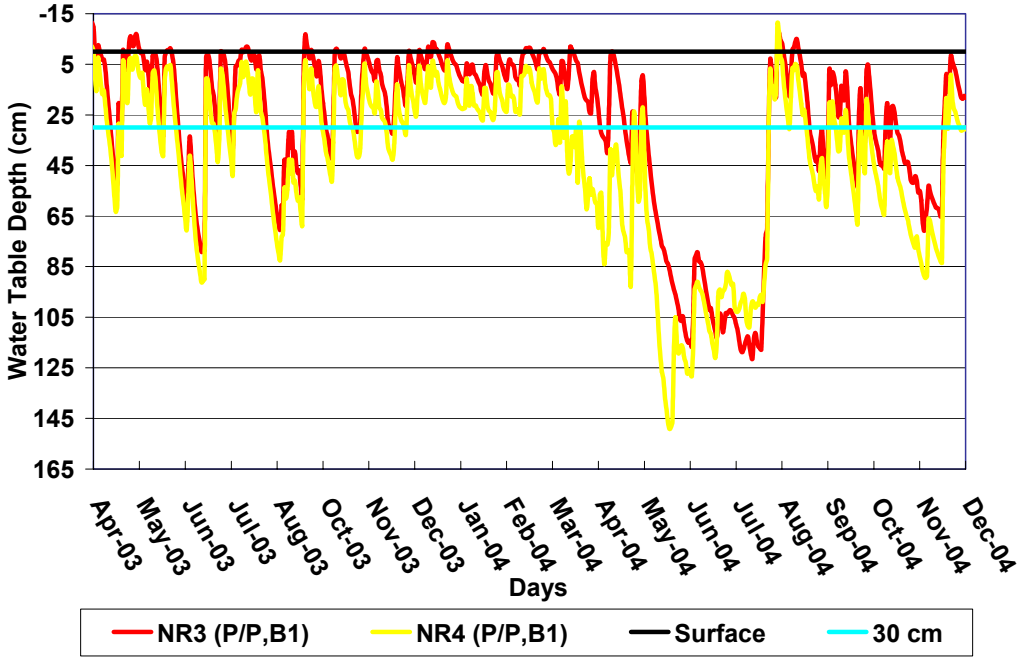


Figure A.14 Water Table Wells in the P/P Treatment in Block 1

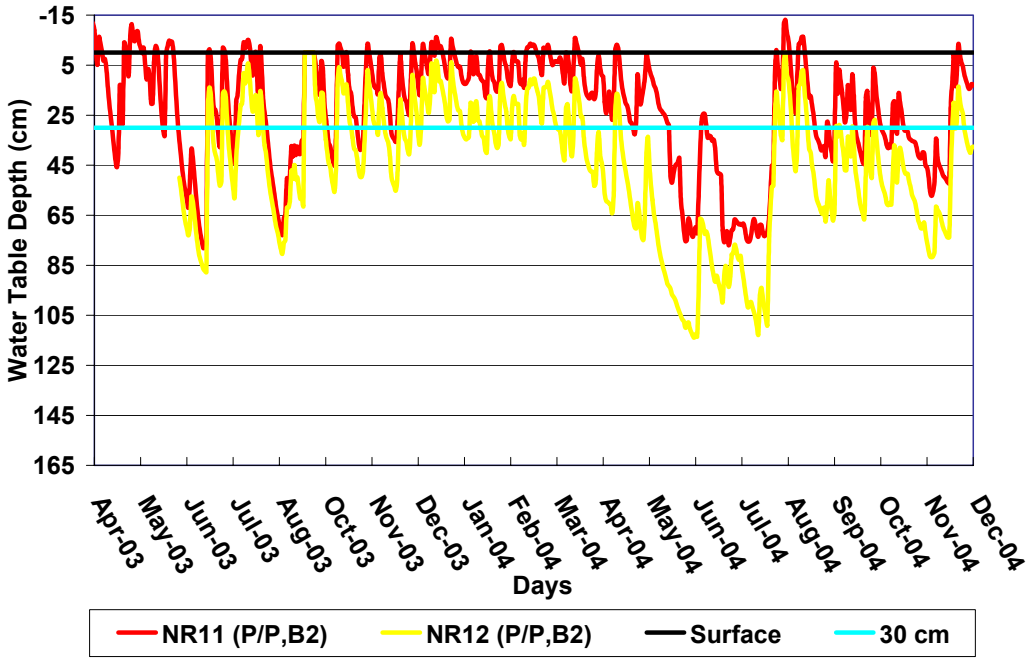


Figure A.15 Water Table Wells in the P/P Treatment in Block 2

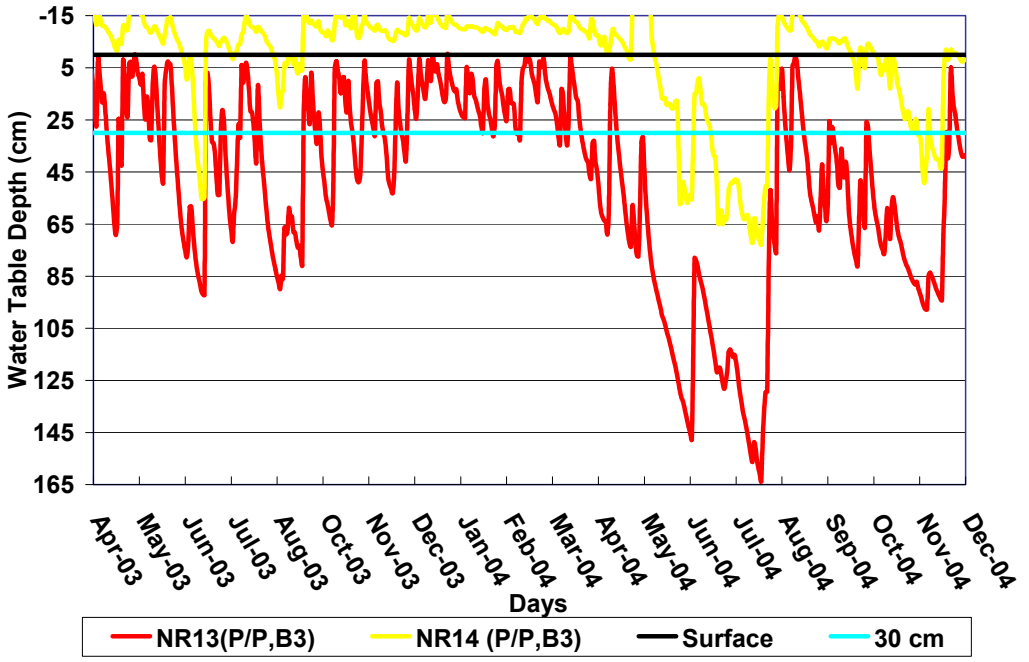


Figure A.16 Water Table Wells in the P/P Treatment in Block 3

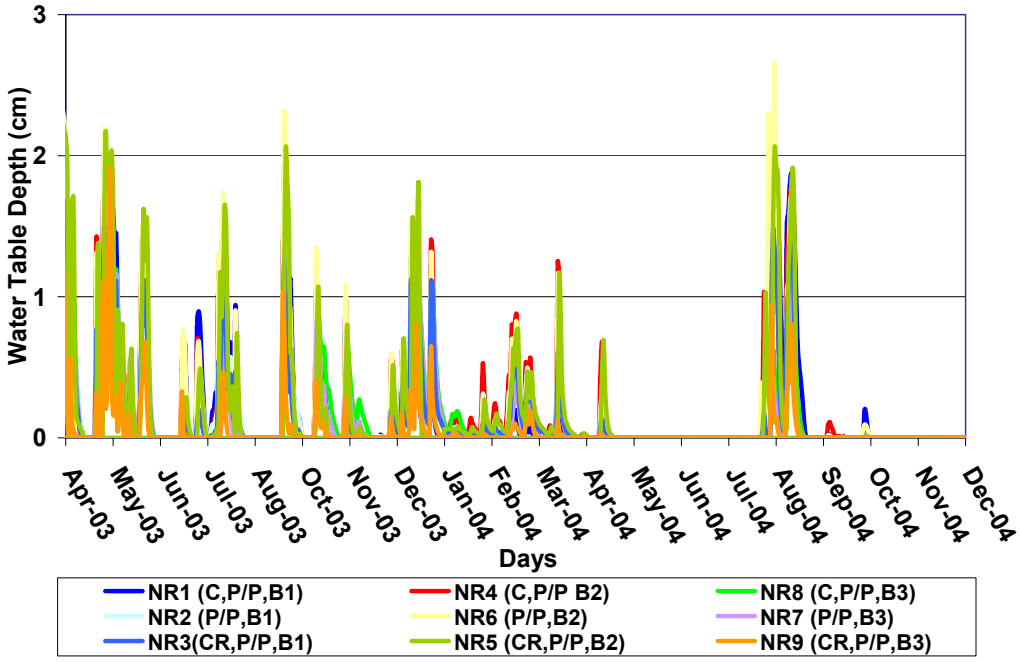


Figure A.17 Flow From Each of the Treatments

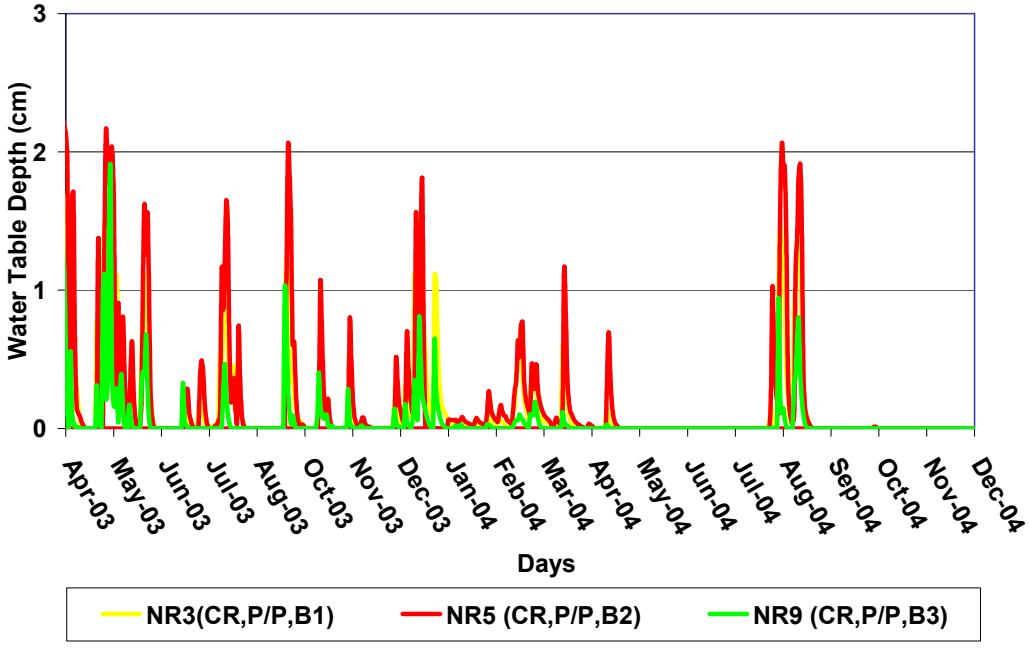


Figure A.18 Flow from the C,P/P Treatment

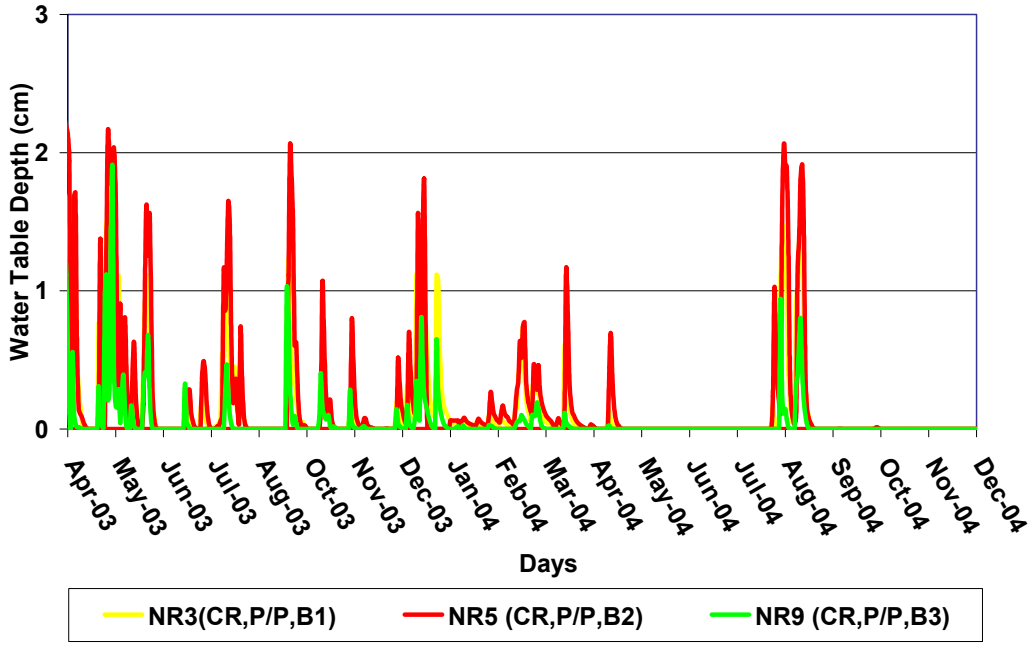


Figure A.19 Flow From the CR,P/P Treatment

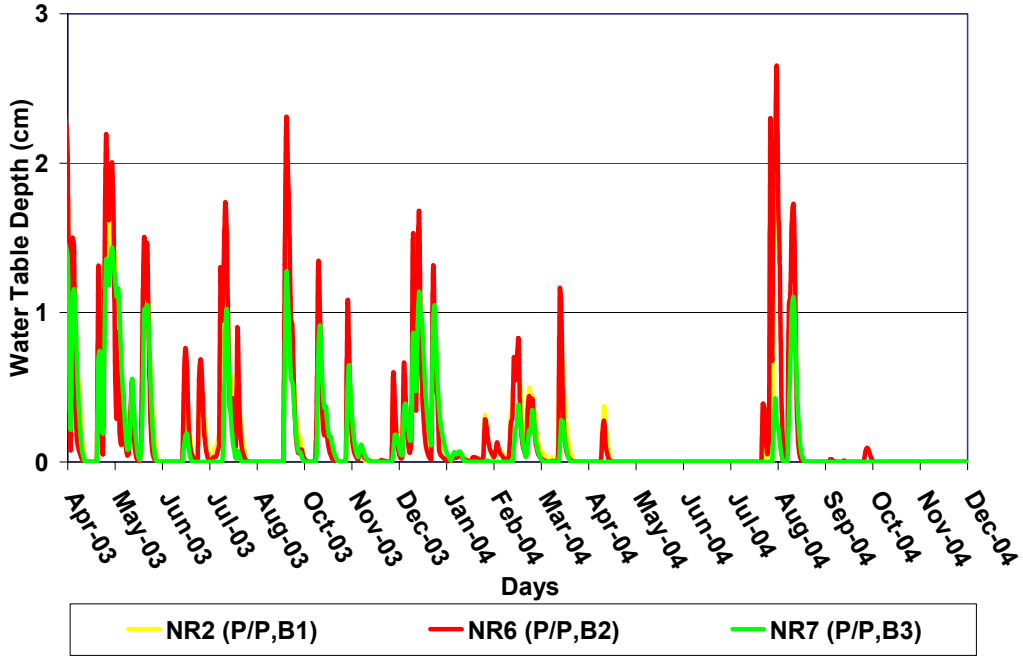


Figure A.20 Flow From the P/P Treatment

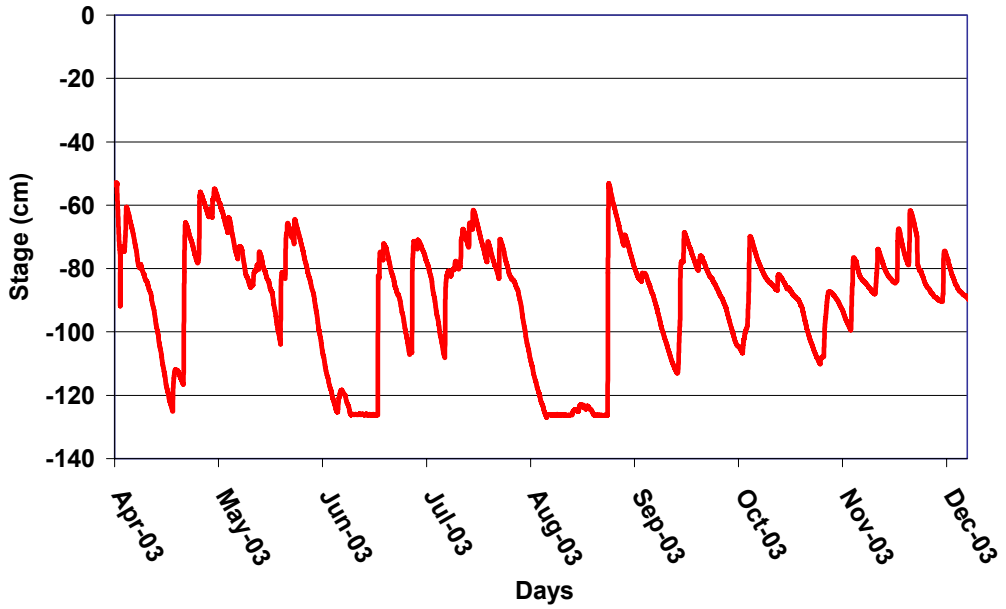


Figure A.21 Stage at Water Control Structure 1 in 2003 (C,P/P Block 1)

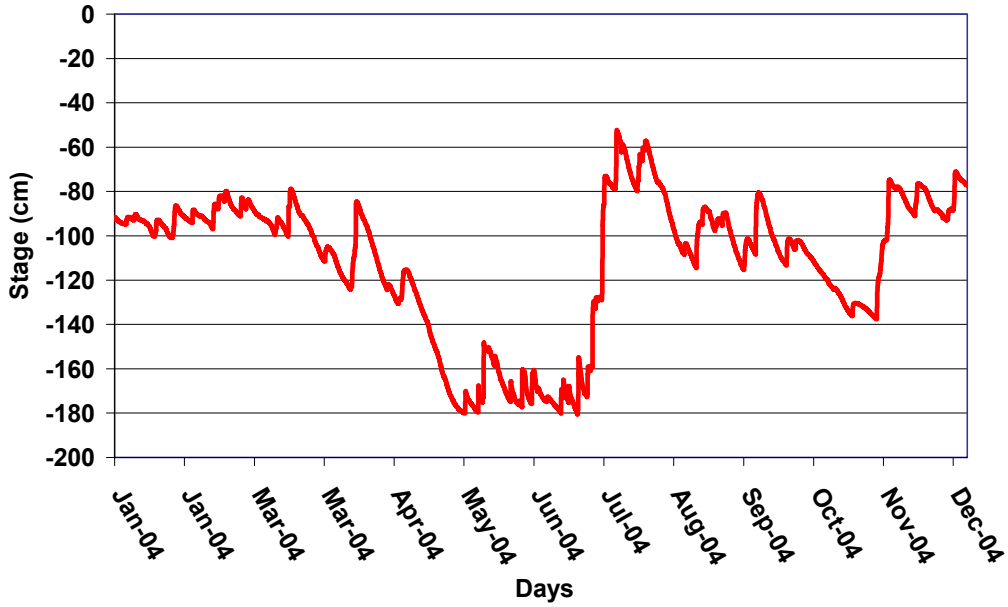


Figure A.22 Stage at Water Control Structure 1 in 2004 (C,P/P Block 1)

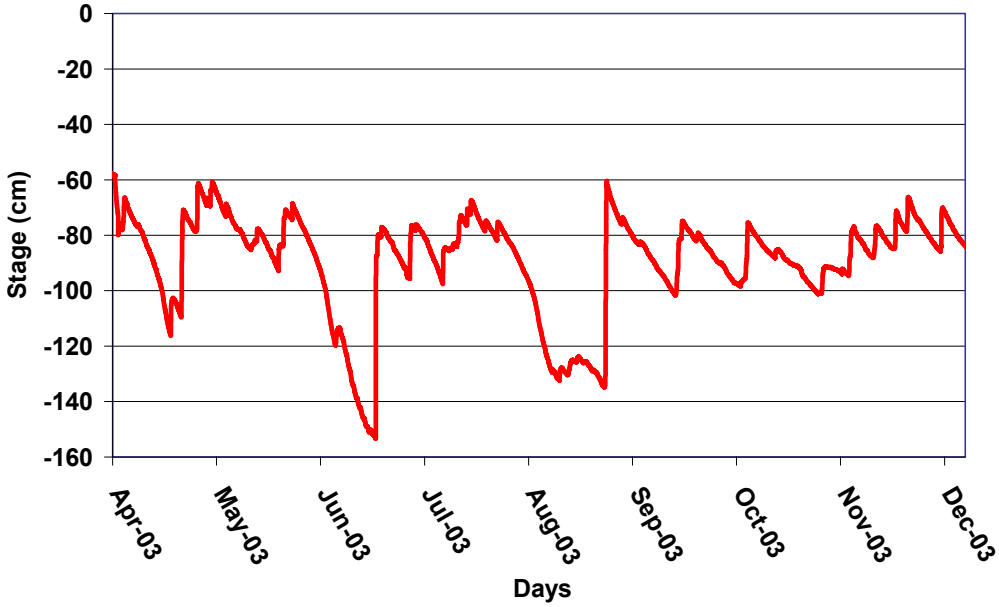


Figure A.23 Stage at Water Control Structure 2 in 2003 (P/P Block 1)

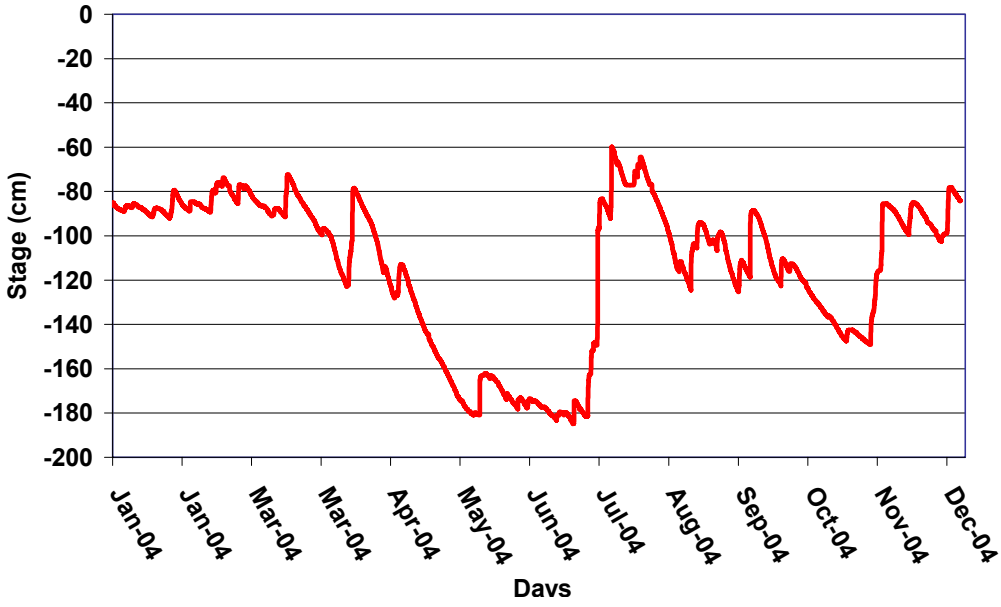


Figure A.24 Stage at Water Control Structure 2 in 2004 (P/P Block 1)

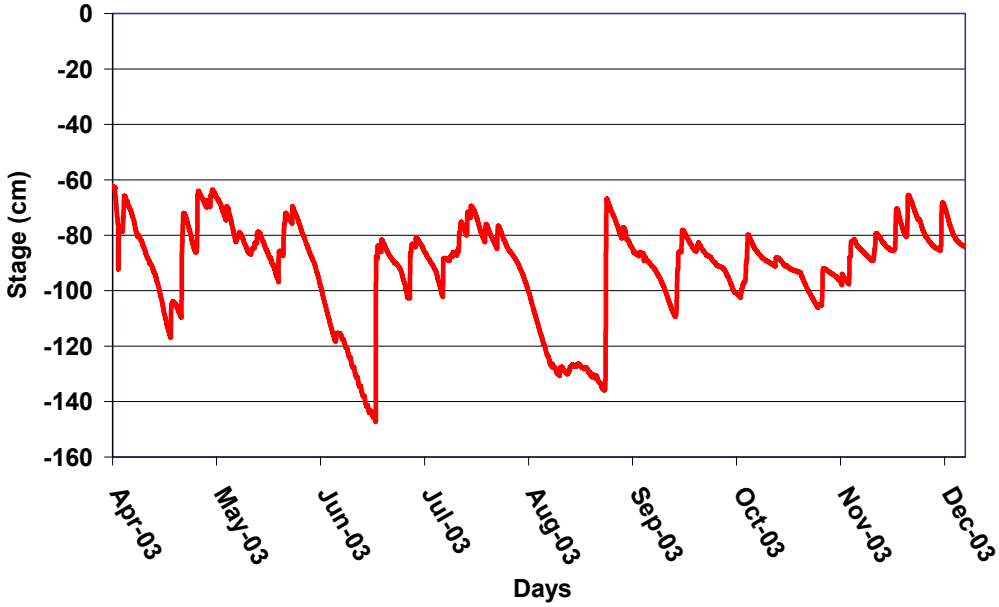


Figure A.25 Stage at Water Control Structure 3 in 2003 (CR,P/P Block 1)

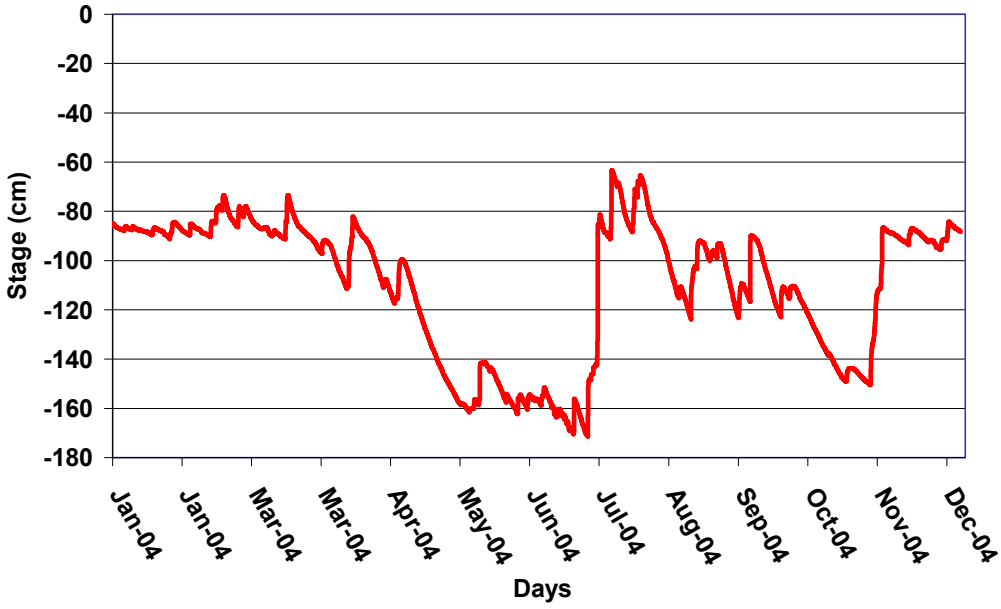


Figure A.26 Stage at Water Control Structure 3 in 2004 (CR,P/P Block 1)

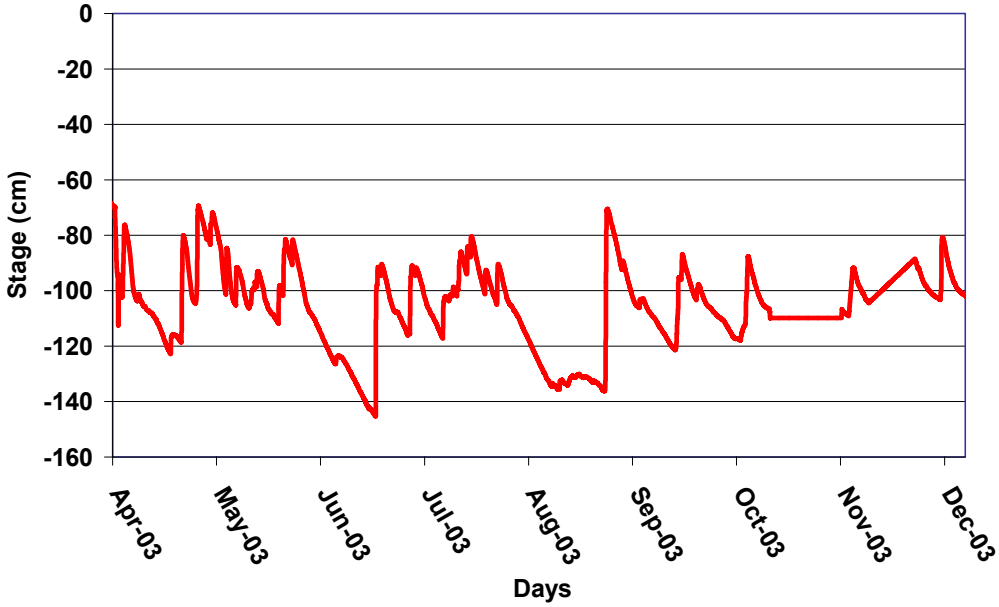


Figure A.27 Stage at Water Control Structure 4 in 2003 (C,P/P Block 2)

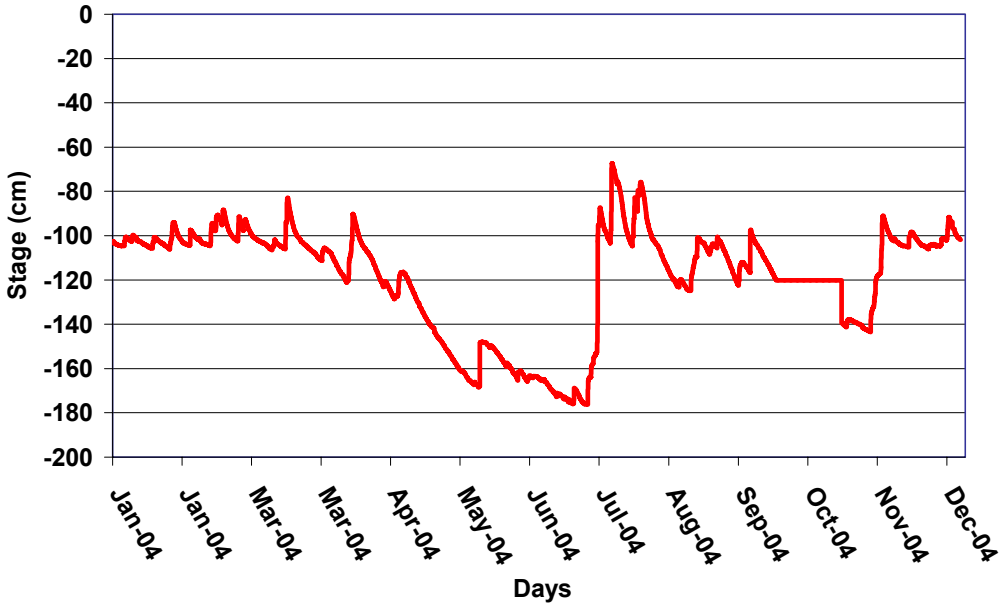


Figure A.28 Stage at Water Control Structure 4 in 2004 (C,P/P Block 2)

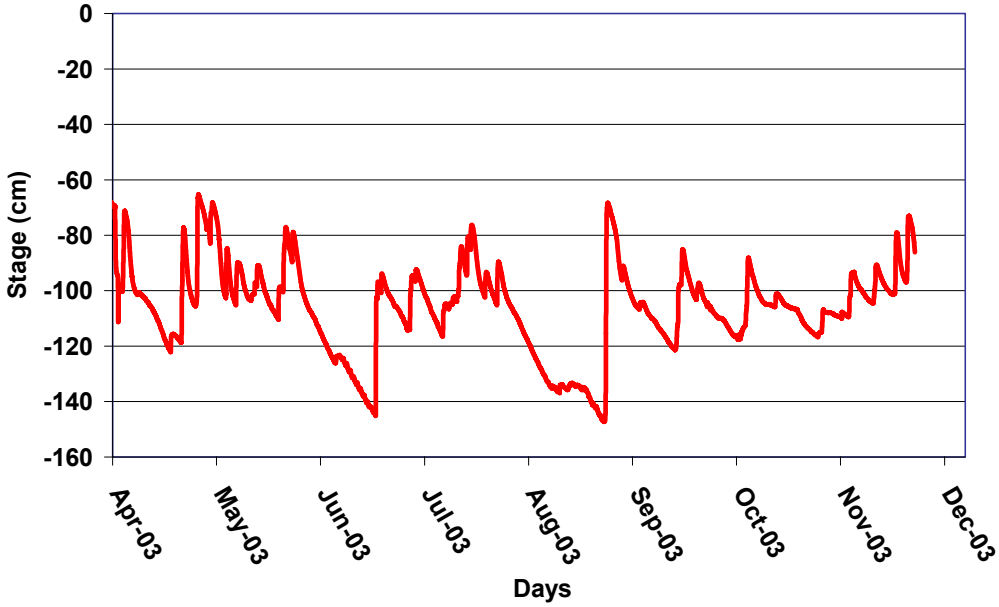


Figure A.29 Stage at Water Control Structure 5 in 2003 (CR,P/P Block 2)

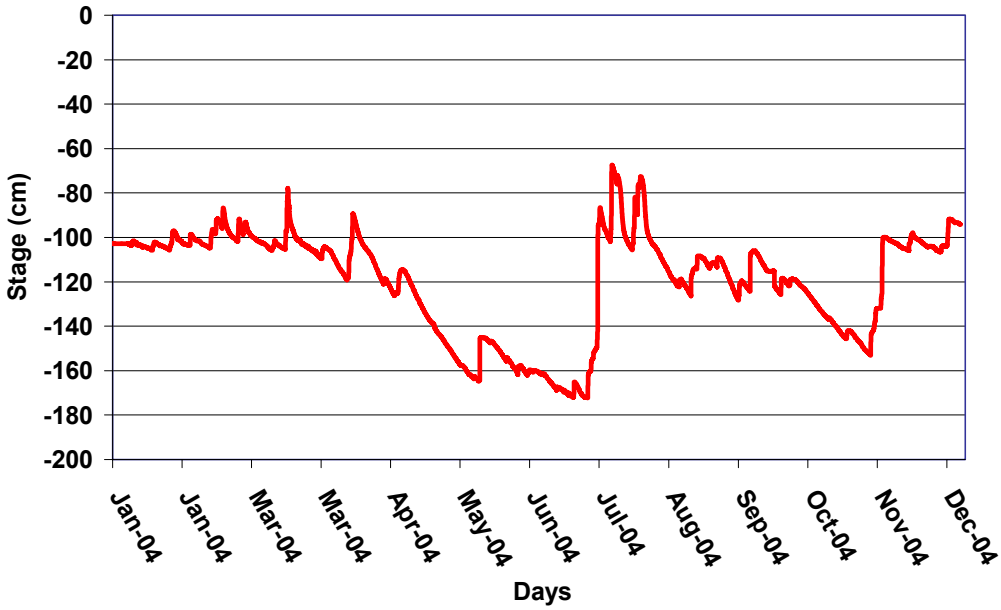


Figure A.30 Stage at Water Control Structure 5 in 2004 (CR,P/P Block 2)

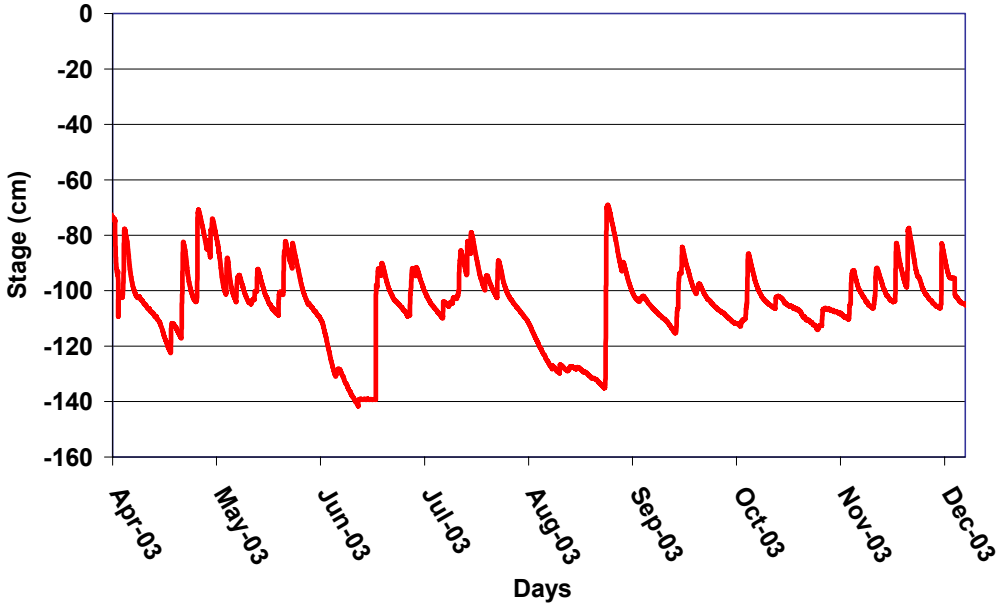


Figure A.31 Stage at Water Control Structure 6 in 2003 (P/P Block 2)

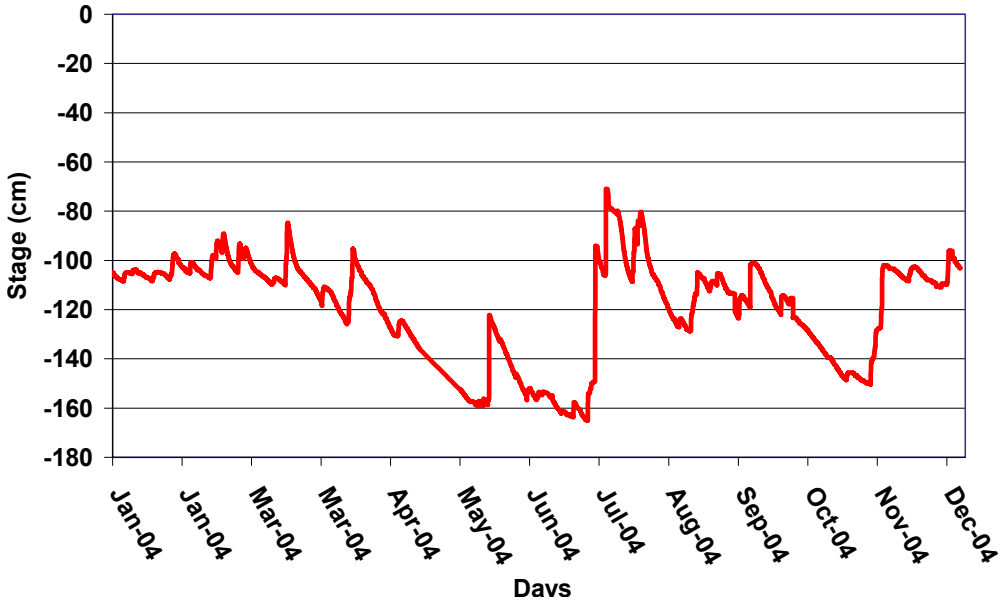


Figure A.32 Stage at Water Control Structure 6 in 2004 (P/P Block 2)

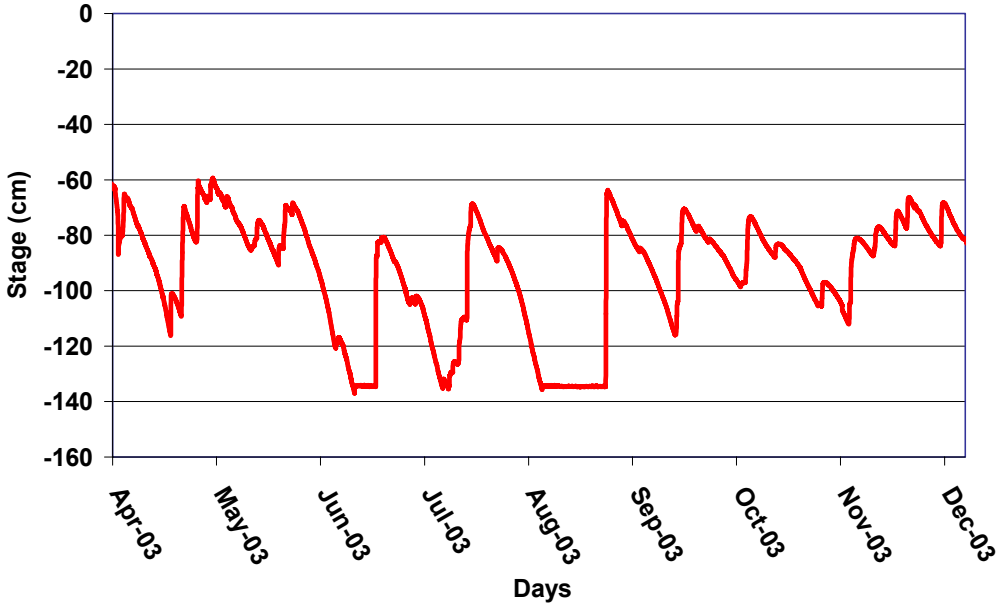


Figure A.33 Stage at Water Control Structure 7 in 2003 (P/P Block 3)

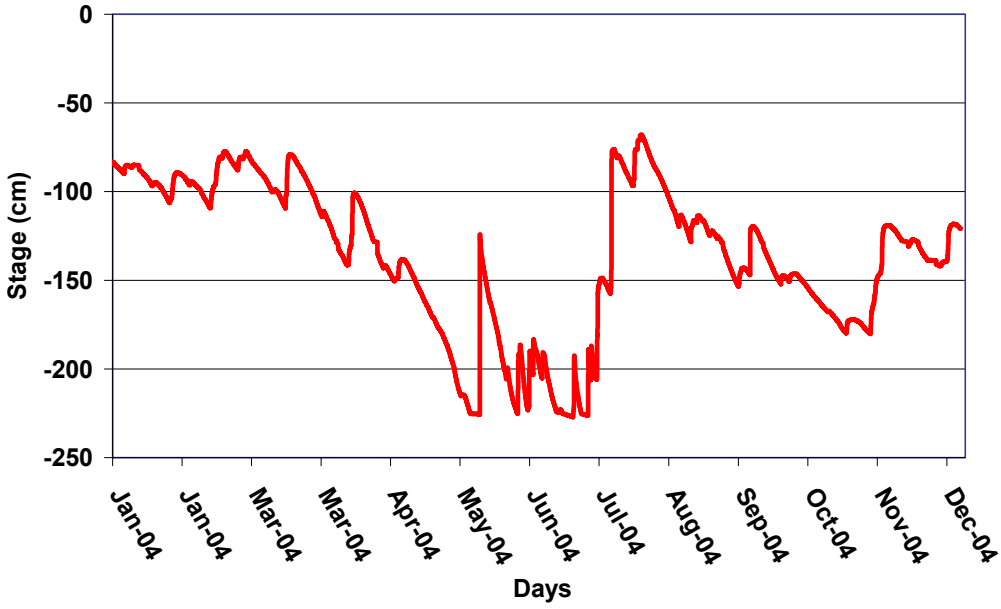


Figure A.34 Stage at Water Control Structure 7 in 2004 (P/P Block 3)

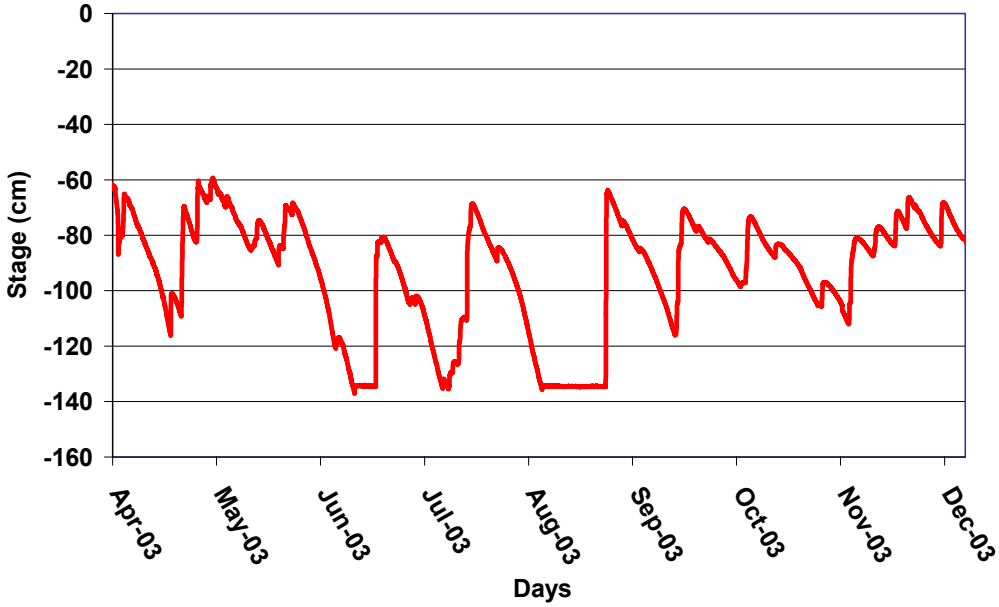


Figure A.35 Stage at Water Control Structure 8 in 2003 (C,P/P Block 3)

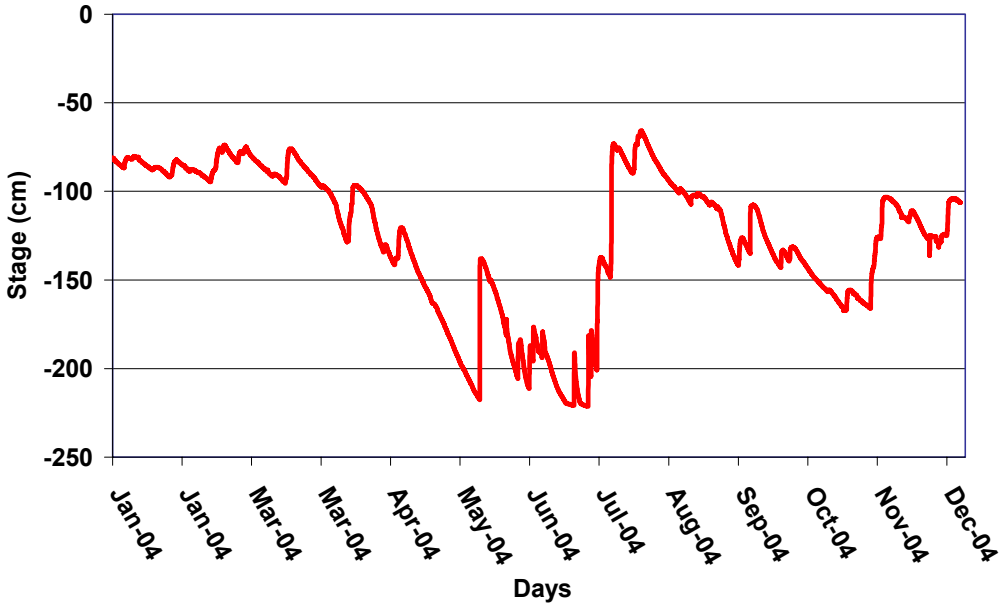


Figure A.36 Stage at Water Control Structure 8 in 2004 (C,P/P Block 3)

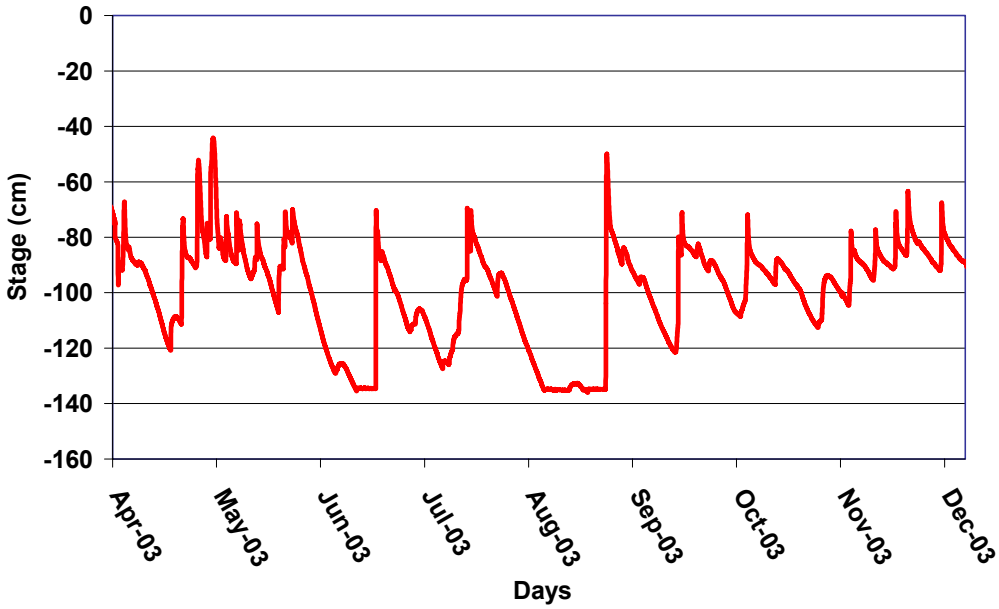


Figure A.37 Stage at Water Control Structure 9 in 2003 (CR,P/P Block 3)

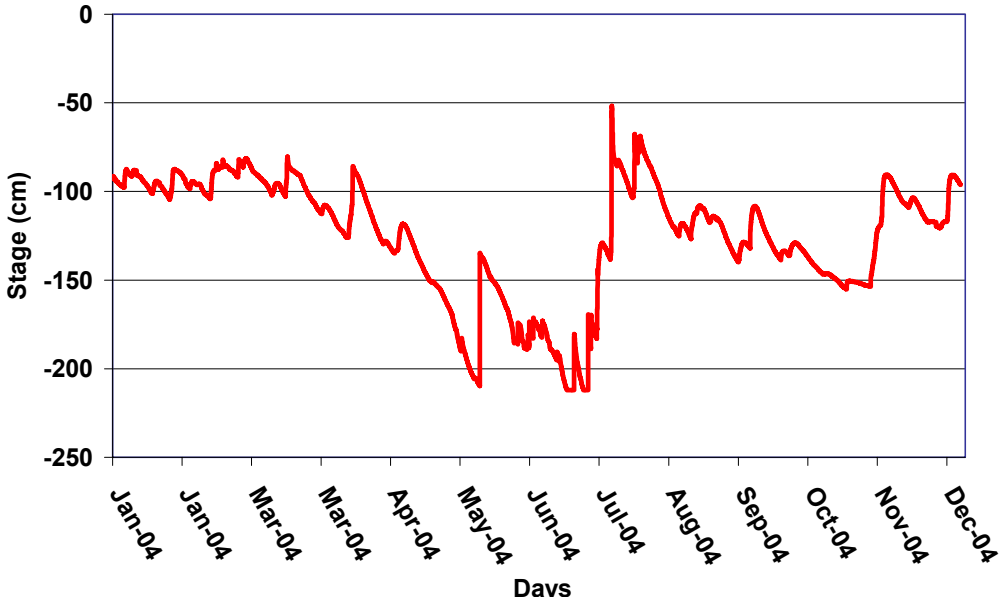


Figure A.38 Stage at Water Control Structure 9 in 2004 (CR,P/P Block 3)

Appendix B: Simulation Inputs and Results From DRAINMOD

Soil Water Characteristic

THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol Drained	Upward Flux
0	0	1.5
10	0.25	1.5
15	0.375	1.5
30	1.725	1.5
40	2.625	0.733
50	3.325	0.0508
60	4.025	0.0083
70	4.725	0.004
80	5.425	0.0008
90	6.125	0.0001
100	6.825	0.0001
110	7.525	0.0001
120	8.225	0.0001
130	8.925	0.0001
140	9.625	0.0001
150	10.325	0.0001
160	11.025	0.0001
170	11.725	0.0001
180	12.425	0.0001
190	13.125	0
200	13.825	0

Green_Ampt Parameters

Water Table	A	B
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.1 Soil Inputs Parameters For Plug and Plant Block 1

Soil Water Characteristic

THETA	HEAD
0.467	0
0.456	-7.6
0.455	-11.5
0.439	-18.1
0.406	-37.6
0.359	-67.6
0.33	-107.4
0.296	-210.3
0.269	-406.2
0.253	-611.7
0.245	-749.1
0.2067	-15000

Water Table	Vol Drained	Upward Flux
0	0	1.5
10	0.25	1.5
15	0.375	1.5
30	1.725	1.5
40	2.625	0.733
50	4.1255	0.0508
60	5.625	0.0083
70	7.125	0.004
80	8.625	0.0008
90	10.125	0.0001
100	11.625	0.0001
110	13.125	0.0001
120	14.625	0.0001
130	16.125	0.0001
140	17.625	0.0001
150	19.125	0.0001
160	20.625	0.0001
170	22.125	0.0001
180	23.625	0.0001
190	25.125	0
200	26.625	0

Green_Ampt Parameters

Water Table	A	B
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.2 Soil input parameters for Plug and Plant Block 2

Soil Water Characteristic

THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol Drained	Upward Flux
0	0	1.5
10	0.25	1.5
15	0.375	1.5
30	1.725	1.5
40	2.625	0.733
50	3.325	0.0508
60	4.025	0.0083
70	4.725	0.004
80	5.425	0.0008
90	6.125	0.0001
100	6.825	0.0001
110	7.525	0.0001
120	8.225	0.0001
130	8.925	0.0001
140	9.625	0.0001
150	10.325	0.0001
160	11.025	0.0001
170	11.725	0.0001
180	12.425	0.0001
190	13.125	0
200	13.825	0

Green_Ampt Parameters

Water Table	A	B
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.3 Soil Input Parameters for Contour Plug and Plant Block 1

Soil Water Characteristic

THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol Drained	Upward Flux
0	0	1.5
10	0.25	1.5
15	0.375	1.5
30	1.725	1.5
40	2.625	0.733
50	3.325	0.0508
60	4.025	0.0083
70	4.725	0.004
80	5.425	0.0008
90	6.125	0.0001
100	6.825	0.0001
110	7.525	0.0001
120	8.225	0.0001
130	8.925	0.0001
140	9.625	0.0001
150	10.325	0.0001
160	11.025	0.0001
170	11.725	0.0001
180	12.425	0.0001
190	13.125	0
200	13.825	0

Green_Ampt Parameters

Water Table	A	B
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.4 Soil input parameters for Contour Plug and Plant Block 2

Soil Water Characteristic

THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol Drained	Upward Flux
0	0	1.5
10	0.25	1.5
15	0.375	1.5
30	1.725	1.5
40	2.625	0.733
50	3.325	0.0508
60	4.025	0.0083
70	4.725	0.004
80	5.425	0.0008
90	6.125	0.0001
100	6.825	0.0001
110	7.525	0.0001
120	8.225	0.0001
130	8.925	0.0001
140	9.625	0.0001
150	10.325	0.0001
160	11.025	0.0001
170	11.725	0.0001
180	12.425	0.0001
190	13.125	0
200	13.825	0

Green_Ampt Parameters

Water Table	A	B
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.5 Soil input parameters for Crown Removal Plug and Plant Block 1

Soil Water Characteristic

THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol. Drained	Upward Flux
0	0	1
10	0.3	0.75
20	0.6	0.5
30	1.2	0.2567
40	1.8	0.0133
50	2.4	0.0108
60	3	0.0023
70	3.65	0.001
80	4.3	0.0008
90	4.75	0.0001
100	5.2	0.0001
110	5.45	0.0001
120	5.7	0.0001
130	5.9	0.0001
140	6.2	0.0001
150	6.6	0.0001
160	7	0.0001
170	7.4	0.0001
180	7.8	0.0001
190	8.2	0
200	8.6	0

Greem Ampt

Water Table	A	B
6		
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.6 Soil input parameters for Crown Removal Plug and Plant Block 2

Soil Water Characteristic

THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol. Drained	Upward Flux
0	0	1.5
5	2.5	1.5
10	5	1.5
15	7.5	1.5
20	10	1.5
30	11	1.5
40	12	0.733
50	13	0.0508
60	14	0.0083
70	15	0.004
80	16	0.0008
90	17	0.0001
100	18	0.0001
110	19	0.0001
120	20	0.0001
130	21	0.0001
140	22	0.0001
150	23	0.0001
160	24	0.0001
170	25	0.0001
180	26	0.0001
190	27	0
200	28	0

Greem Ampt

Water Table	A	B
6		
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.7 Soil Input Parameters for the Wet Area of the Reference

Soil Water Characteristic

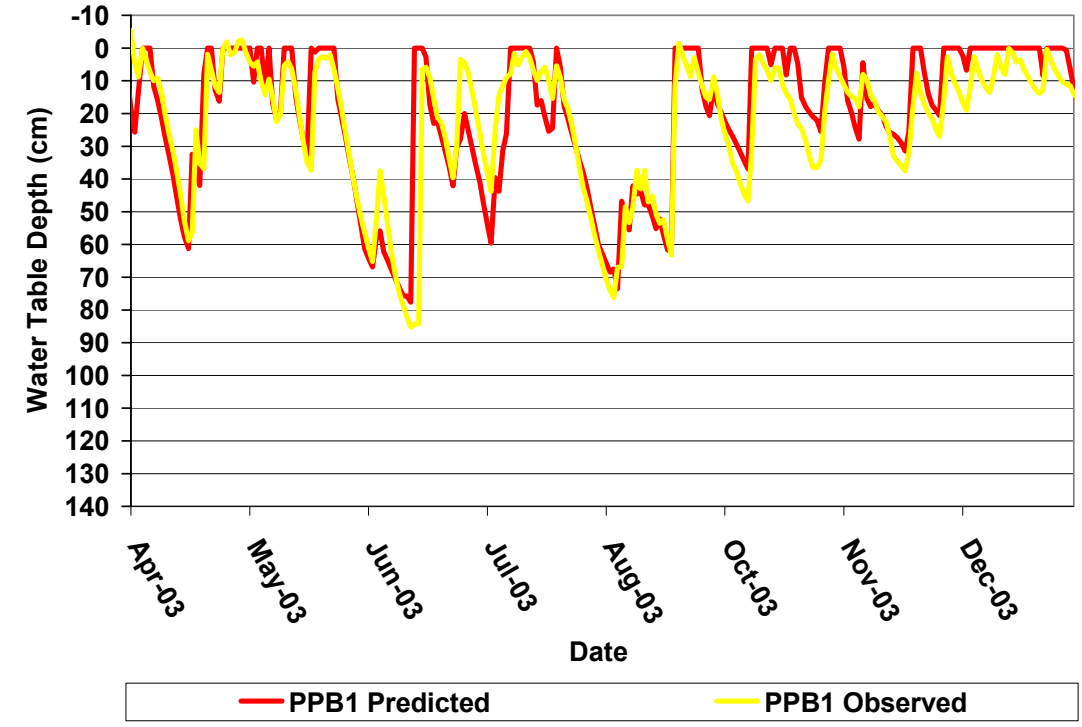
THETA	HEAD
0.562	0
0.556	-7.6
0.551	-11.5
0.54	-18.1
0.508	-37.6
0.484	-67.6
0.463	-107.4
0.432	-210.3
0.407	-406.2
0.389	-611.7
0.379	-749.1
0.379	-15000

Water Table	Vol. Drained	Upward Flux
0	0	1.5
10	1	1.5
20	2	1.5
30	4	1.5
40	6	0.733
50	8	0.0508
60	10	0.0083
70	12	0.004
80	14	0.0008
90	16	0.0001
100	18	0.0001
110	20	0.0001
120	22	0.0001
130	24	0.0001
140	26	0.0001
150	28	0.0001
160	30	0.0001
170	32	0.0001
180	34	0.0001
190	36	0
200	38	0

Greem Ampt

Water Table	A	B
6		
0	0	0
25	0.5	7.4
50	0.5	5.2
250	0.7	2
500	1	2
1000	1	2

Figure B.8 Soil Input Parameters for the Dry Area of the Reference



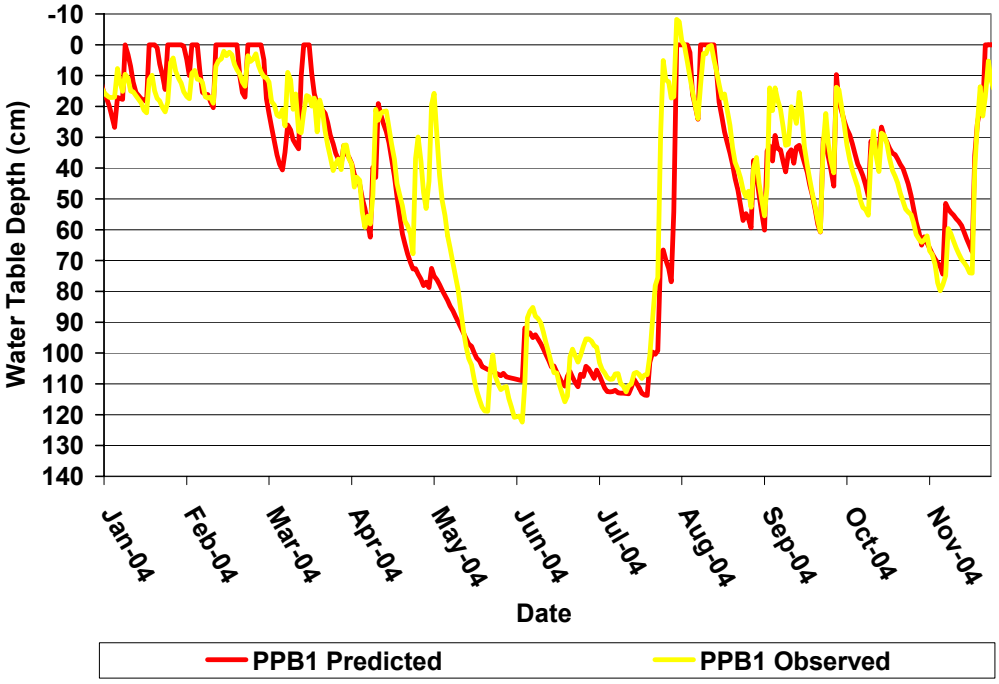


Figure B.9 Comparison of Observed Water Table Depth To Simulated Water Table Depth For Plug and Plant Block 1

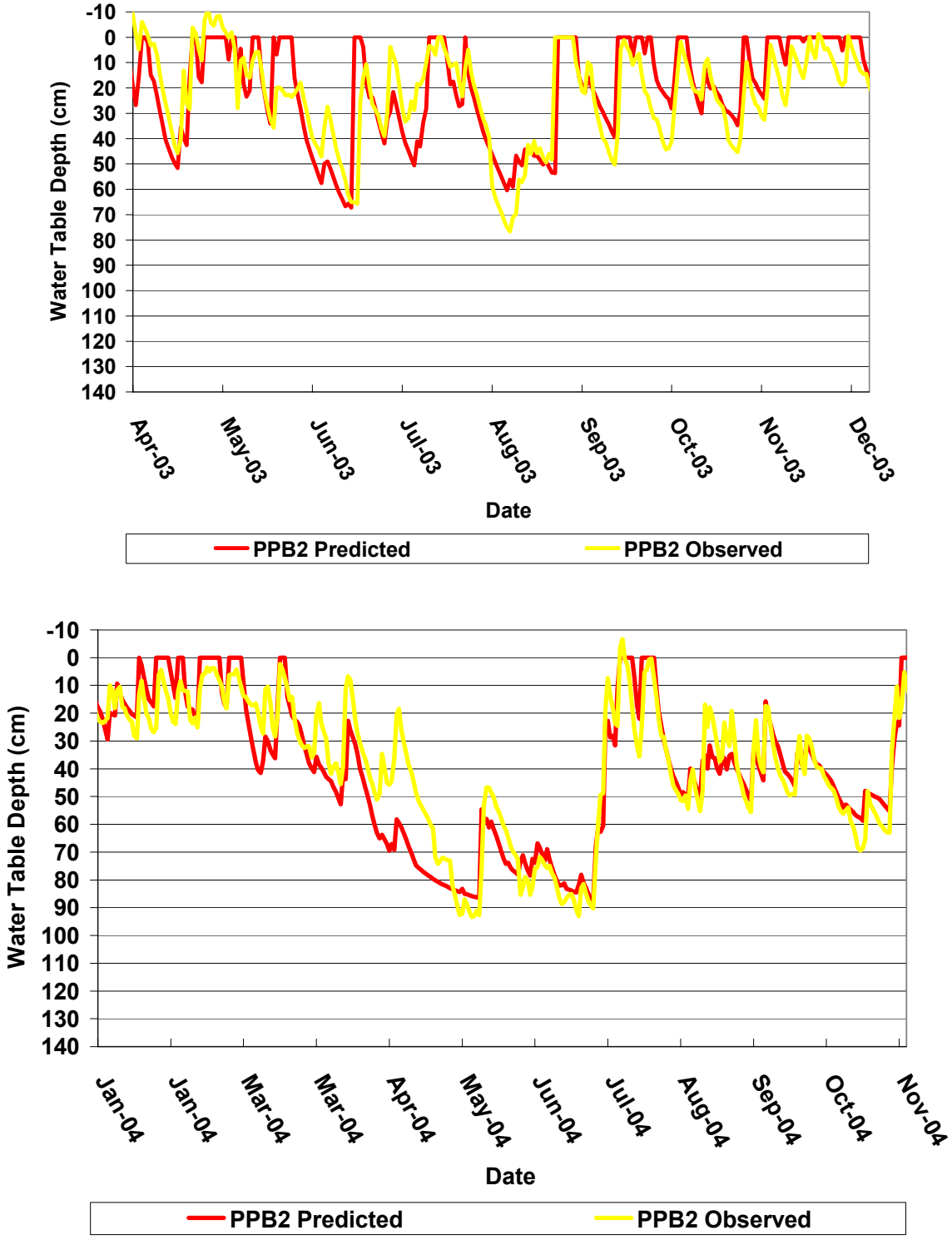


Figure B.10 Comparison of Observed Water Table Depth To Simulated Water Table Depth For Plug and Plant Block 2

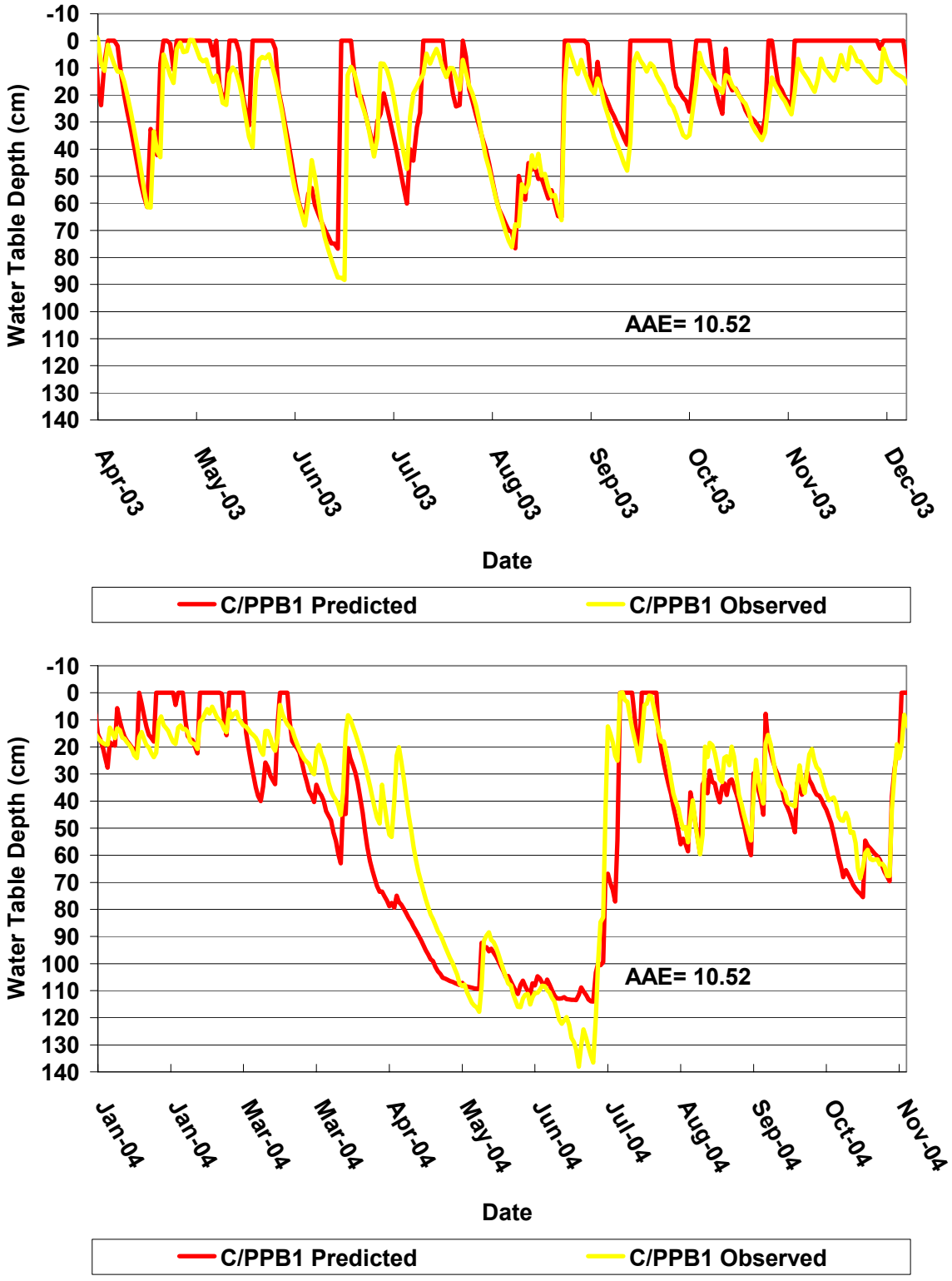


Figure B.11 Comparison of Observed Water Table Depth To Simulated Water Table Depth For Contour Plug and Plant Block 1

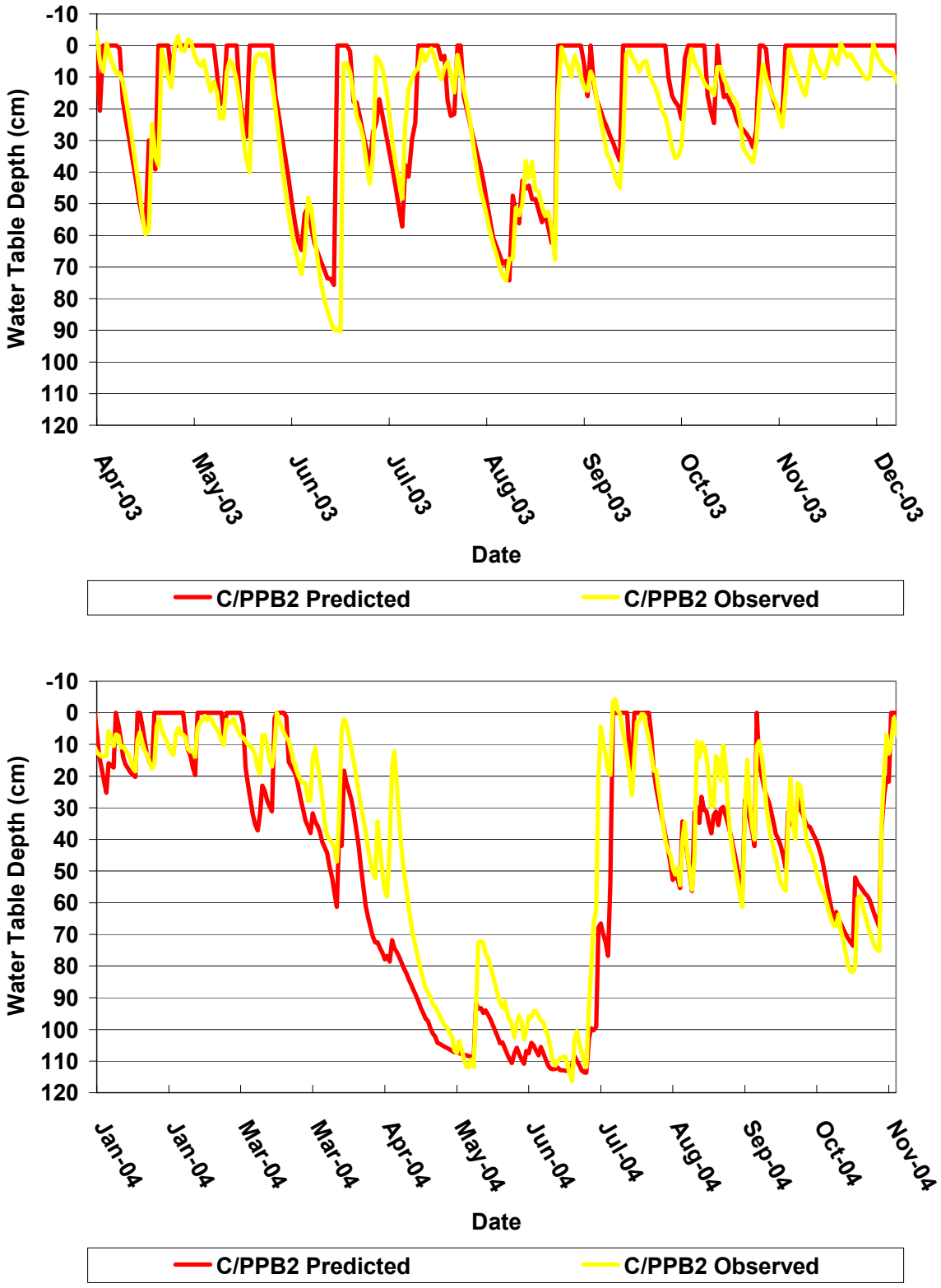


Figure B.12 Comparison of Observed Water Table Depth To Simulated Water Table Depth For Contour Plug and Plant Block 2

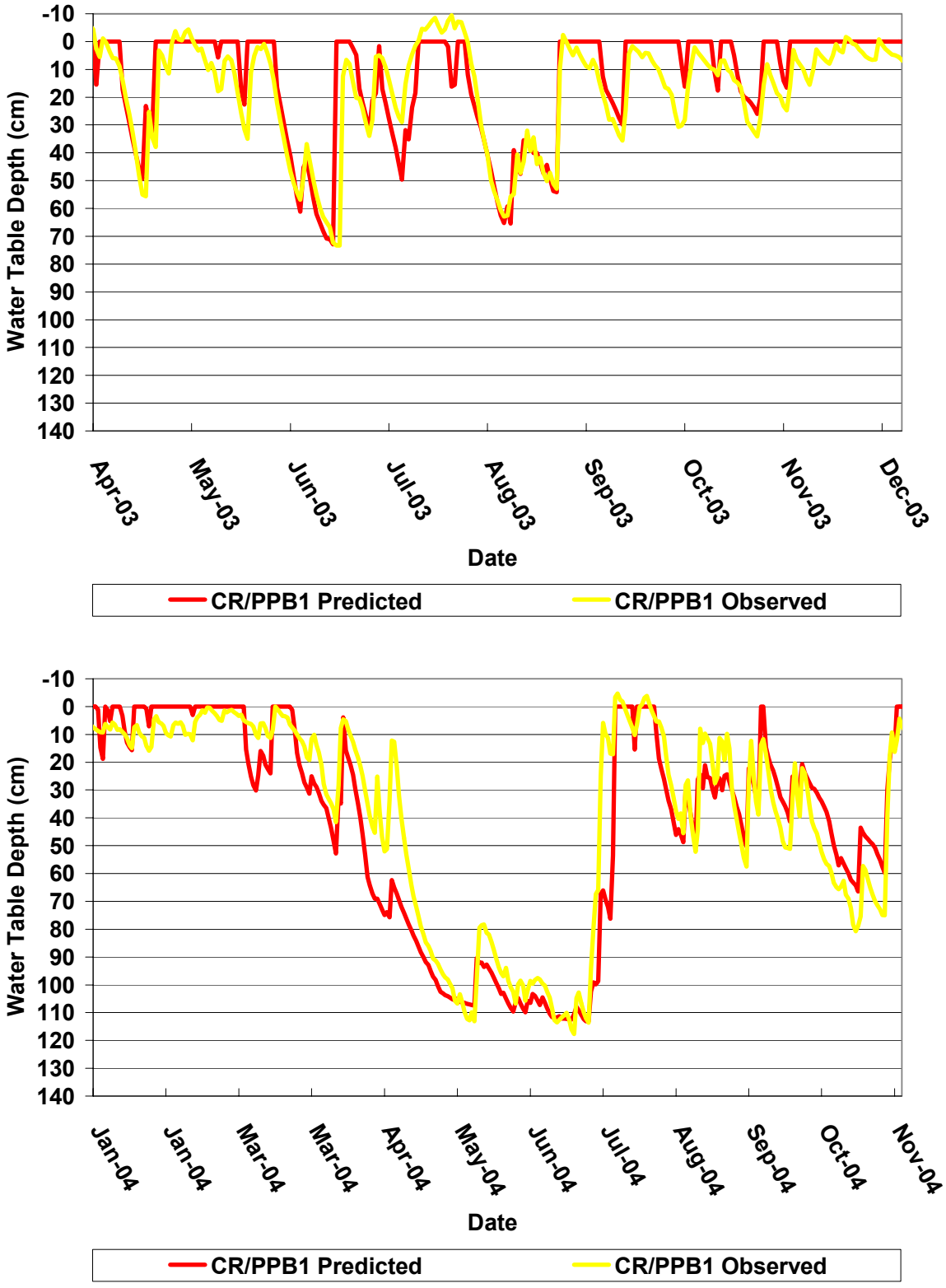


Figure B.13 Comparison of Observed Water Table Depth To Simulated Water Table Depth For Crown Removal Plug and Plant Block 1

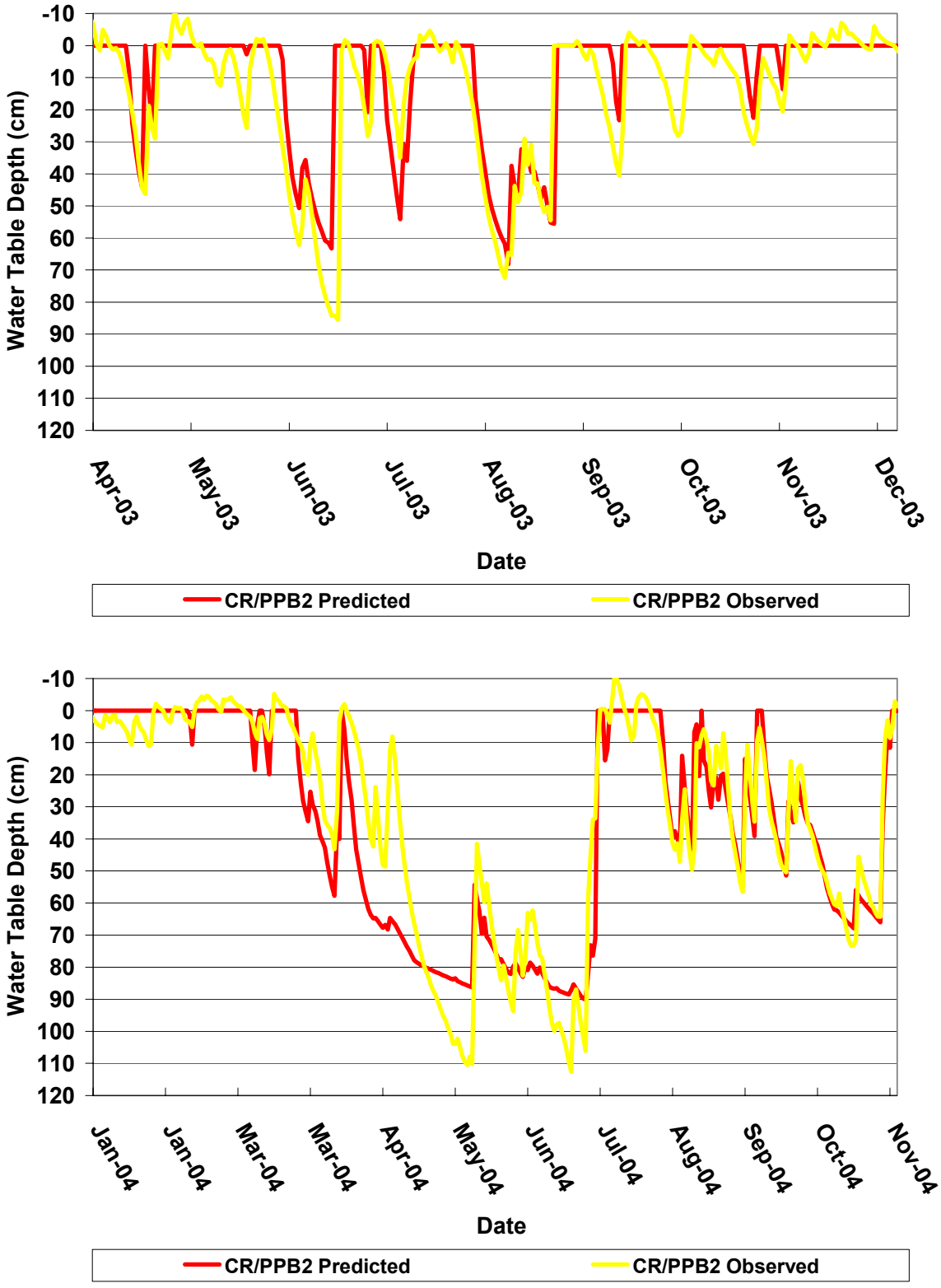


Figure B.14 Comparison of Observed Water Table Depth To Simulated Water Table Depth For Crown Removal Plug and Plant Block 2

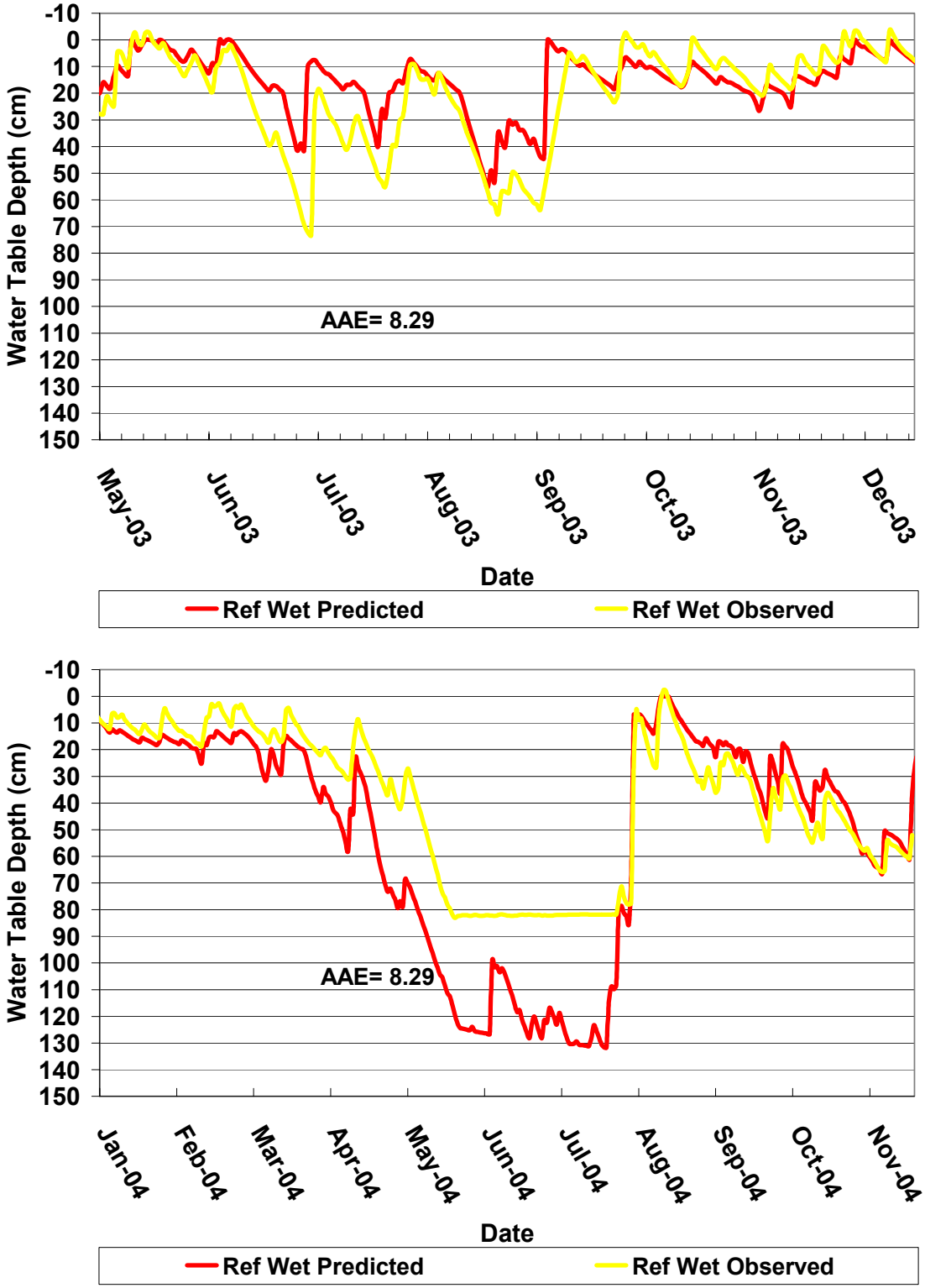
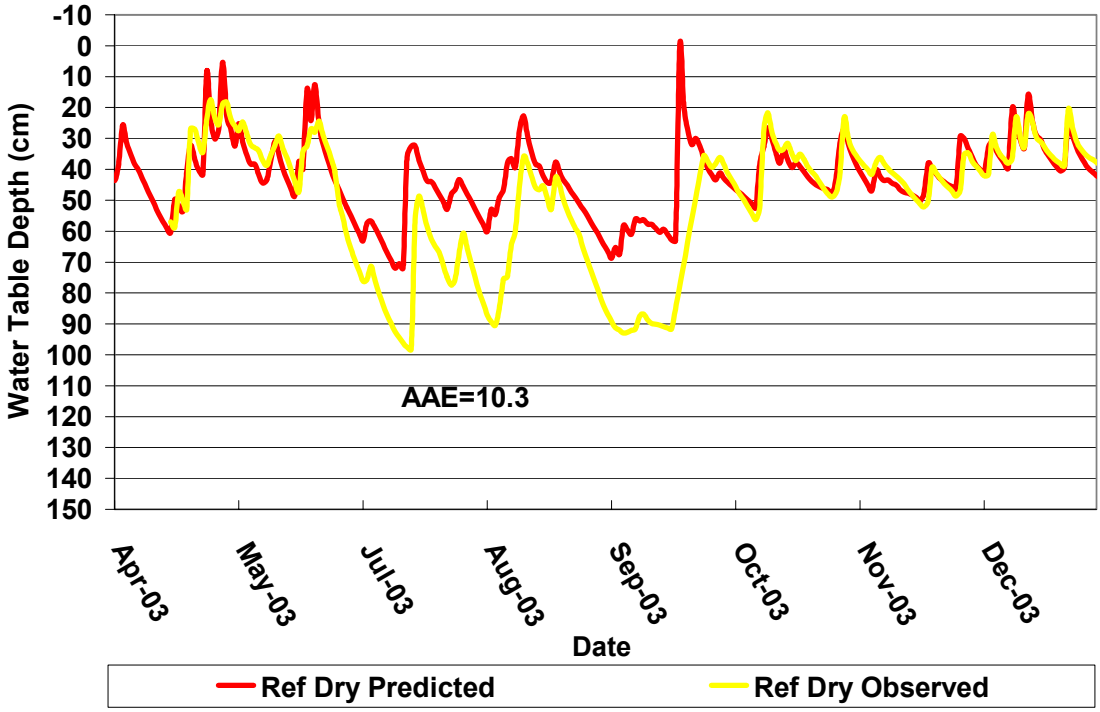
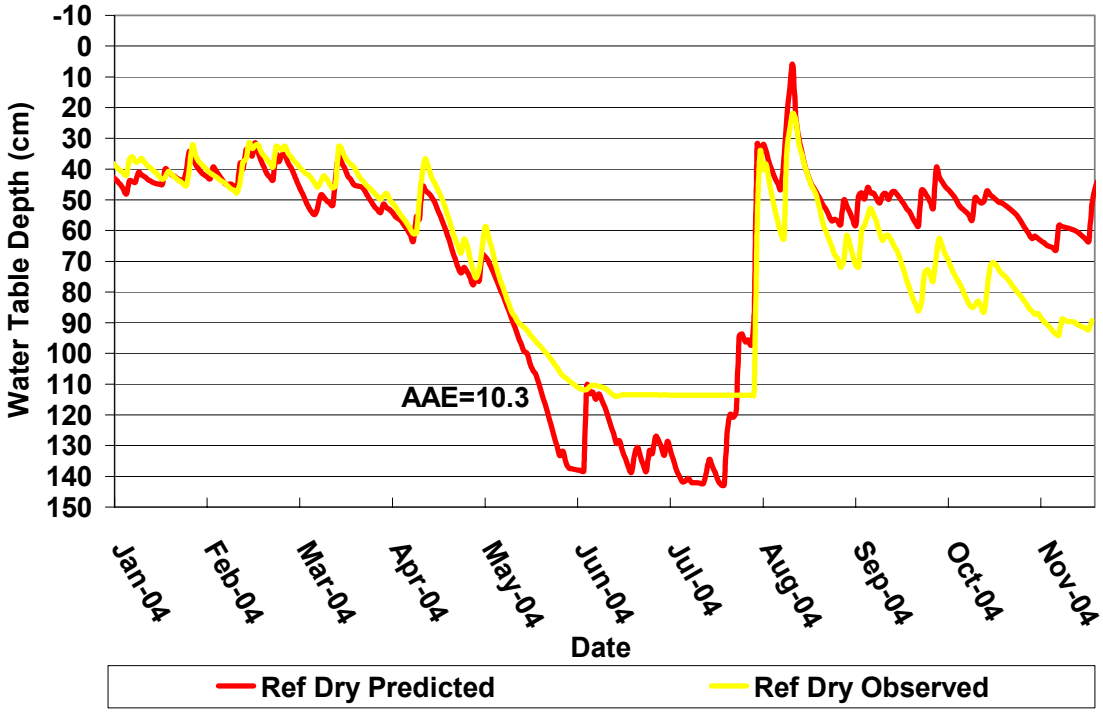


Figure B.15 Comparison of Observed Water Table Depth To Simulated Water Table Depth in the Wet Area of the Reference





B.16 Comparison of Observed Water Table Depth To Simulated Water Table Depth in the Dry Area of the Reference

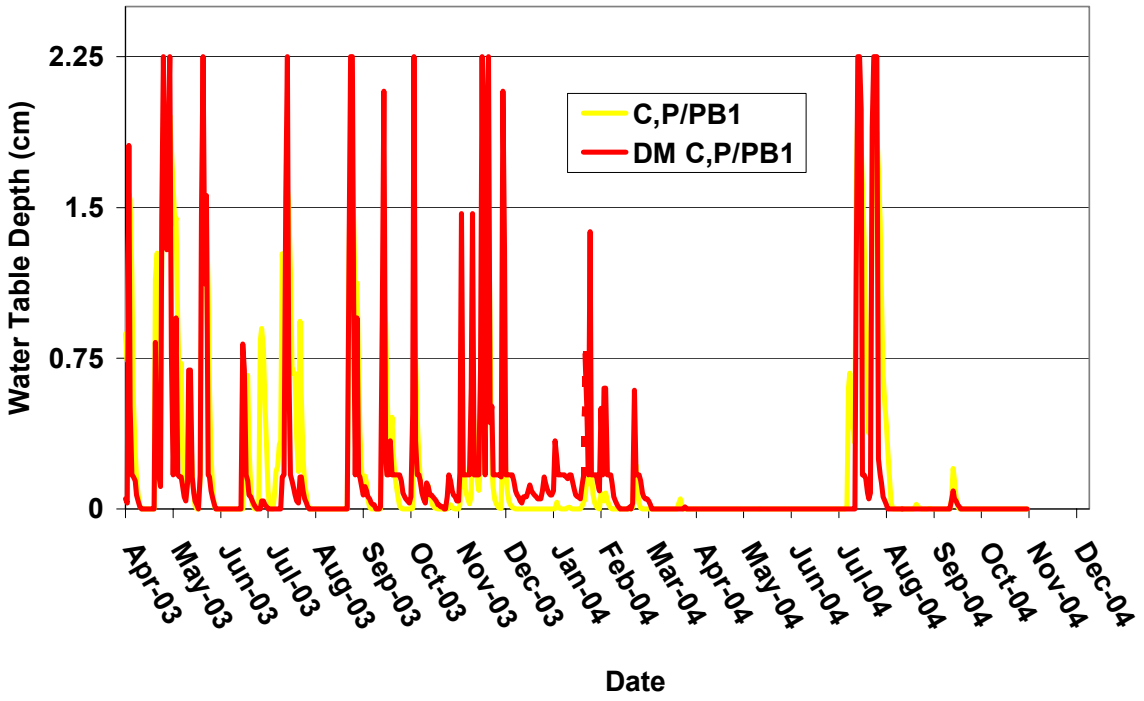


Figure B.17 Comparison of Observed Flow to Simulated Flow in the C,P/P Block 1 Treatment

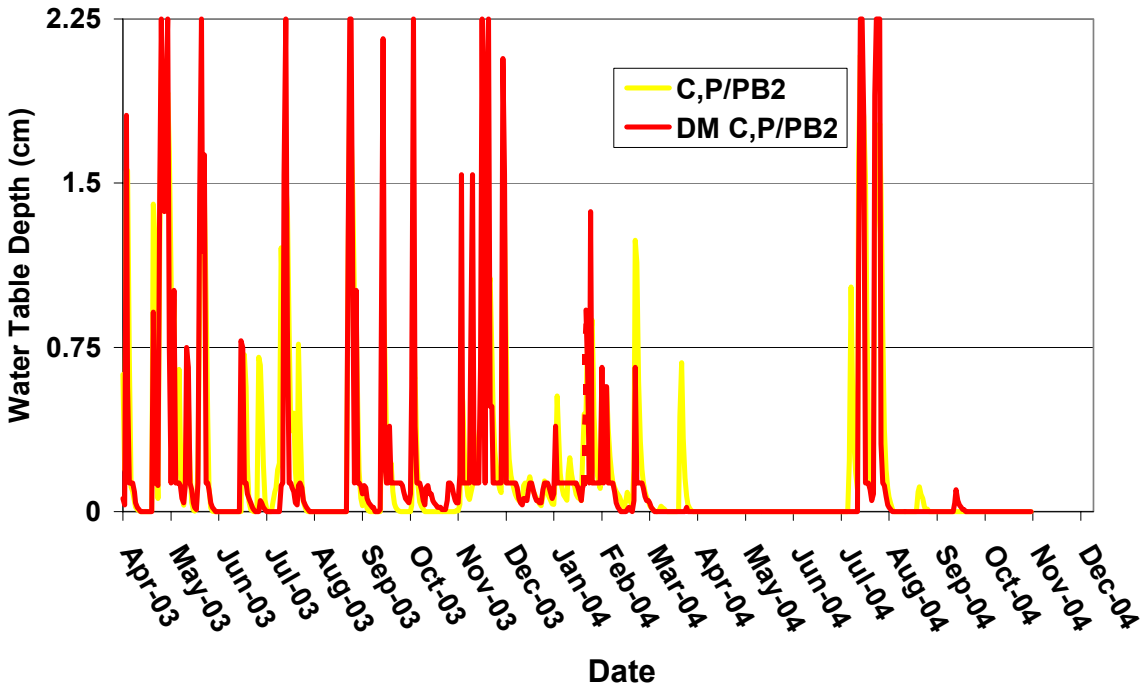


Figure B.18 Comparison of Observed Flow to Simulated Flow in the C,P/P Block 2 Treatment

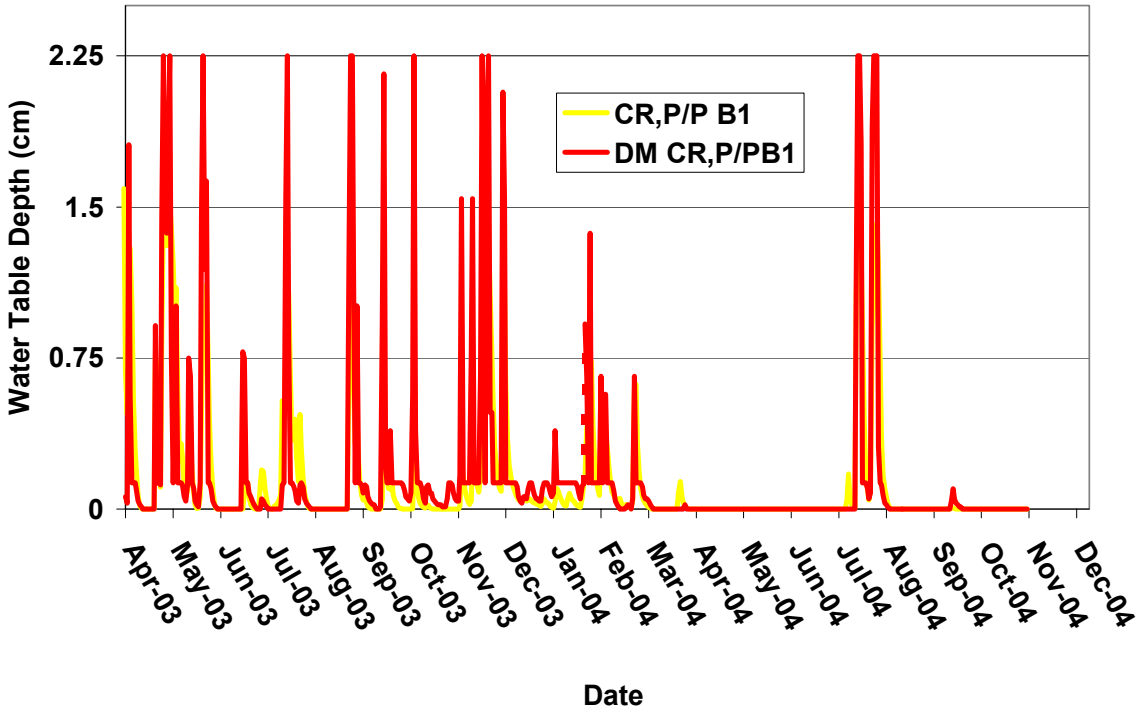


Figure B.19 Comparison of Observed Flow to Simulated Flow in the CR,P/P Block 1 Treatment

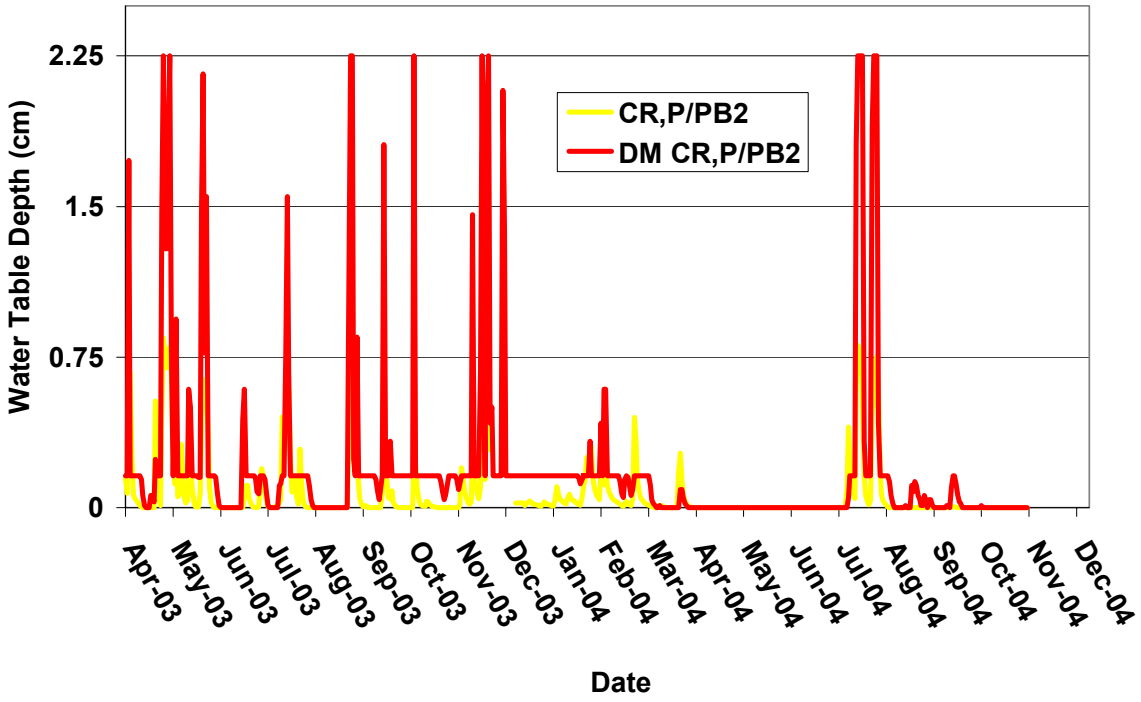


Figure B.20 Comparison of Observed Flow to Simulated Flow in the CR,P/P Block 2 Treatment

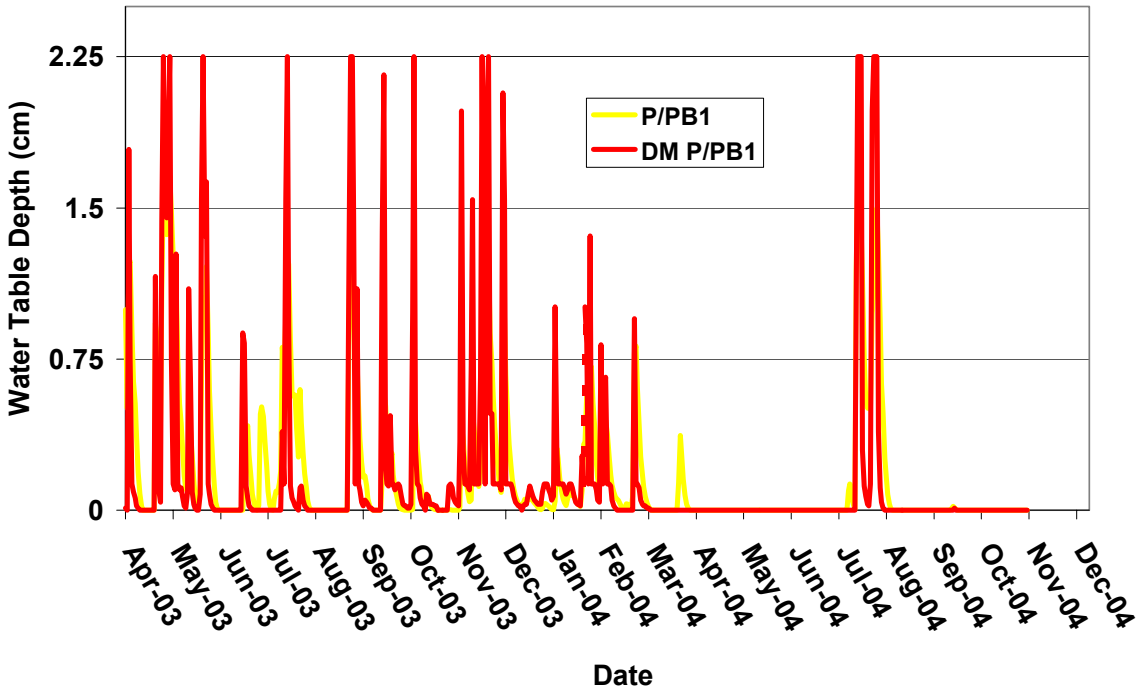


Figure B.21 Comparison of Observed Flow to Simulated Flow in the P/P Block 1 Treatment

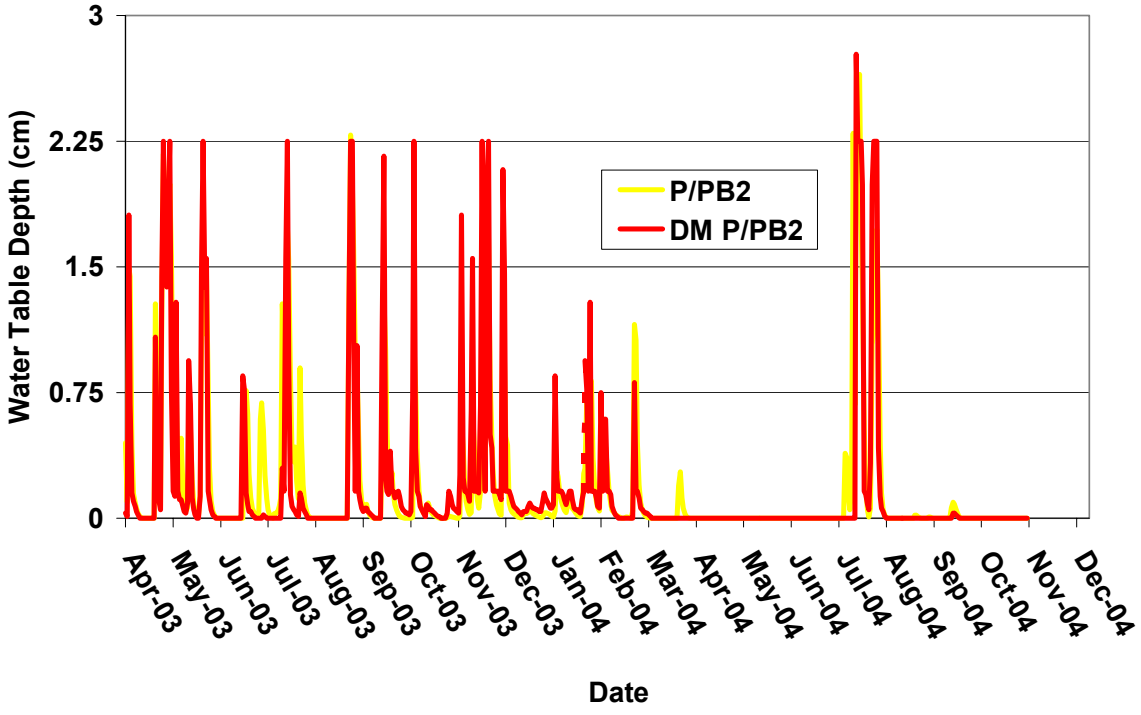


Figure B.22 Comparison of Observed Flow to Simulated Flow in the P/P Block 2 Treatment

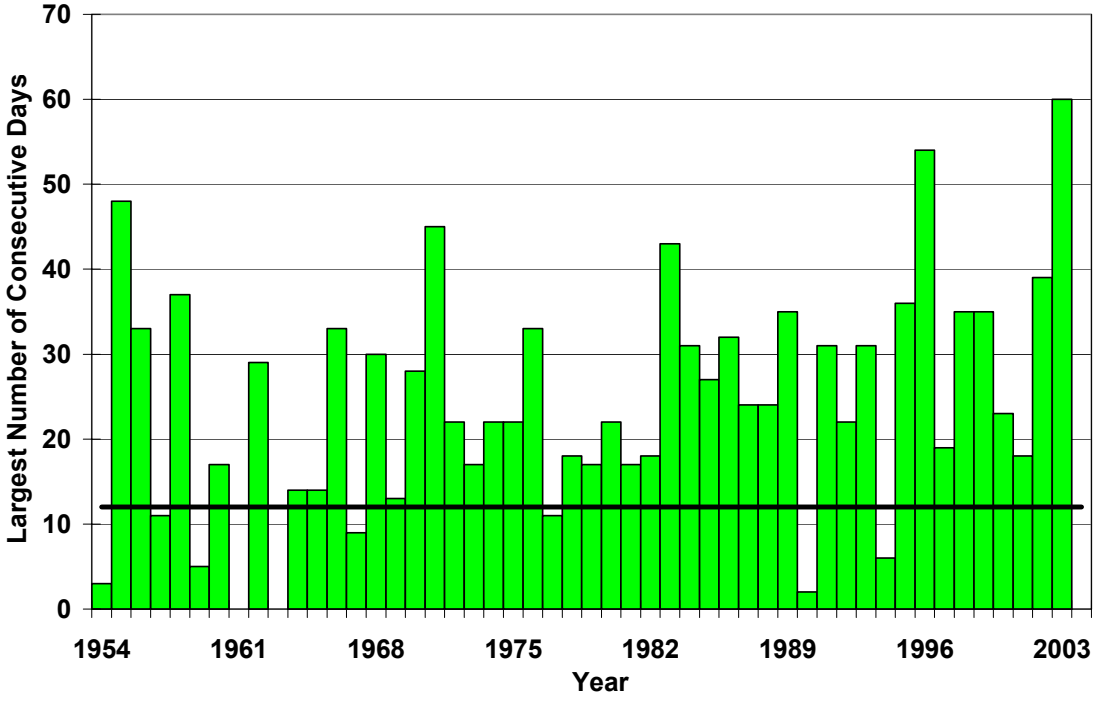


Figure B.23 Longest Consecutive Days Per Year in the C,P/P Block 1 Treatment

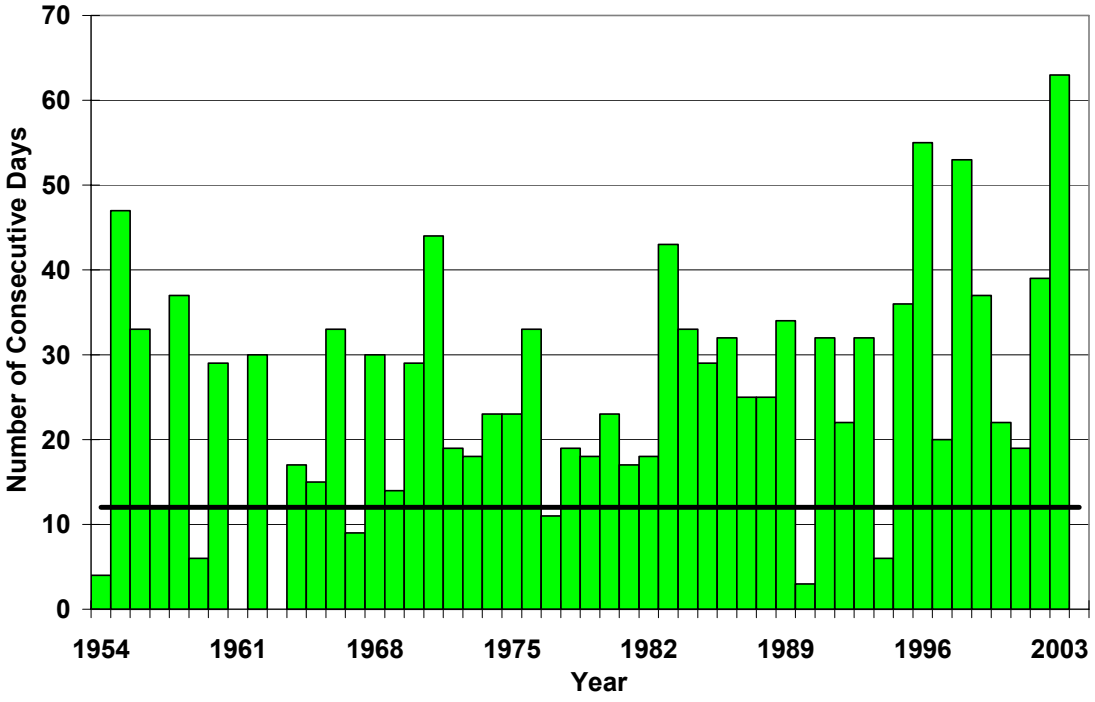


Figure B.24 Longest Consecutive Days Per Year in the C,P/P Block 2 Treatment

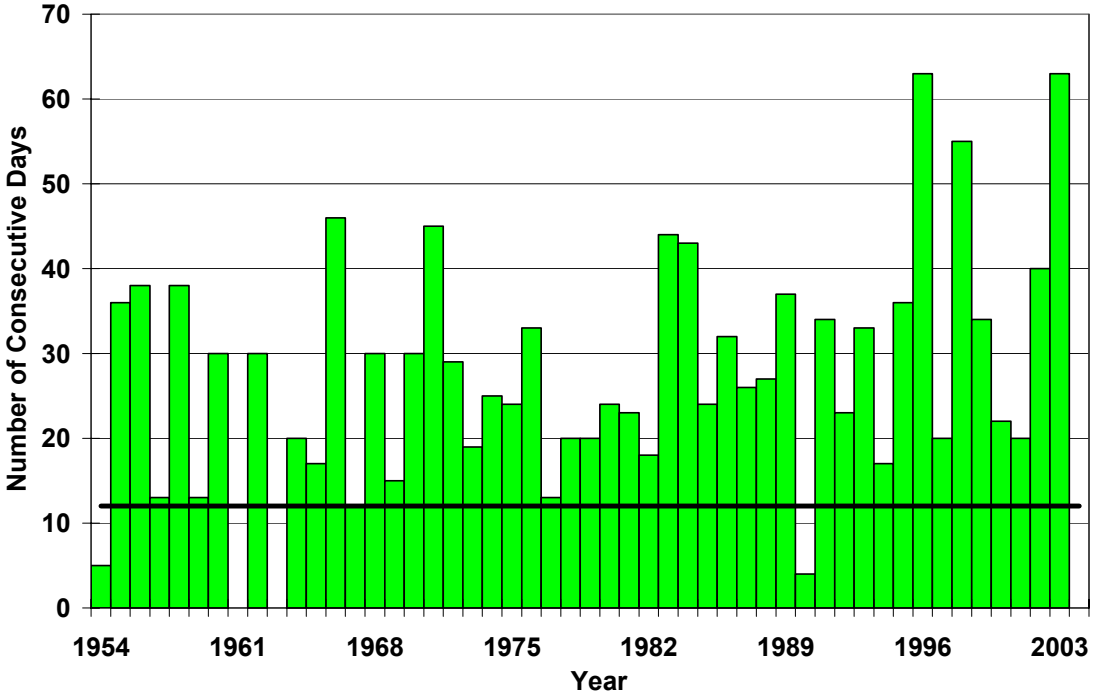


Figure B.25 Longest Consecutive Days Per Year in the CR,P/P Block 1 Treatment

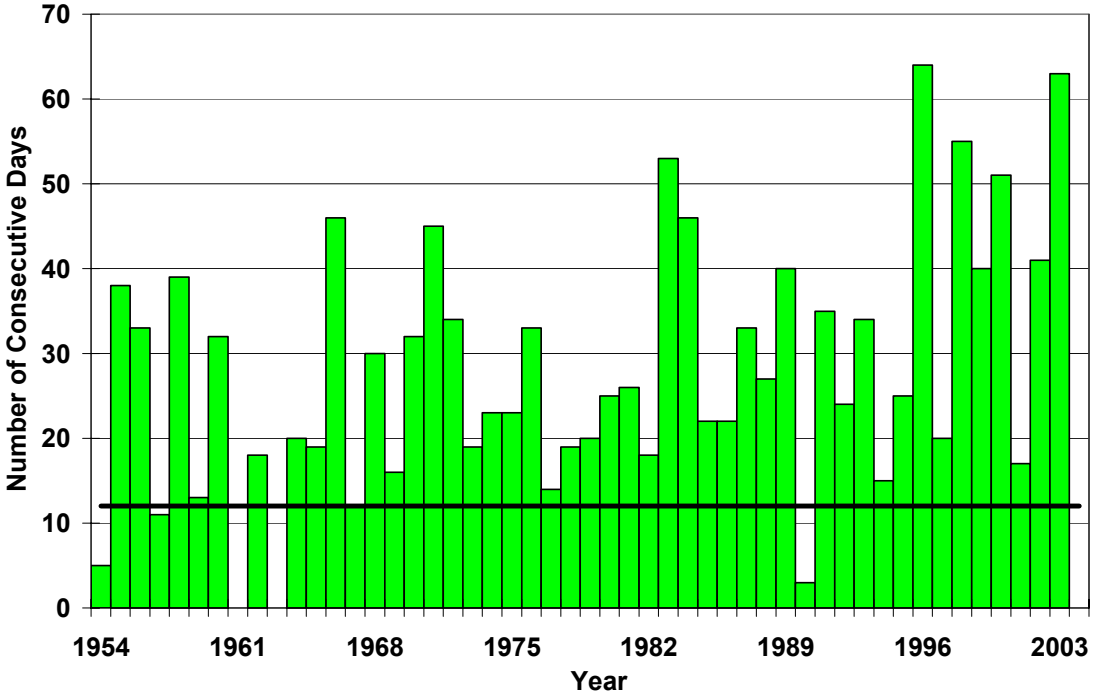


Figure B.26 Longest Consecutive Days Per Year in the CR,P/P Block 2 Treatment

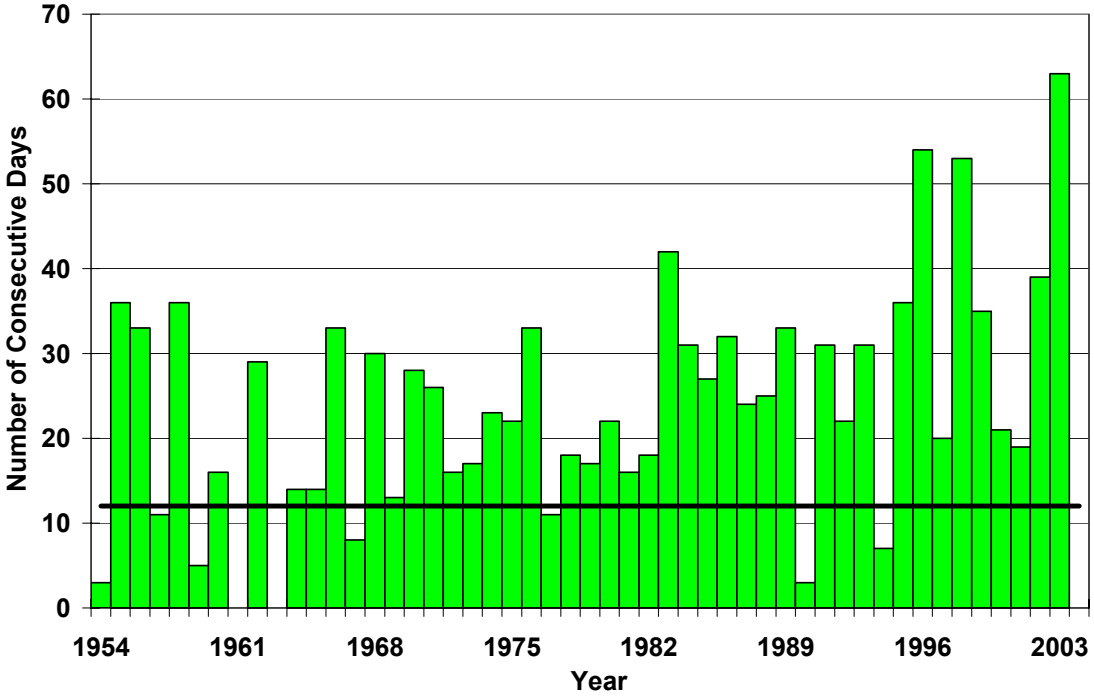


Figure B.27 Longest Consecutive Days Per Year in the P/P Block 1 Treatment

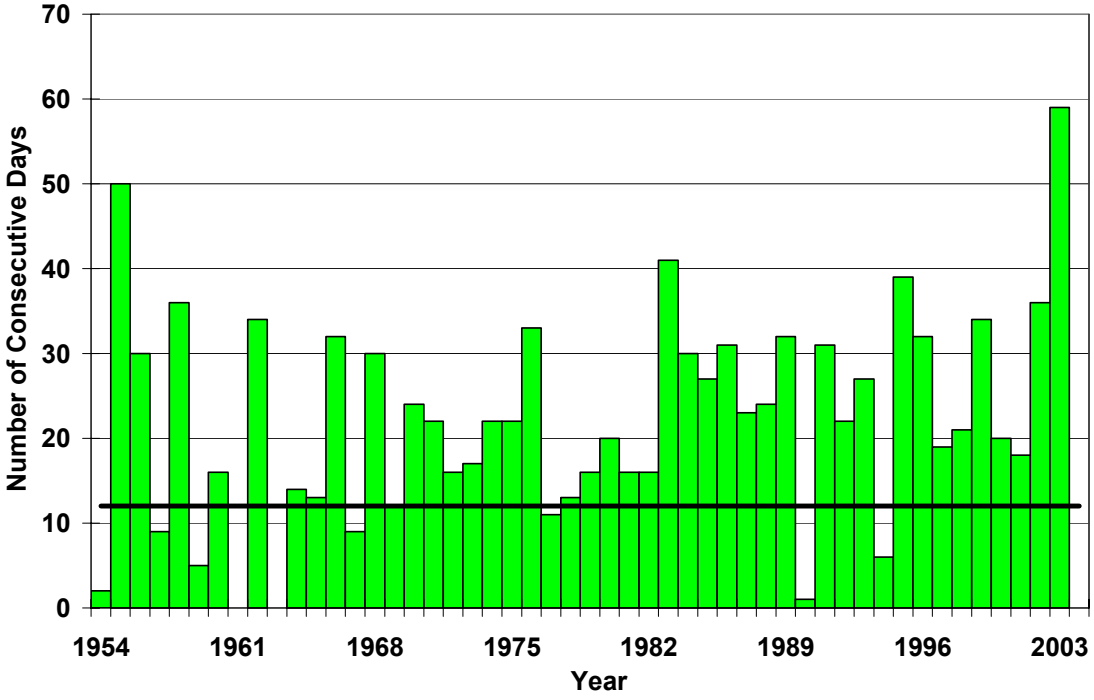


Figure B.28 Longest Consecutive Days Per Year in the P/P Block 2 Treatment