ABSTRACT

JARZEMSKY, ROBERT D. Hydrologic Evaluation of a Restored Wetland in Eastern North Carolina. (Under the direction of Dr. Michael Burchell).

A prior-converted wetland in coastal North Carolina was restored in an attempt to re-establish a non-riverine hardwood wet forest Community. Topography was restored using three surface techniques to determine the effect surface topography had on wetland hydrology in coastal areas. The three treatments were: plugging field ditches without altering the surface (PLUG), plugging the field ditches and contouring the surface (CONT), and plugging the field ditches and removing the field crown (CR). The treatments were replicated three times forming a randomized complete block design. It was hypothesized that CR would produce the wettest site followed by CONT and then PLUG. A nearby reference wetland was also monitored and evaluated.

Water table response and surface outflow was evaluated for 2006-2008. Few significant differences were found between the water tables of each treatment; however CR and PLUG appeared wetter than CONT. Surveying of the restoration revealed that the as-built topography of the PLUG and CONT treatments in block 3 were different than their intended design causing PLUG to produce wetter conditions and CR to produce drier conditions than intended.

Based on these observations, the treatments were re-evaluated using only blocks 1 and 2, and using all three blocks with block 3 PLUG and CR data switched. These evaluations found CR produced the wettest hydrology followed by CONT and then PLUG, which matched the original hypothesis.

Based on the alternate evaluations, CR produced wetter conditions than the reference (3 of 4 hydrologic criteria were significantly wetter) while PLUG produced drier conditions

than the reference (3 of 4 hydrologic criteria were drier). CONT matched reference hydrology the closest but only one hydrologic criteria was not significantly different than the reference ($\alpha = 0.05$). All three treatments produced significantly more surface inundation than the reference likely due to pre-restoration surface compaction and organic subsidence due to farming practices and also some soils differences.

Surface outflow evaluation found that CONT produced significantly more outflow than PLUG and CR. PLUG was hypothesized to produce the most outflow, but it is believed that CONT produced the most outflow due to conveyance pathways which may have formed in the contours.

A second study, evaluated the hydrology of the restored wetland during tropical weather. Three periods were evaluated from 2004 – 2007. In 2004, a 34 day period of tropical weather including, Hurricane Alex and Tropical Storm Charley produced 41 cm of rainfall and 21 cm of outflow. In 2005, a 15 day period including Hurricane Ophelia produced 33 cm of rainfall and 11 cm of outflow, and in 2007, an 11 day period including Tropical Storm Gabrielle produced 21 cm of rainfall and 7.5 cm of outflow.

The restored wetland performed similarly during 2005 and 2007, retaining 67% and 64% of the rainfall. During 2004, the restored wetland retained only 49% of the rainfall. It performed less efficiently due to lower antecedent soil moisture condition and increased rainfall. Soil moisture conditions were high prior to both Alex and Charley which limited the wetlands ability to store water. Prior to Ophelia and Gabrielle, soil moisture conditions were low which provided large amounts of water-free pore space in the soil for storage.

DRAINMOD was used to simulate pre-restoration, agricultural hydrology. DRAINMOD predicted the restoration reduced peak daily outflow during all three storm

periods by at least 70%. Total outflow reduction was found to be dependent on soil moisture conditions. In 2005 and 2007 antecedent soil moisture conditions were low; the simulation predicted the restoration reduced total outflow by 44% and 29%. In 2004, soil moisture conditions were high prior to Hurricane Alex and Tropical Storm Charley and the simulation predicted the restoration did not reduce total outflow. The modeling predicted the restoration reduced annual outflow by 6 – 31% depending on the year.

Hydrologic Evaluation of a Restored Wetland in Eastern North Carolina

by
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Biography

Robert (Bobby) Jarzemsky grew up in Raleigh, North Carolina with his parents, Dave and Marge and his older sister Laurie. His parents still reside in Raleigh, while Laurie now lives in New York City. After graduating from Sanderson High School in Raleigh in 2002 Bobby attended NC State where he pursued a degree in civil engineering. Though initially interested in structures and construction, a few courses on structural analysis and an internship in the construction industry convinced him to focus on water resources and the environment. Upon graduation in December 2006, Bobby accepted an offer to study ecological engineering under Dr. Mike Burchell in the BAE department also at NC State; his research focused on wetland restoration. Following completion of his Master's degree Bobby plans to focus on restoring ecosystems and protecting our natural resources.

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I would like to first thank my committee chair, Mike Burchell for being an advisor, mentor, and friend. I would also like to thank my other committee members, Greg Jennings and Mike Vepraskas for their guidance and support throughout this project.

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I also like to thank all the friends I've made a long the way in BAE. My grad school experience would not have been the same if it wasn't for all the people which make this department great. I was lucky to have officemates who were often willing to put their real work on the backburner to hang out and talk. There are few things better than spending two years with a bunch of people who love the Wolfpack and hate UNC.

I have been very lucky to share my graduate school experience with my wonderful girlfriend Lorna, who currently pursuing her own Master's degree in Landscape Architecture. Thank you for pretending to listen to me ramble on about wetland hydrology and microtopography.

Finally I would like to thank my family for all of their support and groceries over the last few years.

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1. INTRODUCTION TO COASTAL PLAIN RESTORATION

Wetlands serve an important role to both the human and natural landscape. Wetlands provide flood mitigation, prevent erosion, improve the quality of both surface and groundwater, and serve as an important habitat to many plant and animal species (Dennison and Berry, 1993). In the United States, 95% of commercially harvested fish and 50% bird species are wetland dependent (EPA, 2001). Many of the environmental benefits were diminished as millions of hectares of wetlands were altered and destroyed in the twentieth century. Nationally, it is estimated that only 53% of the original 89 million hectares remained by the 1980s (Dahl, 1990). Similarly, in the North Carolina coastal plain less than 50% of the original wetlands remain unaltered (Cashin et al., 1992). Alterations have affected both freshwater and estuarine wetlands, but recently (1986-1997) 98% of wetland losses have been freshwater (Dahl, 2000).

For a site to be delineated as wetland, it must exhibit three parameters: 1) wetland hydrology, 2) hydric soil, and 3) hydrophytic vegetation. The presence of wetland hydrology requires that the soil is saturated long enough to support the formation of anaerobic conditions and support the growth of hydrophytic vegetation. Research has shown that saturation usually must occur for at least three weeks to promote anaerobic conditions. However factors such as availability of iron-oxides and organic carbon as well as soil temperature can affect the required saturation time (Vepraskas et al., 2006).

When Fe(II) is detected in a soil, it is considered both anaerobic and reduced (McBride, 1994). The United States Army Corps of Engineers (USACE) defines jurisdictional wetland hydrology in its Wetland Delineation Manual (Environmental Laboratory, 1987). The jurisdictional criterion defines hydrology as the water table being within 30 cm of the surface for a continuous period of 5% of the growing season for at least 50% of the years. The growing season is defined as the period between the last average frost in the spring and the first average frost in the fall for that particular area. The frost free period is an approximation of the time period when the average daily soil temperature is above 5^{o} Celsius, considered by some researchers as biological zero. Wetland hydrology must be exhibited during the growing season because it is generally assumed that microbial activity necessary to generate anaerobic conditions ceases below biological zero (Environmental Laboratory, 1987). This criterion is based on hydrologic criteria established during a workshop by Clark and Benforado (1981), which determined that the water table must be within 30 cm for a continuous period of 5-12.5% of the growing season in 50% of years to exhibit minimum wetland hydrology. A site was only considered to definitely exhibit wetland hydrology if the water table remains within 30 cm for more than 12.5% of the growing season.

Both nationally and locally, one of the main reasons for converting wetlands has been agriculture. Between the 1950s and 1980s, 95% of wetland alterations were caused by the agriculture and forestry industries (Cashin et al., 1992). In many cases forestry conversion only degrades wetland, which allows some function and value to remain.

Agriculture usually results in the full conversion to upland which not only destroys the local wetland function but also may increase the potential for environmental harm from agricultural practices themselves (i.e. export of nutrient and pesticides through drainage water).

The North Carolina coastal plain is comprised of a large percentage of poorly drained soils. It is estimated that 52% of the land area in the coastal plain once contained hydric (wetland) soils (Cashin et al., 1992). Because of this poorly drained soil, more than 40% of agriculture lands require artificial drainage, which has been linked to water quality degradation (Thomas et al., 1995). Studies show that subsurface drainage can lead to a ten fold increase in NO_3-N losses compared to undrained areas (Gilliam and Skaggs., 1986). Similarly, NO_3-N losses were found to increase as drainage intensity increased (Skaggs et al., 2005). Agricultural development has also been found to increase peak runoff rates by 300-400% and lead to higher sediment and fecal organism loadings into drainage waters (Skaggs et al., 1980). Although research and implementation of newer farming practices such as controlled drainage (Evans et al., 1995) and the use of shallow subsurface drains (Burchell et al., 2005) may lead to a reduction in NO_3-N losses, the strategic restoration of prior converted (PC) wetlands in these agricultural watersheds has the potential to reverse water quality degradation.

Alterations of wetlands are regulated jointly by the United States Army Corps of Engineers (USACE) and the Environmental Protection Agency (EPA). Dredged or fill material cannot be discharged into United States waters without a permit issued under section 404 of the Clean Water Act (National Research Council, 2001). The Clean Water Act did not originally apply to wetlands because they were not considered waters of the United States. Later amendments and court decisions broadened the scope of the law to not just include navigatable waters but all waters, including wetlands. The Swampbuster Provisions of the Food Security Act of 1985 also plays a large role in protecting wetlands in agricultural lands. The Food Security Act discourages the conversion of wetlands for agricultural production by offering loans, subsidies, and insurance to farmers with the stipulation that benefits cannot be received if agricultural commodities are produced on a wetland which was converted after December 1985 (FWS, 2003). To receive a permit to alter a wetland, the USACE requires compensatory mitigation in the form of wetland enhancement, restoration, or creation in an effort to achieve zero net loss of wetland function (National Research Council, 2001).

Over the past twenty years, there has been a major focus on preserving and restoring wetlands by both governmental and nongovernmental organizations (NGO). For example, on the federal level, the Wetland Reserve Program (WRP) has restored over 1 million aces of prior converted wetlands nationally with over 6,500 projects (NRCS, 2002). Thousands of acres have also been restored through state agencies and through NGOs such as mitigation banks and non-profit groups.

More research is needed to ensure a better success rate for restoration projects. There are large costs associated with wetland restoration and many have not been successful (Kusler and Kentula, 1990). Holman and Childress (1995) estimate that 40-

50% of wetland restoration problems are caused from poor site selection. A proper reference location must also be selected as a blue print for the restoration. The restored site should be designed to mimic the reference site. After construction, the reference should be used to measure the success of the restoration (Brinson and Rheinhardt, 1995). Using a reference based approach to restoring hydrology is a better strategy than simply trying to achieve saturation between 5-12.5% of the growing season because it targets a specific wetland community native to the surrounding area.

Restoration success is usually determined by reestablishing wetland structure (hydrology and vegetation), with little emphasis placed on restoring wetland function (biogeochemical). A study by Hunter and Faulkner (2001) found that restored bottomland hardwood wetlands had a lower denitrification potential than natural ones. The study also concluded that denitrification was linked to wetland hydrology. Wetlands with fully restored hydrology removed more nitrogen than wetlands with partially restored hydrology. Wetland hydrology is also imperative for restoring wetland soils and vegetation. Without proper saturation, hydric soils will not develop or be restored to their former condition and upland vegetation will grow instead of targeted hydrophytic vegetation.

A difficulty in design and construction is producing the heterogeneousness of a natural wetland. A study of eastern North Carolina wetlands found that elevation changes of 10 cm could cause the frequency of surface flooding to alter by 20% (Bledsoe and Shear, 2000). The variability of wetland hydrology makes it very difficult to plan and design a wetland to match an existing reference. Furthermore, it can be difficult to pick an appropriate reference because different sites could have a very similar location, setting, and topography yet could vary in hydrology or vegetation significantly, and it can be very difficult to determine if historical alterations have occurred. To address this problem, Bledsoe and Shear (2000) recommend using multiple references when possible to gain a broader understanding of wetland behavior for the particular area. Depending on the watershed, future urbanization may also need to be accounted for when restoring a wetland. Changes in impervious area can rapidly alter a watershed's hydrology so a diverse selection of plant species should be chosen to ensure that vegetation can thrive with varying amounts of soil saturation and surface flooding (Simmons et al., 2006).

Many restoration attempts have failed not because the sites were too dry but because they were too wet. In many cases permitting requires a restoration site to meet jurisdictional criteria over a very short time frame, usually three out of five years (Cole and Brooks, 2000). To ensure permitting, many designers overcompensate in their design which creates sites with large amounts of open water. While this practice may restore jurisdictional hydrology criteria, it does not restore the wetland. Deep, open water will create saturated conditions, but they do not support wetland vegetation which is a required component of a jurisdictional wetland. The water must be shallow enough to support rooted-emergent or woody plant species. Submergent aquatic vegetation is not considered hydrophytic by USACE (Environmental Laboratory, 1987). A successful restoration should restore the site to its original hydrogeomorphic (HGM) setting and not create a new HGM setting that is not found in the watershed nor matches the reference site (Cole and Brooks, 2000).

Too much water can also have a negative effect on the water quality benefits of wetlands. A study by Hernandez and Mitsch (2007) compared denitrification (the anaerobic microbial conversion of NO_3^- - N_2 gas) potential of shallow pools, deep open water, and forested areas of created wetlands. They concluded that the highest denitrification potential was found in permanently flooded shallow pools (20-30 cm deep) with emergent macrophytic vegetation to provide a sustainable carbon source for denitrification. The open water did not support enough vegetation growth while the forested edge areas were not wet enough to slow organic decomposition (i.e. provide a carbon source) and provide ample anaerobic conditions.

Continued research is still needed to improve the restoration of non-riverine wetlands. Non-riverine wetlands do not remain wet year round and rely that wet and dry cycling to support certain water quality processes as well as native species. Both anaerobic and aerobic conditions are necessary for nitrogen removal; nitrification is an aerobic process while denitrification is an anaerobic process. In some cases, NO_3^- is a limiting factor for maximizing denitrification (Vepraskas and Richardson, 2001). For a vegetation perspective on hydroperiod, consider the bald cypress (*Taxodium distichum*) a common species found in non-riverine wetlands. While it is very tolerant to flooding and often found in swampy conditions, it requires dry conditions for germination.

A 100 ha non-riverine wet hardwood forest was restored at North River Farms in Carteret County, NC in 2003 (a low elevation coastal area). The land was purchased by the North Carolina Coastal Federation in 2002 using a grant from the North Carolina Clean Water Management Trust Fund. NC State oversaw design, construction, and monitoring of the restoration with a grant from the North Carolina Ecosystem Enhancement Program (NCEEP).

Water table levels were managed using water control structures out the outlets of the drainage ditches and surface storage was created by implementing features such as artificial tree falls and open water areas throughout the entire site. Also approximately 89,000 wetland tree species were planted at the site. Additionally three different surface treatments were implemented:

- Plugging the drainage ditches to raise the water table.
- Plugging the ditches as well as contouring the surface
- Plugging the ditches as well as removing the existing field crown.

The site was bermed to impede surface runoff from leaving the restoration area and to hydrologically isolate each treatment. The overall goal of the restoration was to determine if intensive surface treatments are necessary for restoring hydrology in low elevation coastal regions

Wright (2005) evaluated the hydrology of each treatment through field monitoring and long term modeling for the purpose of making a design recommendation to NCEEP.

Field data was collected from 2003 -2004 and was used to calibrate a DRAINMOD model which simulated 50 years of hydrology using historic climate data.

Using both field data and modeling results, Wright found the crown removal treatment produced a slightly wetter hydrology with the lowest amount of drainage but the surface contouring treatment appeared to match the reference hydrology the closest. The results were mostly observational, hydrology differed little between the three treatments and conclusive statistical differences were not achieved. Wright recommended additional monitoring, the installation of more wells, and an improved survey to better understand the connection to topography and water table.

This research continues Wright's evaluation of the treatment effect on the hydrology of the restored wetland. Following Wright's recommendations, additional water table monitoring wells were installed and a more detailed survey was performed. Hydrology monitoring was continued from 2006 – 2008 to expand the current set to better understand hydrologic differences of each treatment.

An additional investigation to understand the flood storage ability of the restoration during hurricanes and tropical storms was conducted. The site's hydrologic response to several large tropical events which were monitored from 2003-2007 was evaluated, and modeling was performed to predict the hydrologic response of the site during its pre-restoration, agricultural condition. Improving flood storage will help reduce the large volumes of fresh (and often polluted) water which drain into the North River Estuary following large tropical events. Estuary systems are very sensitive to changes in water chemistry which can have negative impacts on fisheries populations (fin and shell) which causes both environmental and economic harm.

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2. HYDROLOGIC EVALUATION OF A WETLAND RESTORED USING THREE SURFACE TREATMENTS

Introduction

Over the past few centuries, millions of hectares of wetlands have been destroyed impacting fish and bird habitat, water quality, and flooding frequency. Nationally, it is estimated that only 53% of the original 89 million hectares remained by the 1980s (Dahl, 1990). Both nationally and locally, one of the main causes of wetland alteration is agriculture. Between the 1950s and 1980s, 95% of wetland alterations were caused by the agriculture and forestry industries (Cashin et al., 1992).

In the North Carolina coastal plain less than 50% of the original wetlands remain unaltered (Cashin et al., 1992). It is estimated that 52% of the land area in the coastal plain once contained hydric (wetland) soils (Cashin et al., 1992). Because of these poorly drained soils, more than 40% of agriculture lands require artificial drainage (Thomas et al., 1995). Agricultural development has been found to increase peak runoff rates by 300-400% as well as leading to higher sediment, nutrient, and fecal organism loadings into drainage waters (Skaggs et al., 1980). Studies have also found that improved drainage can lead to a ten fold increase in NO_3-N losses compared to undrained areas (Gilliam and Skaggs., 1986). Artificial drainage typically incorporates both subsurface drains as well as surface crowning to improve surface drainage. As drainage intensity increases, NO_3-N losses were found to increase (Skaggs et al., 2005). Although best management practices such as controlled drainage (Evans et al., 1995) and the use of shallow subsurface drains (Burchell et al., 2005) may lead to a reduction in drainage and NO_3-N losses, artificial drainage will still result in greater drainage, nutrient and sediment losses than would be found in unaltered areas. The strategic restoration of prior converted (PC) wetlands agricultural watersheds has the potential to reverse water quality degradation caused from agricultural conversion.

Over the past twenty years, there has been a major focus on preserving and restoring wetlands by both governmental and nongovernmental organizations. In an effort to achieve a zero net loss of wetland function, the United States Army Corps of Engineers (USACE) requires compensatory mitigation in the form of wetland enhancement, restoration, or creation for any wetland alterations (National Research Council, 2001). The Swampbuster Provisions of the Food Security Act of 1985 also plays a large role in protecting wetlands in agricultural lands. This act discourages the conversion of wetlands for agricultural production by offering loans, subsidies, and insurance to farmers with the stipulation that benefits cannot be received if agricultural commodities are produced on a wetland which was converted after December 1985 (FWS, 2003).

There are large costs associated with wetland restoration and many have not been successful (Kusler and Kentula, 1990). Many restorations fail due to poor planning and design. Holman and Childress (1995) estimate that 40-50% of wetland restoration problems are caused from poor site selection. A proper reference location must also be selected as a blue print for the restoration. The restored site should be designed to mimic the reference site. After construction, the reference should be used to measure the success of the restoration (Brinson and Rheinhardt, 1995).

A difficulty in restoration design and implementation is accounting for the heterogeneousness of a natural wetland. A study of eastern North Carolina wetlands found that elevation changes of 10 cm could cause the frequency of surface flooding to alter by 20% (Bledsoe and Shear, 2000). The variability of wetland hydrology makes it very difficult to plan and design a wetland to match an existing reference. Furthermore, it can be difficult to pick an appropriate reference because different sites could have a very similar location, setting, and topography, yet could vary in hydrology or vegetation significantly. To address this problem, Bledsoe and Shear (2000) recommend using multiple references when possible to gain a broader understanding of wetland behavior for the particular area. Depending on the watershed, future urbanization may also need to be accounted for when restoring a wetland. Changes in impervious area can rapidly alter a watershed's hydrology so a diverse selection of plant species should be chosen to ensure that vegetation can thrive with varying amounts of soil saturation and surface flooding (Simmons et al., 2006).

Restored wetlands tend to have homogeneous near surface soils compared to natural wetlands. During wetland construction, heavy machinery is used to excavate, scrape, and mix the topsoil. This process homogenizes the upper layer of soil and leaves it compacted with little relief (Stolt et al., 2000). Sustained agricultural use (the prior land use of many restored wetlands) also leads to a much less diverse upper soil layer due to tillage and smoothing. Initially, restored wetlands tend to have a spatially homogeneous soil chemical distribution which limits the development of critical soil biogeochemical processes. Eventually, natural processes such as erosion, scouring, tree falls, and animal burrowing and scraping should create soil variations initially lacking in restored wetlands and add microrelief to the topography (Stolt et al., 2000).

Microtopography can be added to a restoration design to create small variations in elevation across the site which will encourage heterogeneity and will allow a wider range of plant species to flourish (Simmons et al., 2006). The NRCS recommends implementing both macrotopography (vertical relief 15 cm – 1 m) and microtopography (vertical relief less than 15 cm) into a design for both hydrologic and habitat reasons (NRCS, 2003). Macrotopography is implemented by constructing large open water depressions and swales. These features should retain water for long periods of time and provide significant water storage. Macrotopography is important for water fowl habitat where large areas of open water are needed for feeding and resting. It is recommended that approximately 30% of the restoration area should contain macrotopography while the remaining area should contain microtopography. Microtopography can be implemented in a variety of ways. Roughing the surface with construction/farm equipment can be used to create small pocket depressions and scours which will retain water for short periods of time. These features are important for amphibian habitat because the small depressions do not support permanent water which protects against predation by fish. While microtopography does not provide deep water storage, it does create small pockets of storage which will lengthen hydroperiod and slow surface drainage (NRCS, 2003).

A study by Tweedy and Evans (2001) found that ditch plugging may not be enough to restore wetland hydrology. In the study, two prior converted wetlands in eastern North Carolina were restored with ditch plugging and using both smooth and rough surface treatments. The rough treatments resulted in a more surface ponding and a higher water table during drier periods. The rough treatments also had a greater storage volume and reduced total outflow, outflow duration, and outflow intensity compared to the smooth treatments. The study found that surface topography had a greater influence hydrology as the relative wetness decreased. The site with a drier soil (Leaf) required enhanced surface topography to restore only marginal wetland hydrology, while the site with the wetter soil (Roanoke) did not require enhanced surface topography to restore jurisdictional wetland hydrology.

A study by Wright (2005) evaluated the hydrology of a 100 ha restoration in eastern North Carolina from 2003-2004. The prior converted site was restored using three different topographical techniques: 1) plugging the ditches and planting wetland trees species, 2) plugging the ditches, contouring to create microtopography, and planting, and 3) plugging the field ditches, removing the existing crown, and planting. The treatments were replicated three times using a randomized block design. Hydrologic differences between the treatments were compared for both observed short term data and long term simulations using DRAINMOD (Skaggs, 1999). Wright hypothesized the contouring and crown removal techniques would produce the wettest conditions because of increased surface storage, but when evaluating the data found very little significant difference between the treatments for the short term or the long term simulations. A second evaluation of only 2 of the replication blocks which were immediately adjacent to each other found that the crown removal treatment yielded the shallowest water table and least outflow, followed by contouring, and the plug only technique. Block 3 was excluded from the evaluation because it is isolated from blocks 1 and 2 and was approximately one meter higher in elevation.

During the study all three treatments were successful in meeting jurisdictional criteria. The long term simulation also showed that all treatments easily met jurisdictional hydrologic criteria for a 50 year period.

To better understand the differences between the replication blocks, Wright recommended additional monitoring be performed at the site and installing more water table wells. It was also recommended that a more detailed survey of the restored be performed so the relationship between the topography and the water table could be better understood.

Following Wright's study, the hydrologic monitoring was continued. Additional wells were installed in December 2006 and a survey was performed in March 2006. This study will evaluate the hydrologic field data from 2006-2008 in an effort to make final conclusion about the hydrologic impact of the surface treatments. Specific objectives of this study were to:

- Evaluate the hydrology of a wetland restored using three different topographic treatments and determine if there was a significant treatment effect on hydrology.

- Evaluate the hydrology of a reference wetland and determine which restoration treatment resulted in a hydrology which best mimicked the reference hydrology.

- Determine if the hydrology observed in years 4-6 of the restoration (2006-2008) differed from the hydrology observed in years 1-2 of the restoration (2003-2004).

- Provide guidance and recommendations to the North Carolina Ecosystem Enhancement Program on the necessity of microtopography in low elevation, coastal wetland restorations.

Materials and Methods

Site Description:

Research was conducted at North River Farms (a large scale wetland restoration) in Carteret County, North Carolina in the White Oak River Basin (figure 2.1). The site was drained in the mid 1970s using a network of parallel ditches to facilitate agriculture. As typical in this region, field ditches were spaced at 100 m and dug 1 m deep. The fields were crowned approximately 20 cm in between the ditches to increase surface drainage.

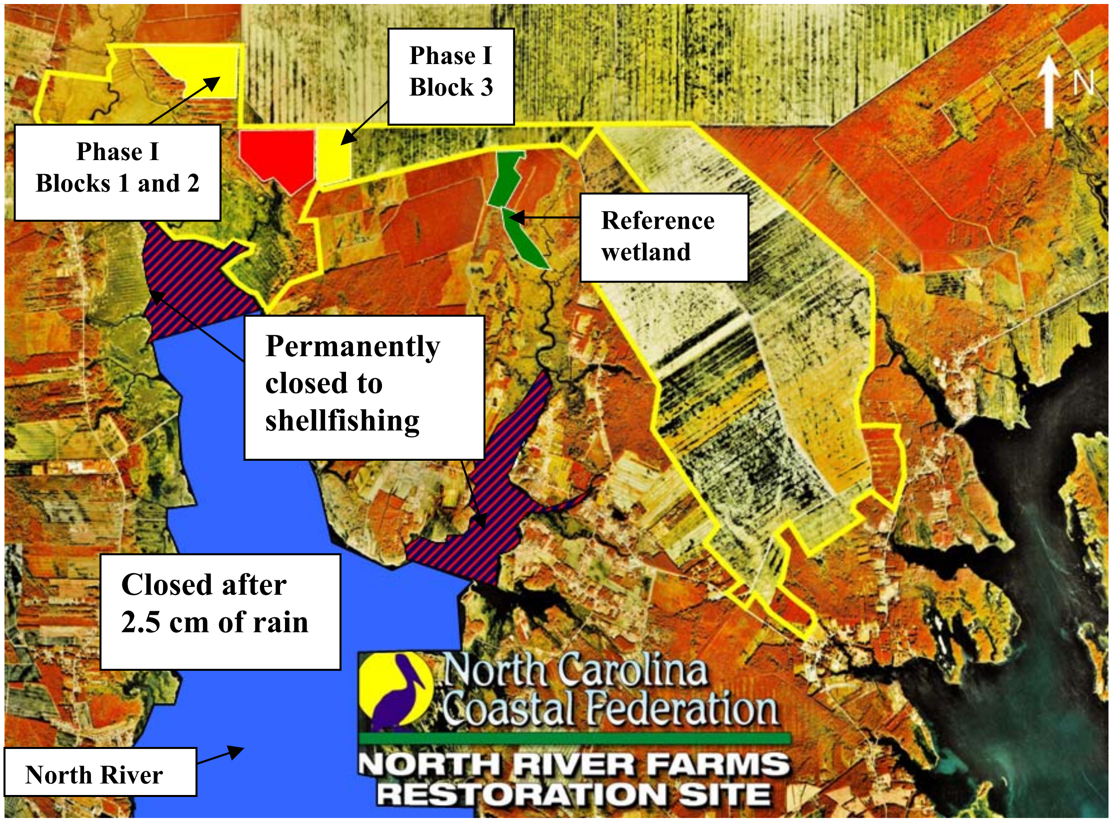

Figure 2.1 North River Farms Restoration

The North Carolina Coastal Federation purchased North River Farms in 2002 for the purpose of a large scale restoration with a grant from the North Carolina Clean Water Management Trust Fund. North Carolina State University through a grant from the North Carolina Ecosystem Enhancement Program was contracted to oversee design, construction, and monitoring of the restoration. The major goals of the project were to create habitat, improve water quality, and improve understanding of coastal area restoration techniques. Research for this study was conducted in Phase I of the restoration, a 100 ha non-riverine wet hardwood forest which was constructed from December 2002 – March 2003.

The location of the site was considered strategic and ideal for improving water quality in the North River due to its close proximately. The North River is a sensitive estuarine system currently exhibiting poor water quality attributed to stormwater from the surrounding agricultural and urban areas. A high bacteria presence in the estuary has been documented detrimental to the local shellfishing industry. Currently shellfishing is permanently prohibited in the upper reaches of the North River and temporarily prohibited in the entire waterway following a 2.5 cm (one inch) or greater rain event (figure 2.2) (NC DENR, 2009). Development in the watershed had resulted in increased stormwater runoff to the estuary during larger storm events. Water quality improvements from the restoration were hoped to provide ecological and economical benefits for the area.

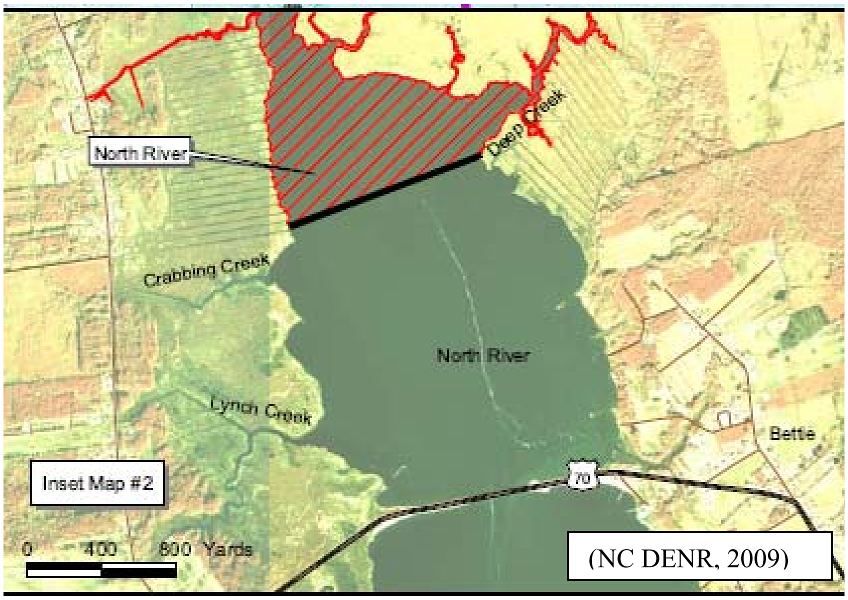

Figure 2.2 Hatched red areas are currently prohibited from shellfishing. Research site is located upstream of prohibited areas and drains into Deep Creek.

Restoration:

Reference Selection

The targeted wetland community for the restoration was non-riverine wet hardwood forest. A nearby non-riverine wet hardwood forest was selected as a reference for design and monitoring of the restoration (figure 2.3). The reference was a bowl shaped depression which exhibited drier conditions on the higher edges and wetter conditions in the lower center. The southern portion of the reference is drained by several small channels which flow south towards Ward's Creek which ultimately drains into the downstream portion North River. The reference vegetation community is dominated by hardwood trees whose canopy limits thick herbaceous undergrowth.

Figure 2.3 Non-riverine wet hardwood forest reference.

Restoration Techniques

100 ha of prior-converted agricultural land were restored for this phase of the restoration. The restoration was designed to restore hydrology using several components and techniques. Water control structures with flashboard risers were installed at the outlet of each drainage ditch to manage the water table and control drainage leaving the

site. Earthen ditch plugs were also installed within the field ditches to further impede subsurface drainage. Several surface features were incorporated into the design to improve surface storage to the level found in the reference. Open water areas and simulated tree falls (figure 2.4) were implemented to create additional surface storage. Approximately 89,000 saplings of various wetland tree species were planted at the site including Atlantic white cedar (*Chamecyparis thyoides*), bald cypress (*Taxodium distichum*,), black gum (*Nyssa sylvatica*), Carolina ash (*Fraxinus caroliniana*), green ash (*Fraxinus pennsylvanica*), long leaf pine (*Pinus palustris*), water oak (*Quercus nigra*), and water tupelo (*Nyssa aquatica*

Figure 2.4 Open water areas within the restoration (Photo courtesy of NC Coastal Federation).

Three different topographic treatments were implemented into the design to test the effect of varying levels of microtopography:

1. Plugging the field ditches without altering existing surface topography (PLUG).
2. Plugging the field ditches and contouring the surface to create microtopography (CONT).
3. Plugging the field ditches and removing the existing crown (CR).

Each treatment was established in approximately 6.5 ha plots. Each plot as well as the entire restoration was surrounded raised berms (approximately 50 cm high) to hydrologically isolate them and impede surface runoff. The treatments were replicated three times forming a randomized complete block design. Blocks 1 and 2 were located next to each other in a similar landscape. Elevation within blocks 1 and 2 ranged from 1.11 – 1.86 m above msl following construction. Block 3 was forced to be located southeast of blocks 1 and 2 to accommodate the desired plot size for the treatments. Block 3 was approximately one meter higher in elevation than the other blocks with elevations ranging from 2.23 – 2.74 m above msl following construction. Elevation differences within the restoration were not expected to have any effect on hydrology as long as all water control structures were set to the same elevation relative to the average ground surface.

Monitoring:

The site was instrumented in 2003 to intensively monitor rainfall, water table fluctuations and outflow. This study evaluated the hydrologic field data for 2006-2008.

Rainfall

Rainfall data was collected at two locations in the study area. Rainfall was measured using an automatic tipping bucket (Davis Instruments, Hayward CA, model 7852) and recorded using a HOBO data logger (Onset Computer Corporation) which logged every 0.254 mm (0.01 in) of rain (Figure 2.5). The rainfall data was downloaded using a HOBO shuttle data logger (Onset Computer Corporation, part H09-003-08). A manual rain gauge was also utilized at the location for backup and calibration of the automatic gauge.

Figure 2.5 Automatic tipping bucket and manual rain gauges.

Water Table Fluctuations

Water table depth in the restoration and reference was continuously monitored using 4 inch PVC water table monitoring wells (figure 2.6) which were screened and installed to approximately two meters in depth. The water table was recorded hourly using Infinities water table data loggers (Infinities USA Inc, Daytona Beach, FL). Water table data was downloaded with a Hewlett Packard 48G+ calculator using Infinities USA software. The Infinities sensor included a pressure transducer to measure the depth of water. Manual water table depth measurements taken during data downloads were used to convert the Infinity readings to a water table depth below ground surface as well as absolute water table elevation. Automatic water table wells were installed in March,

2003. The majority of wells were installed in 2003, but some additional wells were installed in the reference in 2005.

Figure 2.6 Water table well with Infinities automatic water table logger.

Water table fluctuations were monitored continuously at eighteen locations (NR01 – NR18) located within the blocks (figure 2.7 and figure 2.8). Two wells were placed in each treatment plot for a total of six wells per treatment.

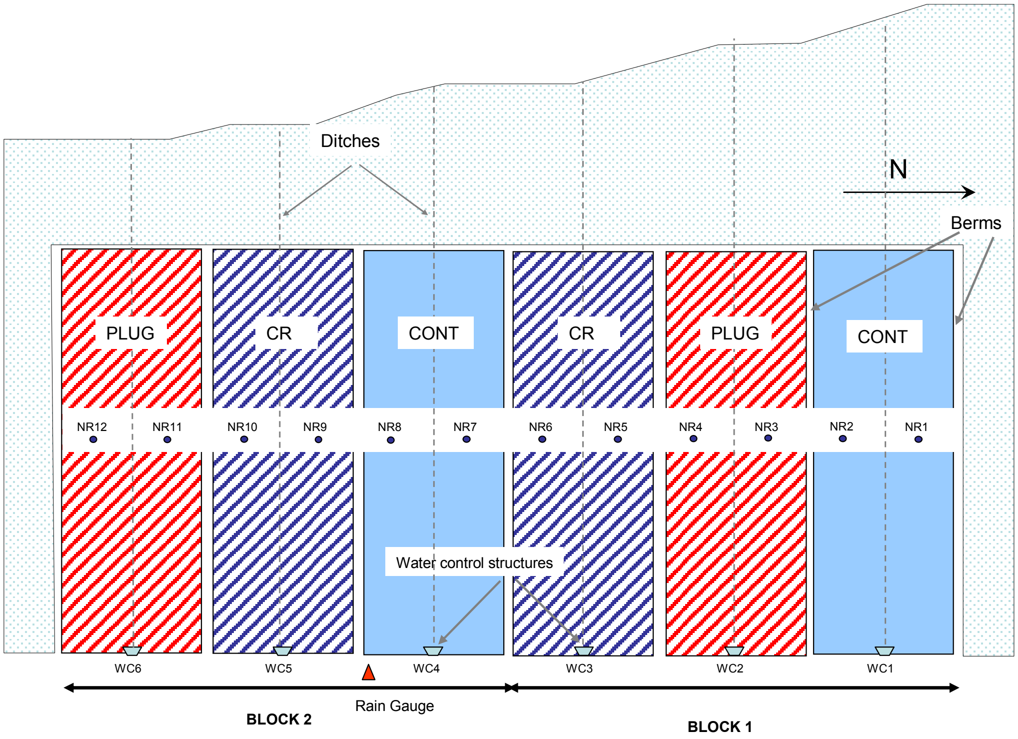

Figure 2.7 Block 1 and 2 monitoring layout (not to scale).

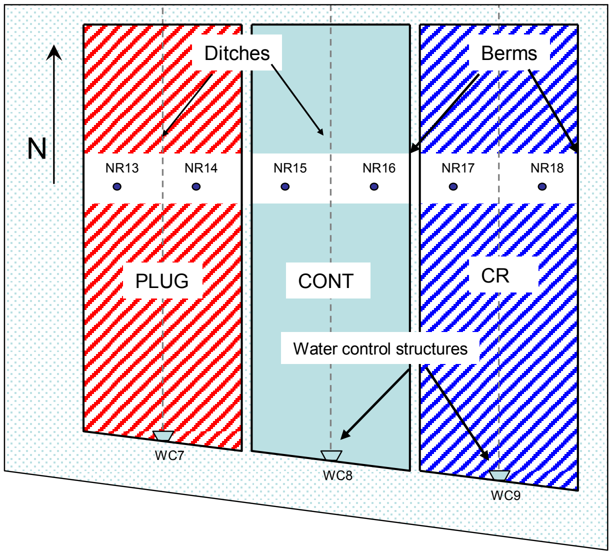

Figure 2.8 Block 3 monitoring layout (not to scale).

To intensify the original continuous water table monitoring, thirty-six additional manual water table wells were installed in the treatments in December, 2006. An “A” and “B” well were installed on opposite sides of the automatic water table wells to gain a more detailed understanding of the water table profile near the surface across a wider portion of each treatment (figure 2.9). The wells were installed to a depth of approximately one meter and were monitored monthly by taking manual readings with a Solinst water level meter. Fifteen usable data points were collected from each manual well between 3/2007 and 12/2008; readings could not be taken when the water table was deeper than one meter.

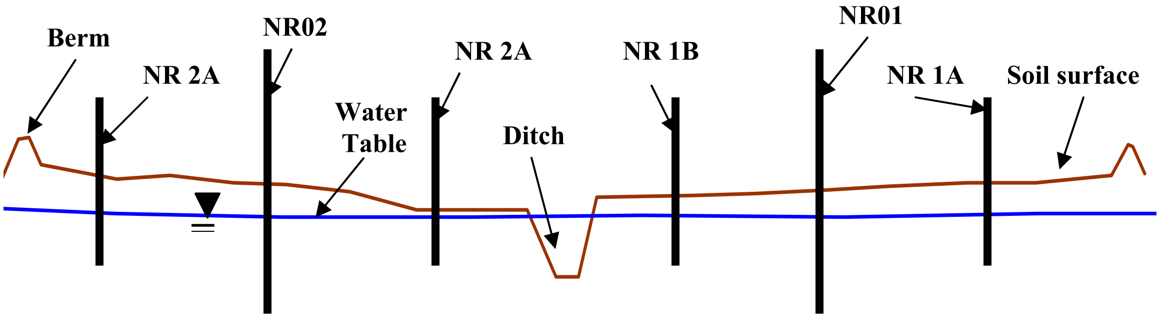

Figure 2.9 Manual well placement in block 1 CONT treatment.

Water table fluctuations in the reference were monitored continuously at thirteen locations located in three transects (figure 2.10). Outer wells along the edge of the reference were classified as Ref-edge and inner wells were classified as Ref-center.

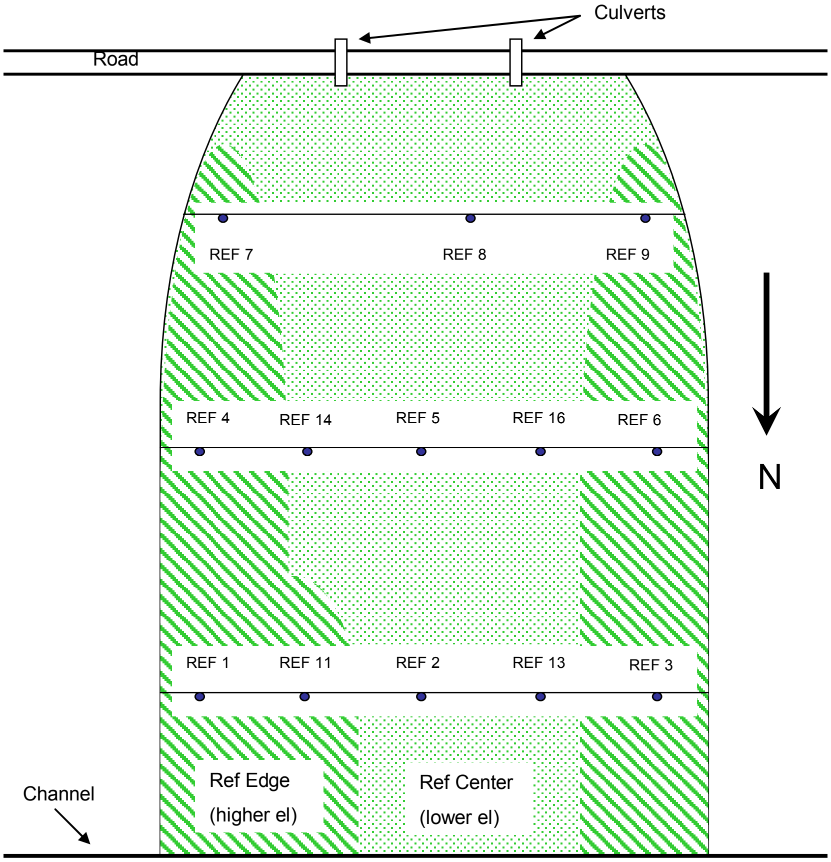

Figure 2.10 Reference wetland monitoring layout (not to scale).

Surface Outflow

Surface outflow was only monitored in the restoration. It was not monitored in the reference wetland because the area immediately downstream of the reference wetland is tidally influenced which can create backwater conditions within the southern portion of the reference. Due to backwater conditions, the traditional weir-based flow monitoring approach could not be implemented.

The restoration contained nine lateral field ditches which were originally constructed to drain the site for agriculture. The ditches drained excess water to a large main canal that transported water south to the North River. During construction, water control structures and earthen ditch plugs were implemented to control the drainage from the site and manage the water table. Water control structures were installed at the outlet of each drainage ditch, on the eastern side of the restoration area in the center of each treatment, to maintain water table depth, control outflow, and provide location for outflow monitoring (Figure 2.11). Water table levels were managed using a flashboard riser with a 30^{o} V-notch weir. Invert elevations of weirs ranged from 0.98 – 1.23 m above msl in blocks 1 and 2, and 1.97 – 2.02 m above msl in block 3 where land surface was higher (Table 2.1).

Figure 2.11 Water control structure with flashboard riser 30^o V-notch weir.

Table 2.1 Weir invert elevations of water control structures.

Water Control Structure	Treatment	Invert Elevation (m)
1 (block 1)	CONT	1.22
2 (block 1)	PLUG	1.23
3 (block 1)	CR	1.21
4 (block 2)	CONT	1.01
5 (block 2)	CR	0.98
6 (block 2)	PLUG	0.98
7 (block 3)	PLUG	2.00
8 (block 3)	CONT	2.02
9 (block 3)	CR	1.97

Water level was measured at each water control structure using a float/pulley system (Figure 2.12). The system used a 4 inch PVC well containing a weighted float which moved freely with water level fluctuations. As the float moved, it turned a pulley connected to a potentiometer. The changes in voltage produced by the potentiometer were recorded every 30 minutes by a two channel, 12-bit Sargent data logger (SGT engineering, Champagne, IL). The data logger was downloaded using the software, Zterm (coolstuff.com) on a TDS Recon mobile pc. Manual water level measurements were used to create a linear regression to convert the potentiometer voltages to water depths.

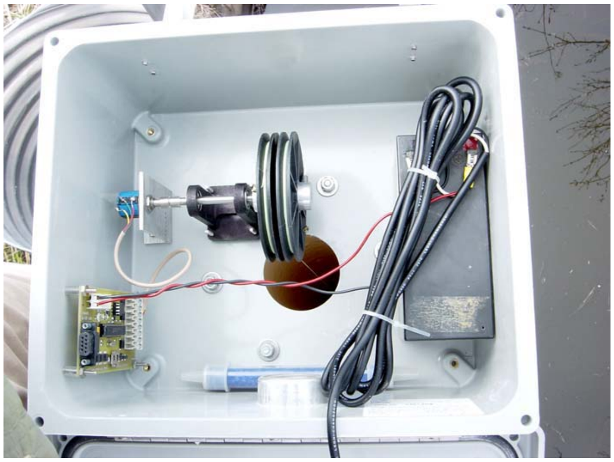

Figure 2.12 Sargent float/pulley system.

Flow was calculated based on depth of flow over a 30^o V-notch weir. When the water depth was above the invert of the weir, flow was calculated using the 30^o V-notch weir equation (Grant and Dawson, 2001). When the water depth exceeded the top of the weir, flow was then calculated using the appropriate orifice equation (Bedient and Huber, 2002).

Equation 2.1. Flow through a 30^o V-notch weir.

$$Q = 0.01914H^{5/2}$$

Q = flow (m^3s^{-1})
H = head above invert of weir (m)

Equation 2.2. Flow through an orifice.

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

Q = flow (m^3s^{-1})
C_d = discharge coefficient = 0.589
A_o = orifice area (m^2)
g = gravitational coefficient
h = elevation of water above centerline (m)
h_o = elevation of orifice centerline (m)

Surveying:

A three-dimensional Total Station survey of the treatments was performed in March, 2006. Points were shot approximately every 5 m along two transects which paralleled the water table well transect (figure 2.13). All continuous and automatic wells within the treatments were also surveyed. Earlier surveying data from construction and the initial instrumentation was obtained from Wright (2005).

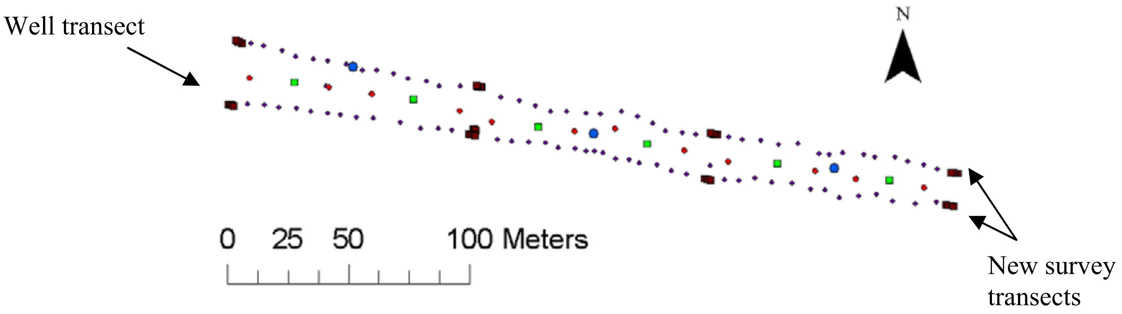

Figure 2.13 Example of block 3 survey points.

Data Analysis:

Water table fluctuations for both the reference and the treatments were recorded every hour but were analyzed using the average daily water table depth for each well. Water table data was evaluated using four hydrologic criteria. In addition, outflow from each water control structure was recorded every 30 minutes and analyzed using daily total discharge and yearly total discharge.

Hydrologic Criteria:

Water table data from the restoration and the reference was evaluated using four hydrologic metrics:

- Jurisdictional wetland hydrology criteria
- Average water table depth
- SEW_{30}
- Number of days the water table inundates the surface

Jurisdictional wetland hydrology criterion is defined by the USACE and is used for determining wetland hydrology for jurisdictional/legal purposes. To achieve jurisdictional wetland hydrology, a site must remain saturated (water table within 30 cm of the surface) for a continuous period of 5% of the growing season (Environmental Laboratory, 1987). The growing season is an approximation of the period when the soil temperature remains above 5^{o} C (Considered biological zero by USACE). The longest period of continuous saturation per year during the growing for each treatment was used in the evaluation. At the research site, the growing season is listed as between March 20 and November 19 by to the Carteret County Soil Survey; therefore 5% of the growing season was 12 days.

The jurisdictional wetland hydrology criteria while used for regulatory purposes is not considered an accurate measure for determining wetland hydrology by some researchers due to its assumption that average daily soil temperature (at 50 cm below the surface) drops below 5^{o} C during the non-growing season, and that microbial activity ceases to exist below 5^{o} C. Several studies have found that soil temperatures in the southeast rarely drop below 5^{o} C and that microbial activity exists year round. Other studies have found that soils below 5^{o} C and still exhibit microbial activity but at slower rates than found in warmer soils (Wakely, 2002). Given that microbial activity increases with temperature, sites with a longer growing season should require a shorter period of saturation to produce anaerobic conditions than sites with a shorter growing season. Due to these inconsistencies with the applicability of minimum jurisdictional wetland hydrology criteria in temperate climates, three other criteria were also used and were based on the entire year not just the growing season.

Average water table depth was evaluated because it is a very simple and understandable metric. The average water table depth of each treatment was calculated by taking the mean of the daily water table depths on a yearly and total basis for each particular area of interest. It can however be misleading (in terms of wetland hydrology) without understanding the range of water table depth which occurs. Two locations may experience identical periods of saturation but location A may have a much deeper water table during the summer than a second location B. This will affect the average water table depth and cause it too appear drier than location B even though it may have no effect on near surface wetland hydrology.

Sum of excess water (SEW) is a tool used for measuring both the duration and intensity at which the water table is above a threshold depth. Sum of excess water above 30 cm (SEW_{30}) is commonly used in both wetland and agricultural water table analysis. SEW_{30} is calculated by subtracting the daily water table depth from the threshold depth only if the water table is above the threshold, and summing all of the differences for the period of interest (equation 2.3). SEW_{30} for each area of interest was calculated on a yearly and total basis. SEW_{30} was measured in cm*days.

Equation 2.3 SEW_{30}

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

SEW30 = sum of excess water above 30 cm (cm*days)
X_i = Daily average water table depth (cm)
n = number of days of interest

SEW_{30} can also be described visually as the area under the curve of the water table fluctuation and above the threshold line (figure 2.14). The water table profile with a larger shaded area has a higher SEW_{30} than profile with a smaller shaded area. Site A experiences the same period of saturation as site B but clearly exhibits a different hydrology than site B. The SEW_{30} value for site A would be greater than calculated at site B because the water table would be nearer the surface over the same period.

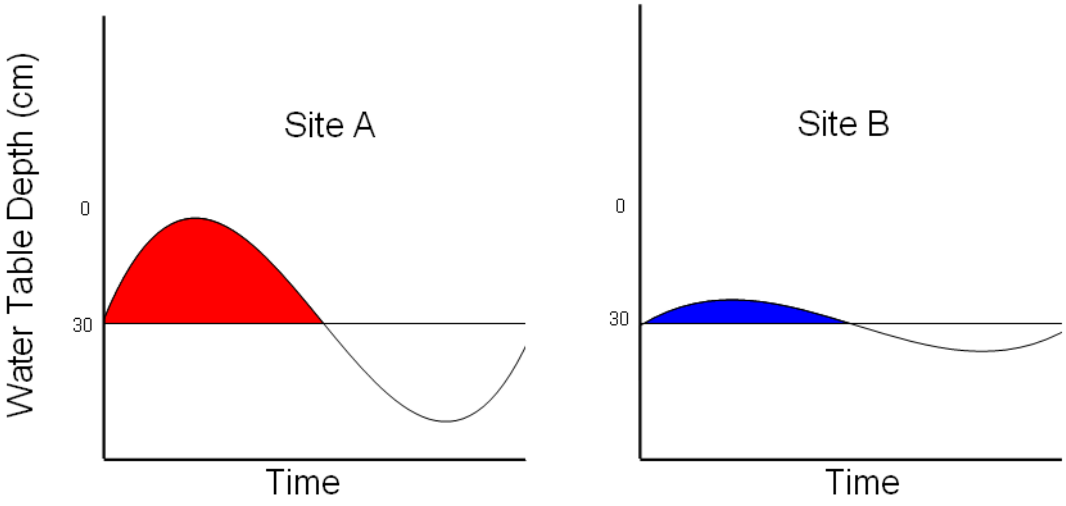

Figure 2.14 Visual example of SEW_{30}, the area of the shaded area represents the SEW_{30} for each water table profile [SEW_{30} (A) > SEW_{30} (B)].

The number of days each wetland treatment experienced the water table inundating the surface was the final hydrologic criteria. The number of days of surface inundation was summed for each year and for the total period of study. Surface inundation was selected as one of the hydrologic criteria because for reducing conditions to occur in the upper portions of the soil profile, it must be fully saturated. Jurisdictional wetland hydrology criteria assumed that the soil is sufficiently saturated when the water table is within 30 cm of the surface due to capillary action pulling soil water into upper 30 cm of soil (Environmental Laboratory, 1987). Capillary action can vary greatly among different soil types and may not always provide 30 cm of rise. A conservative approach to assess saturation is to only treat the soil as fully saturated when the water table rises to the surface.

Manual Water Table Wells

Water table readings from the additional manual wells were analyzed in conjunction with the topographic survey data to evaluate how the water table behaves with respect to larger surface macrotopographical features in terms of both water table depth and water table elevation. This was performed by creating water table profiles which could be superimposed on surveyed cross-sections of each treatment. The manual wells could only be used for evaluating conditions when the water table was within one meter of the surface because this was the maximum installation depth of the wells.

Statistical Analysis

SAS statistical software (SAS Institute Inc, 1985) was used to analyze hydrologic data from the restoration treatments and the reference wetland. Daily water table and outflow data were analyzed using an analysis of variance (ANOVA) test. The Tukey method was applied to the ANOVA test to control the type-I experiment-wise error rate since multiple pair-wise comparisons were made. The model used a treatment, block, and treatment*block interaction term.

Results and Discussion

Rainfall:

The site received an average of 141 cm of rainfall from 2006-2008 which is approximately the 50-year average rainfall of 143 cm recorded at nearby Morehead City. 2006 was the driest year during the study recording 120 cm of rain (figure 2.15). Rainfall remained below average for the entire year and finished the year 23 cm below average; eight of twelve months experienced below average rainfall. While 2007 was a year marked by severe drought across most of North Carolina; the research site received above average rainfall (154 cm). The yearly rainfall remained well below average for most of the growing season (rainfall was 16 cm below average on July 1) but heavy rainfalls in July and September (Tropical Storm Gabrielle) raised the yearly rainfall total above average and the year finished 11 cm above average. Tropical Storm Gabrielle was the only tropical storm to have an impact at the research site from 2006-2008 and only impacted a very small portion of the North Carolina coastline. 2008 was also a wetter than average year receiving 150 cm of rainfall. The cumulative rainfall was approximately average for most of the year. Following October the research site was 8 cm below average but a very wet November (26 cm) raised the yearly rainfall above average. The site finished the year 7 cm above average.

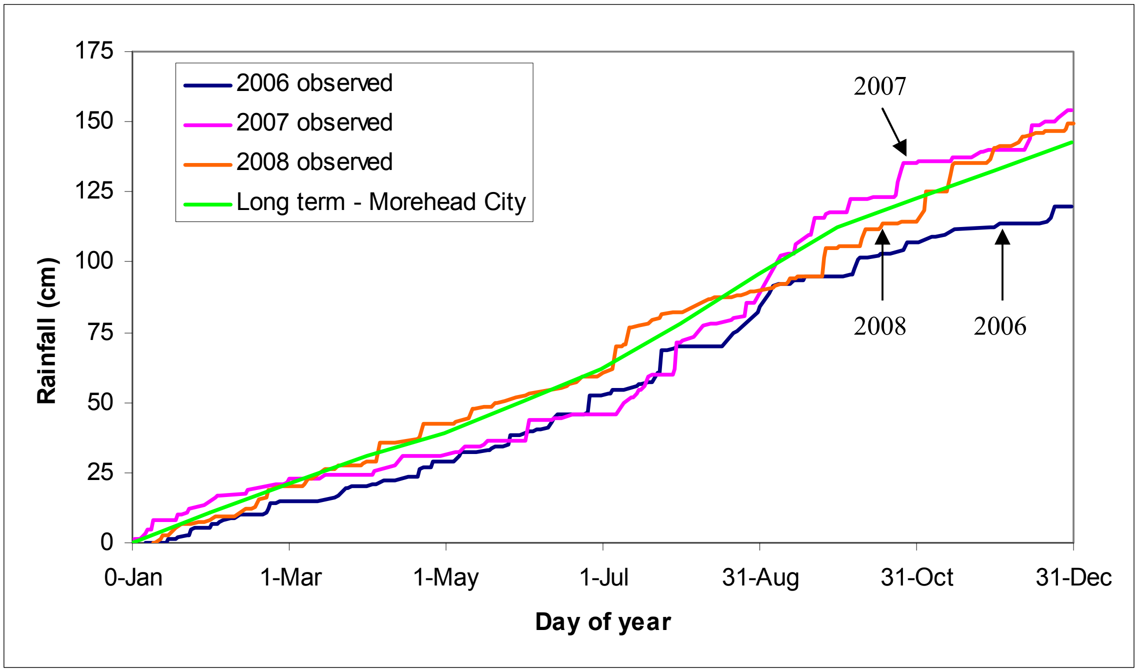

Figure 2.15 2006-2008 observed rainfall compared to long term average.

Water Table:

Evaluation of Reference Wetland

Due to the bowl shape of the reference wetland, the hydrology varied throughout the site. The wells placed near the edge of the reference are located at a higher elevation than the wells placed in the center of the reference and are located near the wetland/upland boundary. Based on the evaluation of the hydrology of the reference water table wells using the four selected hydrologic criteria, the wells were classified into two groups for further analysis: Ref-center and Ref-edge.

- Ref-center wells:REF02, REF05, REF08, REF13, REF14, and REF16
- Ref-edge wells:REF01, REF03, REF04, REF06, REF07, REF09, and REF11

A schematic of the reference layout and classification can be found in figure 2.10 found in the Material and Methods section. The average water table depth of the seven Ref-edge wells was approximately 20 cm deeper than the average water table depth of the six Ref-center wells for the entire period of study (figure 2.16). The hydrology found in the Ref-center wells represents the portion of the reference the restoration was intended to match.

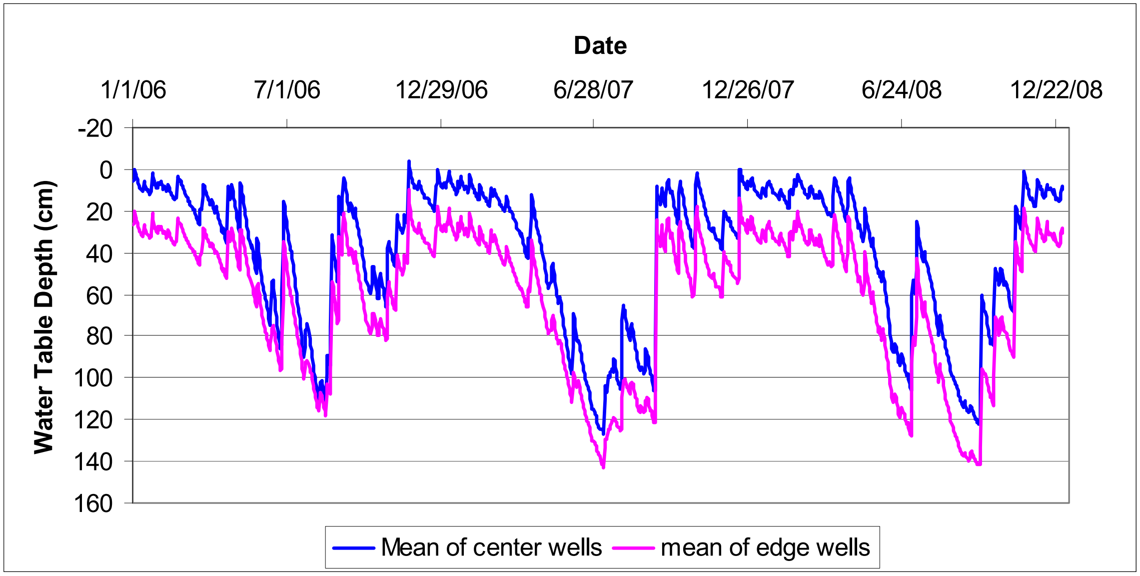

Figure 2.16 Water table fluctuations for Ref-center and Ref-edge.

Water Table Response of the Reference and Restoration

Water table fluctuations of the reference wells and the restoration wells were first evaluated to determine if the water table at the two locations exhibits similar behavior and response to climate changes. The average daily water table depth of all six automatic Ref-center wells was compared to the average daily water table depth of all 18 automatic restoration wells for the years 2006, 2007, and 2008.

In 2006, both water table profiles started the year near the surface but as spring approached the restoration water table in the restoration fell deeper than in the reference and remained deeper through most of the summer. The water table in the restoration appeared flashier than in the reference, mostly likely due to differences in drainable porosity (figure 2.17). The water table deepened throughout the spring due to low rainfall and increasing evapotranspiration (ET) losses. In the late June the water rose approximately 60-70 cm due to the above average rainfall in June and July. The water table then fell below 100 cm until September rains raised the water table near the surface. The water table fell below 60 cm during the fall before it rose back near the surface as ET rates lowered during the winter. The restoration water table fluctuations matched the reference fluctuations much better in the fall and winter than it did in the spring and summer.

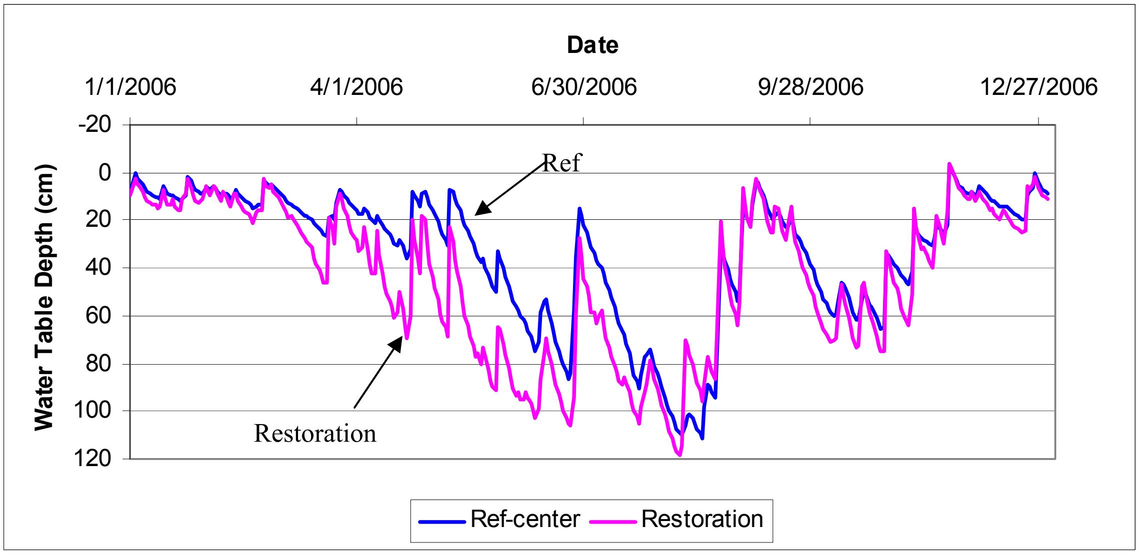

Figure 2.17 Mean Ref-center and mean restoration water table fluctuations for 2006.

In 2007, both water table profiles began the year near the surface and experienced similar fluctuations until the water table in the restoration started falling deeper in mid-March (figure 2.18). The water table slower deepened throughout the spring and summer due to low rainfall and increasing ET rates. By late June the water table was deeper than 120 cm in the reference and deeper than 140 cm in the restoration due to a very dry early 2007. This was the deepest the water table was observed during the study period. July rainfall raised the water table in the restoration substantially higher than the water table in the reference. Following Tropical Storm Gabrielle in September, the water table rose approximately 100 cm in both the reference and restoration. The water table remained shallow for the rest of the year due to low ET rates and higher than average fall rainfall.

Similar to 2006, the restoration water fluctuations matched the reference much closer during the fall and winter than in the spring and summer.

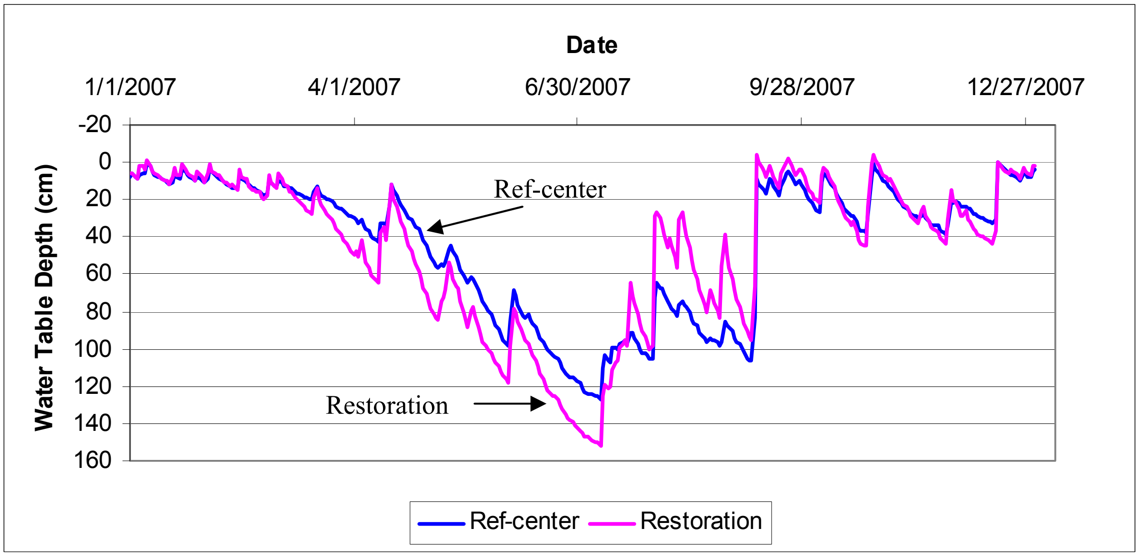

Figure 2.18 Mean Ref-center and mean restoration water table fluctuations for 2007.

In 2008, both water table profiles experienced very similar water table fluctuations for most of the year (figure 2.19). The water table remained near the surface until May when increasing ET rates caused the water table to drop. By late June, the water table dropped down to 100 cm in the reference and to 120 cm in the restoration when above average July rainfall raised the water table by 80-100 cm. By mid-September, the water table had dropped again down below 120 cm before lowered ET rates and heavy November rains raised the water table back near the surface. The water table fluctuations in the restoration were more noticeably flashier during the fall than in other parts of the year.

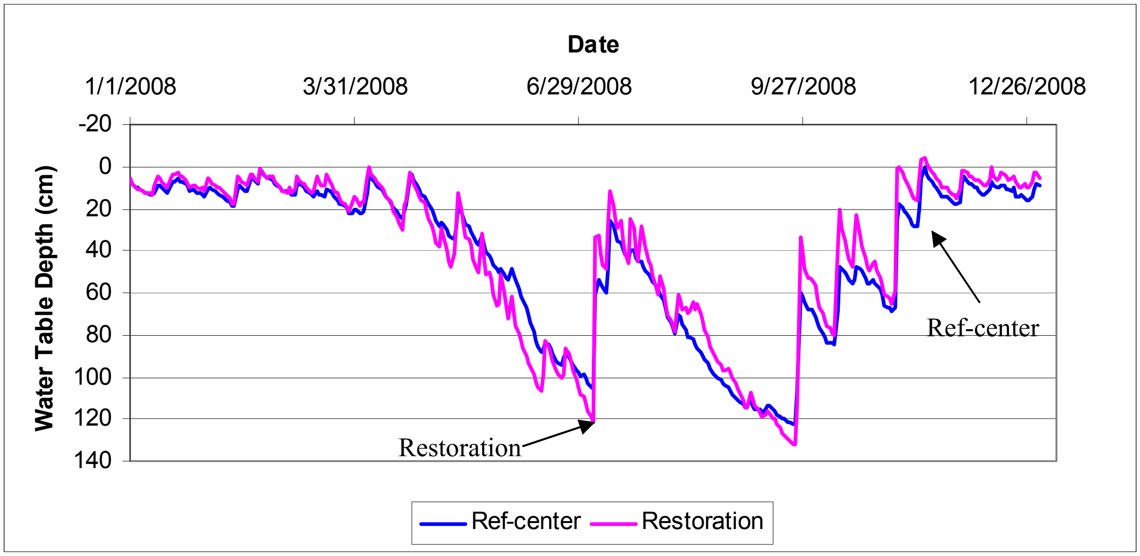

Figure 2.19 Mean Ref-center and mean restoration water table fluctuations for 2008.

For 2006-2008, the reference water table fluctuations appeared to be less flashy than the restoration fluctuations. The restoration water table typically was deeper during dry times and sometimes shallower during wet times. The water table in the restoration rose above the surface several times during the study but rarely occurred in the reference. This may be due to the reference soil having a higher drainable porosity than the restoration which would require a greater volume of water be imported/exported for the soil profile to raise/lower the water table. The near-surface drainable porosity may be different due to the approximate 30 years of agricultural production on the land prior to the restoration. Farming practices would have compacted the soil and lead to a loss of organic matter due to subsidence which both would lower drainable porosity. Drainable porosity at deeper depths also appeared to differ between the restoration and reference which is mostly likely due to slightly different soil properties. The majority of both sites were mapped as a Deloss fine sandy loam, but that does not ensure identical physical soil properties.

Evaluation of Hydrologic Criteria

A more analytical approach was applied to evaluating the hydrology of the various treatments verses the reference area. Water table data for Ref-center, Ref-edge, PLUG, CONT, and CR was evaluated using four hydrologic criteria: jurisdictional wetland hydrology criteria, average water table depth, SEW_{30}, and number of days of surface inundations. Multiple tests were used account for inherent weaknesses of each criterion.

Jurisdictional Wetland Hydrology Criteria

Jurisdictional wetland hydrology criteria is the standard metric used to make regulatory decisions pertaining to wetland hydrology. For a site to meet jurisdictional wetland hydrology criteria it must remain saturated (water table within 30 cm) for a continuous period of 5% of the growing season, which is twelve days for this location. A site with 5% saturation is considered likely a wetland by the USACE and is considered definitely a wetland with 12.5% saturation, which is 30 days for this location. For this evaluation, the criterion was applied to a single average daily water table profile for each grouping of wells.

In 2006, all three treatments as well as the Ref-center met the jurisdictional wetland hydrology criteria while Ref-edge did not. PLUG, CONT, and CR all experienced continuous saturation for 9% of the growing season, Ref-center experienced saturation for 13% of growing season while Ref-edge only experienced saturation for 2% of the growing season (figure 2.20). Only Ref-center experienced continuous saturation for more than 12.5% of the growing season.

In 2007, the restoration treatments and Ref-center all experienced longer periods of continuous saturation than in 2006. 2007 experienced above average rainfall but was below average for most of the growing season. Plug and CR experienced continuous saturation for 15% of the growing season while CONT and Ref-center experienced continuous saturation for 16% of the growing season. Ref-edge did not meet jurisdictional wetland hydrology criteria in 2007 as it was only saturated for 2% of the growing season. PLUG, CONT, CR, and Ref-center all experienced continuous saturation for more than 12.5% of the growing season.

In 2008, most of the areas experienced longer periods of continuous saturation during the growing than in 2006 or 2007. In 2008, the area received above average rainfall. PLUG experienced continuous saturation for 12% of the growing season while

CONT and CR experienced continuous saturation for 18% of the growing season. Ref-center experienced the longest period of continuous saturation at 20% of the growing season while Ref-edge only experienced continuous saturation for 2% of the growing season.

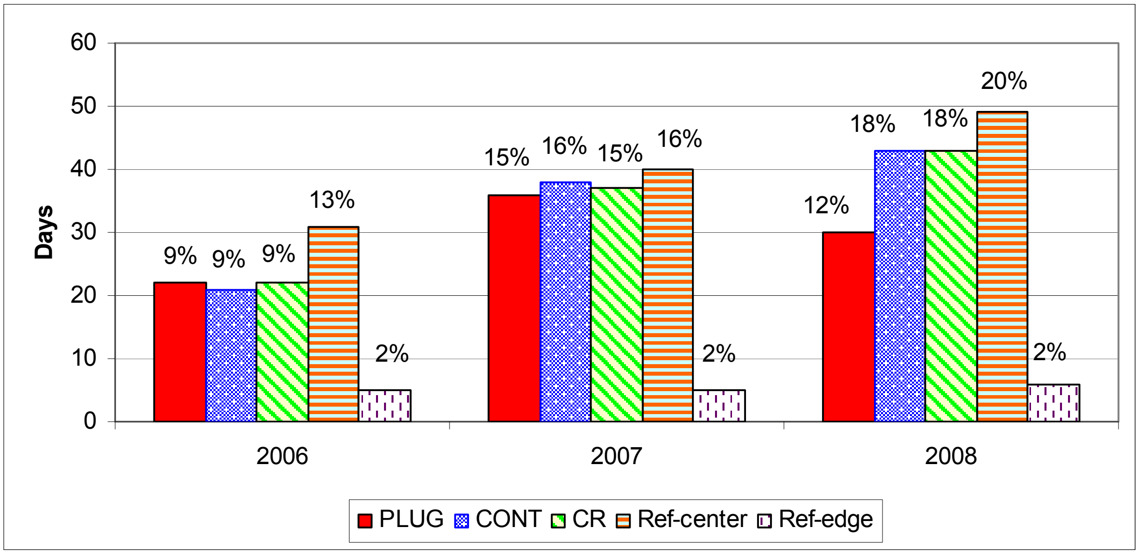

Figure 2.20 Longest continuous period of saturation within the growing season and percentage of growing season.

For all three years of study (2006-2008) all three restoration treatments as well as Ref-center met the jurisdictional wetland hydrology criteria based on 5% saturation. In 2007 and 2008 (wetter years) the treatments and Ref-center all met jurisdiction wetland hydrology criteria based on 12.5% as well. In 2006 and 2007, all three treatments experienced continuous saturation for approximately the same percentage of the growing season. In 2008 though, PLUG experienced continuous saturation by a much lower percentage of the growing season than CONT or CR but still met the jurisdiction criteria easily. In 2006 and 2008, Ref-center experienced continuous saturation for a greater percentage of the growing season than any of the treatments but in 2007 all treatments were approximately the same.

Ref-edge failed to meet jurisdictional wetland hydrology criteria for all three years. Considering that 2007 and 2008 both experienced above average rainfall, it is unlikely that Ref-edge exhibits wetland hydrology. However, since the water table data used for the test was an average based on seven reference wells, it is likely that saturation was not constant throughout the entire area and some of the wells may have met jurisdictional wetland hydrology criteria. An evaluation of each individual Ref-edge well found that two of the wells met jurisdictional wetland hydrology criteria for at least one year during the study. Well REF06 met the criteria in 2006 and 2007 while well REF11 met the criteria in 2006. Neither well met the criteria based on 12.5% saturation. Given that some of Ref-edge met jurisdictional wetland hydrology criteria and some of it did not, the wetland/upland boundary most likely exists somewhere within the Ref-edge classified area.

When considering only jurisdictional wetland hydrology criteria, the treatments while wet enough to achieve wetland hydrology do not appear to be as wet as the reference. However continuous saturation can be a difficult and unreliable tool for evaluating hydrology though because it only considers consecutive days of saturation. A site could experience a water table within 30 cm of the surface for 22 of 23 days but if the one day with a deeper water table occurred on day 12, the site would only have experienced continuous saturation for 2 periods of 11 days which is not considered minimum wetland hydrology.

Wright (2005) found similar results in his evaluation of 2003 and 2004 data. He found Ref-center to experience the longest periods of continuous saturation while all the treatments were similar and Ref-edge experienced the least number of days of continuous saturation. This implies that any treatment effect on hydrology has changed very little over the six years of the restoration.

Average Water Table Depth

The water table for each treatment and reference area was evaluated based on the average water table depth for the entire year and for the entire study period. The average yearly water table depth was used instead of the average growing season water table depth because of potential flaws in the growing season theory. The average water table depth for each treatment was compared using an ANOVA means test which compared the average water table depth of each well on a daily basis.

In 2006, Ref-center had the shallowest average water table at 33 cm while Ref-edge had the deepest average water table at 51 cm (figure 2.21). The three treatments all had very similar average water table depths, PLUG 42 cm, CONT 45 cm, and CR 44 cm. Ref-center had a much shallower average water table depth due to a period due to an approximate three month period between April and June where the reference was substantially wetter than the restoration (figure 2.16 located in a previous section).

2007 did not have as the magnitude of difference between Ref-center and the restoration treatments. Ref-center and CONT experienced the shallowest average water table, both at 44 cm. PLUG and CR were slightly deeper at 46 and 47 cm while Ref-edge was much deeper at 65 cm.

In 2008, the reference and treatments behaved similar to 2007 with respect to average water table depth. PLUG and CR experienced the shallowest average water table both at 39 cm while CONT and Ref-center were slightly deeper at 41 and 42 cm respectively. As expected, Ref-edge was much deeper at 65 cm. 2008 experienced the highest (nearest to the surface) yearly water table depths for the study period. 2007 received the highest yearly rainfall for the study period, but spent much of the year below average and did not receive excess rainfall until the fall. 2008 received average or above average rainfall for most of the year which limited the water table from dropping as deep in the summer months as it did in 2007.

For the entire study period (2006-2008) there was no statistical difference ($\alpha = 0.05$) between the average water table of PLUG (42 cm), CONT (43 cm), and CONT (43). Ref-center had a slightly shallower average water table of 40 cm which was statistically different from the treatments and Ref-edge. Ref-center was most likely statistically different due the higher water table it experienced in spring of 2006. In 2007 and 2008, Ref-center was within the range of average water tables found in the treatments. Despite the statistical differences, all three treatments were did a good job matches the average water table depth of the reference as all were within 3 cm. Ref-edge experienced a three year average water table of 61 cm below the surface which was statistically different than the others.

Based on 2007 and 2008 results, CONT did the best job mimicking Ref-center hydrology when evaluating based on average yearly water table depth. In 2007 CONT experienced the same average water depth as Ref-center and in 2008 is was the closest to matching Ref-center, off by 1 cm. For the entire study however, all treatments were significantly different than Ref-center (P<0.0001).

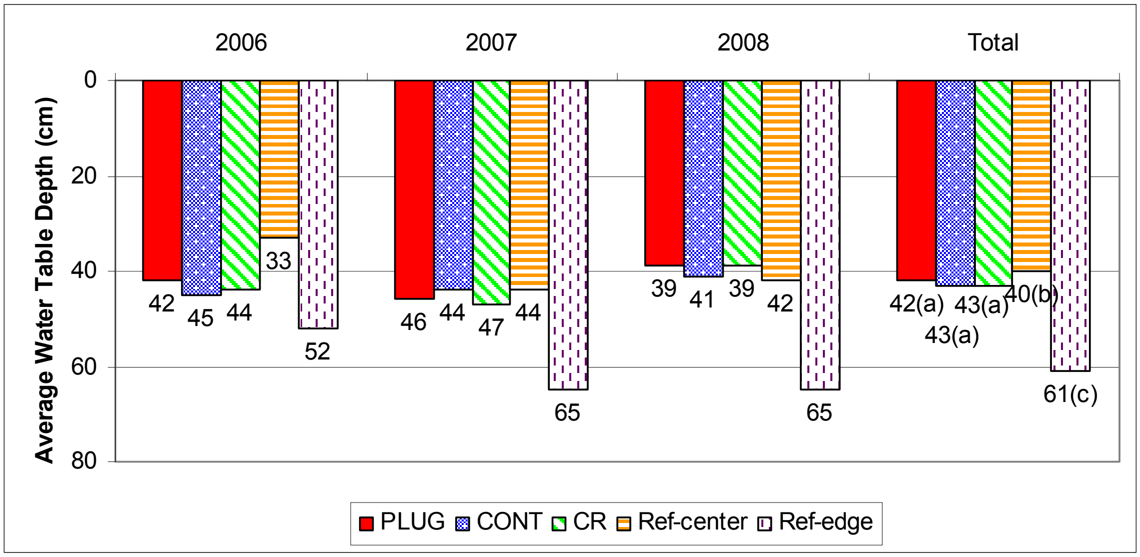

Figure 2.21 Average water depth per year.

SEW_{30}

SEW_{30} can be an important tool for evaluating wetland hydrology since it measures both duration and intensity of saturation, in this case when the water table is within 30 cm of the surface. A high SEW_{30} value implies wet/shallow water table conditions for an extended duration, while a low SEW_{30} implies the water table rarely rose and remained within 30 cm of the surface. SEW_{30} results for each treatment were compiled by taking the mean of the yearly SEW_{30} of each well within the treatment. The total SEW_{30} of each treatment was evaluated statistically by comparing the daily SEW_{30} values of all the wells per treatment for the entire study period using an ANOVA means test.

In 2006 Ref-center experienced the highest SEW_{30} (3507 cm*days) which corresponds to it having the shallowest average water table as well. PLUG and CR experienced similar SEW_{30}, 3015 and 3139 cm*days respectively, while CONT was much lower at 2332 cm*days. Ref-edge experienced the lowest SEW_{30} only 574 cm*days (figure 2.22). The low SEW_{30} of Ref-edge was expected since it never experienced a water table within 30 of the surface for more than 5 consecutive days.

In 2007, Ref-center had a lower SEW_{30} (3054 cm*days) than all the treatments. The treatment with the highest SEW_{30} was CONT (3620 cm*days) followed by CR (3569 cm*days) and PLUG (3288 cm*days). Similar to 2006, Ref-edge had the lowest SEW_{30} with only 490 cm*days.

In 2008, most areas experienced higher SEW_{30} results than in 2006 or 2007. Ref-center experienced a lower SEW_{30} (3240 cm*days) than all the treatments. The treatment with the highest SEW_{30} was CR (4162 cm*days) followed by PLUG (4100 cm*days) and CR (3828 cm*days). Similar to 2006 and 2007, Ref-edge had the lowest SEW_{30} with only 426 cm*days.

For the entire study period (2006-2008) CR and PLUG experienced the highest SEW_{30}, 10870 and 10404 cm*days respectively. There was no statistical difference ($\alpha = 0.05$) between SEW_{30} of CR and PLUG. They were followed by Ref-center (9,801 cm*days) and CONT (9,780 cm*days) which were not statistically different from each other. Ref-edge experienced the lowest SEW_{30} (1,490 cm*days) and was statistically lower from all the other areas. Statistically, CONT did the best job of the treatments in mimicking the SEW_{30} of Ref-center since they were not statically different over the three year stretch. However, CONT and Ref-center did not have the most similar yearly SEW_{30} results. The yearly ranking of SEW_{30} results was highly variable and no patterns were ever established except for Ref-edge being much lower than the treatments and Ref-center.

Wright (2005) in his evaluation of 2003 and 2004 data found PLUG to have the highest SEW_{30} while CONT, CR, and Ref-center were all very similar and Ref-edge was much lower.

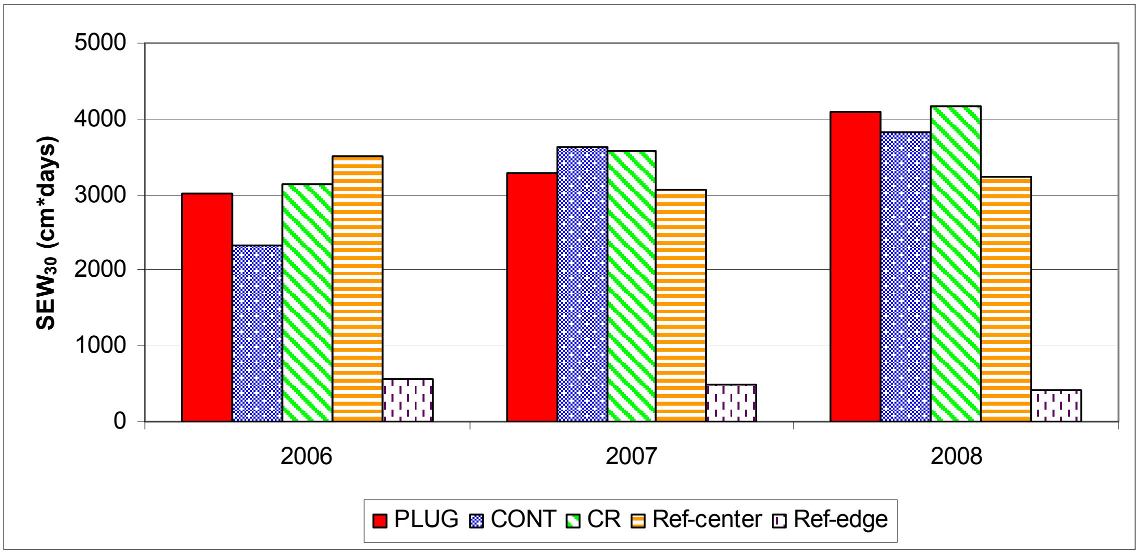

Figure 2.22 SEW$_{30}$ per year

Surface Inundation

The last criterion used for evaluation of water table data was number of days of surface inundation per year. The surface was considered inundated when the average daily water table is at or above ground surface. Yearly inundation results for each treatment were compiled by taking the mean of the number of days inundated per year of each well within the treatment. The total number of days inundated of each treatment was evaluated statistically by comparing the daily inundation of all the wells per treatment for the entire study period using an ANOVA means test ($\alpha = 0.05$).

In 2006, PLUG experienced to most days of surface inundations with 31 followed by CR with 22. The other areas all experienced less than five days of surface inundation; CONT experienced 2, Ref-center 4, and Ref-edge 0 (figure 2.23). CONT's low number of inundated days may be explained by its low SEW$_{30}$ in 2006. However, Ref-center had the highest SEW$_{30}$ in 2006 and a very low number of days inundated. Ref-edge did not experience any days of surface inundation.

In 2007, Ref-center experienced only 2 days of surface inundation while PLUG experienced the most (39 days) followed by CONT (29 days) and CR (27 day). Ref-edge did not experience any days of surface inundation.

Similar to the SEW30 results, 2008 saw some of the highest counts of inundation due to the consistent above average rainfall. Ref-center experienced only 2 days of surface inundation while PLUG experienced the most (45) followed by CR (36) and CONT (27). Again, Ref-edge did not experience any days of surface inundation.

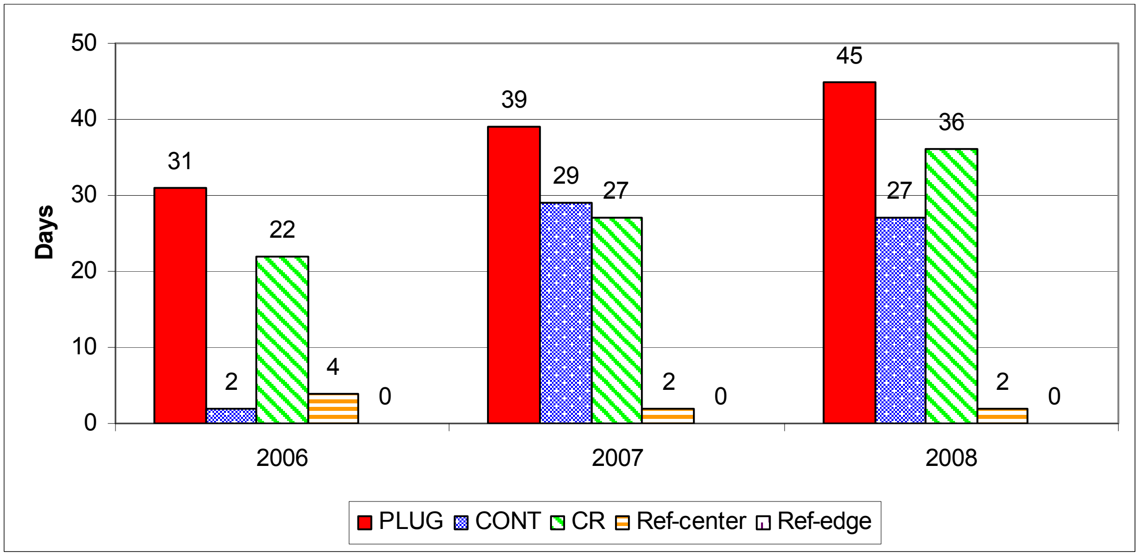

Figure 2.23 Number of days of surface inundation per year.

For the entire period of study (2006-2008) PLUG experienced the most days of surface inundation (115) followed by CR (85) and CONT (58). Ref-center and Ref-edge only experienced 8 and 0 days respectively. All the areas experienced statistically different amounts of surface inundation except Ref-center and Ref-edge. The inundation data yielded much more variable results than the other criteria. One of the reasons is that this metric was very sensitive to wells located in areas which experienced frequent ponding. The PLUG results were greatly influenced by a single well, NR14 which experienced 532 days of surface inundation during the study period while CR was greatly influenced by NR09 which experienced 412 days of surface inundation during the study period. Wright's (2005) evaluation of 2003 and 2004 surface inundation also yielded similar results. Similar to this study, Wright found that PLUG resulted in the greatest number of days of surface inundation and that Ref-center experienced less surface inundation than any of the restoration treatments. In Wright's evaluation, Ref-center experienced more surface inundation than was found during 2006-2008, however there are some differences in the studies. Following Wright's study, four new wells were installed in the Reference (REF11, REF13, REF14, and REF16). All of those wells except for REF11 were classified as Ref-center. Some of those wells are located in areas that are typically not quite as wet as the areas where the previous Ref-center wells were placed.

Hydrologic Criteria Summary

Four hydrologic criteria were used to evaluate the water table fluctuations of the reference wetland and three restoration treatments: jurisdictional wetland hydrology criteria, average water table depth, SEW_{30}, and days of surface inundation.

It was difficult to distinguish the hydrologic differences between the three restoration treatments. All three experienced very similar periods of continuous saturation during the growing season expect for in 2008, when PLUG remained saturated for a noticeably shorter period. Ref-center remained saturated for longer periods than any of the restoration treatments.

There was no statistical difference between the average water table depths of the three treatments (table 2.2). For the study period, the average water table depth for the treatments was within 1 cm. Ref-center's average water table depth was significantly shallower; however this is mostly due to a three month period in 2006 where Ref-center's water table was substantially shallower than the restoration. In 2007 and 2008 Ref-center experienced a similar average water table depth to the restoration treatments.

There were some statistical differences with SEW_{30} values. The PLUG and CR SEW_{30} was significantly higher than CON and Ref-center, while Ref-edge was significantly lower than everything else. A high SEW_{30} corresponds to a water table which is frequently shallower than 30 cm.

There was a large variation between the number of days of surface inundation of each restoration treatment and the reference areas. The treatments all experienced significantly different amounts of surface inundation and significantly more surface inundation than the reference. The treatment with the lowest amount of surface inundation, CONT, still experienced more than six times the amount of surface inundation than Ref-edge.

Given the success at which the restoration treatments mimicked the reference in the other criteria, it is surprising that none of the treatments were close to matching the surface inundation found in Ref-center. The water table in the reference rarely if ever rose to the surface, while ponding frequently occurred in the restoration. This is most likely explained by the reference wetland soils having a higher drainable porosity.

In general, the water table fluctuations in the reference were less flashy than in the restoration. This allowed it to experience the longest periods of continuous saturation and the shallowest water table while rarely inundating the surface. These differences in the soil properties were likely caused by soil compaction which would have occurred in the restoration due to decades of farming.. Compacted soils, loses pore space which can be used for water storage. Over time the apparent compaction in the restoration should be reduced due to the absence of heavy equipment on it and natural processes such as root growth and animal burrowing. The buildup of slowing decomposing organic matter on the surface of restoration should also provide soil-water storage and reverse subsidence which should help reduce the frequency of surface inundation closer to reference levels.

Table 2.2 Summary of hydrologic criteria

		2006	2007	2008	Total
Average Water Table Depth (cm)	PLUG	42	46	39	42 (a)
	CONT	45	44	41	43 (a)
	CR	44	47	39	43 (a)
	Ref-Center	33	44	42	40 (b)
	Ref-Edge	52	65	65	61 (c)
SEW_{30} (cm*days)	PLUG	3015	3288	4100	10404 (a)
	CONT	2332	3620	3828	9780 (b)
	CR	3139	3569	4162	10870 (a)
	Ref-Center	3507	3054	3240	9801 (b)
	Ref-Edge	574	490	426	1490 (c)
Days of surface inundation	PLUG	31	39	45	115 (a)
	CONT	2	29	27	58 (b)
	CR	22	27	36	85 (c)
	Ref-Center	4	2	2	8 (d)
	Ref-Edge	0	0	0	0 (d)

Values followed by same letter within each criteria are not statistically different ($\alpha = 0.05$).

Water Table Elevation Profiles

The evaluation of the treatments using the hydrologic criteria yielded very similar results as to what was reported by Wright (2005). Also similar to Wright, very little hydrologic difference between the restoration treatments were observed, and in some cases, PLUG appeared to be the wettest treatment. This contradicts his original hypothesis and the current hypothesis for this study that PLUG should be the driest restoration treatment since it should provide the least surface storage and best facilitate surface runoff. Following Wright's suggestions, an additional 36 wells were installed in the restoration treatments and an as built survey was performed. Water table depths in the additional wells were recorded manually on a monthly basis. The total dataset included fifteen days of water table data recorded between 2007 and 2008 (The wells were only installed 1 m deep so measurements could only be taken when the water table in all wells was within 100 cm). The water table data along with the survey data was used to develop water table profiles of each block of treatments to determine how surface elevation and topography may have affected water table depth and elevation. The treatments were evaluated based on three water table conditions: shallow water table conditions (1/23/2008), deep water table conditions (10/08/2008), and the average water table depth from the fifteen days of data that were collected during the study.

Block 1

In block 1, the CR treatment maintained the shallowest average water table depth relative to the surface (29 cm) while PLUG and CONT had similar average water table depths, 33 and 32 cm respectively. CR also maintained the highest average water table *absolute* elevation (118 cm) followed by PLUG (114 cm) and CONT (110 cm). The average surface elevation for each treatment was consistent across the block at approximately 1.48 m. The average elevation was found by taking a mean of all the ground survey shots taken within each treatment. Since average surface elevation was consistent across all treatments, water table differences were most likely caused by a treatment effect as opposed to elevation differences (i.e. closer to the water table). Removing the crown flattened the surface which created more storage and reduced runoff towards the ditches which appeared to raise the water higher closer to the surface (figure 2.24). The PLUG and CONT treatments both have higher surface elevations on the edges of the treatment due to the crown which could have resulted in increased surface runoff towards the ditches. The CONT treatment was expected to result in a higher water table than PLUG which it did not. However, the high spot in the CONT treatment appears to be the cause for a very noticeable drop in water table elevation, which most likely is the reason that CONT had a lower average water table elevation than PLUG. At deeper soil depths, the surface topography seems to have less impact on the water table; this resulted in water table elevations fairly constant across the block during drier periods.

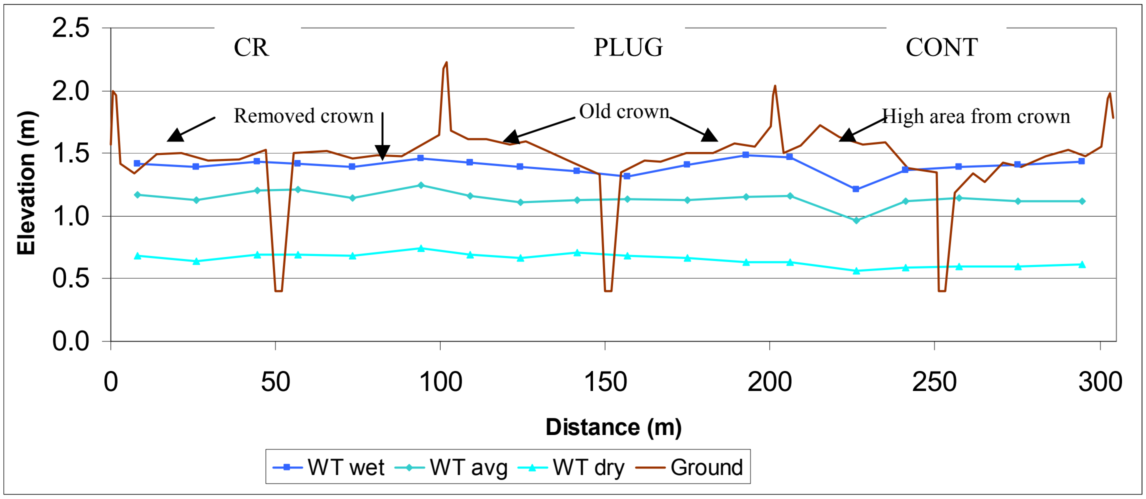

Figure 2.24 Water table profile of block 1 for 3 water table conditions.

Block 2

In block 2, CR maintained the shallowest average water table depth (26 cm) followed by CONT (27 cm) and PLUG (30). CONT maintained the highest average absolute water table elevation (104 cm) followed by CR (100 cm) and PLUG (99 cm).

All three treatments experienced shallower average water table depths than the block 1 replicates. This was partially due to the fact that the average surface elevation in block 2 is 12-24 cm lower. As intended during design, the CR treatment had the lowest average elevation at 1.24 m while PLUG and CONT had similar average surface elevations at 1.34 and 1.36 m. It is likely the CR had the lowest average surface elevation due to the crown removal process, but the elevation was lower than observed in block 1. The CONT treatment appeared to have had the most impact on raising the water table elevation but that was also not observed in block 1. However, the isolated high spot in block 1 CONT may have limited its treatment effect. The block 2 profiles suggest that the contouring contributed to a shallower water table by raising the water table as opposed to lowering the ground surface which may have occurred with CR (figure 2.25). The low areas created by surface contouring should limit surface water movement and increase infiltration. The PLUG treatment appeared to result in deepest average water table depth and lowest average water table elevation because of the enhanced surface drainage which occurred due to the prior-existing field crown.

A low area next to the berm in CR appeared to result in deeper water table for the wet, average, and dry conditions. This seemed unusual given that low areas usually result in ponded water. Field investigation found that to low area was not a depression but a long trench which was probably the result of the crown removal or berm construction This trench acted as a ditch/channel and drained the area next to the berm for a length of approximately a quarter of the treatment.

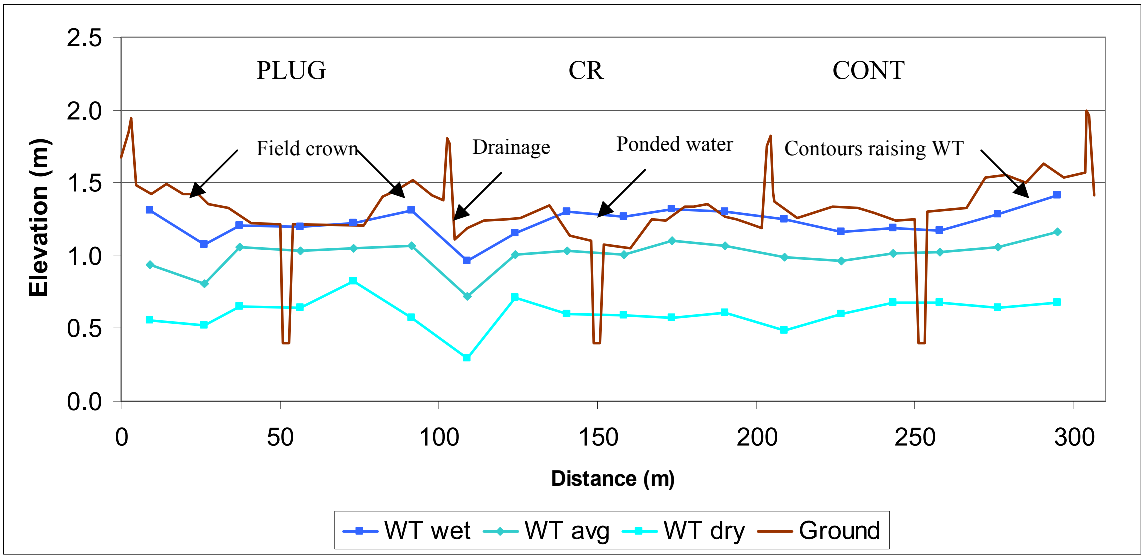

Figure 2.25 Water table profile of block 2 for 3 water table conditions.

Block 3

The treatments in block 3 appeared to have the opposite effect on the water table than they did in blocks 1 and 2. In block 3, PLUG resulted in the shallowest average water table depth (29 cm) while CR resulted in the deepest average water table depth (48 cm). This data contradicts the hypothesis that crown removal should increase storage and result in a shallower water table. However the as-built survey showed that this particular transect of block 3 does not have the topographical features expected for each treatment.

The left side of PLUG between 0-50 m (figure 2.26) looks like the intended PLUG treatment design. The existing crown is noticeable which seems to result in a deeper water table. However on the right side of PLUG between 50-100 m, no crown is noticeable. The treatment looks more like a CR treatment which explains why experiences a high water table and surface ponding. That area is also at a much lower surface elevation relative to the rest of block 3.

The CONT treatment appears to have been constructed as designed. Its average water table depth (30 cm) is almost as shallow PLUG (29 cm) which seemed to be constructed like CR, and its average water table elevation is just as high as PLUG (199 cm).

The CR treatment behaves very differently than was observed in blocks 1 and 2; in fact it was the driest treatment within the entire restoration. It has a much deeper average water table depth (48 cm) than was observed in the rest of block 3 and has the lowest average water table elevation as well (195 cm). Much of this is explained by fact the average surface elevation in CR is 15-16 cm higher than in the other treatments in block 3. Most likely, the CR treatment was constructed on a naturally higher field. The crown removal practice was expected to lower the surface elevation but if this did occur is it was negligible. If this area was much higher pre-construction, then it should have been identified and lowered. Because of this high area, parts of block 3 CR may only have marginal wetland hydrology. Additional analysis of the two automatic water table wells located in block 3 CR (NR17 and NR18) found that NR17 met jurisdictional wetland hydrology criteria for all years of study (2006-2008) but NR18 (located in the highest area of CR) only met the criteria in 2006. The CR treatment in block 3 shows why it is important to have a good preliminary survey before designing a wetland and good oversight during construction of all portions of a wetland to ensure the entire area will meet hydrologic criteria.

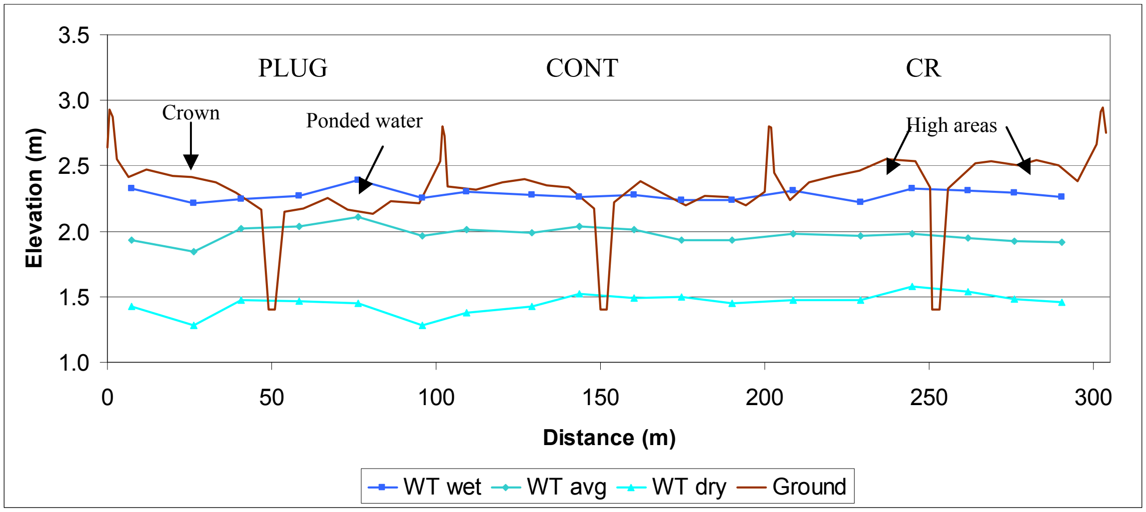

Figure 2.26 Water table profile of block 3 for 3 water table conditions.

Water Table Profiles Discussion

By tripling the number of wells in each treatment, a more detailed cross-section of the water table was able to be developed as compared to the automatic wells, although with only fifteen days of data, statistical tests do not provide much power of analysis. The average water table depth of block 3 CR was the only water table value which was statistically different. When combining with the as built survey, the impact of topography and elevation on the water table was able to be analyzed.

In blocks 2 and 3, the treatment with the lowest average surface elevation also had the shallowest average water table relative to the ground surface, while in block 1 all three treatments had the same average surface elevation (table 2.3). In blocks 1 and 2, CR resulted in the shallowest average water table depth, while in block 3 CR had the deepest average water table depth due to its high surface elevation. While it was expected that CR would result in the lowest surface elevation due to lowering of the crown this was only the case in one of the block. This is likely due to variations in pre-construction surface elevation.

In general, surface elevation appeared to have the most impact on average water table depth relative to the surface. CR was the only treatment which had any effect on post-construction surface elevation since soil was removed from the parcel of land. The survey did not show CR to always have the lowest average surface elevation; simply a result of variations in the pre-construction surface elevation.

The CONT treatment is likely to result in a higher water table elevation due to the increase of surface storage and therefore increase in infiltration. In blocks 2 and 3, CONT had either equal to or had the highest average water table absolute elevation. In block 1, CONT had the lowest average water table absolute elevation which was mostly due to an isolated high spot caused a drastic drop in the water table below it.

The PLUG treatment appeared to have the least effect on influencing shallower water table conditions in blocks 1 and 2. Due to the residual crown and lack of surface storage, PLUG resulted in a deeper average water table depth and lower average water table elevation. The exception occurred in block 3 where PLUG experienced the shallowest average water table depth. However the survey showed that PLUG had the lowest average surface elevation which was likely due to pre-construction elevation levels in the fields.

The observations in block 3 show the importance for preliminary survey and construction oversight.

Table 2.3 Hydrologic summary of manual water table readings, n=15.

		PLUG	CONT	CR
Block 1	Average WTD from surface (cm)	33 (a)	32 (a)	29 (a)
	Average WT EL (cm)	114 (a)	110 (a)	118 (a)
	Average Treatment EL (m)	1.48	1.48	1.48
Block 2	Average WTD from surface (cm)	30 (a)	27 (a)	26 (a)
	Average WT EL (cm)	99 (a)	104 (a)	100 (a)
	Average Treatment EL (m)	1.34	1.36	1.24
Block 3	Average WTD from surface (cm)	29 (a)	30 (a)	48 (b)
	Average WT EL (cm)	199 (a)	199 (a)	195 (a)
	Average Treatment EL (m)	2.26	2.27	2.42

Values with the same letter horizontally are not significantly different ($\alpha = 0.05$)

Alternative Water Table Evaluation:

Due to the differences observed when evaluating the as-built survey and water table profiles, it was decided that the topography of the PLUG and CR treatments in block 3 may have been unrepresentative of their intended design. In fact, it is believed that block 3 PLUG as constructed was more similar to CR, and the block 3 CR elevations were more similar to the design for the PLUG treatments in the areas monitored. These two treatment plots may have skewed the results of the four hydrologic criteria to a point where hydrologic differences between the treatments could not be established. Example typical cross-sections for each treatment are shown in figures 2.27 – 2.29.

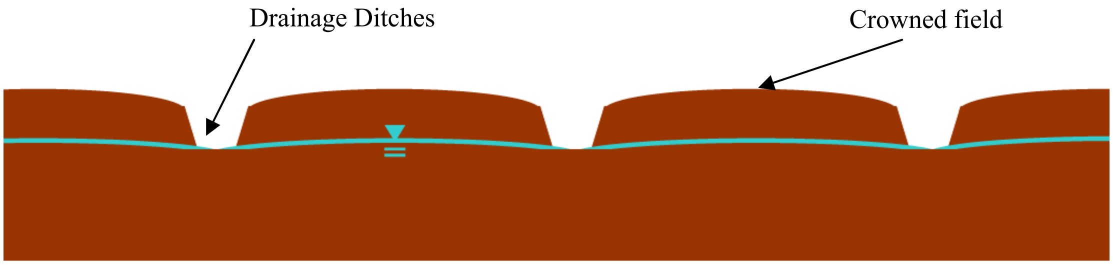

Figure 2.27 Example of typical pre-restoration topography with artificial free drainage.

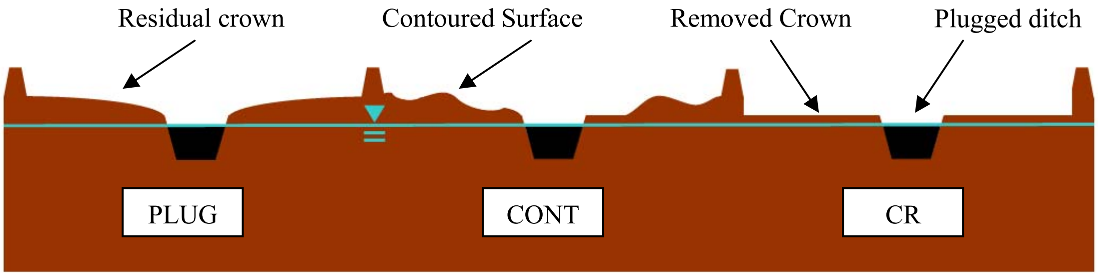

Figure 2.28 Example of typical designed topography for each surface treatment.

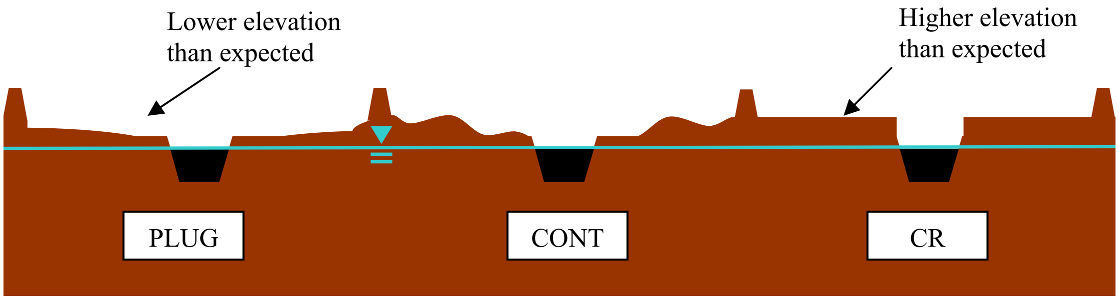

Figure 2.29 Example of as-built topography observed in block 3.

In response to this conclusion, two alternative water table evaluations were performed:

- The four hydrologic criteria were used to evaluation the water table data from blocks 1 and 2 only.
- The four hydrologic criteria were used to evaluate the water table data from all 3 blocks, except block 3 PLUG was considered CR and block 3 CR was considered PLUG in an effort to account for as-built elevation observations.

Water Table (Block 1 and 2)

Due to the observations that block 3 may have been unrepresentative of the intended treatment design, water table data from 2006-2008 was re-evaluated using only block 1 and block 2 data for the restoration treatments. The same four hydrologic criteria were used for the evaluation. Due to similar observations, Wright evaluated 2003-2004 water table data only using blocks 1 and 2 as well. Ref-edge hydrology will not be discussed in this section because it was significantly drier than Ref-center and the treatments in the previous evaluation, Ref-edge results for each hydrologic criterion will still be reported in the figures and tables

Jurisdictional Wetland Hydrology Criteria (Block 1 and 2)

In 2006, Ref-center experienced a longer continuous period of saturation during the growing season (13%) than any of the restoration treatments (figure 2.30). In the restoration, CR experienced the longest period of saturation (10%) followed by CONT

(7%) and PLUG (5%). All three treatments met jurisdictional wetland hydrology for 2006.

2007 was a wetter year in terms of rainfall than 2006 which lead to longer periods of saturation. Ref-center experienced continuous saturation for the same percentage of the growing season as CR (16%). They were followed by CONT and PLUG which both experienced continuous saturation for a period of 15% of the growing season.

2008 experienced the longest continuous periods of saturation. Ref-center experienced the longest continuous period of saturation during the growing season for the entire study (20%). In the restoration, CR experienced the longest periods of continuous saturation (18%) followed by CONT (12%) and PLUG (11%).

In all three years, the areas experienced consistent rankings in terms of duration of continuous saturation. Ref-center experienced the longest periods of saturation followed closely by CR (both experienced continuous saturation for 16% of the growing season in 2007). The next wettest was CONT followed closely by PLUG (both experienced continuous saturation for 15% of the growing season in 2007). These four areas all met jurisdictional hydrology for all three years of study.

When evaluating all three treatments blocks, there was not a clear distinction between the three treatments in terms of continuous periods of saturation and none of the treatments were able to remain saturated for as long as was observed in Ref-center. When evaluating only blocks 1 and 2 there was a clear distinction between the treatments. CR remained saturated for longest duration followed by CONT then PLUG.

Of the three restoration treatments, CR did the best job mimicking the saturation found in Ref-center. It was able to match the duration in 2007, and was close to matching Ref-center in 2006 and 2008.

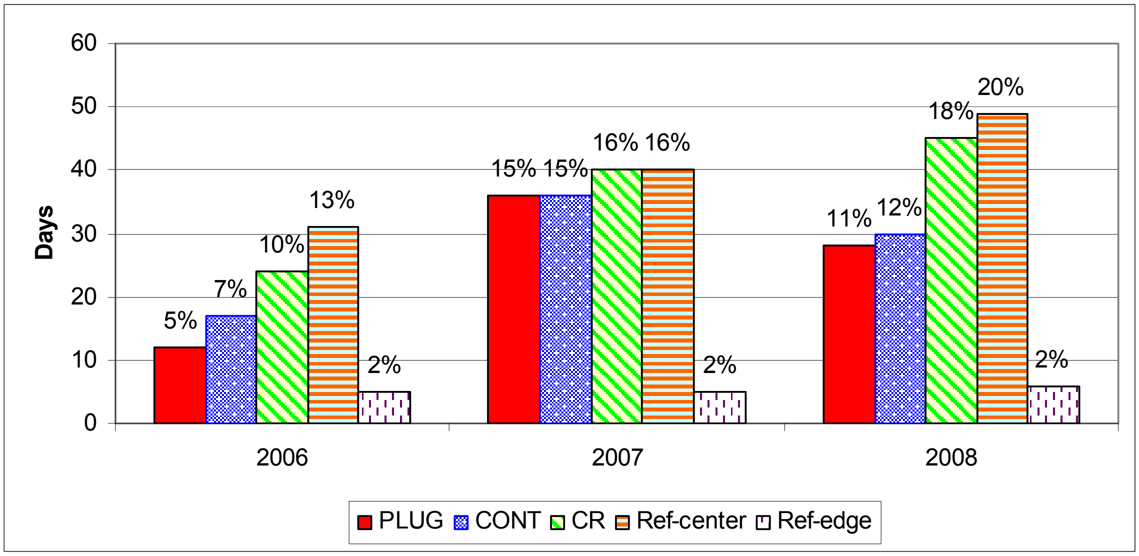

Figure 2.30 Longest continuous period of saturation within the growing season, percentage of growing season in parenthesis (block 1 and 2).

Average Water Table Depth (Block 1 and 2 only)

The hydrology of the restoration treatments and the reference was evaluated using the average water table depth for the entire year. In 2006, Ref-center experienced the shallowest average water table depth (33 cm) followed closely by CR (35 cm) (figure 2.31). PLUG and CONT had very similar average water table depths (42 and 43 cm respectively).

2007 monitoring revealed deeper average water table depths despite 2007 being a wetter year than 2006 in terms of rainfall. This is likely due to the fact that 2005 was an extremely wet year which would have influenced early the early 2006 water table. CR experienced the shallowest average water table (37 cm). Ref-center and PLUG experienced very similar average water table depths, 44 and 45 cm respectively while CONT was deeper (50 cm)..

Similar to 2007, CR had the shallowest average water table depth (31 cm) in 2008. PLUG was substantially deeper at 39 cm followed Ref-center and CONT which had average water table depths of 42 and 43 cm.

Overall (2006-2008) CR had the shallowest average water table (34 cm) followed by Ref-center (40 cm). PLUG and CONT both had the same average water table depth (42 cm). Statistical analysis ($\alpha = 0.05$) found all area to have significantly different average water table depths except for PLUG and CONT for which no significant difference was found. Both PLUG and CONT matched the average water table depth of Ref-center closely (within 2 cm) however they were still significantly different.

While the evaluation using all three blocks found no significant differences between the three treatments, but this evaluation using only blocks 1 and 2 found CR to have a significantly shallower average water table then PLUG and CONT.

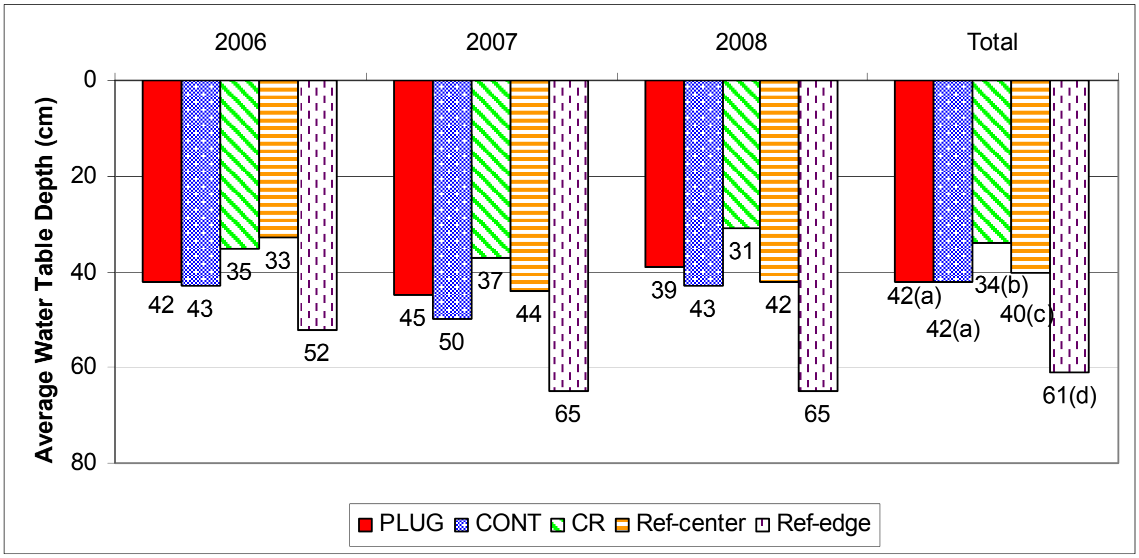

Figure 2.31 Average water table depth per year (block 1 and 2).

<u>SEW$_{30}$ (Blocks 1 and 2)</u>

In 2006, CR had the highest SEW$_{30}$ (4166 cm*days) however it did not have the shallowest average water table, Ref-center did. This means that CR experiences more intense and frequent saturation than Ref-center but also had a deeper average water table. This was likely caused by CR having a deeper water table during the drier times of the year which have no impact on SEW$_{30}$. Ref-center was still a wet area having the second highest SEW$_{30}$ (3507 cm*days). It was followed by PLUG and CONT which had very similar SEW$_{30}$ (2394 and 2255 cm*days) (figure 2.32).

2007 was a wetter year than 2006; the three restoration treatments all experienced a highest SEW$_{30}$ value but the reference areas did not. CR continued to have the highest

SEW_{30} (4502 cm*days) followed by CONT (3672 cm*days), Ref-center (3054 cm*days), PLUG (3054 cm*days) and Ref-center (490 cm*days).

In 2008, CR experienced the highest SEW_{30} of the entire study period (5301 cm*days). PLUG, CONT, and Ref-center all experienced very similar SEW_{30} values (3488, 3360, and 3240 respectively.

For the entire study period (2006-2008) CR experienced the highest SEW_{30} (13969 cm*days). CR was followed by Ref-center (9801 cm*days), CONT (9287 cm*days), and PLUG (8403 cm*days). Statistical analysis found all areas except Ref-center and CONT significantly different ($\alpha = 0.05$).

The evaluation using blocks 1 and 2 differed from the evaluation using all three blocks. When only considering blocks 1 and 2, CR had a lower SEW_{30} (although it was still the highest) while PLUG and CONT had a higher SEW_{30}. In the analysis using blocks 1 and 2 there was a statistical difference between all three treatments while in the evaluation using all three blocks, CONT was significantly different but there was no different between CR and PLUG. In both analyses, only CONT did not have a significantly different SEW_{30} Value than Ref-center. Based on the statically analysis, CONT did the best job mimicking the SEW_{30} experienced in Ref-center.

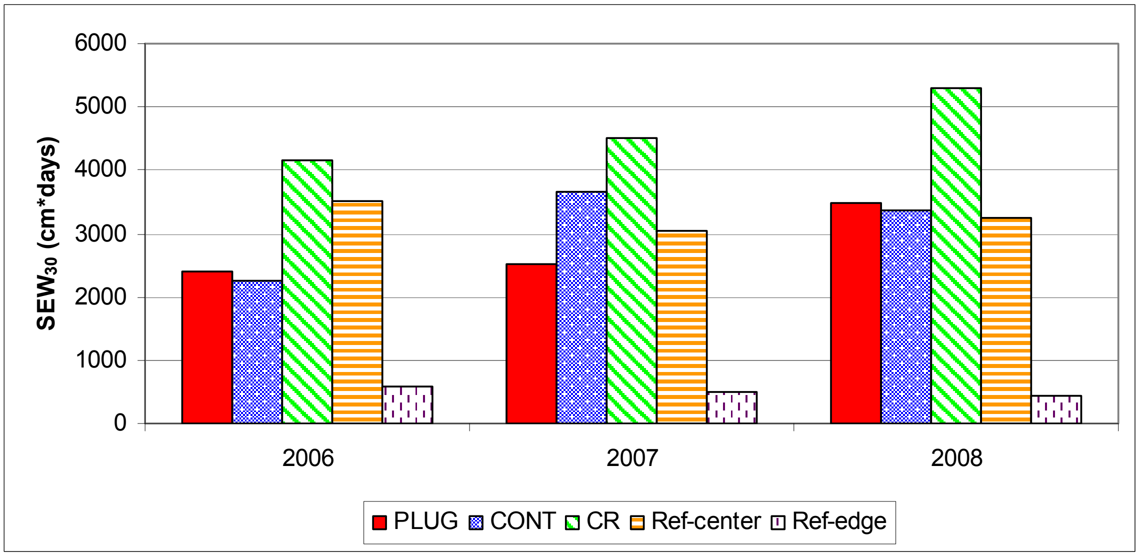

Figure 2.32 SEW$_{30}$ per year (block 1 and 2).

Surface Inundation (Blocks 1 and 2)

The surface is considered inundated when the average daily water table is at or above ground surface. In 2006, CR experienced dramatically more days of surface inundation than any of the other areas. CR experienced 33 days of surface inundations while next highest was PLUG at 9 days. Ref-center experienced 4 days followed by CONT with 3 days (figure 2.33)

In 2007, CR again experienced the most surface inundation with 41 days followed closely by CONT (38 days). PLUG experienced 12 days of surface inundation followed by Ref-center (2 days).

In 2008 CR continued to experience the highest amount of surface inundation (53 days) but saw a major drop off in surface inundation experience by CONT (5 days). PLUG experienced 18 days, while Ref-center only experienced 2 days.

For the entire study period (2006-2008) CR was four times more days of surface inundation than any other treatment or area. CONT and PLUG experienced a similar number of days of surface inundation (46 and 39 days). There was no significant difference ($\alpha = 0.05$) between CONT and PLUG. Ref-center experienced significantly few days of surface inundation than any of the restoration treatments.

The evaluation using only blocks 1 and 2 revealed very different results than the evaluation using all three blocks. When evaluating all three blocks, PLUG experienced the highest number of days of surface inundation (115 days) while both CR and CONT were above 50 days. When evaluating only block 1 and 2, CR experienced over 100 days of surface inundation while PLUG and CONT both experienced less than 50. PLUG is so dramatically different because parts of the PLUG treatment in block 3 (where well NR18 was located) remained inundated for months at a time. The three treatments all experienced significantly more surface inundation than the reference. The least inundated treatment, PLUG, still experienced more than four times the year inundation as Ref-center. The difference in surface inundation between the reference and restoration is most likely due to near surface compaction which occurred in the restoration area due to the years of farming practices. The compaction decreased the storage in the near surface soil which resulted in the water table in the treatments to often rise above the surface while that same volume of water could be stored within the soil profile in the reference.

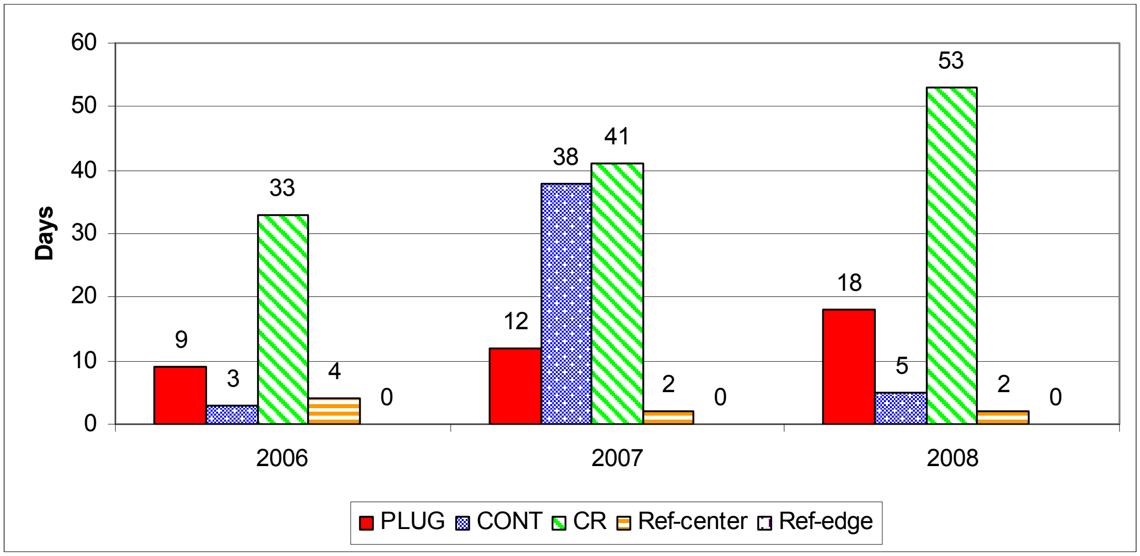

Figure 2.33 Number of days of surface inundation per year (block 1 and 2).

Hydrologic Criteria Discussion (Block 1 and 2)

Hydrologic evaluation of just blocks 1 and 2 of the restoration treatments yielded results more similar to the original hypothesis than was found when evaluating all three treatment blocks. When evaluating all three blocks, PLUG was found to be the wettest treatment followed closely by CR. CONT was significantly drier than the other treatments for most of the criteria. However when evaluating the hydrology using only blocks 1 and 2, CR was by far the wettest treatment for all criteria, while PLUG was the driest treatment. CR and PLUG had very different results for the criteria when excluding block 3 because block 3 PLUG was wetter than designed and block 3 CR was drier than designed. CONT had similar results for the criteria regardless of which blocks were used in the evaluation.

The evaluation using block 1 and 2 found similar results to what Wright (2005) found when evaluating blocks 1 and 2, which also matched his original hypothesis for which treatments would produce the wettest site. CR was the wettest treatment followed by CONT and then PLUG. Based on the four criteria, CR appeared to produce wetter conditions while CONT and PLUG may have produced drier conditions when compared to reference conditions. All the treatments produced significantly more surface inundation than was found in the reference. CONT appeared to do the best overall job mimicking the reference hydrology because there was no significant difference between CONT and Ref-center SEW_{30} values and CONT was within 2 cm of Ref-center's average water table depth (although it was still significantly different). CR produced a very similar hydrology to Ref-center when evaluating jurisdictional wetland hydrology but produced much wetter conditions based on the average water table depth and SEW_{30} evaluations. No wetland treatment matched reference hydrology exactly, but the treatments did produce a similar hydrology to the reference when blocks 1 and 2 alone were evaluated.

Table 2.4 Summary of hydrologic criteria (block 1 and 2).

		2006	2007	2008	Total
Average Water Table Depth (cm)	PLUG	42	45	39	42 (a)
	CONT	43	50	43	42 (a)
	CR	35	37	31	34 (b)
	Ref-center	33	44	42	40 (c)
	Ref-edge	52	65	65	61 (d)
SEW_{30} (cm*days)	PLUG	2394	2521	3488	8403 (a)
	CONT	2255	3672	3360	9287 (b)
	CR	4166	4502	5301	13969 (c)
	Ref-center	3507	3054	3240	9801 (b)
	Ref-edge	574	490	426	1490 (d)
Days of surface inundation	PLUG	9	12	18	39 (a)
	CONT	3	38	5	46 (a)
	CR	33	41	53	127 (b)
	Ref-center	4	2	2	8 (c)
	Ref-edge	0	0	0	0 (c)

Values followed by same letter vertically are not statistically different ($\alpha = 0.05$).

Water Table (Alternate Version of Block 3)

The as-built survey was very revealing of the actual as-built elevations of the wetland treatments. Due to the conclusion that block 3 PLUG elevation may have been more representative of the CR design and block 3 CR elevations may have been more representative of the PLUG design, water table data for all three blocks was re-evaluated; block 3 data for PLUG was evaluated as CR and vice-versa. The same four hydrologic criteria were used for the evaluation. Wright (2005) did not perform this evaluation of the restoration treatments. Ref-edge hydrology will not be discussed in this section because it was significantly drier than Ref-center and the treatments in the previous evaluation, Ref-edge results for each hydrologic criterion will still be reported in the figures and tables

Jurisdictional Wetland Hydrology Criteria (Alternate Version of Block 3)

In 2006, Ref-center and CR experienced the longest continuous periods of saturation during the growing season,13% (figure 2.34). They were followed by CONT (9%) and PLUG (5%). All three treatments met jurisdictional wetland hydrology for 2006. 2007 was a wetter year in terms of rainfall than 2006 which lead to longer periods of saturation. Ref-center experienced continuous saturation for the same percentage of the growing season as CR and CONT (16%). CONT actually experienced saturation for two less days than Ref-center and CR but was still rounded to 16%. They were followed by PLUG (14%).

2008 experienced the longest continuous periods of saturation. Again Ref-center and CR experienced the longest continuous periods of saturation during the growing season (20%). They were followed by CONT (12%) and PLUG (11%).

In all three years, the areas experienced consistent rankings in terms of duration of continuous saturation. Ref-center and CR experienced the longest periods of saturation followed by CONT then PLUG. These four areas all met jurisdictional hydrology for all three years of study.

The evaluation using the alternate version of block 3 showed very similar results to what was found when evaluating only blocks 1 and 2. For the restoration, CR remained saturated for longest duration followed by CONT then PLUG. CR did the best job mimicking the saturation found in Ref-center. CR and Ref-center soils experienced continuous saturation for the same percentage of the growing season in all three years of study.

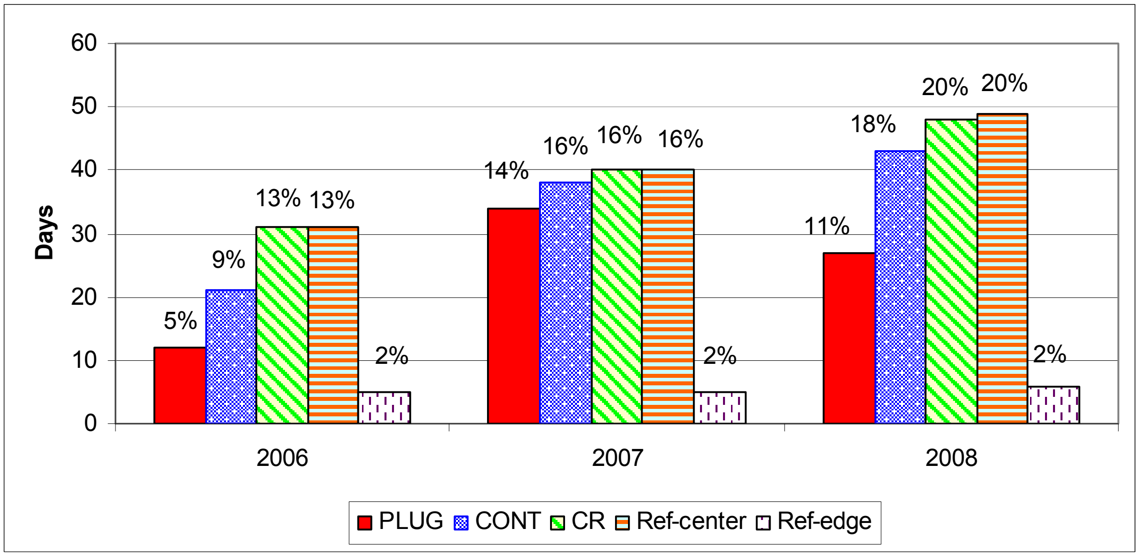

Figure 2.34 Longest continuous period of saturation within the growing season, percentage of growing season in parenthesis (with alternate block 3).

Average Water Table Depth (Alternate Version of Block 3)

In 2006, Ref-center experienced the shallowest average water table depth at 33 cm (figure 2.35). Within the restoration, CR had the shallowest average water table depth (37 cm) followed by CONT (45 cm) and PLUG (49 cm).

In 2007, average water table depths were deeper than 2006 despite 2007 being a wetter year than 2006 in terms of total rainfall. This is likely due to the fact that 2005 was an extremely wet year which would have influenced early the early 2006 water table.

2007 also experienced drought conditions (although it finished with above average rainfall) for much of the year resulting in a very deep summer water table. CR experienced the shallowest average water table (40 cm). Ref-center and CONT the same average water table depth (44 cm), followed by PLUG (52 cm) and Ref-edge (65 cm).

Similar to 2007, CR had the shallowest average water table depth (34 cm) in 2008. CONT and Ref-center had very similar average water table depths (41 and 42 cm) followed by PLUG (45 cm).

Overall (2006-2008) there was a ranking of average water table depth using this alternate analysis. CR had the shallowest average water table (37 cm) followed Ref-edge (40 cm), CONT (43 cm), and PLUG (49 cm). Statistical analysis found all areas to be significantly different ($\alpha = 0.05$). Of the three treatments, CR and CONT did the best job matching the average water table depth found in Ref-center. CR was shallower by 3 cm while CONT was deeper by 3 cm.

Similar to the evaluation using only blocks 1 and 2, this evaluation found more distinction between the treatments than was found in the original evaluation using all three blocks. Using all three blocks with the alternate version of block 3 clearly showed CR to have the shallowest water table followed by CONT and then PLUG.

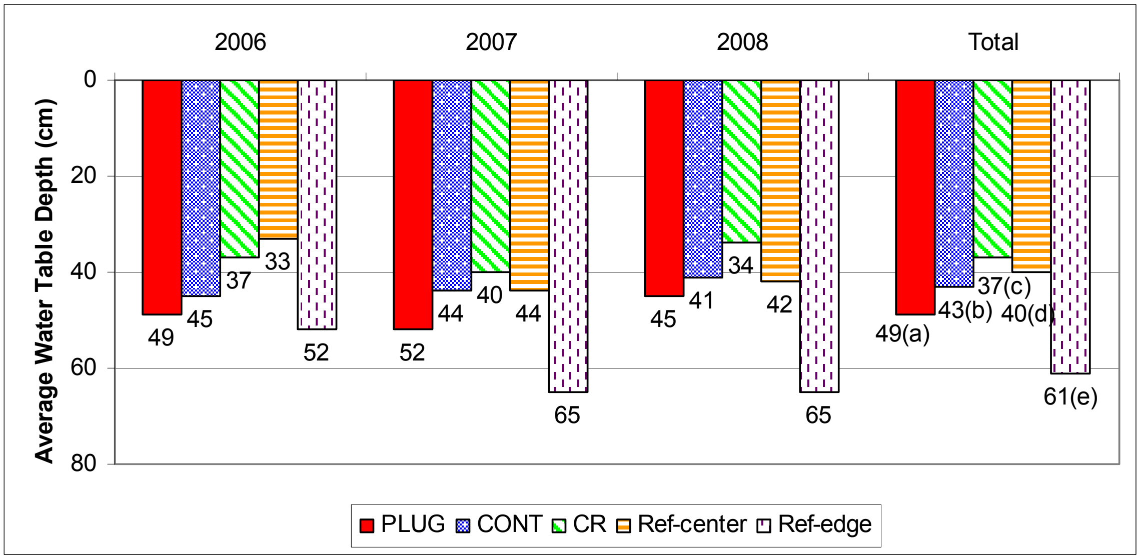

Figure 2.35 Average water table depth per year (with alternate block 3).

SEW$_{30}$ (Alternate Version of Block 3)

In 2006, CR had the highest SEW$_{30}$ (4197 cm*days) however it did not have the shallowest average water table, Ref-center did. This means that CR experiences more intense and frequent saturation than Ref-center but also had a deeper average water table. This was likely caused by CR having a deeper water table during the drier times of the year which have no impact on SEW$_{30}$. Ref-center was still a wet area having the second highest SEW$_{30}$ (3507 cm*days). It was followed by CONT and PLUG which had similar SEW$_{30}$ (2332 and 1957 cm*days) (figure 2.36).

2007 was a wetter year than 2006; the three restoration treatments all experienced higher SEW$_{30}$ but the reference areas did not. CR continued to have the highest SEW$_{30}$

(4609 cm*days) followed by CONT (3620 cm*days), Ref-center (3054 cm*days), PLUG (2249 cm*days) and Ref-center (490 cm*days).

In 2008, CR experienced the highest SEW_{30} of the entire study period (5308 cm*days). CR was followed CONT (3828 cm*days), Ref-center (3360 cm*days), and PLUG (2954 cm*days).

For the entire study period (2006-2008) CR experienced the highest SEW_{30} (14114 cm*days). CR was followed by Ref-center (9801 cm*days), CONT (9780 cm*days), and PLUG (7159 cm*days). Statistical analysis ($\alpha = 0.05$) found all areas except Ref-center and CONT significantly different.

The evaluation using the alternate block 3 was very similar to the evaluation using blocks 1 and 2 only. The ranking from highest SEW_{30} to lowest was the same for both evaluations. Observation and statistical differences were found between the three restoration treatments. CONT did the best job mimicking the SEW_{30} of the reference as it was the only treatment which did not experience a statically different SEW_{30} than Ref-center. The SEW_{30} values of Ref-center and CONT were not significantly different for any of the evaluations.

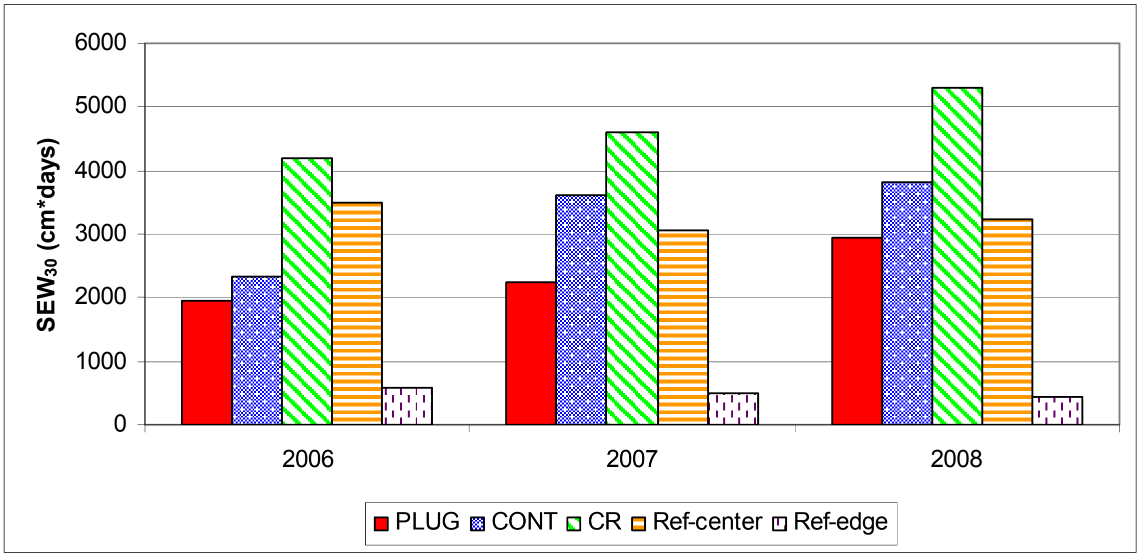

Figure 2.36 SEW$_{30}$ per year (with alternate block 3).

Surface Inundation (Alternate Version of Block 3)

In 2006, CR experienced dramatically more days of surface inundation than any of the other areas (figure 2.37). CR experienced 47 days of surface inundations followed by PLUG (6 days), Ref-center (4 days) and CONT (2 days).

In 2007, CR again experienced the most surface inundation with 58 days followed somewhat closely by CONT (29 days). PLUG and Ref-center only experienced 8 and 2 days of surface inundation respectively.

2008 was a very similar year as 2007 in terms of surface inundation. CR experienced the most days (68) followed by CONT (27 days) and PLUG (12 days). The referenced continued to experience very little surface inundation with Ref-center only experiencing 2 days.

For the entire study period (2006-2008) CR (173 days) experienced more than three times more days of surface inundation than any other treatment or area. CR was followed by CONT (58 days), PLUG (26 days) and then the reference. Ref-center experienced only 8 days of surface inundation while ref-edge never experienced surface inundation. All three treatments experienced significantly different amounts of surface inundation from each other and the reference. There was also no significant difference between Ref-center and Ref-edge.

The evaluation using the alternate blocks 3 yielded similar results to the evaluation using blocks 1 and 2. In both evaluations found CR to experienced the most surface inundation followed by CONT and then PLUG. When considering only blocks 1 and 2, CONT and PLUG were not significantly different but were when considering all blocks with the alternate block 3. CR experienced a much largest number of days of surface inundation in this evaluation due to the inclusion of well NR18 which experienced the most ponding of any well in the restoration due to its placement in a lower elevation area.

In all three evaluations, the treatments produced significantly more surface inundation than was found in the reference. The least inundated treatment, PLUG, still experienced more than three times the year inundation as Ref-center. As explained earlier, the treatments most likely experienced significantly more surface inundation than the reference due to near surface compaction which occurred in the restoration area due to the years of farming practices. The compaction decreased the storage in the near surface soil which resulted in the water table in the treatments to often rise above the surface while that same volume of soil could be stored within the soil profile in the reference.

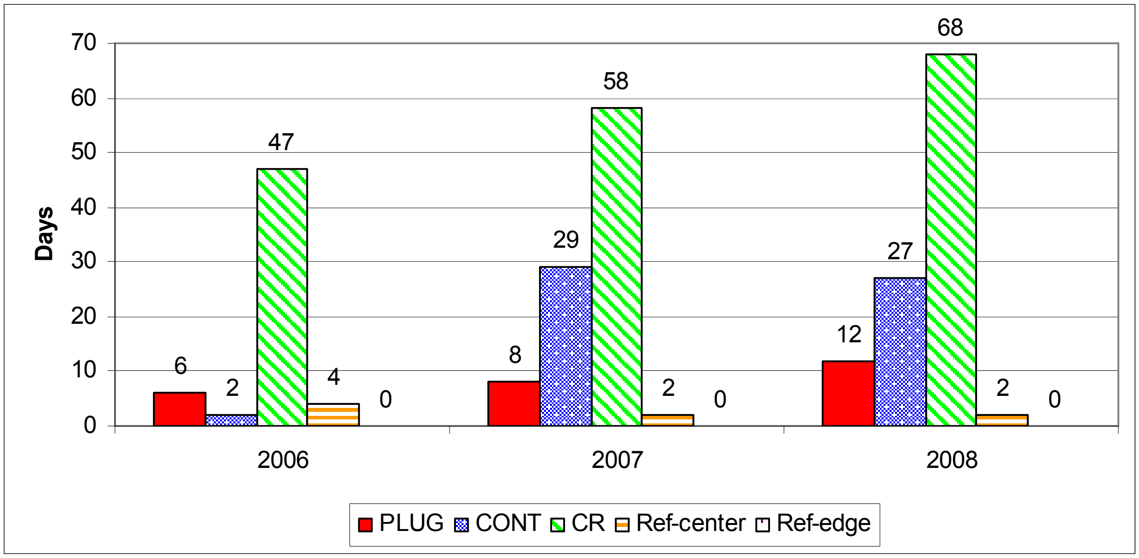

Figure 2.37 Number of days of surface inundation per year (with alternate block 3).

Hydrologic Criteria Discussion (Alternate Version of Block 3)

The hydrologic evaluation using all three treatment blocks with the alternate version of block 3 yielded different results than was found when evaluating all three treatment blocks and similar results to what was found when evaluating only blocks 1 and 2. By switching the data for block 3 PLUG and CR, the treatments had more consistent hydrology in all three blocks. CR had the wettest hydrology followed by CONT and then PLUG. This matches Wright's (2005) original hypothesis that CR should produce the wettest site since surface elevation will be lowered and surface storage should increase due to the flattening of the surface and that PLUG should produce the driest site since it provides the least surface storage.

In general, CR appeared to produce wetter conditions compared to the reference while CONT and PLUG may have produced drier conditions than the reference based on the hydrologic criteria. With the exception of surface inundation, all three restoration treatments appeared to produce a hydrology similar to what was observed in the reference, however statistical analysis found the treatments significantly different than Ref-center for most of the hydrologic criteria (table 2.5). CONT and CR appeared to do the best job mimicking reference hydrology. There was no statistical difference between the SEW_{30} found for CONT and Ref-center and CONT was within 3 cm of the average water table depth at Ref-center (it was significantly different though). CR experienced continuous inundation for the exact same percentage of the growing season Ref-center and was also within 3 cm of the average water table depth at Ref-center (also significantly different). CR did however have an extremely high SEW_{30} compared to Ref-center and experienced grossly significantly higher number of days of surface inundation than Ref-center or any other treatment. It is arguable that of the four criteria, SEW_{30} most accurately describes near-surface hydrology and hydroperiod since it is the only metric which accounts for both intensity and duration of shallow water table conditions. In that case, CONT may best mimic reference hydrology.

Table 2.5 Summary of hydrologic criteria (with alternate block 3).

		2006	2007	2008	Total
Average Water Table Depth (cm)	PLUG	49	52	45	49 (a)
	CONT	45	44	41	43 (b)
	CR	37	40	34	37 (c)
	Ref-center	33	44	42	40 (d)
	Ref-edge	52	65	65	61 (e)
SEW_{30} (cm*days)	PLUG	1957	2249	2954	7159 (a)
	CONT	2332	3620	3828	9780 (b)
	CR	4197	4609	5308	14114 (c)
	Ref-center	3507	3054	3240	9801 (b)
	Ref-edge	574	490	426	1490 (d)
Days of surface Inundation	PLUG	6	8	12	26 (a)
	CONT	2	29	27	58 (b)
	CR	47	58	68	173 (c)
	Ref-center	4	2	2	8 (d)
	Ref-edge	0	0	0	0 (d)

Values followed by same letter vertically are not statistically different ($\alpha = 0.05$).

Surface Outflow:

In addition to the water table evaluation, the hydrology of the restoration was also evaluated by comparing the observed surface outflow from each treatment during the study period (2006-2008). Surface outflow was calculated by applying weir equations to stage readings which were monitored at each water control structure. This setup was possible because perimeter berms allowed each treatment to drain to a single point.

Surface outflow was not monitored in reference wetland because such a setup was not possible. While the majority of the reference does drain towards the south, much of the surface flows occurs as sheet flow and does not drain to well defined channels which could be monitored. Furthermore, the reference wetland drains into a tidally influenced stream where high tides often result in backwater conditions near the outlet of the reference wetland.

Surface outflow from each treatment was compared statistically using an ANOVA means test. The test compared daily outflow from each water control structure for the three year study period.

The main objective of the surface outflow evaluation was to establish outflow differences between the three treatments. Unlike the water table evaluation, it is impossible to determine whether one treatment mimics reference conditions better than another since the reference was not monitored. However this evaluation should be able to establish which treatment produced the least outflow which in turn should imply the lowest export of freshwater and nutrients into the estuary.

2006 was the driest year (in terms of rainfall) for the study and also experienced the lowest amount of annual outflow for the study period (2006-2008). In 2006 CONT produced the greatest annual outflow of 34 cm (table 2.6). CR and PLUG both produced very similar annual outflow (24 and 23 cm respectively).

2007 was a much wetter year than 2006; receiving 34 cm more rainfall. This resulted in a higher annual outflow in 2007 as well. CONT continued to produce the greatest outflow (42 cm) followed by PLUG (33 cm) and CR (24 cm). The reported values of surface outflow in 2007 are most likely underreported. Surface outflow was not monitored for a 34 day period in fall of 2007 (10/11/2007 – 11/13/2007). DRAINMOD modeling performed in Chapter 3 predicted that approximately 7.5 cm of outflow would occur during this time period when all treatments were considered. This data is not included in this evaluation because the model did not simulate hydrology for each treatment.

In 2008, the highest outflow volumes were observed, however due to the missing data in 2007, it is difficult to know which year actually experienced the greatest outflow. It is hypothesized that 2008 experienced greater total outflow than 2007 based on the pattern of rainfall. While 2007 did experience slightly higher yearly rainfall than 2008 (154 cm compared to 150 cm) for most of the year, the site received below average rainfall. It was not until heavy rainfall in September and November did total rainfall rise above average. This resulted in a very dry spring and summer where the water table dropped to its deepest depths for the study period. As a result, rain storms which would typically produce outflow did not because the soil profile was dry enough to store all the rainfall without producing outflow. In 2008 though, the site received average or above average rainfall for most of the year. Because of this, the water table did not drop as deep during the summer months which allowed outflow events to occur more easily than in 2007. In 2008, CONT continued to produce the greatest total outflow (65 cm). It was followed by PLUG (44 cm) and then CR (40 cm).

For the entire period of study (2006-2008) CONT produced the greatest total outflow, 141 cm (figure 2.38). CONT produced significantly more outflow than PLUG or CR which produced 100 cm and 89 cm respectively. There was no significant different between the outflow produced by PLUG and CR ($\alpha = 0.05$). CONT consistently produced the greatest amount of annual outflow. This correlates well with the original water table evaluation which found that CONT experienced the lowest total SEW_{30} and least number of days of surface inundation of the treatments. The data suggests that CONT experiences more surface drainage when the water table is near or at the surface. While Wright (2005) found the same results in his evaluation of 2003-2004 data, this does not fit the hypothesis that PLUG should produce the greatest surface outflow due to the crown and lack of surface storage. It is believed that CONT may experience increased surface outflow due to the process by which the contouring was performed. During construction farm equipment was used to create microtopography by randomly creating rills and mounds. It is likely that many of the rills may have connected to create conveyance paths by which the surface water could more easily flow towards the outlet. CR experienced the least total surface outflow during the study period. The crown removal process likely created surface storage but also likely reduced the gradient which drives surface flow.

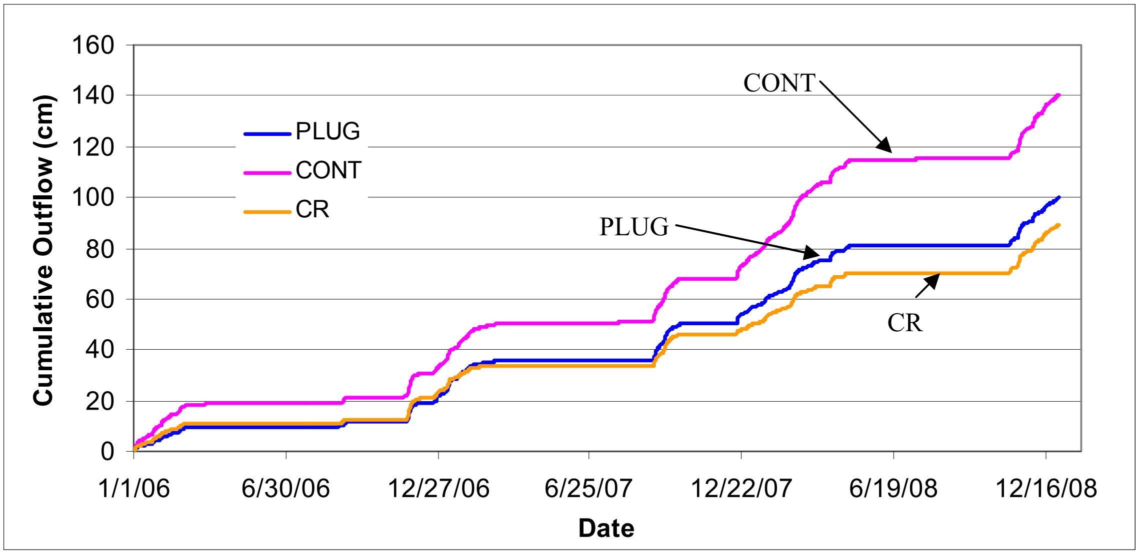

Figure 2.38 Cumulative surface outflow from each treatment.

Table 2.6 Yearly surface outflow from each treatment.

Treatment	2006	2007	2008	Total
PLUG	23	33	44	100 (a)
CONT	34	42	65	141 (b)
CR	24	25	40	89 (a)

Values followed by same letter vertically are not statistically different (α = 0.05).

Alternate Surface Outflow Evaluation

Due to the very different results found in the water table analysis when different blocks were evaluated, surface outflow was also evaluated using the same alternate methods:

- Surface outflow from each treatment was evaluated using only data from blocks 1 and 2.
- Surface outflow from each treatment was evaluated using all three blocks but with an alternate version of blocks 3. The CR treatment was classified as PLUG and the PLUG treatment was classified as CR.

The evaluation of surface outflow using the two alternate evaluations found no difference in the ranking of treatment outflow but did find differences in the statistical analysis of the treatment outflow.

When only blocks 1 and 2 were evaluated, CONT continued to produced the most outflow for the study period (136 cm) followed by PLUG (129 cm) and then CR (104 cm) (figure 2.39). Different from the original evaluation though, there was no significant different between CONT and PLUG ($\alpha = 0.05$) but CR continued produce significantly less outflow (table 2.7).

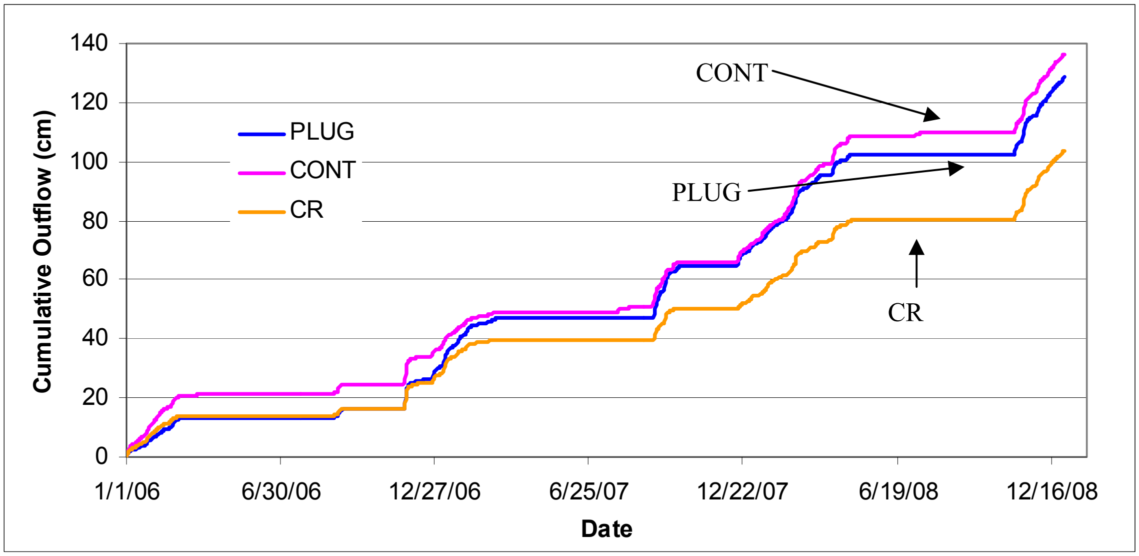

Figure 2.39 Cumulative surface outflow from each treatment (block 1 and 2).

Table 2.7 Yearly surface outflow from each treatment (block 1 and 2).

Treatment	2006	2007	2008	Total
PLUG	30	41	58	129 (a)
CONT	37	35	65	136 (a)
CR	28	26	50	104 (b)

Values followed by same letter vertically are not statistically different (α = 0.05).

When all three blocks with the alternate version of block 3 were evaluated, CONT continued to produced the most outflow for the study period (141 cm) followed by PLUG (106 cm) and then CR (83 cm) (figure 2.40). Different from the other two evaluations though, all three treatments produced significantly different amounts of surface outflow for the study period.

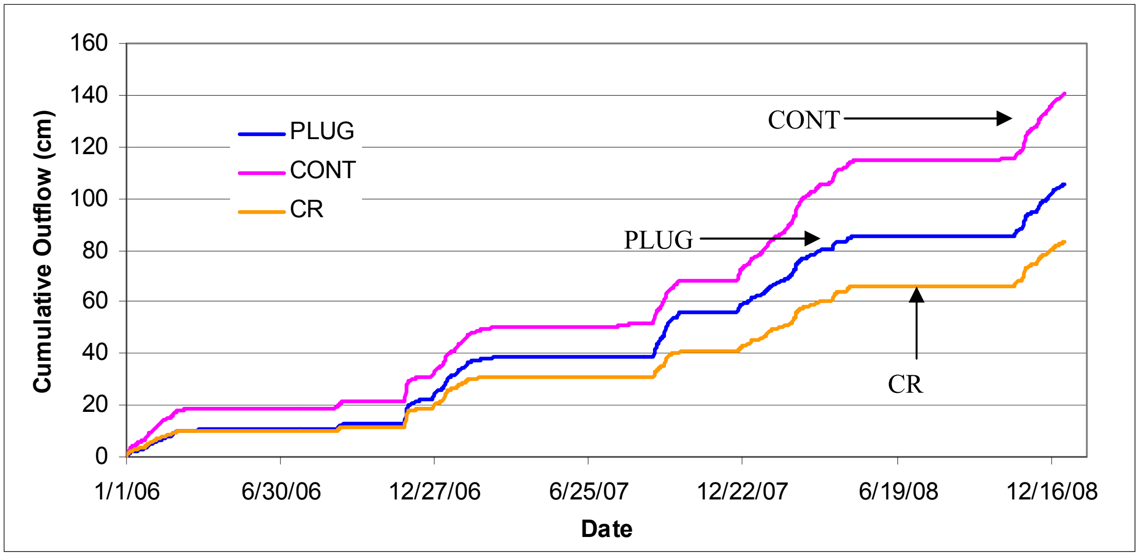

Figure 2.40 Cumulative surface outflow from each treatment (with alternate block 3).

Table 2.8 Yearly surface out from each treatment (with alternate block 3).

Treatment	2006	2007	2008	Total
PLUG	26	35	45	106 (a)
CONT	34	42	65	141 (b)
CR	21	23	39	83 (c)

Values followed by same letter vertically are not statistically different (α = 0.05).

Surface Outflow Discussion

Surface outflow from each treatment was evaluated for each treatment. The evaluation found CONT to produce the most outflow followed by PLUG and then CR. While these results correspond to what was reported by Wright (2005) in his evaluation of the treatments, it does not match original hypothesis that PLUG should produce the most outflow due to it possessing the least surface storage. It is theorized that when the surface contouring (CONT) was implemented during construction, the low spots and rills which were cut into the surface formed conveyance pathways which facilitated surface drainage instead of providing localized storage zones. Furthermore, the micro highs and lows created by the contouring may have created a higher surface gradient along the cross-section which would increase surface flow from the residual crown into the old ditches. If this occurred, it was unintended and is something that needs to be carefully watched on future. CR as hypothesized and observed by Wright produced the least outflow because the crown removal process reduced the surface flow gradient and created surface storage. Since the reference could not be monitored, it is impossible to make a claim as to which treatment best mimicked reference conditions with respect to surface outflow. What can be stated is that CR resulted in the least outflow which will result in lower loadings of freshwater and most likely residual nutrients being exported out of the restored wetland and into the North River estuary.

Conclusions

A prior-converted wetland in eastern, North Carolina was restored using three surface techniques: plugging field ditches without altering the surface (PLUG), plugging the field ditches and contouring the surface (CONT), and plugging the ditches and also removing the field crown (CR). The treatments were designed with the original hypothesis that CR should produce the wettest site because the crown removal process would level the surface and create surface storage. CONT was thought to produce the next wettest site because the surface roughening should create small pockets of surface storage. PLUG was thought to produce the least wet site because the surface was not altered which left the prior-existing crown intact. With increased surface manipulation comes an increased construction cost for wetland restorations. Following construction in March 2003 monitoring began in the three blocks of treatments as well as a nearby by reference wetland to determine if enhanced surface manipulation was necessary to restore appropriate wetland hydrology.

An earlier study by Wright (2005) evaluated monitoring data from 2003-2004. His evaluation found no significant difference between the water table in the three treatments. Due to inconsistent constructed elevations in block 3, the water table was re-evaluated using only blocks 1 and 2. This evaluation found CR to be the wettest site, experiencing a shallower water table for longer periods of time. Still no significant differences were found between CONT and PLUG implying that the surface contouring had no effect on hydrology. CR was also found to produce significantly less outflow than the other treatments. To better understand the hydrologic differences between the treatments and the blocks, Wright recommended continued monitoring as the restoration matured as well as installing additional wells and performing a detailed topographic survey in the treatment areas.

This study enacted Wright's recommendations and evaluated monitoring data for 2006-2008. Similar to Wright's study, very few significant differences were found between the treatments but CR and PLUG appeared to be wetter than CONT. There was no statistical difference found between the average water table depths of the treatments but PLUG and CR did experience longer periods of continuous saturation than CONT and had a significantly higher SEW_{30}. CR experienced the most days of surface inundation. CR and PLUG were also found to produce significantly less outflow than CONT.

Analysis of the surveying and additional wells found that surface elevation played an important role in establishing wetland hydrology in various areas across the site. Areas with a lower surface elevation tended to have a shallower average water table depth regardless of desired surface treatment. It was believed that CR treatments should have produced the lowest surface elevation due to the crown removal process but this was not always the case due to uneven pre-construction elevations in the fields. Block 3 produced unexpected water table results because the CR treatment was constructed in the highest area of block 3 while PLUG was constructed in the lowest area of block 3. This in turn caused the as-built versions of the treatment to look and behave opposite than expected.

The CONT treatment was found to produce the highest water table in terms of absolute elevation in some of the blocks, but this did not necessarily result in the shallowest water table depths due to the high spots which can be created with surface roughening. After surveying, the land surface elevations observed in the CONT areas were found to be the best replicated treatment in the study.

Due to the elevation differences in block 3, two additional evaluations were performed: an evaluation of just blocks 1 and 2 and an evaluation of all three blocks but block 3 PLUG and CR were switched for the analysis. Both evaluations found similar results compared to what Wright found in his evaluation of blocks 1 and 2. CR was found to be significantly wetter than the CONT and PLUG for all hydrologic criteria. In general, CONT was found to be wetter than PLUG but this did not hold true for all hydrologic criteria. The hydrology of the CONT treatment very similar based on all three evaluations suggesting that CONT was more consistently replicated than the other two treatments.

The evaluation of surface outflow found that CR produced the least outflow followed by PLUG and then CONT. When all three blocks were evaluated there was no significant difference between CR and PLUG and when only blocks 1 and 2 were evaluated there was no significant difference between PLUG and CONT. The evaluation with the alternate form of block 3 found all three treatments to be significantly different.

It is believed that CONT experienced the highest outflow because the surface contouring process may have unexpectedly created conveyance paths which drained the surface of the treatment.

All three treatments resulted in the restoration of wetland hydrology. The restoration was designed using a reference based approach therefore ultimate success come from successfully mimicking reference hydrology. While all three treatments created hydrologic conditions similar to the reference, no treatment was found to match reference conditions within the realm of statistical error for multiple hydrologic criteria. CONT may have matched reference conditions the closest as there was no significant difference between CONT and Ref-center for SEW_{30}. All three treatments experienced vastly more surface inundation than the reference which was believed to be the result of near-surface compaction and less organic material within the restoration due to decades of farming practices.

For restoration sites like North River which are located in very low elevation coastal settings, surface contouring and crown removal may not be necessary for ensuring hydrologic success. However it was found that small differences in elevation can result in tremendous differences in hydrology. A high quality preliminary survey is highly recommended for identifying isolated high and low spots on the terrain. Less surface manipulation may be required to ensure wetland hydrology in the low areas while additional surface manipulation may be required in the high areas. Overly wet areas in the North River farms restoration experienced significant amounts of ponding which made vegetation establishment much more difficult than in less wet areas. The selective use of surface manipulation could be the most cost-effective way of designing and constructing a successful wetland restoration in these conditions. Furthermore, careful construction oversight is also recommended since small changes in elevation can have significant effects of wetland hydrology.

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3. HYDROLOGIC RESPONSE OF A RESTORED WETLAND DURING EXTREME WEATHER IN EASTERN NORTH CAROLINA

Introduction

Flood storage is one of the well documented beneficiary functions of natural wetlands. This function is especially important in coastal regions where there is potential for tropical storms and hurricanes on a yearly basis. These extreme weather events often lead to flooding and possible water quality degradation. Wetlands can play an important role during these events by temporarily storing flood waters and slowly releasing to downstream areas. By storing flood waters, wetlands can help mitigate the high peak flows and flow volumes associated with tropical storms which can help protect coastal communities from flooding and estuaries from water quality degradation.

Coastal towns and cities are under constant threat of being impacted by tropical storms. In North Carolina there is a 30% annual chance of landfall by a hurricane and the likelihood of impact from other tropical systems is much higher. Further south in Florida, the yearly odds of a hurricane strike increases to 70% (Costanza et al., 2008).

Following hurricanes and tropical storms, there is a very high export of freshwater, nutrients, and bacteria from inland areas to the estuaries. This can lead to altered water chemistry resulting in large algae blooms which often leads to eutrophication and fish kills (finfish and shellfish) due to hypoxia. For example, a six week period of hurricanes activity in 1999 (Dennis, Floyd, and Irene) floodwaters exported the average annual load of nitrogen into the Pamlico Sound, reduced its salinity by 70%, and drastically reduced the dissolved oxygen content. (Paerl et al., 2006). Following the storms fish disease and kills were prevalent. Within a year, most finfish populations had rebounded but blue crab (the most valuable fishery in North Carolina) numbers remained low. There was a 32% decrease in blue crabs landings in the five year period following Hurricane Floyd compared to the five year period prior (Paerl et al., 2006). Hurricanes Floyd, Dennis, and Irene inflicted almost $7.5 billion worth of damage to Atlantic coastal states with the majority of the damage occurring from Floyd (Costanza et al., 2008).

The negative effects of tropical storms may be further enhanced by human alterations to the coastal plain landscape. Thousands of hectares of natural wetland have been cleared for agricultural and development needs, which almost always requires the use of artificial drainage. It is estimated that in the North Carolina coastal plain, 52% of the land once contained hydric (wetland) soils, however less than 50% of the natural wetlands remain today (Cashin et al., 1992). Due to these poorly drained soils, more than 40% of agricultural lands require artificial drainage, which has been linked to water quality degradation as a result of increased freshwater volume and nutrients, as well as increased pollutant exports (Thomas et al., 1995).

The implementation of artificial drainage drastically alters the hydrology of a wetland (Figure 3.1). Unaltered wetlands tend to have both a high water table and a large amount of surface storage. A study by Skaggs et al. (1994) found that forested wetland coastal plain wetlands typically have a surface storage between 1.5 and 5 cm. Wetlands also tend to have high evapotranspiration (ET) rates which when accompanied with the large surface storage, results in reduced losses to runoff.

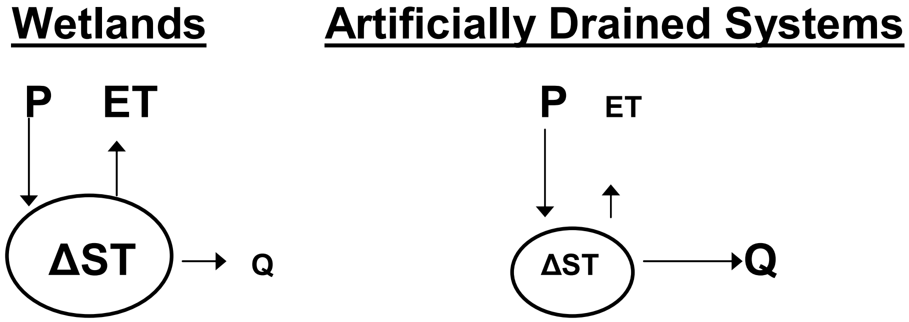

Figure 3.1 Example water budget for wetlands and artificially drained lands, larger letters imply a larger component of the budget (ET=evapotranspiration, P=precipitation, Q=outflow, ΔST=storage).

When a wetland is converted to agriculture, drainage ditches or subsurface drains are installed and the surface is usually smoothed and crowned as described by Lilly (1981). This practice along with deforestation will create a lower water table, poor surface storage, and lower ET rates which will increase water export due to surface runoff and subsurface drainage. Higher ET rates are commonly found in wetlands due to thick, year round vegetation and because soils are not usually moisture deficient so actual evapotranspiration (AET) often equals potential evapotranspiration (PET). Agricultural development has been shown to increase peak runoff rates by 300-400% and lead to higher sediment and fecal organism loadings in drainage water (Skaggs et al., 1980). The increased export of nitrate (NO_3-N), a highly soluble nitrogen compound, is often linked to artificial drainage. Studies have shown that subsurface drainage can lead to a ten fold increase in NO_3-N losses compared to undrained areas (Gilliam and Skaggs, 1986) and NO_3-N losses were found to increase as drainage intensity increased (Skaggs et al., 2005).

While agricultural development has been shown to increase drainage and nutrient export during normal weather conditions, its negative environmental effects can be accelerated by the very large rainfall events associated with tropical storms and hurricanes. A watershed monitoring study (Shelby, 2002) found significant differences in the hydrology and water quality response of forested and agricultural land uses during hurricanes in eastern North Carolina. The forested subwatershed was dominated by artificially drained loblolly pine plantation with organic soils while the agricultural subwatershed was dominated by artificially drained and fertilized cropland (corn, winter wheat, and soybeans) with mineral soils. During a six week period in 1999, multiple hurricanes (Dennis, Floyd, and Irene) produced 516 mm of rainfall over the research watershed (Table 3.1)

The forested subwatershed had significantly lower flows for each storm. During the largest storm, Hurricane Floyd, the peak flow of the forested subwatershed was 81% lower than the agricultural subwatershed while the total flow volume was 47% lower.

During the six week period of storms, both subwatersheds exported over 61% of their annual load of total nitrogen (TN) and nitrate (NO_3). The forested watershed exported 5.2 NO_3 kg/ha and 10.4 TN kg/ha while the agricultural subwatershed exported 7.5 NO_3 kg/ha and 10.9 TN kg/ha. Clearly, the impact of the increase storage of the forested system was mostly in flood water mitigation. The forested subwatershed exported 31% less NO_3 per hectare than the agricultural subwatershed, but only 5% less TN per hectare than the agricultural subwatershed. This is likely due the forested subwatershed containing organic soils rich in organic nitrogen compared to the mineral soils found in the agricultural subwatershed.

Table 3.1 Flow for each storm and subwatershed.

Storm Event	Storm Flow	Agriculture	Forest
Hurricane Dennis 29 Aug - 1 Sept Rain: 60 mm	Peak flow (mm/day) Total flow (mm)	1 3	0 0
Hurricane/tropical storm Dennis 3-7 Sept Rain: 163 mm	Peak flow (mm/day) Total flow (mm)	16 59	3 11
Hurricane Floyd 14-16 Sept Rain: 162 mm	Peak flow (mm/day) Total flow (mm)	63 164	12 109
Hurricane Irene 17-18 Oct Rain: 109 mm	Peak flow (mm/day) Total flow (mm)	39 113	5 57
Total	Total flow (mm)	339	177

The strategic implementation of wetlands restoration could be a useful tool for mitigating the high flows and floodwaters associated with hurricanes and tropical storms. A study by Costanza et al. (2008) estimated that wetlands in coastal North Carolina provide over $9,500 per hectare per year worth of storm protection. A statistical model was developed which compared damage from 34 hurricanes, the frequency of hurricane strikes, and the area of coastal wetlands and local GDP for vaious coastal states. Given the approximately 65,000 ha of wetland located within 100 km of the coast, North Carolina's coastal wetland are valued at over $600 billion per year. Costanza states that "coastal wetlands provide horizontal levees that are maintained by nature and are far more cost-effective than constructed levees." While wetland preservation and restoration have become a major focus of governments and environmental organizations there are very few studies which support the claim that wetlands protect against tropical disasters (Kerr and Bard, 2007). In one example however, the storm surge from Hurricane Andrew (1992) was dampened by 4.4 – 4.9 cm for every linear kilometer of marsh in Louisiana (LA DNR, 1998); the storm energy was dissipated due to the storage the marsh provide.

If flood storage is an intended goal of a restoration certain techniques can be implemented to increase storage capabilities. The NRCS (2003) recommends implementing macrotopography and berms for creating long term water storage. Macrotopography consists of larger swales and open water areas (15 cm – 1 m deep) which provide long term permanent storage. In cooler winter months when ET rates are low, the features will often remain inundated due to the seasonal high water table. In late summer and early fall (hurricane season) ET rates are high and the water table is usually low which increases available soil and surface storage. If macrotopography is implemented across 30% of a restoration according to NRCS recommendations at an average depth of 0.4 m, the features will provide 1,200 m^3/ha of permanent storage if the water table is below the bottom of the features.

Berms are typically implemented around the perimeter of a restoration to restrict runoff and storage. Perimeter berms will temporarily store all floodwaters until they exit the site at a designed outlet at a much lower flowrate than would have occurred via surface runoff (NRCS 2003). Depending on the constructed height of the berms, they will provide between 3,000 – 10,000 m^3/ha of temporary storage. Floodwater detention results in peak flow mitigation and should also reduce the total surface flow volume since some floodwater will either be incorporated into groundwater or be lost to ET. Longer detention times will result in higher ET losses.

Berms can also be implemented in floodplain areas to create small dams and diversions which will limit surface runoff from entering streams and help detain flood waters in the back swamp of a floodplain which should help reduce downstream flows and flooding.

While berms and macrotopography are useful tools for increasing flood detention capabilities of a restoration, they should be designed in conjunction with conditions found within wetland reference sites. Wetland restorations should be designed using a reference based approach where the restoration is designed to mimic the topography, hydrology, and vegetation of an unaltered nearby wetland. The overuse of storage features can result in a wetland that is wetter than the targeted reference hydrology. In fact, many restoration attempts have failed not because the sites were too dry but because they were too wet. In many cases permitting requires a restoration site to meet jurisdictional criteria over a very short time frame, usually three out of five years (Cole and Brooks, 2000). To ensure permitting, many designers overcompensate in their design which creates sites with large amounts of open water. While this practice may restore jurisdictional hydrology criteria, it does not necessarily restore other key wetland components. Deep, open water will create anaerobic conditions, but they do not support wetland vegetation which is a required component of a jurisdictional wetland. The water must be shallow enough to support rooted-emergent or woody plant species. Submergent aquatic vegetation is not considered hydrophytic by USACE (Environmental Laboratory, 1987). Also, a successful restoration should restore the site to its original hydrogeomorphic (HGM) setting and not create a new HGM setting that is not found in the watershed or does not match the reference site (Cole and Brooks, 2000).

Many wetlands, especially non-riverine wetlands, do not stay wet year round. Wet and dry cycling is can be very important for vegetation success and nitrogen cycling. More specifically to flood storage, a site which is dry in summer months will provide much more storage and detention than a wet site because it will already be saturated and/or inundated with water. This is provided that the dry site has the sufficient soil and surface features required for flood storage

Wright (2005) conducted long-term simulations at a non-riverine wet hardwood forest restoration in eastern North Carolina using the hydrologic model, DRAINMOD (Skaggs et al., 1999). Using 20 months of monitoring data, Wright calibrated

DRAINMOD and then simulated restored wetland hydrology and pre-restoration agricultural hydrology using 50 years of historical climate data for the site. The model predicted that restoring the prior-converted agricultural land back to wetlands would result in a 30-40% reduction in outflow from the site which drains almost directly into the North River Estuary. The research presented in this chapter will build upon Wright's monitoring and modeling by focusing on the hydrology of the research site specifically during periods of extreme tropical weather as opposed to over long periods of time.

The restoration of prior-converted agricultural lands should both improve water quality in the estuaries and mitigate flood waters. Restorations should improve water quality by eliminating fertilizer treatments, naturally treating the water through biogeochemical processes, and reducing outflow, which should likely reduce the overall load of pollutants from the site. They should mitigate flooding by providing improved surface and soil storage and increasing ET. This should dampen peak flows, lengthen the release of stormwater, and reduce the total flow volume.

The overall objective of this study was to determine the effects the wetland restoration had on outflows during hurricanes and tropical storms. This study was conducted at a 100 ha restoration of a prior-converted non-riverine wet hardwood forest near the town of Beaufort in eastern North Carolina. The site was intensively monitored for precipitation, water table fluctuations, and outflow from 2003-2008. Specific objectives were to:

- Quantify and evaluate the hydrologic response of the restored wetland to extreme storm events during 2003-2008.
- Use the monitored data to calibrate hydrologic response of the site during the storm events in DRAINMOD.
- Use DRAINMOD to simulate the site in pre-restoration agricultural conditions to evaluate the hydrologic differences between the observed wetland hydrology and the simulated agricultural hydrology, and to predict the reduction of peak flows and drainage volumes to the nearby estuary.

Agricultural hydrology was simulated instead of direct measurement of outflow because all lands which were monitored for the study were completely restored to wetland.

Materials and Methods

Site Description:

Research was conducted at a large scale wetland restoration site at North River Farms in Carteret County, North Carolina in the White Oak River Basin. The site was drained in the mid 1970s using a network of parallel ditches to facilitate agriculture. As typical in this region, field ditches were spaced at 100 m and dug 1 m deep. The fields were crowned approximately 20 cm in between the ditches to improve surface drainage.

The North Carolina Coastal Federation purchased North River Farms in 2002 for the purpose of a large scale restoration with a grant from the North Carolina Clean Water Management Trust Fund. Construction on Phase I, a 100 ha non-riparian hardwood wetland was completed in March, 2003 (Figure 3.3). Research for this study was conducted in Phase I. The major goals of the project were to create habitat, improve water quality, and improve understanding of coastal area restoration techniques.

The location of the restoration was ideal for improving conditions in the North River due to its close proximity to the waterway. The North River is a sensitive estuarine system currently exhibiting water quality problems attributed to stormwater from the surrounding agricultural and urban areas. A high bacteria presence in the estuary has been documented detrimental to the local shellfishing industry. Currently shellfishing is permanently prohibited in the upper reaches of the North River and temporarily prohibited in the entire waterway following a 2.5 cm (one inch) or greater rain event (figure 3.2) (NC DENR, 2009). The existing development in the watershed results in too much stormwater runoff to the estuary during larger storm events. Water quality improvements from the restoration were hoped to provide ecological and economical benefits for the area.

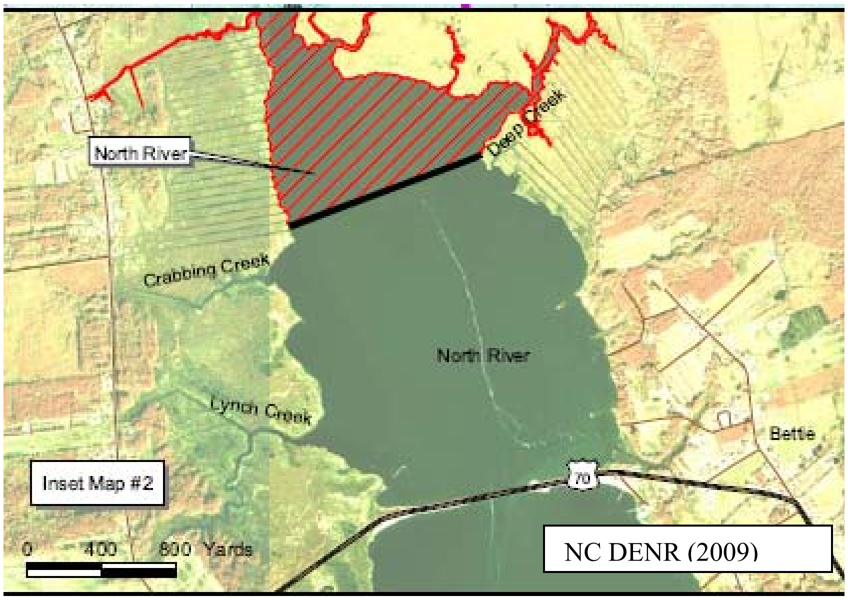

Figure 3.2 Hatched red areas are currently prohibited from shellfishing. Research site is located upstream of prohibited areas and drains into Deep Creek.

Research for this study was conducted within Phase I, the 100 hectare non-riverine wet hardwood forest restoration. The restoration was designed to restore hydrology using several components and techniques. Earthen plugs were installed in the field ditches to block subsurface drainage and water control structures were installed to control the drainage leaving the site. Several surface features were incorporated into the design to improve surface storage to the level found in natural reference conditions. Open water areas and simulated trees falls were constructed to create additional surface storage and the entire site was surrounded by raised perimeter berms to restrict surface runoff from leaving the restoration. Three difference surface contouring techniques were also incorporated to create varying levels of microtopography (see Chapter 2 for more on surface treatments).

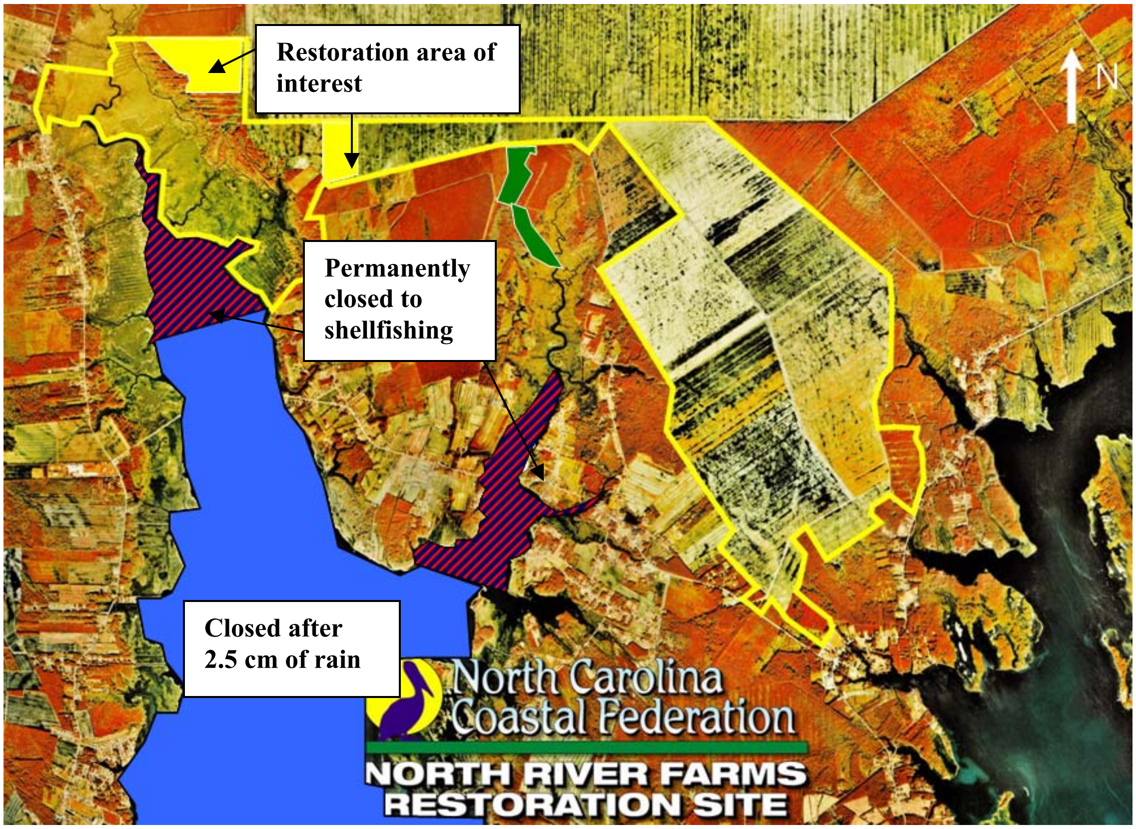

Figure 3.3 North River Farms Restoration

Monitoring was conducted at six, approximately 6.5 hectare plots, which were established within the restoration (Figure 3.5). Each plot was surrounded by raised berms to hydrologically isolate them, see figure 3.6 for a typical cross-section. The berms prevented surface runoff between plots which forced all drainage to flow to a single point in each plot where a water control structure was installed for outflow control and flow monitoring. More detail and description on the restoration design and construction can be found in Wright (2005).

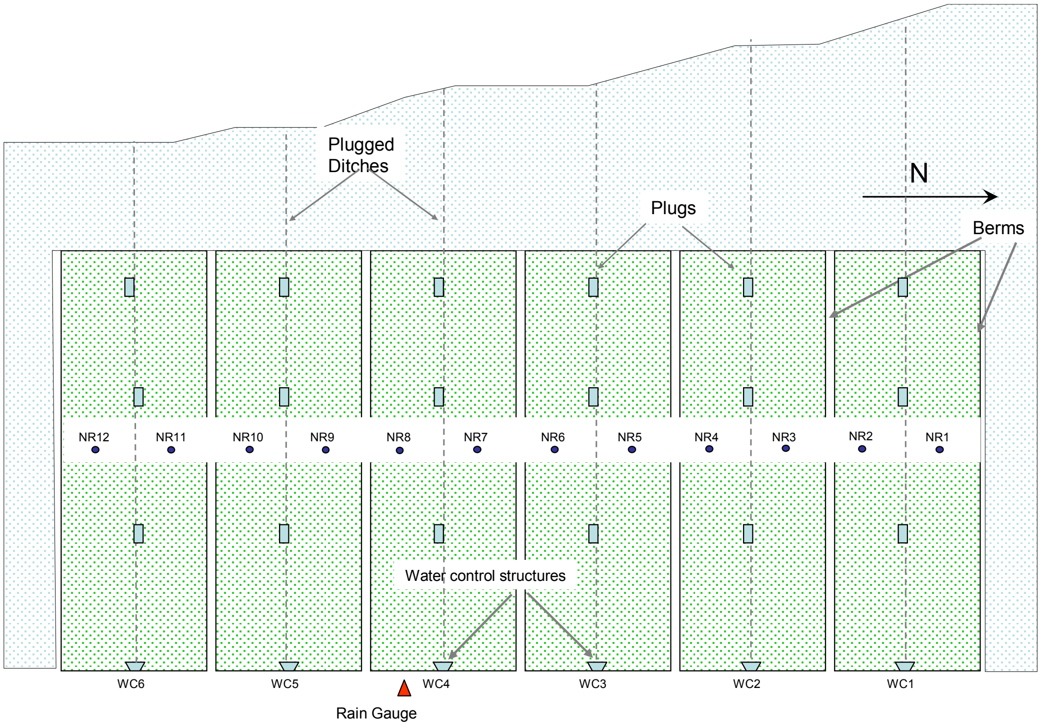

Figure 3.4 Hydrologic monitoring layout (not to scale).

Figure 3.5 Typical cross-section of restoration.

Hydrologic Monitoring:

The restored wetland was intensively monitored for rainfall, water table fluctuations, and outflow from 2006 – 2008. During this time period, three periods of extreme weather were monitored at the restored wetland. These periods were selected because named hurricanes and tropical storms produced large amounts or rainfall (>10 cm) which resulted in high outflows (>1.0 cm/day) from the restored wetland.

Rainfall

Rainfall data was collected at one location within the study area. Rainfall was measured using an automatic tipping bucket (Davis Instruments, Hayward CA, model 7852) and recorded using a HOBO data logger (Onset Computer Corporation) which logged every 0.254 mm (0.01 in) of rain (Figure 3.6). The rainfall data was downloaded using a HOBO shuttle data logger (Onset Computer Corporation, part H09-003-08). A manual rain gauge was also utilized at the location for backup and calibration of the automatic gauge.

Figure 3.6 Automatic tipping bucket and manual rain gauages

Water Table

Water table depth was monitored continuously at twelve locations (NR01 – NR12) along a transect using 4 inch PVC water table monitoring wells (Figure 3.7) which were screened and installed to approximately two meters in depth. The water table was recorded hourly using Infinities water table data loggers (Infinities USA Inc, Daytona Beach, FL). Water table data was downloaded with a Hewlett Packard 48G+ calculator using Infinities USA software (PC Transfer). The Infinities sensor included a pressure transducer to measure the depth of water above of the sensor. Manual water table depth measurements were used to convert the Infinity readings to a water table depth below ground surface. A single water table profile, the average daily water table depth of all twelve wells across the site, was used for data analysis and evaluation.

Figure 3.7 Water table monitoring well with Infinities automatic water table logger.

<u>Surface Outflow</u>

The monitoring area contained six lateral field ditches which were originally constructed to drain the site for agriculture. The ditches drained excess water to a large main canal and eventually south to the North River. During restoration water control structures and earthen ditch plugs were constructed to control the drainage from the site and manage the water table. Water control structures were installed at the outlet of each drainage ditch, on the eastern side of the restoration area to maintain water table depth, control outflow, and provide locations for water quality sampling (Figure 3.8).

Figure 3.8 Water control structure with 30° V-notch weir.

Water level was measured at each water control structure using a float/pulley system (Figure 3.9). The system used a 4 inch PVC well containing a weighted float which moved freely with water level fluctuations. As the float moved, it turned a pulley connected to a potentiometer. The changes in voltage produced by the potentiometer were recorded every 30 minutes by a two channel, 12-bit Sargent data logger (SGT engineering, Champagne, IL). The set up was powered by a 12 V brick battery with a 5 W solar panel. The data logger was downloaded using the software, Zterm (coolstuff.com) on a TDS Recon mobile pc. Manual water level measurements were used to create a linear regression to convert the potentiometer voltages to water depths.

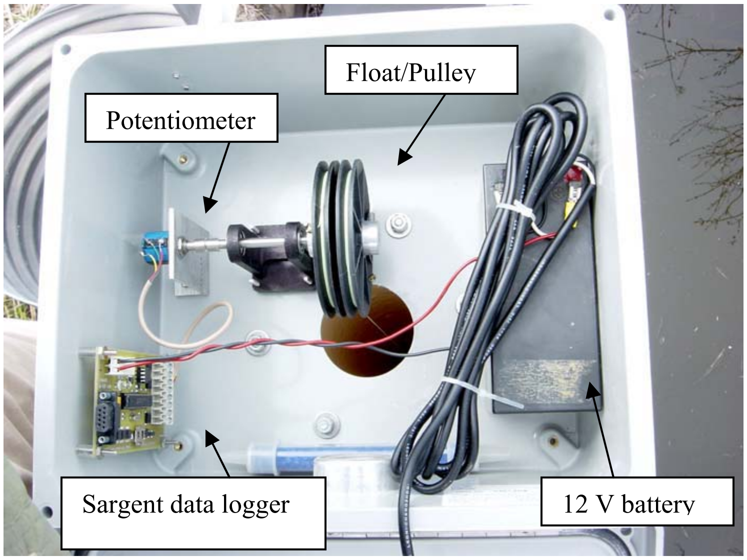

Figure 3.9 Sargent float/pulley system.

Flow was calculated based on depth of flow over a 30° V-notch weir. When the water depth was below the top of the weir flow was calculated using the 30° V-notch weir equation found in equation 3.1 (Grant and Dawson, 2001). When the water depth exceeded the top of the weir, flow was then calculated using the appropriate orifice equation found in equation 3.2 (Bedient and Huber, 2002). The daily outflow volume for each water control structure was summed to create a total daily outflow volume for the entire monitoring area. A period of missing outflow data (10/11/2007 – 11/13/2007) which did not occur during any period of extreme weather was replaced with simulated outflow data from DRAINMOD simulations.

Equation 3.1 Flow through a 30^o V-notch weir (Grant and Dawson, 2001).

$$Q = 0.01914H^{5/2}$$

Q = flow (m^3s^{-1})
H = head above invert of weir (m)

Equation 3.2 Flow through an orifice (Bedient and Huber, 2002).

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

Q = flow (m^3s^{-1})
C_d = discharge coefficient = 0.589
A_o = orifice area (m^2)
g = gravitational coefficient
h = elevation of water above centerline (m)
ho = elevation of orifice centerline (m)

Modeling with DRAINMOD:

To determine the impact the restoration had on the hydrology of the site, the hydrologic model, DRAINMOD (Skaggs, 1999), was used to simulate the pre-restoration conditions of the site. DRAINMOD is a field-scale model used to simulate the hydrology of poorly drained, high water table sites which are drained using a network of parallel drains. The model utilizes drainage parameters, soil properties, and rain and climate data to simulate water table fluctuations, outflow, surface runoff, and ET losses. Though originally designed to model artificially drained sites, multiple studies have determined DRAINMOD suitable for simulating the hydrology of both natural wetlands (Skaggs et al., 1991, Skaggs et al., 1994, and Skaggs and Chescheir, 2002) and restored wetlands (Tweedy, 1998 and Wright, 2005).

DRAINMOD calculates water table depth at the midpoint between the drains on an hourly and daily basis using the water balance shown in equation 3.3. Drainage flux is calculated using the Hooghoudt equation (equation 3.4). When the water table rises to the surface and ponds, DRAINMOD uses the water balance shown in equation 3.5 and calculates drainage flux using Kirkam's method (1957).

Equation 3.3 Water balance midway between drains (Skaggs, 1999).

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

ΔVa = change in water free pore space (cm)
D = drainage (cm)
ET = evapotranspiration (cm)
F = infiltration (cm)

Equation 3.4 Hooghoudt equation for drainage (Skaggs, 1999).

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

q = drainage flux (cm/hr)
k = effective lateral hydraulic conductivity (cm/hr)
d_e = equivalent depth from drain to the impermeable layer (cm)
m = distance from drain to water table at midpoint between drains (cm)
L = drain spacing (cm)

Equation 3.5 Water balance at soil surface (Skaggs, 1999).

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

P = precipitation (cm)
F = infiltration (cm)
ΔS = change in volume of water stored in on surface (cm)
RO = surface runoff (cm)

The DRAINMOD model was calibrated using observed water table data from the site and then modified to simulate the pre-restoration hydrology drainage and surface conditions (table 3.2). The maximum surface storage is the depth which water must pond on the surface before surface runoff will occur. Kirkham's depth is the depth which water must pond before it will flow to the drains. It also represents the amount of depressional storage found on the surface of a site. The weir settings control how high the water table must be before drainage will occur. For the agricultural simulation free drainage was simulated through the drainage ditches. The rooting depths are the depths were the majority of root mass is found and affects the evapotranspiration component of DRAINMOD. For the wetland simulation, a constant rooting depth of 40 cm was used based on natural wetland rooting depths reported by Skaggs (1991). For the agricultural simulation, rooting depths ranged from 3 – 25 cm throughout the year to represent the rooting depths of corn.

Table 3.2 DRAINMOD inputs for wetland and agricultural conditions.

Parameters	Wetland	Agricultural
Max Surface Storage	50 cm	1.5 cm
Kihkham's Depth	2 cm	0.75 cm
Weir Setting	30 cm	No weir

Results and Discussion

Extreme Weather:

During the course of this study, extreme weather from four hurricanes or tropical storms was monitored at the research site. In 2004 Hurricanes Alex and Charley struck, followed by Hurricane Ophelia in 2005 and Tropical Storm Gabrielle in 2007.

2004

The first named storm of 2004 was Hurricane Alex (July 31 – August 6, 2004). At its strongest point, Alex was a category 3 hurricane with sustained winds of 169 km/hr (105 mph). The eye of the storm traveled along the North Carolina coast just east of Cape Lookout and Cape Hatteras, while the western side of the hurricane made landfall as a category 1 and 2 hurricane on August 3 (figure 3.10). Hurricane Alex produced 17 cm of rainfall at the research site (with 14 cm of the rain occurring from 8/2/2004 – 8/3/2004) and 14 cm of rainfall at nearby Beaufort. The highest rainfalls were recorded in Ocracoke (19 cm). The highest storm surges recorded were also near Ocracoke (1.8 m) while the area near the research site experienced storm surges between 0.2 -1.2 m. Hurricane Alex inflicted $7 million worth of damages from wind and flooding and 1 human death (Franklin, 2004).

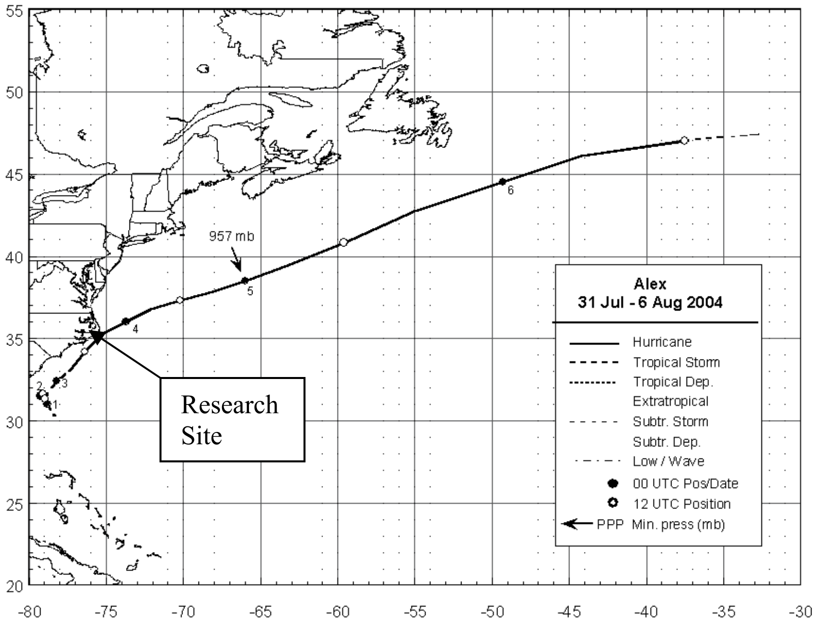

Figure 3.10 Storm path of Hurricane Alex (Franklin, 2004).

The second named storm of 2004 was Hurricane Charley (August 9 – 14, 2004). At its strongest point, Charley was a category 4 hurricane with sustained winds of 201 km/hr (125 mph). Charley made landfall near the NC-SC border as a category 1 hurricane on August 14 then quickly weakened to a tropical storm. The storm traveled across the lower coastal plain of North Carolina throughout the day before returning to sea early August 15 near the NC-VA border (figure 3.11). Charley produced 12 cm of rainfall at the research site (with 12 cm of the rain occurring from 8/12/2004 – 8/15/2004). North Carolina experiences storm surges between 2.1 – 2.4 m. Hurricane Charley inflicted over $14 billion dollars of damage and 10 human deaths, mostly in Florida. Charley inflicted $25 million dollars worth of damage in North Carolina (Pasch et al., 2005).

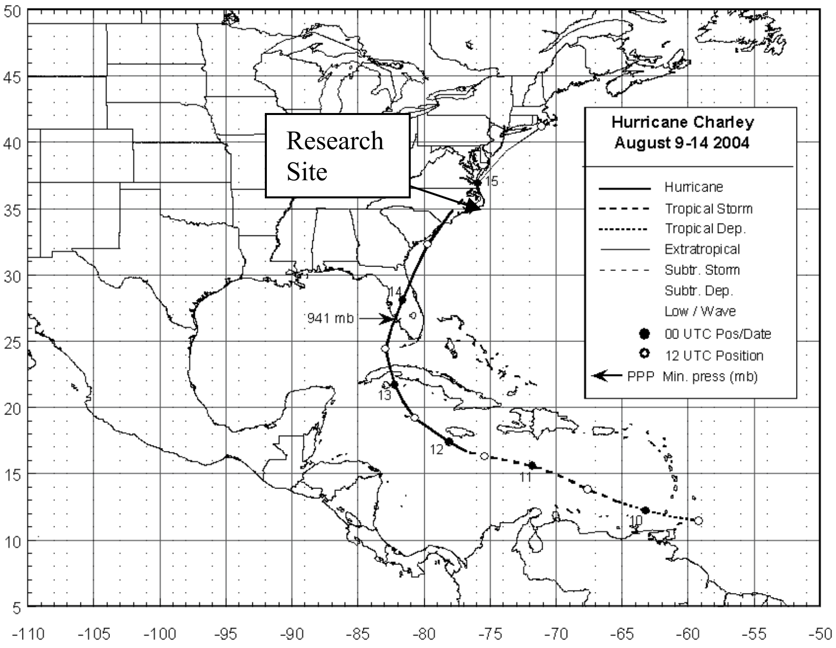

Figure 3.11 Storm path for Hurricane Charley (Pasch et al., 2005).

<u>2005</u>

Hurricane Ophelia (September 6-17, 2005) was the only named storm of 2005 in North Carolina. At its strongest point, Ophelia was a category 1 hurricane with sustained winds of 121 km/hr (75 mph). The eye of the storm traveled along the coast of North Carolina just east of Cape Fear and Cape Lookout while the western side of the storm made landfall as a category 1 hurricane on September 15 (figure 3.12). Ophelia was a very slow moving storm which produced very heavy rains. Hurricane Ophelia produced 28 cm of rainfall at the research site (with 24 cm of rain falling from 9/14/2005 – 9/15/2005); the largest rainfall recorded in the state occurred at Oak Island (44 cm). The strongest winds and storm surges (1.2 – 1.8 m) were recorded near the research site in

Carteret County. Hurricane Ophelia inflicted $70 million worth of damage and 1 human death, with most of the damage occurring in North Carolina (Beven and Cobb, 2006).

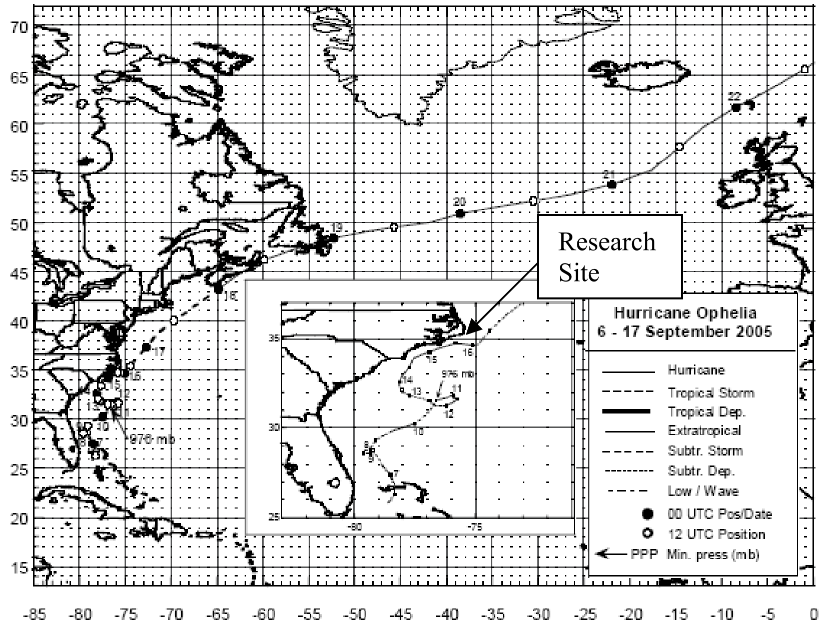

Figure 3.12 Storm path for Hurricane Ophelia (Beven and Cobb, 2006).

2007

Tropical Storm Gabrielle (September 8 -11, 2007) was the only named storm of 2007 in North Carolina. At its strongest point, Gabrielle was a tropical storm with sustained winds of 97 km/hr (60 mph). The storm made landfall near Cape Lookout on September 9 but quickly turned back to sea and lost strength causing only a very small area of North Carolina to be affected by significant wind and rainfall (figure 3.13). It made landfall for less than twelve hours. Tropical Storm Gabrielle produced 17 cm of rainfall on 9/9/2007 at the research site while the highest rainfall recorded was 22 cm also in Carteret County. The highest storm surge (0.6 -0.9 m) was recorded in Dare Country while the waters around Carteret Country experienced a storm surge of 0.3 – 0.6 m. Tropical Storm Gabrielle inflicted minor damage to North Carolina including street closures, minor beach erosion, and minor flood damage (Brown, 2007).

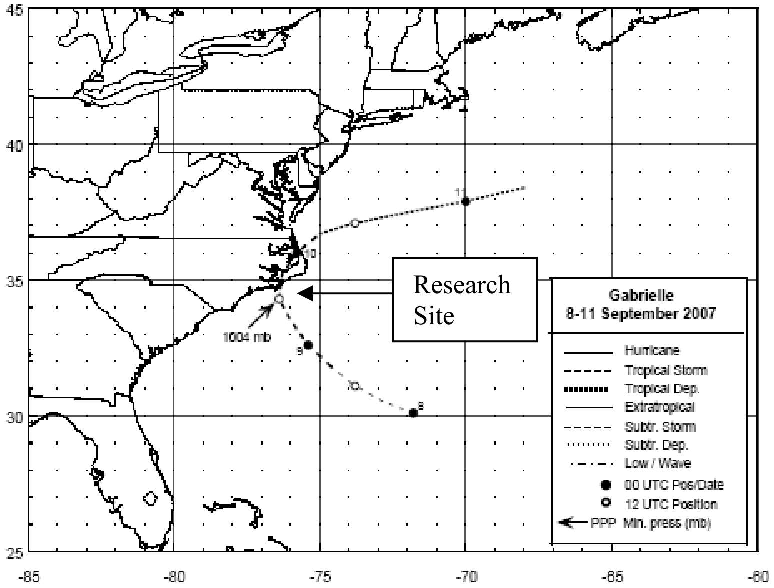

Figure 3.13 Storm path for Tropical Storm Gabrielle (Brown, 2007).

Observed Rainfall:

2004

The year 2004 was a drier than average year despite the occurrence of two named storms: Alex and Charley. The total rainfall measured at the restored wetland was 127 cm compared to a long term average of 143 cm at nearby Morehead City (1948-2008). Through the end of July, yearly rainfall was 13 cm below average and even with 30 cm of rain in August (average August rain is 18 cm), the year still finished 17 cm below average due to a very dry autumn (figures 3.13 and 3.14). During a period of 25 days (07/23/2004 – 08/16/2004) several storm events including Hurricanes Alex and Tropical Storm Charley passed through the research site resulting in 41 cm of rainfall including a single day of 12 cm during Hurricane Alex. The rainfall during this period accounted for 33% of the yearly total in 2004.

2005

The year 2005 was a very wet year even without considering the impacts of Hurricane Ophelia. The total rainfall measured at the research site was 188 cm compared to a long term average of 143 cm at nearby Morehead City. Through the end of August the yearly rainfall was 11 cm above average before the arrival of any tropical weather. After September and Hurricane Ophelia the yearly rainfall was up to 29 cm above average and following a very wet October the yearly rainfall was up to 49 cm above average. The year finished with rainfall totals that were 45 cm (31%) above average (figures 3.13 and 3.14). A 15 day period (9/14/05 – 9/28/2005), storms produced 33 cm of rainfall at the restored wetland including a single day of 15 cm of rainfall during Hurricane Ophelia.

2007

The year 2007 was slightly wetter than average due to the presence of Tropical Storm Gabrielle. The total rainfall measured at the research site was 154 cm compared to a long term average of 143 cm at nearby Morehead City. While most of North Carolina suffered from severe drought, the research site was drier than average for the first half of 2007 and then wetter than average for the latter half. Through the end of August the yearly rainfall was 10 cm below average but following September and Tropical Storm Gabrielle the yearly rainfall 5 cm above average. The tropical weather coupled with a wet October and December helped the site finish 11 cm above average (figures 3.14 and 3.15). A seven day period of rainfall (9/9/2007 – 9/15/2007) produced 21 cm of rainfall at the research site.

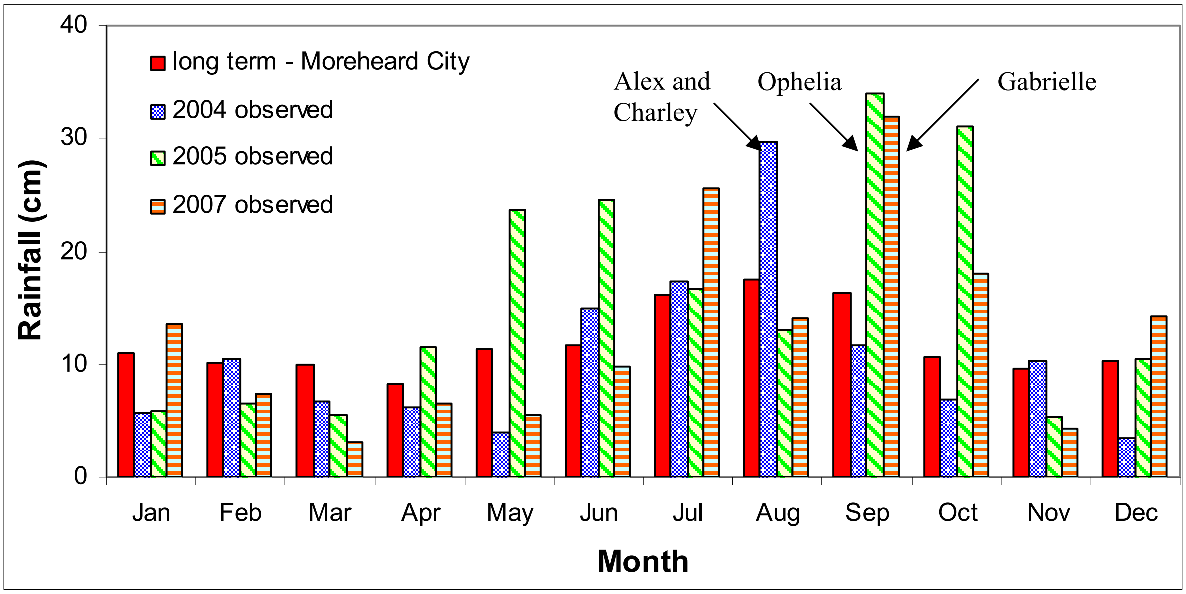

Figure 3.14 Monthly observed and average rainfall for 2004, 2005, and 2007 (no tropical events observed in 2006).

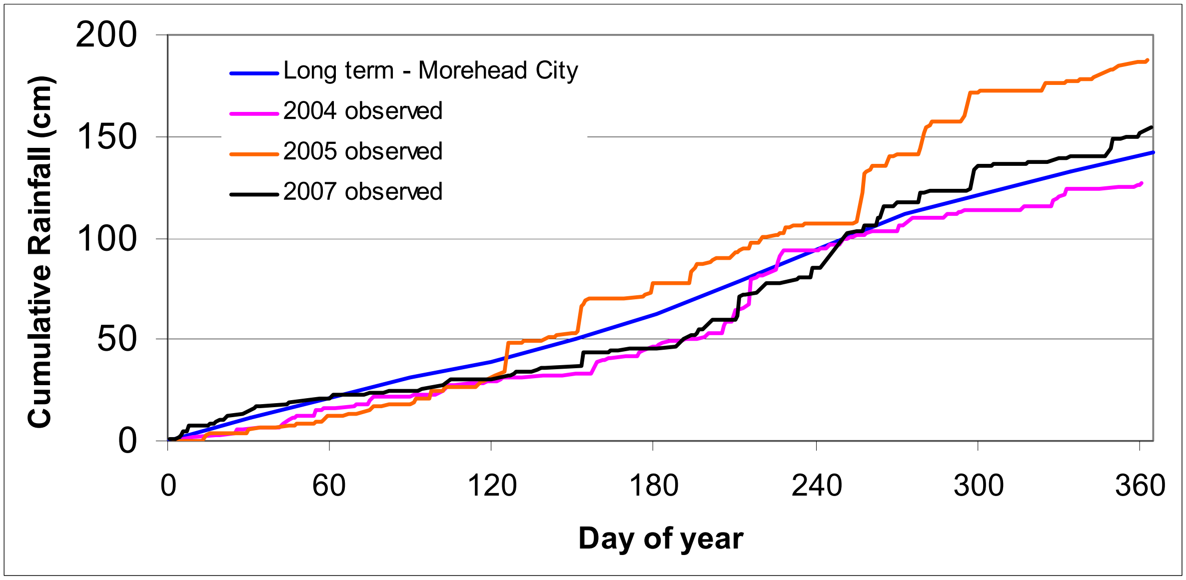

Figure 3.15 Yearly observed and average rainfall.

Observed Water Table Response and Surface Outflow:

For each period of extreme weather, the time hydrologic period evaluated started with day of the rainfall until the day where outflow from the site ceased or was negligible to accurately reflect inputs to and outputs from the restored wetland. The rainfall reported reflects the total rainfall measured during this period, not necessarily the rainfall associated with a particular hurricane or tropical storm.

<u>2004</u>

Non-tropical and tropical storms and wetland outflows that occurred over a period of 34 days in 2004 (7/23 – 7/30) were examined. This period included both Hurricane Alex and Charley. Antecedent moisture conditions were low prior to the initial non-tropical rainfall events on July 23. Prior to this event the water table was an average of 111 cm below the wetland surface (figures 3.16 and 3.17). The water table was at one of its deepest depths for all of 2004.

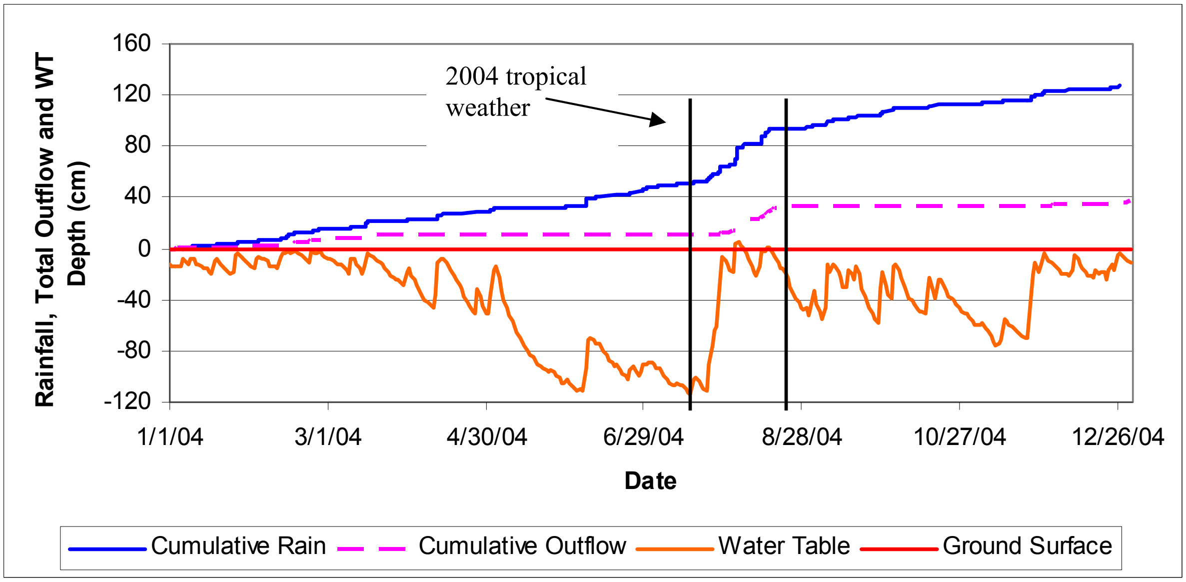

Figure 3.16 Cumulative rainfall, outflow, and water table fluctuations for 2004.

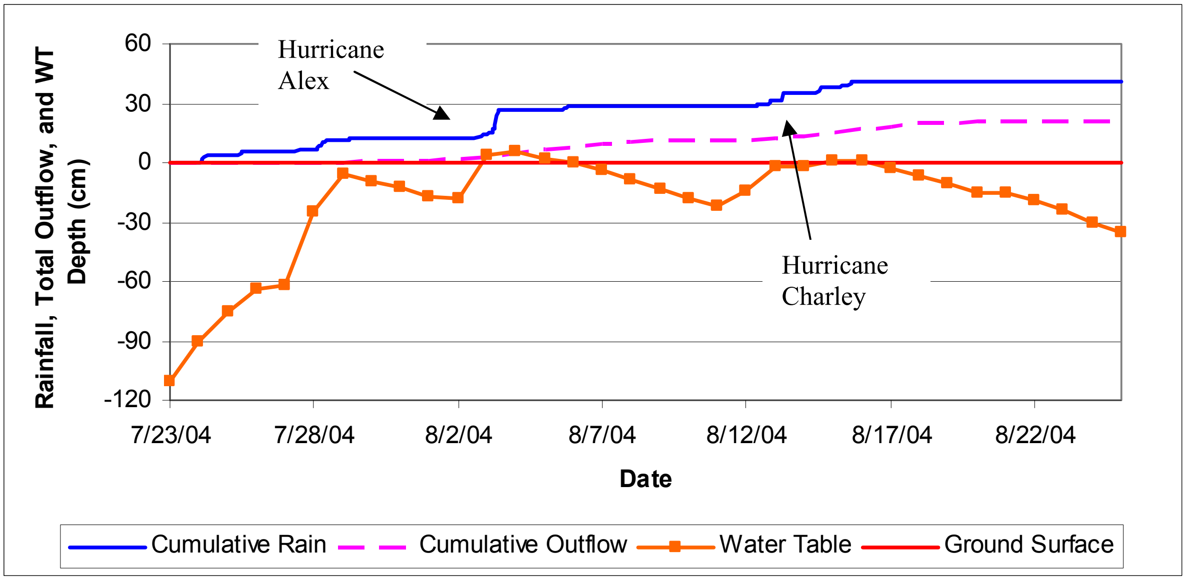

Figure 3.17 Cumulative rain, outflow, and water table fluctuations for 2004 extreme weather.

Prior to the named tropical storms the site received 12 cm of rainfall in several small events (7/23 – 7/30). The water table rose to within 12 cm of the wetland surface which resulted in 0.74 cm of outflow. During this period, the highest single day of rainfall occurred on 7/28 (5.0 cm) and the highest single day of outflow from the wetland occurred on 7/30 (0.43 cm). The restored wetland retained 94% of the rainfall during this period.

Following the non-tropical storms, the site received 17 cm of rainfall from Hurricane Alex (7/31 – 8/11). The antecedent soil moisture conditions were high prior to Alex. Prior to the event, the water table was an average 18 cm below the wetland surface. During the event, the water table rose to an average 5 cm above the wetland surface which resulted in 11 cm of outflow form the wetland (figure 3.18). The highest single day of rainfall occurred on 8/3 (12 cm) and the highest single day of outflow occurred on 8/5 (1.8 cm). The restored wetland retained 36% of the rainfall during this period. While the wetland did store a significant amount of rainfall, the percentage was much lower than the earlier non-tropical storms, because the antecedent soil moisture conditions were much higher prior to Hurricane Alex.

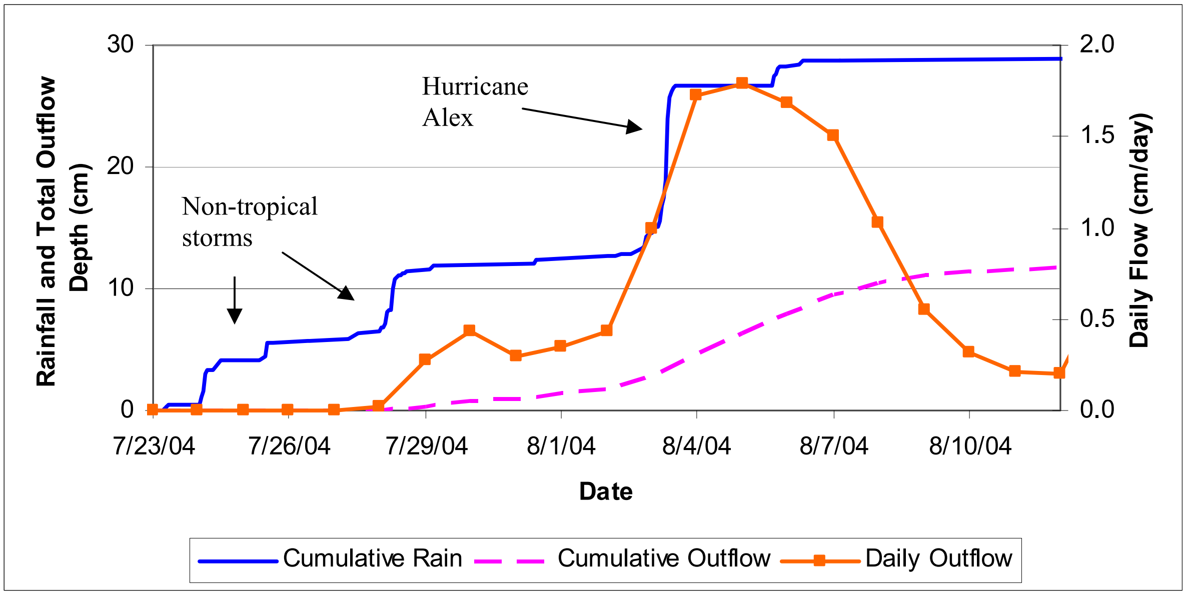

Figure 3.18 Cumulative rain, outflow, and daily outflow for non-tropical storm and Hurricane Alex.

Following Hurricane Alex, the site received 13 cm of rainfall from Tropical Storm Charley (8/12 – 8/25). The antecedent soil moisture conditions were high prior to Charley. Prior to the event, the water table was an average 22 cm below the wetland surface. During the event the water table rose to an average of 1 cm above the wetland surface which resulted in 9.4 cm of outflow from the wetland (figure 3.19). The highest single day of rainfall occurred on 8/13 (4.0 cm) and the highest single day of outflow occurred on 8/13 (1.7 cm). Unlike Hurricane Alex, Tropical Storm Charley produced the majority of its rainfall over four days of rainfall as opposed to one day of extreme rainfall. The restored wetland retained 24% of the rainfall during the period.

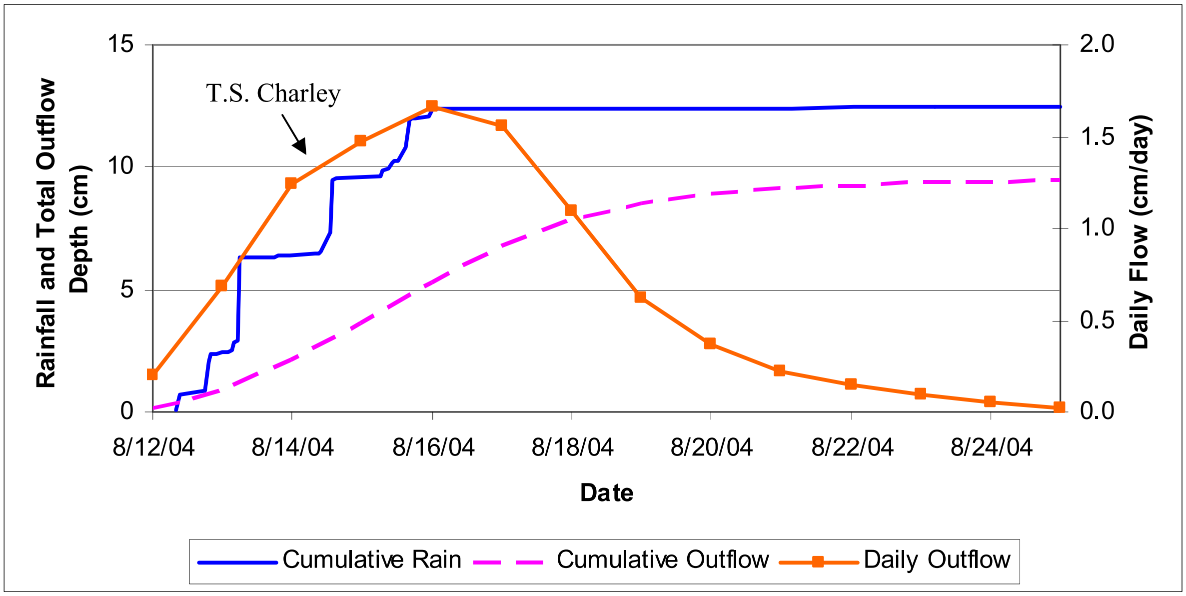

Figure 3.19 Cumulative rain, outflow, and daily outflow for Hurricane Charley.

All three storm periods produced a difference hydrologic response from the restored wetland (figure 3.20). The non-tropical storms produced the least rainfall and the least outflow, while Hurricane Alex produced the greatest rainfall and outflow. Following the initial non-tropical storms, the restored wetland expectedly retained the greatest amount of rainfall (94%) since it was the smallest storm and had a deep water table preceding the storm. The second storm, Hurricane Alex, despite producing the largest amount of rainfall and having the shallowest preceding water table, retained a greater percentage of rainfall than Tropical Storm Charley (36% compared to 24%).

This may be explained by the amount of time following the storm that the soil was allowed to drain prior to the arrival of the next storm. Following the peak rainfall produced by Hurricane Alex, the soil was able to drain for 8 days before the onset of

Tropical Storm Charley. Following the peak rainfall produced by Tropical Storm Charley, the soil was allowed to drain for 12 days before the next rainfall event occurred. The extra drainage time following Charley allowed the water table to drain 13 cm deeper than it did following Alex.

This occurrence may also be the result of hysteresis. Hysteresis states that water retention in soil may vary depending on whether the soil is wetting or drying. Prior to the non-tropical storms, the soil conditions were very dry and there should have been a large volume of entrapped air within the soil pores. Since the water table rises quickly during rain events, not all of the soil pores would have filled with water leaving entrapped air within the saturated soil profile. Following the draining of the soil, the unsaturated zone in the soil profile should have had a higher water content then prior to the storms. This same process should have occurred during Hurricane Alex except this time, more entrapped air should have been flushed out of the pores resulting in more water in the soil pores. Prior to Tropical Storm Charley, the saturated zone below the water should have had minimal entrapped air and the unsaturated zone should have been very close to field capacity. This could result in the soil profile prior to Tropical Storm Charley having a lower volume of water-free pore than prior to Hurricane Alex despite that fact that the water table was deeper. These likely occurrences could explain why the site retained a lower percentage of rainfall following Tropical Storm Charley despite receiving less rainfall and having a deeper initial water table.

For the entire period of extreme weather, the restored wetland experienced 41 cm of rainfall which produced 21 cm of outflow including a single daily maximum outflow of 1.8 cm which occurred following Hurricane Alex. This outflow accounted for 57% of the 2004 yearly outflow yet occurred in approximately one month (figure 3.20). Of the 41 cm of rainfall, the restored wetland was able to retain 49% it from flowing out of the site and into the estuary (table 3.3). The retained water was either stored in the soil profile, ponded on the surface, or lost to ET. For the entire year, the restored wetland retained a much higher percentage of the rainfall, 71% since outflow since outflow was controlled by flashboard risers which were installed approximately 22 - 32 cm lower than the ground elevation at the location of the water table wells.

Table 3.3 Hydrologic summary of 2004 extreme weather.

Storm	Initial Water Table (cm)	Rain (cm)	Outflow (cm)	Percent Retained
non-tropical	111	12	0.74	94%
Hurricane Alex	12	17	11	36%
Tropical Storm Charley	14	13	9.4	24%
Entire Storm Period	111	41	21	49%
2004	-	127	37	71%

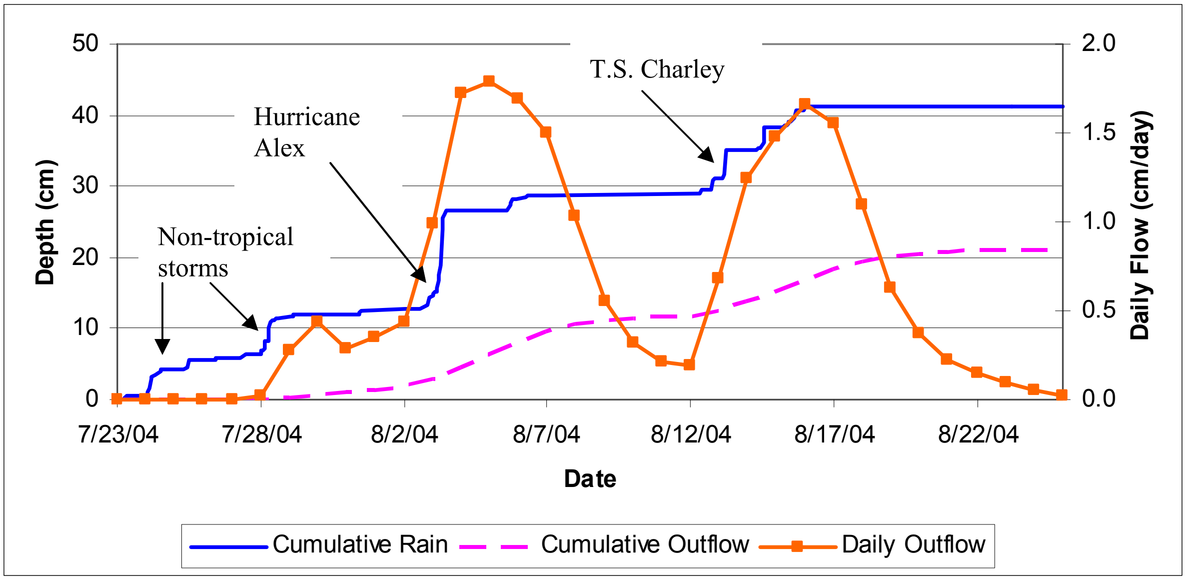

Figure 3.20 Cumulative rainfall, outflow, and daily outflow for 2004 extreme weather.

2005

Non-tropical and tropical storms and wetland outflows that occurred over a period of 14 days in 2005 (9/14 – 9/28) were examined. This period included Hurricane Ophelia. Similar to the period in 2004, antecedent soil moisture conditions were low prior to the initial storm, Hurricane Ophelia. Prior to the event, the water table was an average of 98 cm below the wetland surface (figures 3.21 and 3.22).

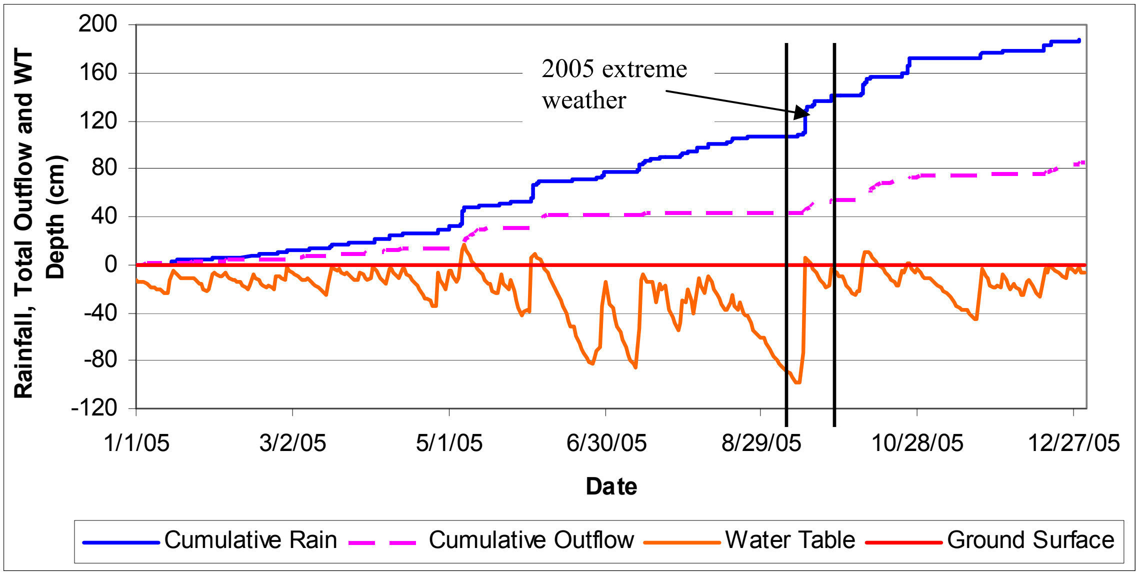

Figure 3.21 Cumulative rainfall, outflow, and water table fluctuations for 2005.

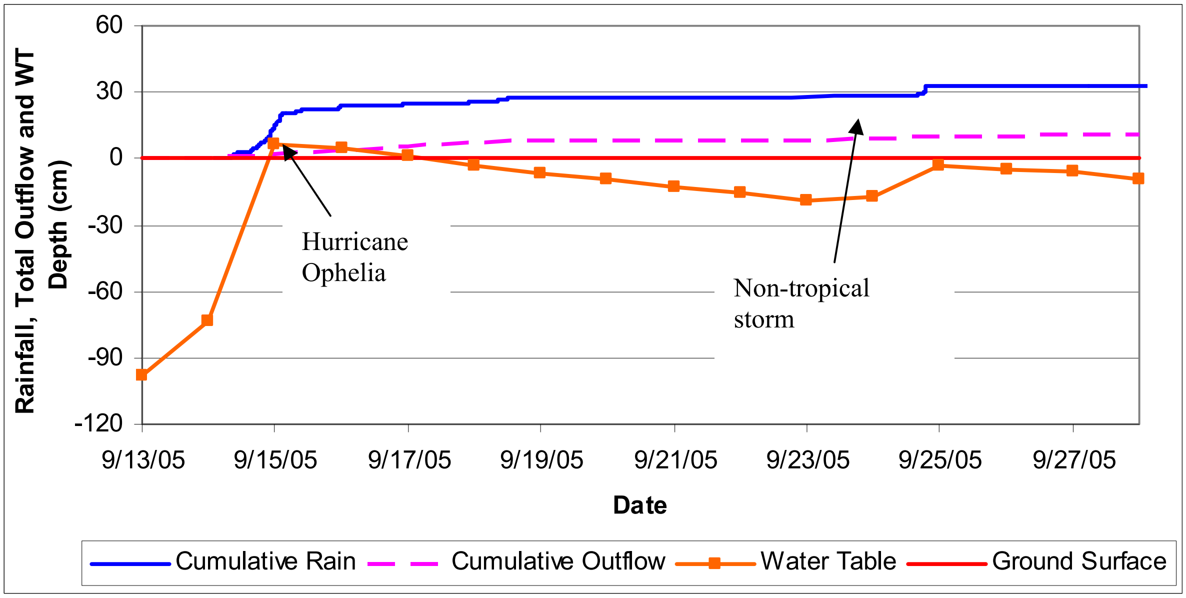

Figure 3.22 Cumulative rain, outflow, and water table fluctuations for 2005 extreme weather.

The initial and largest storm, Hurricane Ophelia (9/14 – 9/23) produced 28 cm of rainfall at the research site. The water table rose to an average of 6 cm above the wetland surface and resulted in 8.6 cm of outflow (figure 2.23). During this period, the highest single day of rainfall occurred on 9/14 (15 cm) and the highest single day of outflow from the wetland occurred on 7/30 (2.0 cm). The restored wetland retained 69% of the rainfall during this period.

Following Hurricane Ophelia, the site received an additional 5.1 cm of rainfall from a non-tropical storm (9/24 – 9/28). The antecedent soil moisture conditions were high prior to the storm; the water table was an average of 19 cm below the wetland surface. During the event, the water table rose to 3 cm below the surface which resulted in 2.2 cm of outflow from the wetland. The highest single day of rain occurred on 9/24 (4.6 cm) and the highest single day of outflow occurred on 9/25 (0.89 cm). The restored wetland retained 56% of the rainfall during this period.

The restored wetland was able to retain a greater percentage of rainfall during Hurricane Ophelia than the non-tropical Storm due to antecedent soil moisture conditions despite the fact that Ophelia produced more than five times the amount of rain as the non-tropical storm. Prior to the Hurricane Ophelia, the water table was on average 79 cm deeper than it was prior to the non-tropical storm. The increased amount of water-free pore space allowed the restored wetland to store more water during Ophelia than the non-tropical storm.

For the entire period of extreme weather, the restored wetland experienced 33 cm of rainfall which produced 19 cm of outflow including a single daily maximum outflow of 2.0 cm occurring during Hurricane Ophelia. Of the 33 cm of rainfall, the restored wetland was able to retain 67% of the water volume from flowing out of the site and into the estuary (table 3.4). The retained water was either stored in the soil profile, ponded on the surface, or lost to ET. For the entire year, the restored wetland surprisingly retained a lower percentage of rainfall, 53% than for the period of extreme weather. This most likely occurred because 2005 was an extremely wet year; the site received 29 cm of rainfall above average. During the two wettest periods of the year in terms of water table depths (January – May and October – December) the restored wetland was only able to retain 43% and 35% of rainfall respectively. Heavy rains and low ET rates would have allowed the water table to remain shallow enough for frequent outflow to occur. During the summer months (June – August) the restored wetland was able to retain 75% of rainfall even while receiving over 54 cm. The wetland was most likely able to retain a much higher percentage of rainfall during the summer months due to higher ET losses. Hurricane Ophelia arrived following the driest water table conditions the restored wetland would experience in 2005. This provided the highest amount of water-free pore space for which to store excess water. This allowed the restored wetland to retain a higher percentage of rainfall during the period of tropical weather than it was able to in other wet periods despite experiencing the more intense rainfall.

Table 3.4 Hydrologic summary of 2005 extreme weather.

Storm	Initial Water Table (cm)	Rain (cm)	Outflow (cm)	Percent Retained
Hurricane Ophelia	98	28	8.6	69%
Non-tropical	19	5.2	2.2	56%
Entire Storm Period	98	33	11	67%
2007	-	188	85	53%

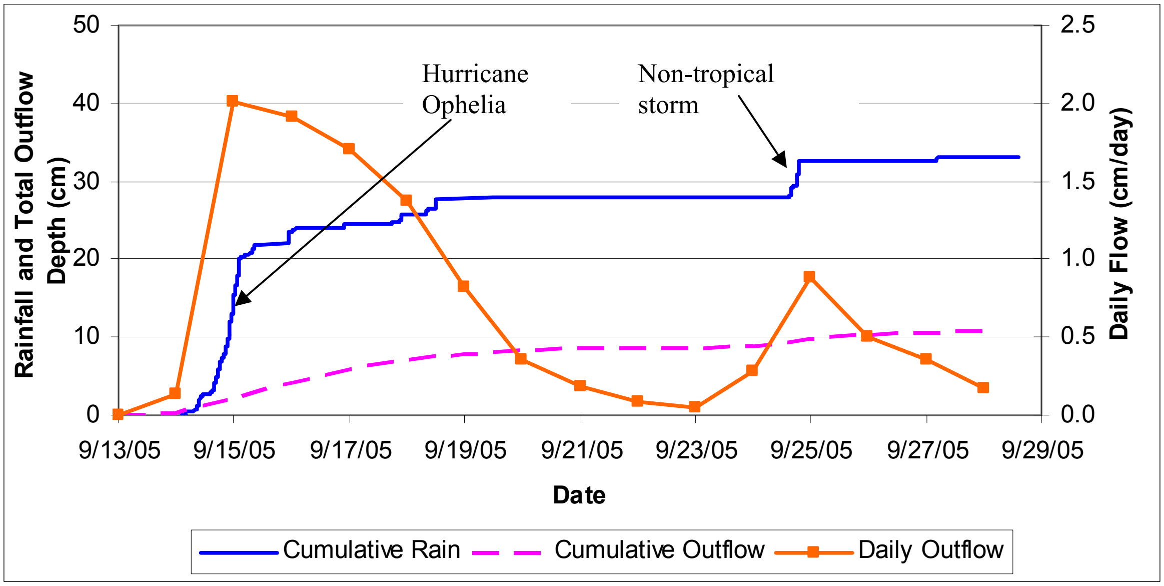

Figure 3.23 Cumulative rain, outflow, and daily outflow for 2005 extreme weather.

2007

Non-tropical and tropical storms and wetland outflows that occurred over 11 days (9/9 – 9/19) were examined. This period included Tropical Storm Gabrielle. Antecedent soil moisture conditions were low prior to the initial storm, Tropical Storm Gabrielle. Prior to this event, the water table was an average 82 cm below the wetland surface, which was the deepest water table since mid-July (figures 3.24 and 3.25).

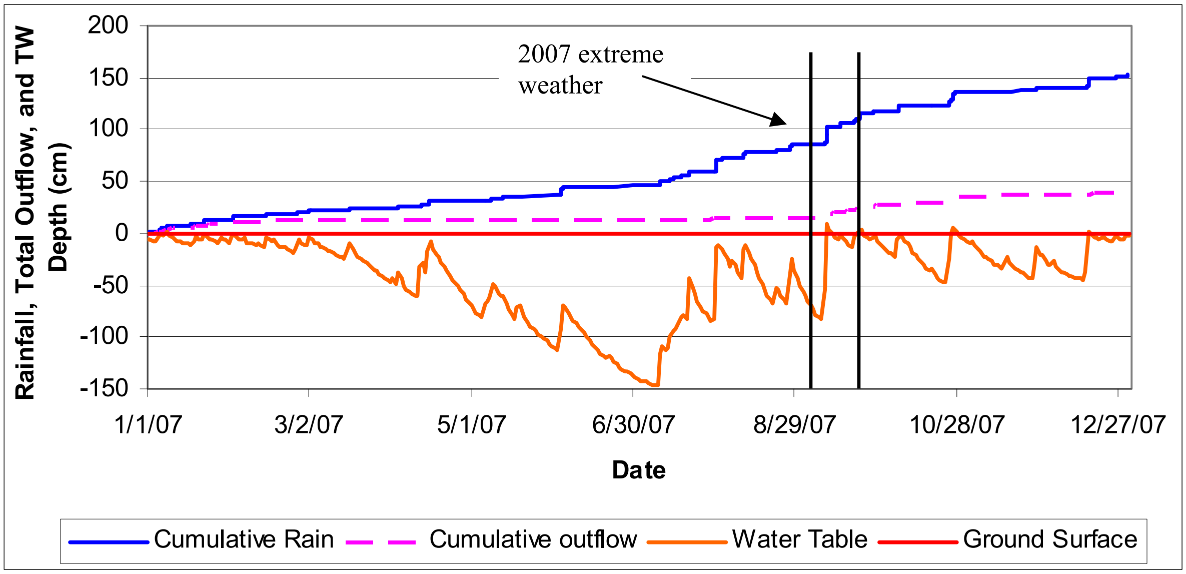

Figure 3.24 Cumulative rainfall, outflow, and water table fluctuations for 2007.

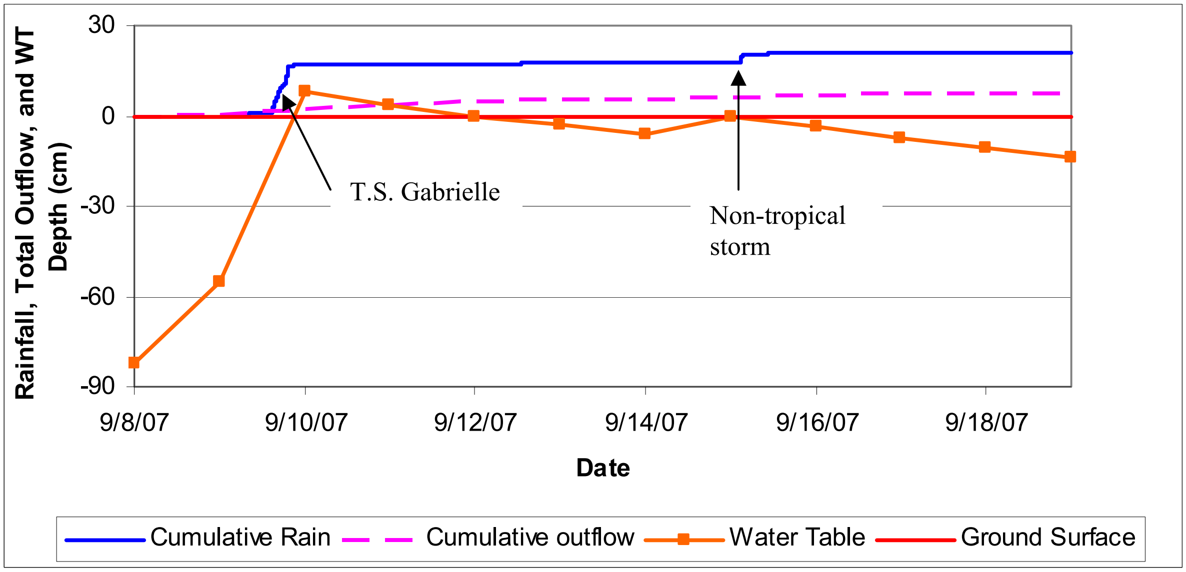

Figure 3.25 Cumulative rainfall, outflow, and water table fluctuations for 2007 extreme weather.

The initial storm, Tropical Storm Gabrielle (9/9 – 9/14) produced 18 cm of rainfall at the site. The water table rose to an average of 8 cm above the surface which resulted in 5.7 cm of outflow (figure 3.26). During this period, the highest single day of rainfall occurred on 9/9 (17 cm) and the highest single day of outflow occurred on 9/10 (1.7 cm). The restored wetland retained 68% of the rainfall during this period.

Following Tropical Storm Gabrielle, the site received an additional 3.0 cm of rainfall from a non-tropical storm (9/15 – 9/19). The antecedent soil moisture conditions were high prior to the storm; the water table was an average of 6 cm below the wetland surface. During the event, the water table rose to the surface which resulted in 1.8 cm of outflow from the wetland. During this period, rain only occurred on 9/15 (3.0 cm) and the highest single day of outflow occurred on 9/15 (0.76 cm). The restored wetland retained 39% of the rainfall during this period.

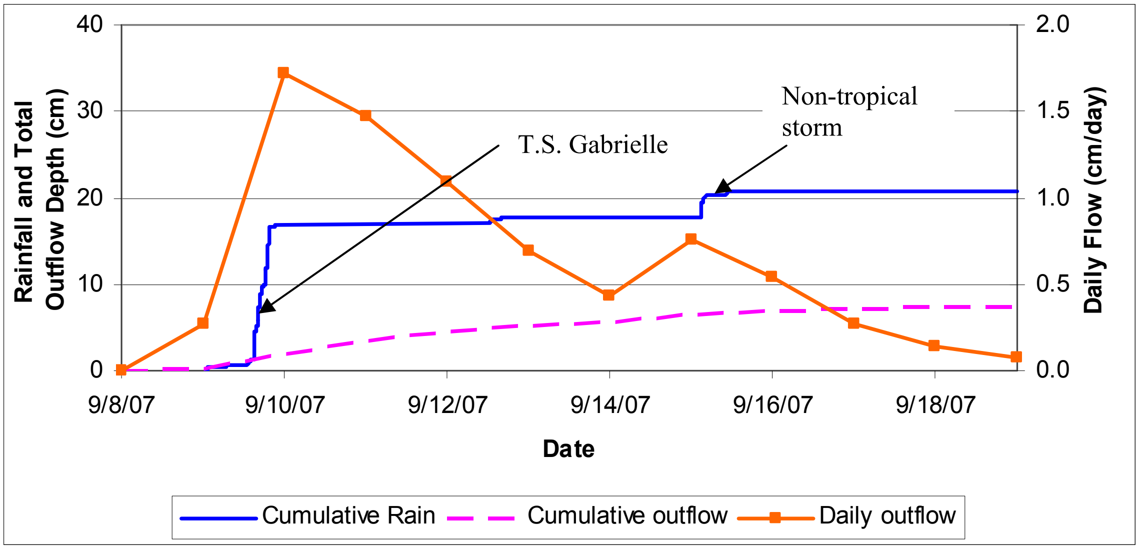

Figure 3.26 Cumulative rainfall, outflow, and daily outflow for 2007 extreme weather.

For the entire period of extreme weather, the restored wetland experienced 21 cm of rainfall which produced 7.5 cm of outflow. The outflow accounted for 18% of the 2007 yearly outflow yet occurred over only 3% of the year (11 days). Of the 21 cm of rainfall, the restored wetland was able to retain 64% from draining out to the estuary (table 3.5). The retained water was either stored in the soil profile, ponded on surface, or lost to ET. For the entire year the wetland retained a much higher percentage of rainfall, 76% since outflow since outflow was controlled by flashboard risers which were installed approximately 22 - 32 cm lower than the ground elevation at the location of the water table wells.

Table 3.5 Hydrologic summary of 2007 extreme weather.

Storm	Initial Water Table (cm)	Rain (cm)	Outflow (cm)	Percent Retained
Tropical Storm Gabrielle	82	18	5.7	68%
Non-tropical	14	3.0	1.8	39%
Entire Storm Period	82	21	7.5	64%
2007	-	154	41	76%

Observed Water Table and Surface Outflow Discussion

The most important hydrologic factors which impacted the retention ability of the restored wetland were total rainfall and antecedent soil moisture condition. The total rainfall determines the total water volume input into the system, while the antecedent soil moisture condition determines the amount of water-free pore space available in the soil profile for storage purposes. During the 2004 period of extreme weather, the restored wetland retained a lower percentage of rainfall (49%) than during 2005 and 2007 periods of extreme weather despite having the lowest antecedent soil moisture condition because it also experienced the highest total rainfall, 41 cm (table 3.6). The dry antecedent soil moisture conditions are misleading however because initial non-tropical storms raised the water table near the surface prior to Hurricane Alex and Tropical Storm Charley. This resulted in the site having very high soil antecedent moisture conditions prior to both named storms which resulted in a low retention percentage. Further more 2004 was the only year during the study which experienced two tropical events.

The wetland performed very similar during the extreme weather periods of 2005 and 2007. Both periods followed the same pattern: low antecedent soil moisture conditions (average water table deeper than 80 cm) followed by a tropical weather event, followed by a non-tropical event. Following the Hurricane Ophelia and Tropical Storm Gabrielle, the wetland was able to retain 69% and 68% and then following the non-tropical storms the wetland was able to retain only 56% and 39% respectively. For the entire storm periods of 2005 and 2007, the wetland was able to retain 67% and 64%.

Table 3.6 Observed hydrologic Summary of tropical weather 2004 – 2007.

Year	**2004**	**2005**	**2007**	**Study**
Named Storms	Hurricane Alex and Tropical Storm Charley	Hurricane Ophelia	Tropical Storm Gabrielle	-
Initial Water Table Depth (cm)	111	98	82	-
Rainfall (cm)	41	33	21	95
Peak Daily Outflow (cm)	1.8	2.0	1.7	-
Outflow (cm)	21	11	7.5	40
Percent Retained	49%	67%	64%	58%
Annual Percent Retained	71%	53%	76%	64%

Water Balance:

A water balance was developed to gain a better understanding of why the rainfall input was either stored or exported during these periods of extreme weather. The water balance considered components: rainfall, outflow, evapotranspiration, and stored water volume. Deep seepage was not considered an important factor due to the short time frames. Rainfall and outflow were monitored at the restored wetland, while daily ET losses were predicted by DRAINMOD using the Thornthwaite equation. The stored water volume was estimated by back calculating with a water balance equation (equation 3.6).

Equation 3.6 Water balance used for estimating change in volume of store water

$$\Delta S = P - Q - ET$$

ΔS = change in volume of stored water (cm)
P = Observed precipitation (cm)
Q = Observed outflow (cm)
ET = Estimated evapotranspiration (cm)

2004

Following each storm, the majority of rainfall was temporarily stored since the perimeter berms prevented runoff and the water control structures limited peak outflow. For each storm that occurred within the period of extreme weather there was a 2 -3 day delay between the date of peak daily rainfall and peak daily outflow. Following each storm, the stored water volume dropped due to outflow and ET losses; outflow losses were approximately double that of ET losses (figure 3.27). Evapotranspiration was a relatively consistent source of water loss. The restored wetland lost on average 3.5 mm/day to ET (daily ET losses ranged from 0.9 – 5.1 mm/day). Of the 41 cm of rainfall inputted during the extreme weather, 51% was lost to outflow (21 cm), 28% was lost to ET (120 mm), and 20% was stored within the restored wetland (8.4 cm).

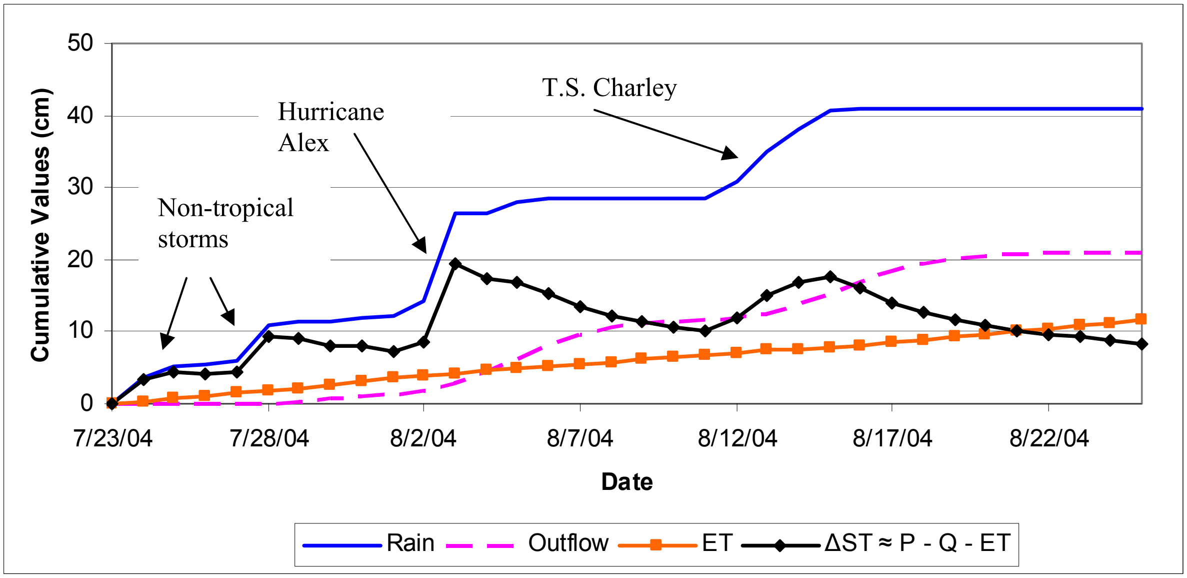

Figure 3.27 Cumulative water balance for 2004 extreme weather.

2005

For each storm that occurred within the period of extreme weather there was a one day delay between the date of peak daily rainfall and peak daily outflow. Following each storm, the stored water volume dropped due to outflow and ET losses; outflow losses were approximately double that of ET losses (figure 3.28). Evapotranspiration was a relatively consistent source of water loss. The restored wetland lost on average 3.5 mm/day to ET (daily ET losses ranged from 0.3 – 4.9 mm/day). Of the 33 cm of rainfall inputted during the extreme weather, 33% was lost to outflow (11 cm), 16% was lost to ET (52 mm), and 51% was stored within the restored wetland (17 cm). This period experienced much lower losses to ET because than 2004 because it occurred over a shorter period of time. Daily ET losses during 2005 extreme weather were similar to 2004.

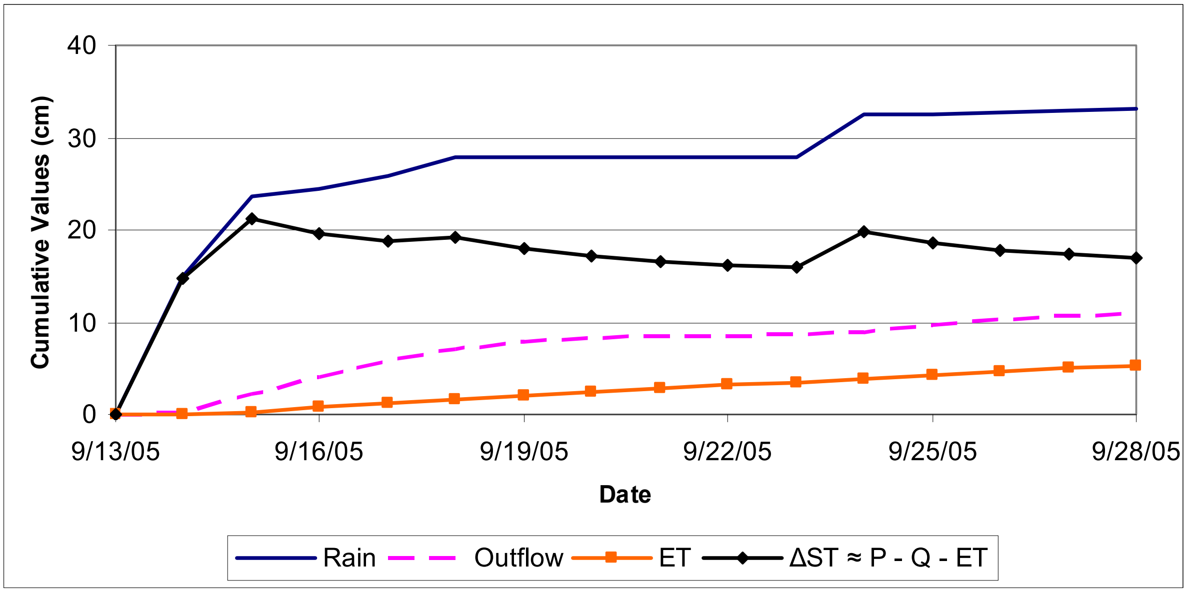

Figure 3.28 Cumulative water balance for 2005 extreme weather.

2007

For each storm that occurred within the period of extreme weather there was a one day delay between the date of peak daily rainfall and peak daily outflow. Following each storm, the stored water volume dropped due to outflow and ET losses; outflow losses were approximately double that of ET losses (figure 3.29). Evapotranspiration was a relatively consistent source of water loss. The restored wetland lost on average 3.4 cm/day to ET (daily ET losses ranged from 1.1 – 5.0 cm/day). Of the 21 cm of rainfall inputted during the extreme weather, 36% was lost to outflow (7.4 cm), 18% was lost to ET (36 mm), and 46% was stored within the restored wetland (9.5 cm). This period experienced much lower losses to ET because than 2004 because it occurred over a shorter period of time. Daily ET losses during 2007 extreme weather were similar to 2004 and 2005.

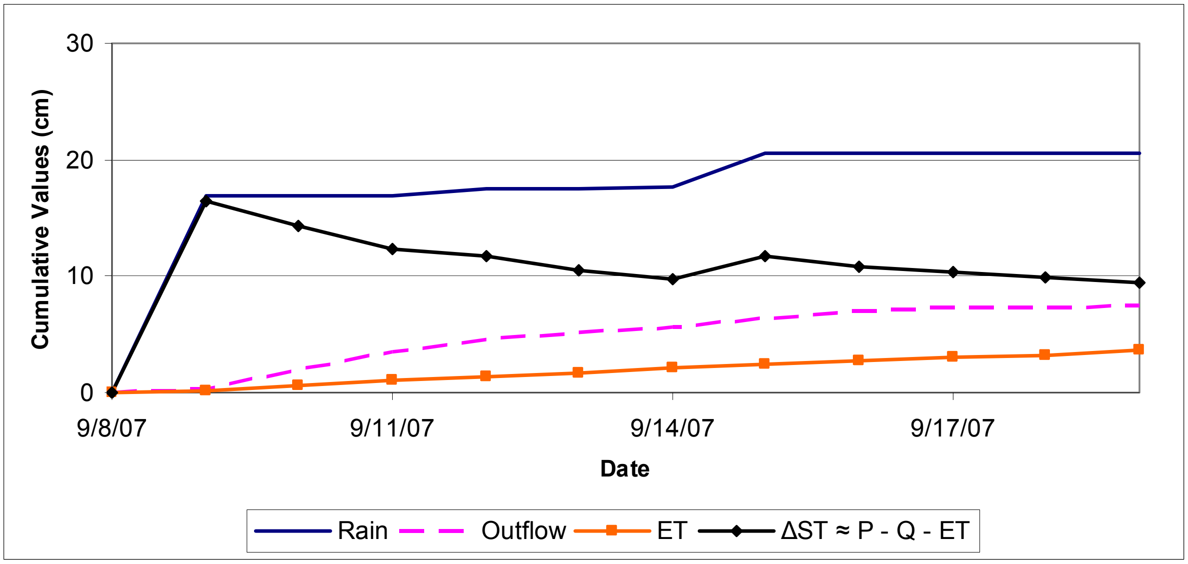

Figure 3.29 Cumulative water balance for 2007 extreme weather.

Water Balance Discussion

During the 2005 and 2007 extreme weather, the restored wetland was able to store 51% and 46% of the rainfall respectively while in 2004 the wetland only stored 28% (table 3.7). The restored wetland stored a smaller percentage of rainfall in 2004 for multiple reasons. The 2004 extreme weather produced 41 cm, which was the highest amount of rainfall. The site has only a finite amount of soil and surface storage available and could not handle that high of rainfall. Due to the initial non-tropical storms, the wetland had a very shallow water table when Hurricane Alex and Tropical Storm Charley arrived, therefore very little storage volume was still available because it had been filled by the first storm. Also the overall period of extreme weather during 2004 was more than twice the amount of days as in 2005 and 2007 causing ET to remove more than twice the volume of water during 2004 than the other years. ET losses were very consistent during the periods of extreme weather due to similar temperatures and available water in the soil profile.

Table 3.7 Each component of water balance as a percentage of rainfall for periods of extreme weather.

Year	2004	2005	2007
Outflow	51%	33%	36%
Evapotranspiration	28%	16%	18%
Storage	20%	51%	46%

Hydrologic Modeling:

The hydrologic model, DRAINMOD (Skaggs et al., 1999) was used to simulate conditions observed at the restored wetland. The preliminary inputs were developed using soil and drainage inputs reported by Wright (2005) for a separate modeling efforts of the site. The model was then re-calibrated using the average daily water table depth observed in 2004 and then validated using the observed average daily water table depth for 2005 and 2007. The model was not tested against 2006 because no tropical weather affected the site in 2006. The drainage inputs and surface condition in the calibrated model were then adjusted to simulate the hydrology for varying surface and drainage condition, including pre-restoration agricultural conditions.

Model Calibration

The model was developed using inputs soil and drainage design inputs developed by Wright (2005). Since this version of the model was used with different intent, Wright's inputs were used as a starting point and then further calibration. The calibration was evaluated by comparing observed and predicted daily water table depth as well and observed and predicted total outflow for 2004. Water table depth was evaluated using average daily difference, ADD (equation 3.7) and absolute average difference, AAD (equation 3.8). The ADD describes whether the model is predicting a deeper or shallower water table than was observed on average while AAD describes the average absolute error for each day for the water table predictions.

Equation 3.7 Average daily deviance of water table depth.

$$ADD = \frac{\sum WTD_O - WTD_P}{n}$$

ADD = Average daily difference
WTD_o = Daily observed water table depth (cm)
WTD_p = Daily predicted water table depth (cm)
n = number of days evaluated

Equation 3.8 Average absolute deviance of water table depth.

$$AAD = \frac{\sum \left| WTD_O - WTD_P \right|}{n}$$

AAD = Absolute average difference
WTD_o = Daily observed water table depth (cm)
WTD_p = Daily predicted water table depth (cm)
n = number of days evaluated

The model calibration was evaluated using 2004 observed and simulated data. The evaluation of the water table data found the model to have an ADD of 1.4 cm and an AAD of 8.7 cm (table 3.8). This means that for 2004, the model predicted the daily water table to be on average 1.4 cm deeper than was observed in the field. Furthermore, on average, the daily water table predicted by the model had an error of 8.7 cm. The outflow evaluation found that the model under-predicted the annual outflow by 7 cm (15%). The ADD proved to be a good indicator of the accuracy of the outflow prediction. The positive ADD represented that the observed water table was shallower than the simulated water table which corresponds to the model under-predicting outflow. By visually examining the outflow plot, it was observed that under-prediction of outflow occurred during the time of tropical weather (figure 3.30). The ADD and AAD values found for this calibration are within the range of values reported by Wright (2005).

Table 3.8 Comparison of observed and simulated hydrology during 2004.

Observed Outflow	37 cm
Predicted Outflow	44 cm
% Error	-15%
Water Table ADD	1.4 cm
Water Table AAD	8.7 cm

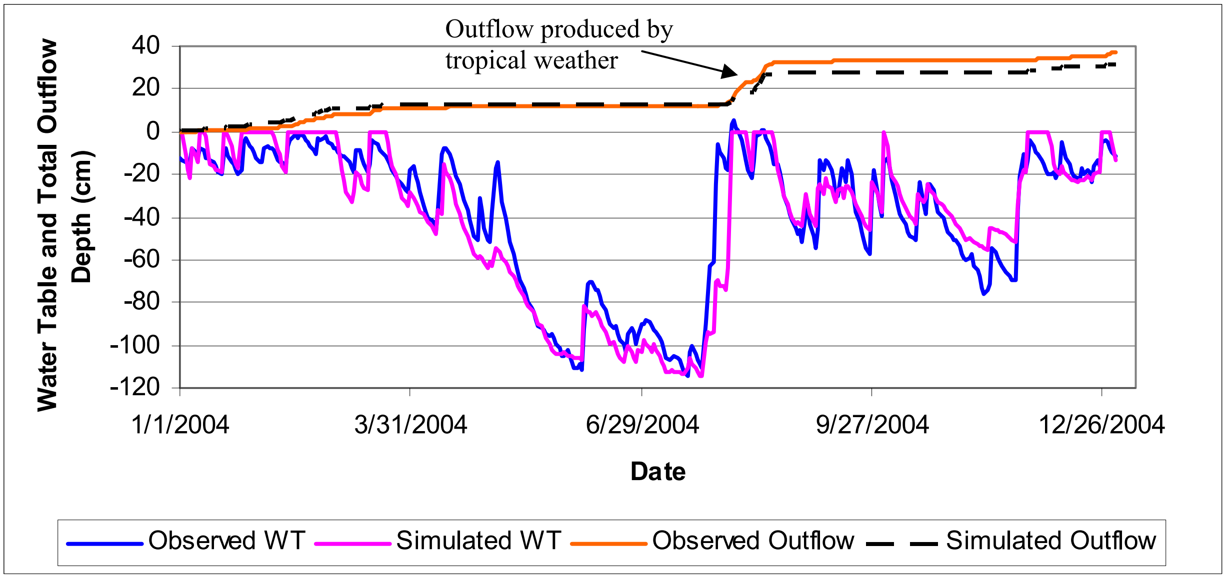

Figure 3.30 Observed and simulated daily outflow and water table depth during 2004.

Model Validation

The calibration was validated using the same tools as the calibration, but they were applied to 2005 and 2007 data. The accuracy of the 2006 simulation was not verified because no tropical weather impacted the site in 2006 and that model output was not used for this study.

The evaluation of the 2005 water table data found the model to have an ADD of -3.4 cm and an AAD of 9.4 cm (table 3.9). This means that for 2005, the model predicted the daily water table to be on average 3.4 cm shallower than was observed in the field. Furthermore, on average, the daily water table predicted by the model had an error of 9.4 cm. The outflow evaluation found that the model over-predicted the annual outflow by 2 cm (1.9%). By visually examining the outflow plot, it was observed that under-prediction of outflow occurred during the time of tropical weather (figure 3.31). The ADD proved to be a good indicator of the accuracy of the outflow prediction. The negative ADD represented that the observed water table was deeper than the simulated water table which corresponds to the model over-predicting outflow. The ADD and AAD values were found to be similar to the values reported for the 2004 calibration.

Table 3.9 Comparison of observed and simulated hydrology during 2005.

Observed Outflow	85 cm
Predicted Outflow	87 cm
% Error	1.9%
Water Table ADD	-3.4
Water Table AAD	9.4

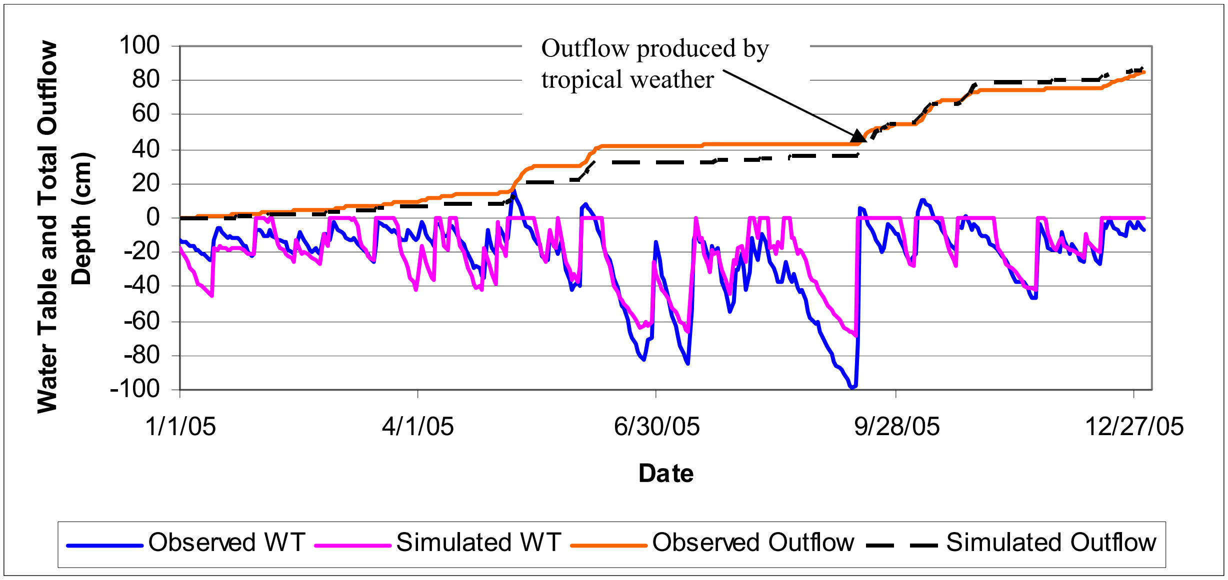

Figure 3.31 Observed and simulated daily outflow and water table during 2005

The evaluation of the 2007 water table data found the model to have an ADD of -1.7 cm and an AAD of 10.7 cm (table 3.10). This means that for 2007, the model predicted the daily water table to be on average 1.7 cm shallower than was observed in the field (figure 3.32). Furthermore, on average, the daily water table predicted by the model had an error of 11 cm. The outflow evaluation found that the model over-predicted the annual outflow by 12 cm (29%). The ADD proved to be a good indicator of the accuracy of the outflow prediction. The negative ADD represented that the observed water table was deeper than the simulated water table which corresponds to the model over-predicting outflow. The ADD and AAD values were found to be similar to the values reported for the 2004 calibration.

Table 3.10 Comparison of observed and simulated hydrology during 2007.

Observed Outflow	41cm
Predicted Outflow	52 cm
% Error	29%
Water Table ADD	-1.7 cm
Water Table AAD	11 cm

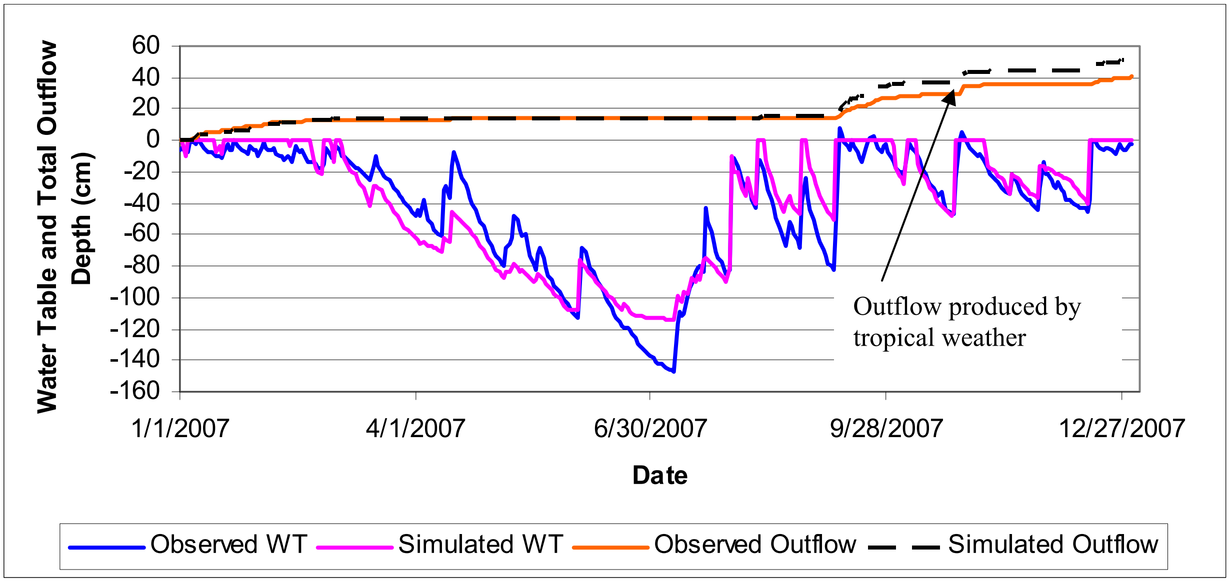

Figure 3.32 Observed and simulated daily outflow and water table depth during 2007.

Validation Discussion

The calibration/validation process showed that the model did an acceptable job in simulating wetland hydrologic conditions. The ADD for the water table for 2005 and 2007 was within ± 4 cm and AAD for all three years was within 11 cm. For the intended uses of this particular model, ADD proved to be a better tool for evaluating the calibration since outflow prediction was the desired output of this modeling effect. A negative ADD corresponded with the model over-predicting annual outflow while a positive ADD corresponded with the model under-predicting annual outflow.

Pre-restoration Agricultural Simulations:

The calibrated model was modified to simulate the hydrologic response of the research site during the tropical weather if the pre-restoration agricultural conditions still remained. Although it would have been ideal to monitor agricultural fields at the site to establish a control, all the acquired fields in the phase of the project were restored and no pre-construction monitoring occurred. The model was modified by adjusting the drainage system, surface conditions, and rooting depths to represent agricultural conditions (table 3.11). Free drainage was established by removing the weir settings which were used to control outflow and the drainage coefficient was increased to 2.5 cm/day to increase the allowable maximum daily drainage. Rooting depths were adjusted to represent corn, which affects the ET calculations. Maximum surface storage and Kirkham's depth were reduced to represent a well managed and crowned field. Maximum surface storage and Kirkham's depth were set to 1.5 cm and 0.75 cm but a range of surface conditions was also simulated to determine the sensitivity of the surface conditions since it is difficult to determine surface conditions without monitoring the actual agricultural field. In an agricultural setting, maximum surface storage is typically double Kirkham's depth.

The modeling was used to predict peak and total outflow during the tropical weather to determine the effectiveness of the restoration at mitigating the large flows associated with hurricanes and tropical storms.

Table 3.11 Model inputs which were adjusted to simulate agricultural conditions.

Inputs	Wetland Conditions	Agricultural Conditions
Weir Depth	30 cm	Free drainage
Drainage Coefficient	2.0 cm/day	2.5 cm/day
Rooting Depths	40 cm	Varies throughout year, 3-25 cm
Surface Storage	50 cm	1.5 cm
Kirkham's Depth	2 cm	0.75 cm

2004

The observed hydrology of the restored wetland was compared to simulated agricultural hydrology during the 2004 extreme weather (7/23 – 8/25) to determine the hydrologic impact of the restoration. During the initial period of non-tropical weather (7/23 – 7/30) the restored wetland experienced 0.74 cm of outflow while the agricultural simulation predicted only 0.26 outflow from the site (figure 3.36). This is most likely due to the fact that the enhanced drainage found in the agricultural model should have created drier antecedent soil moisture conditions.

During Hurricane Alex (7/31 – 8/11), the restoration had a much more dramatic effect on the hydrology then during the non-tropical storms. Alex produced a peak daily outflow of 6.1 cm/day with the simulated agricultural conditions while only a peak outflow of 1.8 cm/day was observed at the restored wetland, a 71% reduction. At the restored wetland, the entire outflow occurred as drainage through the water control structures; outflow via surface runoff is almost impossible at the restoration due to the high perimeter berms. In the agricultural simulation, 4.9 cm of the 6.1 cm exported occurred as surface runoff. The restoration not only dampened the peak flow but also the time to peak. The peak daily outflow was predicted to occur on 8/3 in the agricultural simulation but was observed on 8/5 at the restored wetland. The modeling did not predict any reduction in total outflow however. The agricultural simulation predicted Hurricane Alex would produce 9.0 cm of outflow while 11 cm of outflow was also observed at the restored wetland. This is due the observed water table rising to the surface much quicker than was predicted by the agricultural simulation. In the field the water table rose near the surface on 7/29 but the model did not predict the water table rising near the surface until 8/3. The difference in water table response is the reason the agricultural simulations predicts a lower outflow volume than was observed in the restored wetland.

During Tropical Storm Charley (8/12 – 8/25), the agricultural simulation did not predict as extreme of a hydrograph as during Hurricane Alex. Alex produced a peak daily outflow of 2.8 cm/day with the simulated agricultural conditions while a peak outflow of 1.7 cm/day was observed at the restored wetland, a 41% reduction. Tropical Storm Charley did not produce as large of a peak daily outflow as Hurricane Alex because of the distribution of rainfall for each storm. The majority of the rainfall from Alex fell on a single day of 12 cm while the majority of rainfall from Charley fell over four days with daily rainfall ranging from 2.4 – 4.0 cm/day. Because of the rainfall differences, the agricultural simulation predicted Alex would produce one day of extreme outflow (6.1 cm/day) while Charley produced three days of high outflow (2.3 – 2.8 cm/day). The agricultural hydrograph during Tropical Storm Charley was again flashier than the observed hydrograph. In addition to the restoration reducing the peak outflow, the date of peak outflow occurred two days later at the restored wetland than was predicted to occur in the agricultural simulation. Similar to Hurricane Alex, modeling did not predict the restoration having a major impact on total outflow. The agricultural simulation predicted a total outflow of 10 cm while 9.4 cm of outflow was observed at the restored wetland, a 7% reduction..

For the entire period of extreme weather, the modeling predicted that the restoration had a large impact on peak daily outflow but no impact on total outflow. The agricultural simulation predicted a total outflow of 19 cm while 21 cm of outflow were observed at the restored wetland. There are two likely causes for the modeling predicting that the restoration would increase total outflow. First of all, it was observed during calibration that the wetland simulation under-predicted outflow during the tropical weather period. That would mean that the agricultural simulation most likely under-predicted outflow as well. Second, it was observed in the earlier sections, that the restoration did a poor job of storing excess water during 2004 compared to 2005 and 2007. This is attributed to the fact that the initial non-tropical storms saturated the wetland so that there was very little available water-free pore space within the soil when Hurricane Alex and Tropical Storm Charley arrived. Even without considering any calibration error, it is likely that the restoration did not provide substantial water storage during the extreme weather due to the high antecedent soil moisture conditions prior to both Hurricane Alex and Tropical Storm Charley.

For the entire 2004 year, the modeling predicted a total outflow of 44 cm compared to 37 cm of outflow observed at the wetland. This suggests the restoration resulted in a 16% reduction of the annual outflow.

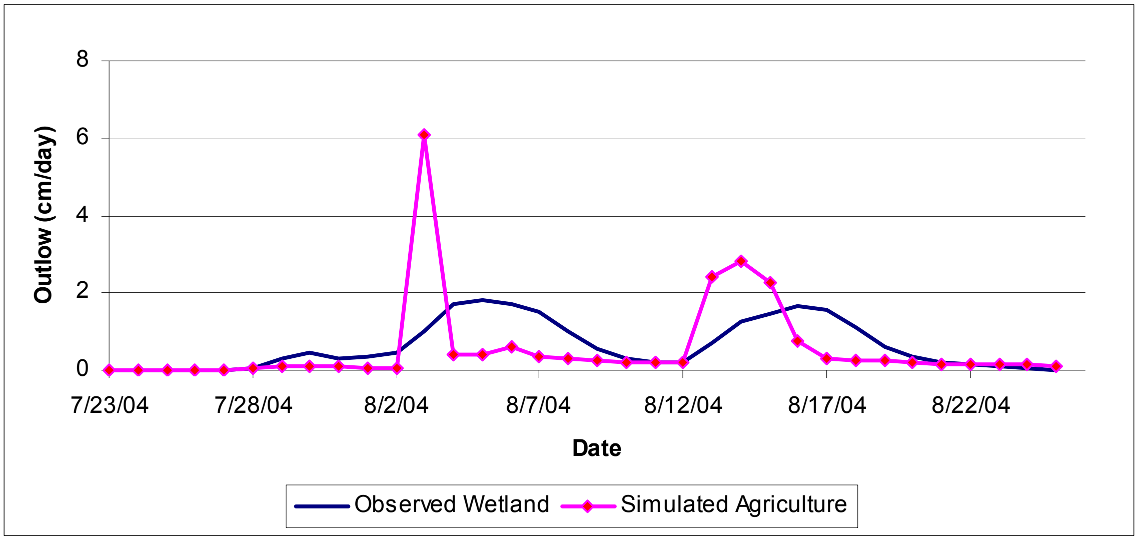

Figure 3.33 Observed and simulated agricultural outflow during 2004 extreme weather.

The agricultural model was simulated with varying maximum surface storage inputs ranging from 1.0 cm to 5.0 cm (figure 3.34). The true maximum surface storage at the site is thought to be between 0.75 cm and 2.0 cm. Kirkham's depth was set as half of maximum surface storage. The simulations found that adjusting the surface conditions had very little impact on the outflow output until the maximum surface storage went up to 5.0 cm which is considered very unlikely for the location. The was an approximately 1.5 cm difference in total outflow between the lowest maximum surface storage (1.0 cm) and the highest maximum surface storage (5.0 cm).

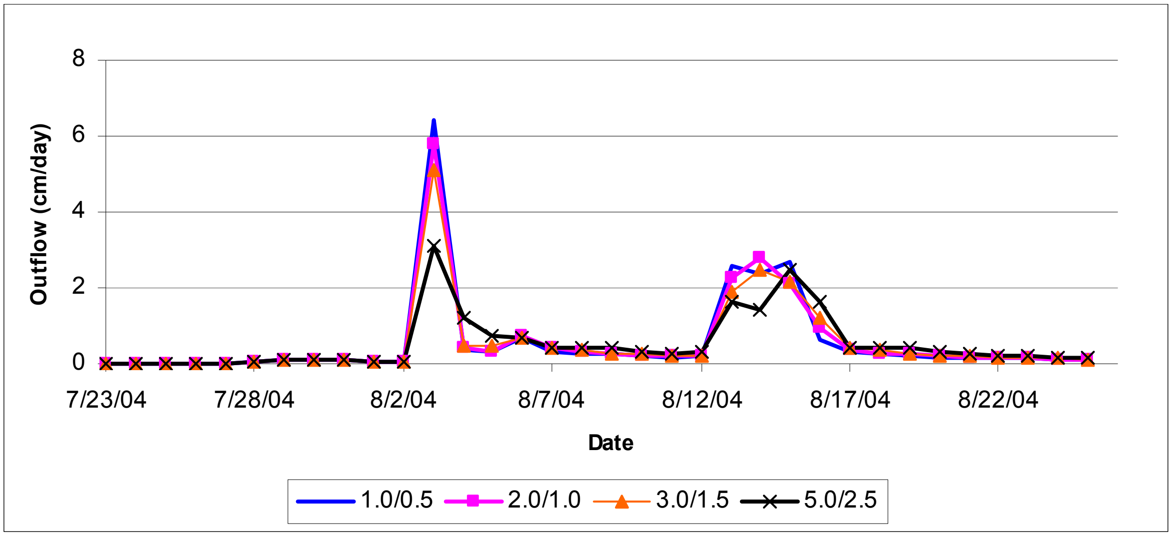

Figure 3.34 Simulated agricultural daily outflow during 2004 extreme weather for varying surface storage conditions.

2005

The observed hydrology of the restored wetland was compared to simulated agricultural hydrology during the 2005 extreme weather (9/14- 9/28) to determine hydrologic impact of the restoration. During the first storm, Hurricane Ophelia (9/14 – 9/23), the restoration had a dramatic effect on the hydrology. Ophelia produced a peak daily outflow of 8.5 cm/day with the simulated agricultural conditions while only a peak outflow of 2.0 cm/day was observed at the restored wetland, a 76% reduction (figure 3.35). At the restored wetland, the entire outflow occurred as drainage through the water control structures but in the agricultural simulations, the outflow occurred as both subsurface drainage and surface runoff. 6.6 of the 8.5 cm of outflow occurred as surface runoff. Similar to Hurricane Alex in 2004, such a high peak outflow occurred due to very high single days of rainfall. On 9/14 the site experienced 15 cm of rainfall which the agricultural simulation predicted would result in 3.8 cm of outflow while the following day, 9/15, the site experienced 8.7 cm of rainfall which when combined with the excess water from the previous day, resulted in a prediction of 8.5 cm of outflow. The distribution of rainfall also resulted in the agricultural simulations predicted a second peak outflow occurring on 9/18 which was not observed at the restored wetland.

The modeling also predicted that the restoration had an impact on total outflow produced by Hurricane Ophelia. The agricultural simulation predicted Ophelia would produce 17 cm of outflow while only 8.6 cm of outflow were observed at the restored wetland, a 51% reduction.

During the second, non-tropical, storm (9/24/2005 – 9/28/2005), the agricultural simulations predicted slightly lower flows than were observed at the restoration. Since agricultural conditions result in more intensive drainage than is found in a wetland, the agricultural simulations predicted a deeper water table following Hurricane Ophelia which resulted in more water-free pore space for storing water from the second storm. The agricultural simulation predicted a peak daily outflow of 0.68 cm/day while 0.89 cm/day was observed in the field. A total outflow of 2.2 cm was both observed at the restoration and predicted by the agricultural model.

For the entire period of extreme weather, the modeling predicted that the restoration had an impact on reducing peak outflow and total outflow. The agricultural simulations predicted a total outflow of 19 cm while only 11 cm was observed at the restoration, a 44% reduction. However due to some calibration error, the reduction in total outflow was may have been over-estimated. It was observed during validation that the wetland simulation appeared to over-predict outflow during the tropical storm period. This would have likely caused the agricultural simulation to also over-predict outflow during the time period. For the entire 2005 year, the modeling predicted a total outflow of 90 cm compared to 85 cm of outflow observed at the wetland. This suggests the restoration resulted in a 6% reduction of the annual outflow. It is not surprising that the predicted yearly reduction in outflow was minimal since 2005 was an extremely wet year and the wetland was found to do a poor job retaining rainfall for that year.

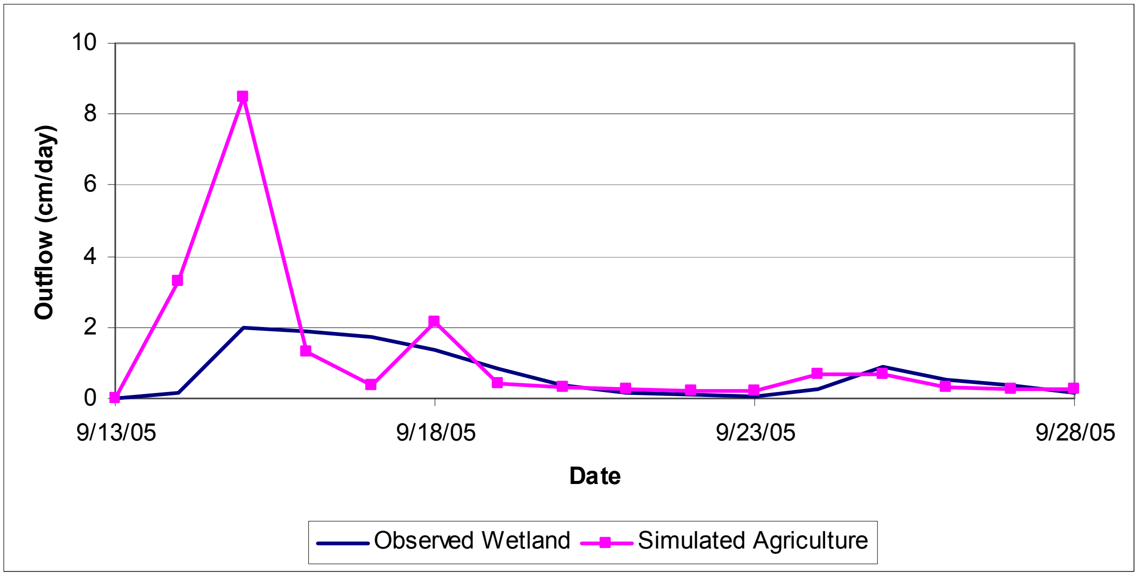

Figure 3.35 Observed and simulated agricultural outflow during 2005 extreme weather.

The agricultural model was simulated with varying maximum surface storage inputs ranging from 1.0 cm to 5.0 cm (figure 3.36). The simulations found that adjusting the surface conditions had very little impact on the outflow output until the maximum surface storage even at 5.0 cm which is considered very unlikely for the location. The was an approximately 1.5 cm difference in total outflow between the smallest maximum surface storage (1.0 cm) and the highest maximum surface storage (5.0 cm).

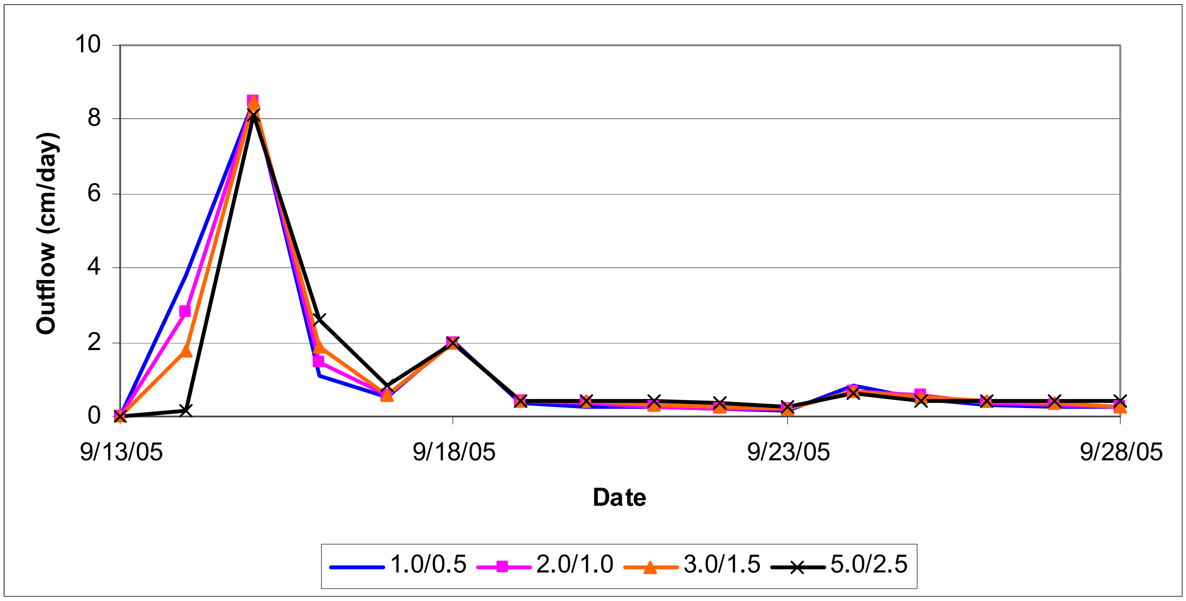

Figure 3.36 Simulated agricultural daily outflow during 2005 extreme weather for varying surface storage conditions.

2007

The observed hydrology of the restored wetland was compared to simulated agricultural hydrology during the 2007 extreme weather (9/9- 9/19) to determine hydrologic impact of the restoration. During the first storm, Tropical Storm Gabrielle (9/9 – 9/14), the restoration had a dramatic effect on the hydrology. Similar to Hurricane Alex (2004) and Hurricane Ophelia (2005), such a high peak outflow occurred due to a very high single day of rainfall. On 9/9 the Gabrielle produced 17 cm of rainfall which the agricultural simulation predicted would result the peak daily outflow of 6.9 cm. The following day (9/10) the peak daily outflow of 1.7 cm/day was observed at the restored wetland, a 71% reduction (figure 3.37). At the restored wetland, the entire outflow occurred as drainage through the water control structures but in the agricultural simulations, the outflow occurred as both subsurface drainage and surface runoff. 6.2 of the 6.9 cm of outflow occurred as surface runoff.

The modeling also predicted that the restoration had an impact on the total outflow produced by Tropical Storm Gabrielle. The agricultural simulation predicted Gabrielle would produce 10 cm of outflow while only 5.7 cm of outflow was observed at the restored wetland, a 42% reduction.

During the second, non-tropical storm (9/15 – 9/19), the agricultural simulations predicted lower flows than was observed at the restoration. Similar to in 2005, the agricultural conditions would have more intensively drained the site following Gabrielle than what was observed at the restoration, so when the second storm hit, the agricultural simulation predicted greater water-free pore space available for storing water than was found at the restoration. The agricultural simulation predicted a peak daily outflow of 0.39 cm/day while 0.76 cm/day was observed in the field. The agricultural simulation also predicted a total outflow of 1.5 cm while 1.8 cm of outflow was observed at the restored wetland.

For the entire period of extreme weather, the modeling predicted that the restoration had an impact on reducing peak outflow and total outflow. The agricultural simulations predicted a total outflow of 10 cm while only 7.5 cm was observed at the restoration, a 29% reduction.

For the entire 2007 year, the modeling predicted a total outflow of 59 cm compared to 41 cm of outflow observed at the wetland. This suggests the restoration resulted in a 31% reduction of the annual outflow.

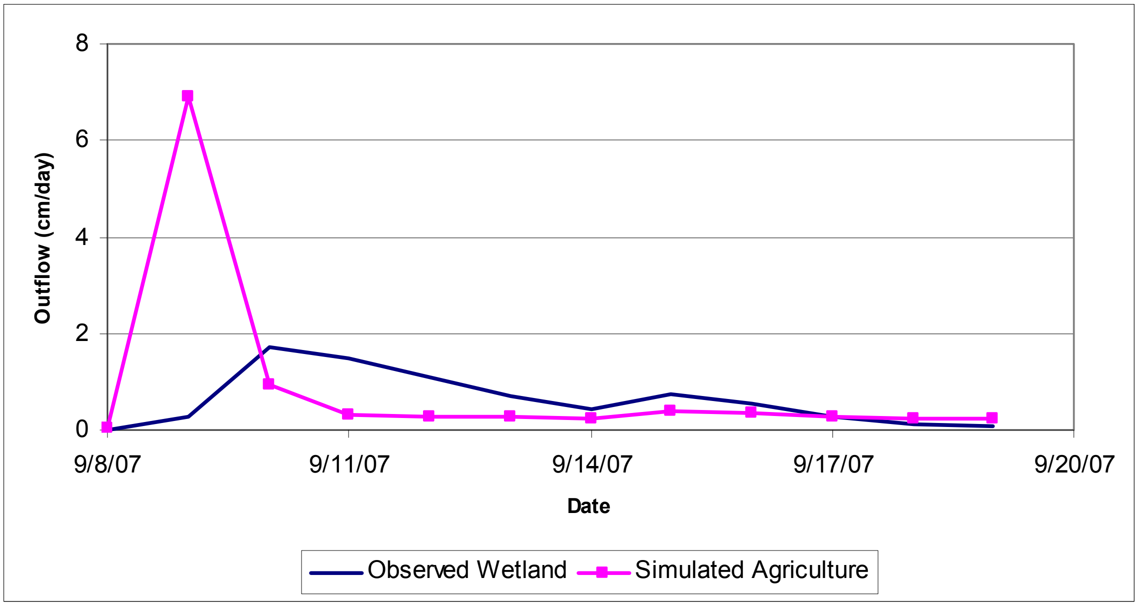

Figure 3.37 Observed and simulated agricultural outflow during 2007 extreme weather.

The agricultural model was simulated with varying maximum surface storage inputs ranging from 1.0 cm to 5.0 cm (figure 3.38). As surface storage increased the peak daily outflow produced during Tropical Storm Gabrielle decreased. The most dramatic decrease occurred when surface storage was increased to 5.0 cm which is not considered likely for the location. The was an approximately 1.0 cm difference in total outflow between the lowest maximum surface storage (1.0 cm) and the highest maximum surface storage (5.0 cm).

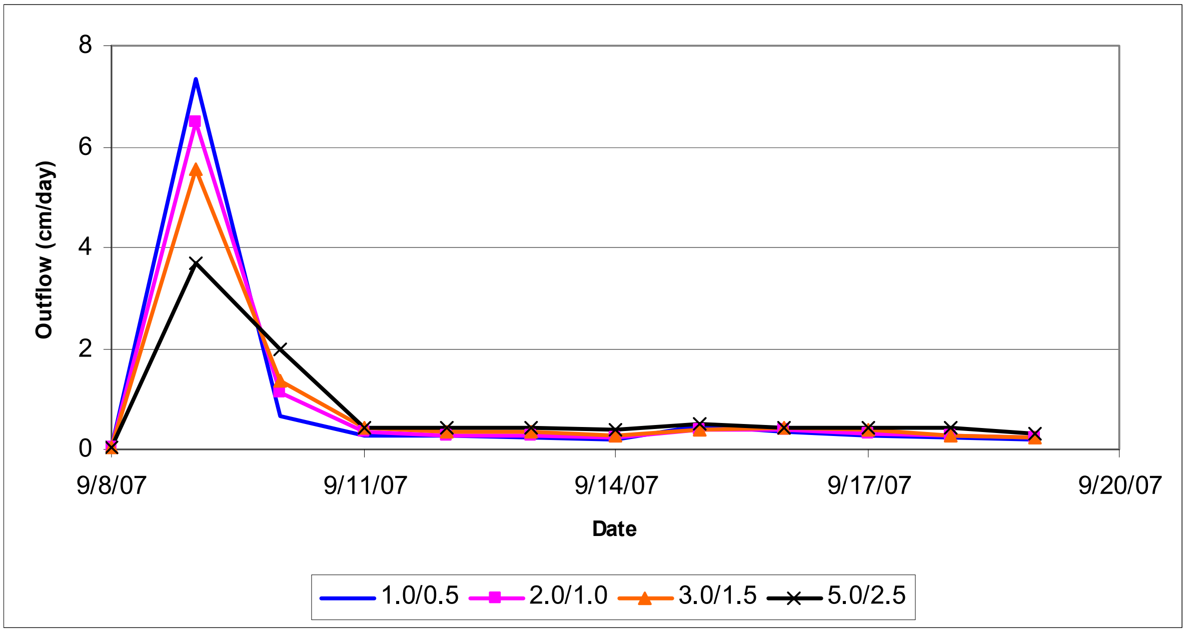

Figure 3.38 Simulated agricultural daily outflow during 2007 extreme weather for varying surface storage conditions.

Agricultural Simulation Discussion

The pre-restoration, agricultural simulations suggest that the restoration had a major impact on reducing peak flows produced by extreme and may have also helped reduce the total outflow from the site during extreme weather. For all three periods of extreme weather, the modeling suggested that the restored reduced peak daily outflow by more than 70% (table 3.12). The peak flow reduction was mostly attributed to the constructed berms around the perimeter which impeded surface runoff and the water control structures which only allow approximately 2 cm of drainage per day.

The observed and simulated peak daily outflows were higher than Shelby (2002) observed in her study of the 1999 extreme weather. During Hurricane Floyd, the largest storm that year, the agricultural subwatershed experienced a peak daily outflow of 6.2 cm and her forested subwatershed experienced a peak daily outflow of 1.2 cm. However the research watershed for Shelby's study was much larger than for this study. Her forested subwatershed was over 2900 ha and her agricultural subwatershed was over 700 ha. It is likely flow attenuation occurred prior to the outlets where flow was monitored. The North River site features six outlets which each drain approximately 6.5 ha. With a small drainage area there was much less opportunity for flow attenuation.

Table 3.12 Observed wetland and simulated agricultural peak outflow.

Period of Extreme Weather	Simulated Agricultural Peak Outflow (cm/day)	Observed Peak Outflow (cm/day)	Percent Reduction
2004	6.1	1.8	71%
2005	8.5	2	76%
2007	6.9	1.7	71%

The impact the restoration had on total outflow reduction was not as clear as with peak daily outflow; since to the modeling suggested that the wetland restoration increased outflow during the 2004 tropical weather. This was partially caused by the agricultural simulation likely under-predicting outflow during this time period. However, it is clear that the wetland did not store water as effectively in 2004 due to the antecedent soil moisture conditions. Prior to both Hurricane Alex and Tropical Storm Charley, the soil was near saturated so there was very little available water-free pore space for water storage. Prior to Hurricane Ophelia and Tropical Storm Gabrielle, soil moisture conditions were low which allowed the wetland to store water much more effectively.

The agricultural simulations all showed that the wetland restoration reduced the total annual outflow. Not surprisingly, there was very little outflow reduction in 2005. This was expected since 2005 was an extremely wet year in terms of rainfall. As rainfall increases, the restoration is expected to have less mitigation potential because the site will increasingly be saturated. When the site is saturated, storage time is limited, and excess water will likely be exported via surface outflow instead of ET. The annual outflow reduction was less than Wright (2005) found in his long term simulation of the research site. This is likely because two of the three years studies received higher than average rainfall and obviously all three of years experienced tropical weather which produces much larger amounts of outflow than with typical storm events.

Table 3.13 Observed wetland and simulated agricultural total outflow.

Period of Extreme Weather	Obs Wetland Outflow (cm)	Simulated Ag Outflow (cm)	Percent Reduction (storm period)	Percent Reduction (entire year)
2004	21	19	-8.4%	16%
2005	11	19	44%	6%
2007	7.5	10	29%	31%

Limitations of the Modeling

While DRAINMOD is almost exclusively used for simulating long term hydrology, this study used it to simulating short term hydrology. When simulating a short term event, calibration becomes very import for the accuracy of the model because prediction errors will not “average out” over time as can occur with long term simulations.

Since DRAINMOD uses a water balance approach, having the water table at the correct depth prior to the storm event being studied is very important. If the simulated water table is too deep, then more water will be stored in the soil profile resulting in a lower outflow, and if the simulated water table is too shallow, then less water will be stored resulted in greater outflow.

Also, during the initial calibration, it was difficult to accurately represent the water control structures in the drainage inputs because of the V-notch weirs that are used to control flow. DRAINMOD calculates drainage flux using the Hooghoudt equation which does not consider the shape or size of the outlet. When a weir depth is included in the model, the model treats it as a ditch that is as deep as the invert of the weir. This works fine for a typical broad-crested weir, but when flow is additionally restricted with a V-notch it is difficult to represent in the model. If the weir depth is reduced, the model will not drain the water table deep enough and if the weir depth is set correctly, the model may drain soil too quickly. This can partially be accounted for by adjusting the drainage coefficient in the DRAINMOD which sets the maximum daily allowable drainage.

Most of these difficulties should have little to no effect on long term yearly output, but when evaluating simulated hydrology on a short term daily basis, the modeler must be aware of the limitations of the model in properly evaluate the model output.

Wetland Design and Management Considerations:

In an effort to improve the flood mitigation function of the wetland restoration, the weir inverts in the water control structures could be raised up 30 cm to be set even with the wetland surface. This would limit drainage except when the water table rises to the surface. Raising the weirs should result in a lower annual outflow as well as lower outflow during large storms such as hurricanes and tropical storms.

However raising the weirs would most likely have negative consequences on the overall success of the restoration. Wetland restorations should be designed using a reference based approach. The designed structures and topography of the restoration should be implemented to mimic the water table fluctuations and drainage of a targeted wetland community. Raising the weirs may produce an extremely wet restoration if drainage cannot occur at the levels common for the targeted wetland community. Overly wet restorations are already commonplace due to the necessity to prove jurisdictional wetland hydrology over a short time period and are not successful restorations if they do not match a reference conditions (Cole and Brooks, 2000).

Furthermore, excessively wet sites may have trouble establishing vegetation. The areas within the North River restoration which experience frequent ponding do not have the vegetation density or diversity that is found in other parts of the restoration. The commonly ponded areas are sparsely covered with grasses and small trees while other areas of the restoration are densely covered with grasses, shrubs, and larger trees. Vegetation density is very important for a variety of factors including habitat, evapotranspiration, and denitrification. Areas with less vegetation will provide a lower carbon source to the soil which may make it difficult to form the anaerobic conditions vital for denitrification.

This potential strategy was tested by raising the weirs settings in the calibrated wetland model to the surface. The simulations predicted that raising the weirs would produce a much shallower water table throughout the year and would reduce outflow. For example, in 2004 the model predicted that raising the weirs would raise the average daily water table depth for the year from 39 cm to 26 cm. It also predicted that total outflow would be reduced from 37 cm to 29 cm (figure 3.39). The raised weir simulation predicted that the water table would remain at or near the surface for approximately three quarters of the year. This would likely also result in long period of ponding occurring at low spots within the wetland. Ponding cannot be predicted by DRAINMOD because it will not report water table levels above the surface. The hydrology produced by raising the weirs will also not match hydrology found in the restoration's reference wetland (see chapter 2 for reference wetland evaluation).

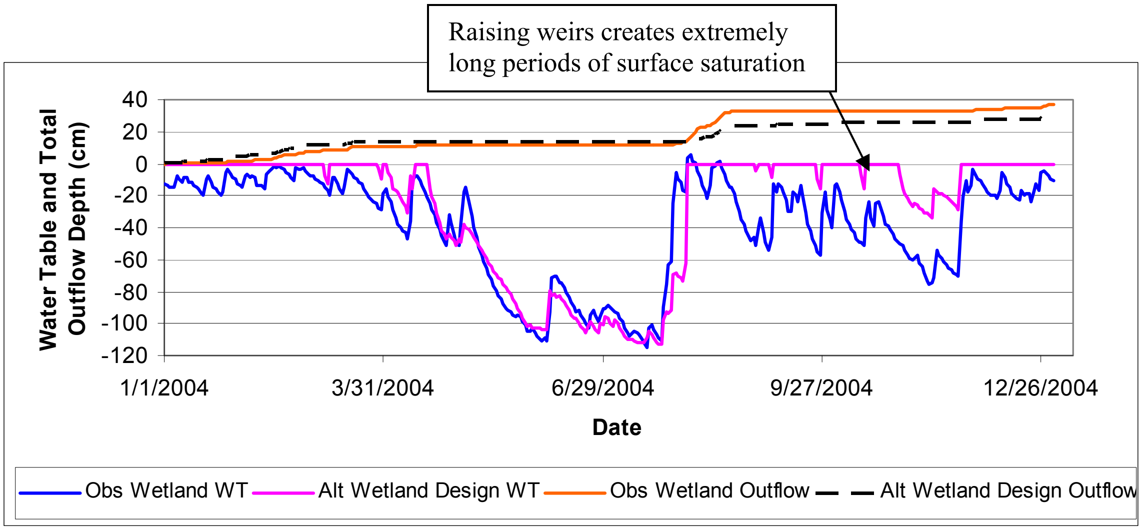

Figure 3.39 Observed wetland water table and outflow compared to simulated alternative design wetland water table and outflow for 2004.

During the 2004 period of tropical weather, the alternative design simulation predicted that raising the weirs reduced peak daily outflow by 40% compared to the actual wetland restoration (1.8 cm/day down to 1.1 cm/day) (figure 3.40). The alternative design simulation also predicted that total outflow would be reduced by 49% compared to the actual wetland restoration (21 cm down to 11 cm). The modeling predicted raising the weirs would likely produce extended periods with a very shallow water table and possibly ponding which may resemble a shallow lake or swamp instead of the desired hardwood wet forest. Creating an overly wet site would be an undesired consequence of raising weir levels resulting in a poor restoration effort. This should not be considered a good overall management practice for enhancing flood control.

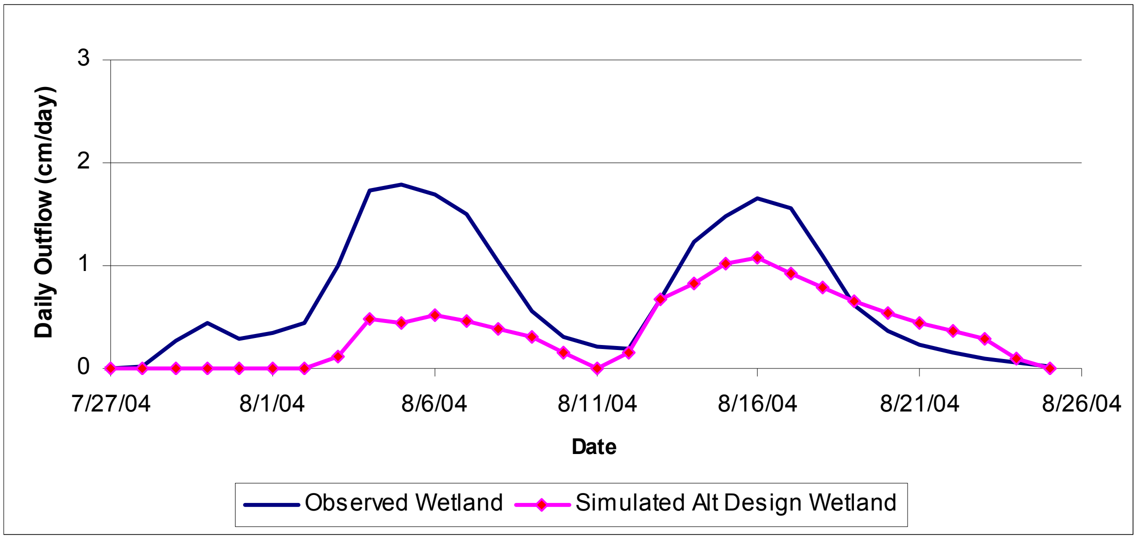

Figure 3.40 Observed and alternative 'raised weir' simulated daily outflow during for 2004 extreme weather.

Conclusion

A prior-converted agricultural site in eastern North Carolina was restored to its original non-riverine wet hardwood forest state in 2003. The location of the restoration was strategic due to its close proximity to the North River, a sensitive estuarine system where water quality degradation due to high levels of fecal bacteria and nutrients has led to the prohibition of shellfishing (an important local industry) in certain parts of the estuary. Water quality impairments are more severe following periods of heavy rainfall, especially hurricanes and tropical storms due to high amounts of runoff and drainage from mainly agricultural areas. This study was performed to determine if the restoration of prior-converted agricultural lands could provide mitigation of the large outflow events associated with extreme weather which are known to impair water quality in the North River.

Three periods of extreme tropical weather were evaluated from 2004 – 2007. In 2004, a 34 day period of tropical weather including, Hurricane Alex and Tropical Storm Charley hit the site producing 41 cm of rainfall and 21 cm of outflow from the wetland. In 2005, a 15 day period including Hurricane Ophelia produced 33 cm of rainfall and only 11 cm of outflow, and in 2007, an 11 day period including Tropical Storm Gabrielle produced 21 cm of rainfall and 7.5 cm of outflow.

The percentage of rainfall which was retained from leaving the site as outflow was used to quantify the amount of temporary storage the restored wetland provided. During the storm periods of 2005 and 2007 the restored wetland performed very similar, retaining 67% and 64% of the rainfall respectively. However during storm period of 2004, the restored wetland retained a much lower percentage of rainfall, only 49%. The restored wetland performed less efficiently in 2004, due to differences in antecedent soil moisture condition and total rainfall. During the 2004 storm period, initial non-tropical storms raised the water table near the surface so when Hurricane Alex struck, there was very little water-free pore space available to provide storage. In 2005 and 2007, the restored wetland had a deep water table when Hurricane Ophelia and Tropical Storm Gabrielle arrived. Also in 2004, the restored wetland experienced a second named storm, Tropical Storm Charley which struck approximately a week after Hurricane Alex. Again, the restored wetland experienced a large tropical storm with a shallow initial water table. Wetlands have finite storage ability, and when the surface and soil profile fills, its flood mitigation properties are diminished.

Modeling was performed to predict the hydrologic impact the restoration had on the prior-converted agricultural lands during times of extreme tropical weather. The restoration's impact on peak outflow was evaluated by comparing the simulated agricultural outflow with the observed outflow. The modeling predicted that the restoration reduced the peak daily outflow during each period of tropical weather by greater than 70%. Most of the peak outflow reduction was a result of surface runoff being limited due to the implementation of perimeter berms and water control structures. The reduction was very consistent and did not appear to be dependent on antecedent soil moisture conditions.

The impact the restoration had on total outflow during tropical weather was not as clear as with peak outflow. The restoration's impact on total outflow was evaluated by comparing the simulated agricultural outflow with the observed wetland outflow. The modeling predicted that the wetland restoration surprisingly slightly increased the total outflow produced by the 2004 tropical weather but did provide a substantial reduction in total during the 2005 and 2007 tropical weather. The predicted increase in total outflow during 2004 tropical weather was most likely attributed to some calibration error and the poor retention performance that was observed due to the high soil moisture conditions prior to Hurricane Alex and Tropical Storm Charley. The modeling did however predict that the restoration reduced total outflow by 44% during 2005 tropical weather and by 29% during 2007 tropical weather.

The modeling was also used to predict what impact the restoration had on total annual outflow. The modeling predicted that the restoration reduced the total annual outflow for all three years of evaluations. The model found the restoration had less effect in extremely wet years because the soil was constantly saturated which provided very little storage for excess rain water.

The modeling confirms that restoring prior-converted agricultural lands to wetlands does provide mitigation of peak flows and total outflow during periods of hurricanes and tropical storms particularly when the storms follow periods of deep water table conditions. Peak daily outflow was found to be reduced by greater than 70% and total outflow was found to be reduced when antecedent soil moisture conditions were low, which is a common during peak hurricane season (August and September) in North Carolina. Lower antecedent soil moisture conditions resulted in the restoration storing more water and mitigating heavy flows more efficiently during periods of tropical weather.

Earlier modeling efforts of the restoration (Wright, 2005) simulated long term hydrology for both the restoration and its pre-restoration agricultural conditions. The results of the modeling found that over 50 years, the restoration reduced total outflow by 30 – 40% which was higher than was found in this study during the short term tropical weather. This helps corroborate the hypothesis that wetlands are more efficient at mitigating flow during less intense rain events or during drier times. Restored wetlands will provide a greater amount of storage than managed agricultural lands. However once all storage is filled which commonly happens during tropical weather, the wetland will then export water at approximately the same rate as rainfall is inputted unless outflow is limited due to designed structures such as water control structures or berms.

The reduction of peak outflow may be more important for estuary water quality than reducing total outflow since high peak flows are often correlated with water quality degradation. Strategic restoration could reduce flooding in human impacted areas as well as reduce the export of nutrients, bacteria, sediment, and fresh water into the sensitive estuarine waters found in coastal North Carolina. This does not only have environmental implications but also economic implications by protecting infrastructure and the fishing/shellfishing industry.

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4. CONCLUSION

A prior-converted wetland in the North Carolina lower coastal plain was restored in an attempt to reestablish a non-riverine hardwood wet forest Community. Goals of the restoration were to improve water quality and habitat to the area as well as test and evaluate multiple restoration techniques.

Topography was restored using three surface techniques: plugging field ditches without altering the surface (PLUG), plugging the field ditches and contouring the surface (CONT), and plugging the field ditches and removing field crown (CR). With enhanced surface manipulation came increased cost. The treatments were replicated three times in a randomized block design. It was hypothesized that CR would produce the wettest site followed by CONT and then PLUG. The major goal of this project was to determine the effect that surface topography had on wetland hydrology in low elevation, coastal areas.

An earlier study (Wright, 2005) evaluated the hydrology of the restoration treatments and a selected reference wetland for 2003-2004. Evaluating the treatment effect proved difficult due to inconsistent hydrology within the third replication block (block 3 was located in a different landscape position and at a higher elevation than blocks 1 and 2). An evaluation of only blocks 1 and 2 matched the original hypothesis. Wright recommended continuing monitoring, installing additional water table wells, and performing a survey of each treatment.

This study implemented Wrights recommendations and evaluated the hydrology of the treatments and reference wetland for 2006-2008. The surface treatments continued to show no significant treatment effect on hydrology when all three blocks were evaluated. However, the survey found that treatments were not consistently replicated with respect to topography. The monitored portion of block 3 PLUG was much lower in elevation than the rest of block 3 while the monitored portion of block 3 CR was much higher than the rest of block 3. PLUG was expected to have the highest elevations due to the residual field crown while CR was expected to have the lowest elevations due to the crown removal. This resulted in PLUG producing a wetter hydrology than designed for and CR producing a drier hydrology than designed for. The survey found the monitored portion block 3 to be a poor replication of the treatment design and not representative of the intended hydrology.

Based on the survey, two additional evaluations were performed to determine the impact of these observations. The treatments were re-evaluated using only blocks 1 and 2, and using all three blocks but data for block 3 PLUG and CR were switched based on the assumption the assumption that PLUG produced desired CR hydrology and vice versa. Both evaluations found CR produced the wettest hydrology followed by CONT and then PLUG. These results matched the original hypothesis on the effects of each treatment.

While no treatment matched reference hydrology perfectly, all three easily met minimum wetland hydrology criteria and were similar to the reference conditions. When considering the results of the two alternate evaluations (which are believed to be more representative of the actual treatment effect) the CR appeared to produce a hydrology wetter than the reference (3 of 4 hydrologic criteria were significantly wetter) while PLUG may have produced drier conditions than the reference (3 of 4 hydrologic criteria were drier). CONT appeared to match reference hydrology the best as there was no significant difference ($\alpha = 0.05$) between CONT and the reference for the most descriptive hydrologic metric used, SEW_{30}. CONT was also the most consistently replicated treatment in terms of hydrology. All three treatments did however experience significantly more surface inundation during the study than the reference. The reference rarely ever experienced ponded conditions but it occurred frequently in certain parts of the restoration (usually in lower areas). This was likely due to near-surface soil compaction and organic subsidence which occurred in the restoration due to decades of farming practices.

The evaluation of surface outflow found that CONT produced significantly more outflow than PLUG or CR. Similar results were found by Wright (2005). PLUG however was hypothesized to produce the greatest outflow due improved surface drainage resulting from the residual crown. It is believed that CONT produced the most outflow because the contouring process may have created conveyance pathways which drained the surface instead of creating random surface pockets that store water. Because the residual crown remained in the CONT treatment, the contouring implementation may have also created an even higher lateral gradient towards the drainage ditches than was found in PLUG which also may have led to increased surface drainage. Both of these possible consequences of the contouring process were unintended and should be avoidable on future projections with careful construction oversight.

A second study, evaluated the hydrology of the restored wetland during periods of extreme tropical weather. Flood mitigation is a well documented function of wetlands, and this study attempted to quantify the mitigation effect through monitoring and modeling. Three periods of tropical weather were evaluated from 2004 – 2007: Hurricane Alex and Tropical Storm Charley in 2004 (41 cm of rainfall), Hurricane Ophelia in 2005 (33 cm of rainfall), and Tropical Storm Gabrielle in 2007 (21 cm of rainfall).

During the storm periods of 2005 and 2007 the restored wetland performed very similarly, retaining 67% and 64% of the rainfall respectively. However during the storm period of 2004, the restored wetland retained a much lower percentage of rainfall, only 49%. The restored wetland performed less efficiently in 2004, due to differences in antecedent soil moisture condition and total rainfall. During the 2004 period, soil moisture conditions were high prior to both Hurricane Alex and Tropical Storm Charley which limited the wetlands ability to store water. Prior to Hurricane Ophelia in 2005 and Tropical Storm Gabrielle in 2007, soil moisture conditions were low which provided large amounts of water-free pore space in the soil for storing excess water.

DRAINMOD (Skaggs et al., 1999) was used to simulate the hydrology for the site’s pre-restoration agricultural conditions. The simulation predicted that the restoration reduced the peak daily outflow during all three storm period by at least 70% compared to the previous agricultural conditions. The majority of the reduction was due to the restoration limiting surface runoff due to the implementation of berms and water control structures. Total outflow reduction was found to be dependent on soil moisture conditions than for peak daily outflow. In 2005 and 2007 soil moisture conditions were low prior to the tropical storms; the simulation predicted the restoration reduced total outflow by 44% (2005) and 29% (2007). In 2004 however, soil moisture conditions were high prior to Hurricane Alex and Tropical Storm Charley, and the simulation predicted the restoration would not reduce total outflow. Wetlands have finite storage ability, and when the surface and soil profile fills, its flood mitigation properties are diminished. The simulations also predicted that restoration reduced annual outflow for 2004, 2005, and 2007 by 6-31% depending on the year. Earlier simulations at the site using 50 years of historic climate data (Wright, 2005) predicted the restoration would eventually reduce annual outflow by 30-40% on average once the wetland fully matured.

The modeling found that a restoration could be designed to further improve water storage and flood mitigation. However, if a restoration is designed to hold too much water in an attempt to improve storage, the project may result in a pond instead of a wetland. This should be avoided since restorations should be designed to reflect reference conditions. A successful restoration should be designed to reflect the topography, hydrology, and vegetation of its targeted wetland community. Failure to match reference conditions could be considered a restoration failure regardless if the site meets minimum jurisdictional requirements. To help ensure restoration success, a high quality survey of the project site and selected reference should be used as a design tool since small differences in elevation can have a significant effect on hydrology in low gradient environments. While topographic heterogeneity is ideal, the elevation range of a restoration should reflect that of the reference wetland. This study showed that in low elevation, coastal areas the extensive implementation of costly surface manipulation may not be necessary to produce minimum wetland hydrology.

However, the selective use surface manipulation may be required to produce desired wetland hydrology. Isolated high areas may need to be lowered to produce the desired hydrology while low lying areas can likely be left alone or partially filled to balance cut/fill.

While the analysis found that all three treatments produced a hydrology similar to reference conditions, CONT was found to produce hydrologic conditions closest to what was observed in the reference wetland. However careful construction oversight is required during the roughening process to ensure conveyance pathways are not accidently cut into the wetland surface. In addition to the hydrology analysis presented, CONT is recommended because surface roughening is a fairly inexpensive process which provides significant additional benefit to a restoration. Roughening creates “micro-pockets” across the surface which should provide hydrologic diversity. This is important for nitrogen cycling which requires both anaerobic and aerobic zones, and should ensure the development of a diverse vegetation population. Wetlands with diverse vegetation are more adaptive and resistant to future hydrologic changes which could occur due to watershed disturbances or climate change.

Differences in vegetation throughout the restoration were very noticeable but it was never evaluated. It was observed that drier areas tended to have better tree development while wetter areas had difficulties establishing vegetation beyond the herbaceous wetland vegetation that developed through the seed bank. It may be beneficial on future restoration projects to initially set weir levels in the water control structures lower than ultimately desired during the first growing season to produce a hydrology on the threshold of wetland and upland. This should reduce the likelihood surface ponding and frequent soil saturation which will allow wetland tree species to establish quicker while maintaining enough wetness to limit upland vegetation growth. Following the first growing season, the weir levels should be adjusted to produce to final desire wetland hydrology. Tree establishment was especially important for this project since the targeted wetland community was a wet hardwood forest.

The relationship between hydrology and vegetation could be a very useful future research topic at the site. Vegetation surveys could be compared with hydrologic data from each monitoring well to determine how various hydrology metrics affect vegetation success. This could help determine hydrologic ranges necessary for the success of targeted wetland plant species which could be used to improve future wetland design as well as help establish future hydrologic and vegetative success criteria.

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APPENDICES

Chapter 2 Appendices

A. Water Table Fluctuations

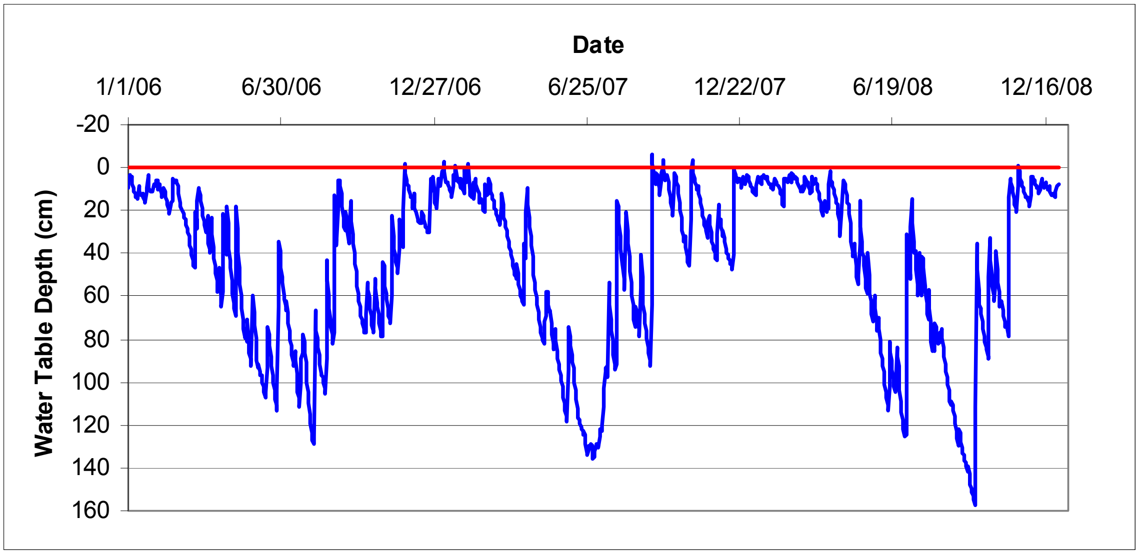

Figure A.1 NR01 water table fluctuations for 2006-2008 (Block 1, CONT).

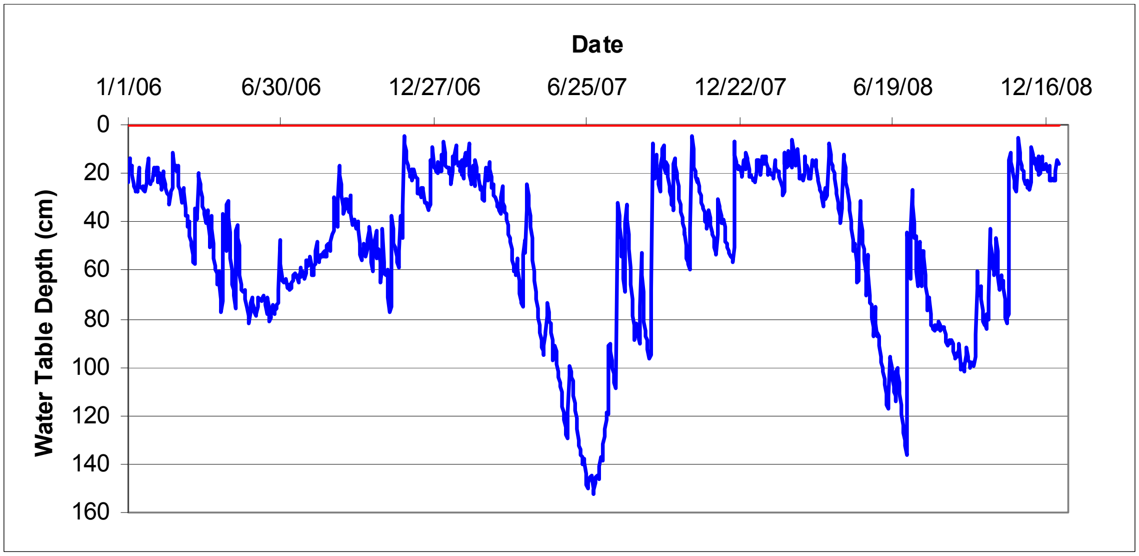

Figure A.2 NR02 water table fluctuations for 2006-2008 (Block 1, CONT).

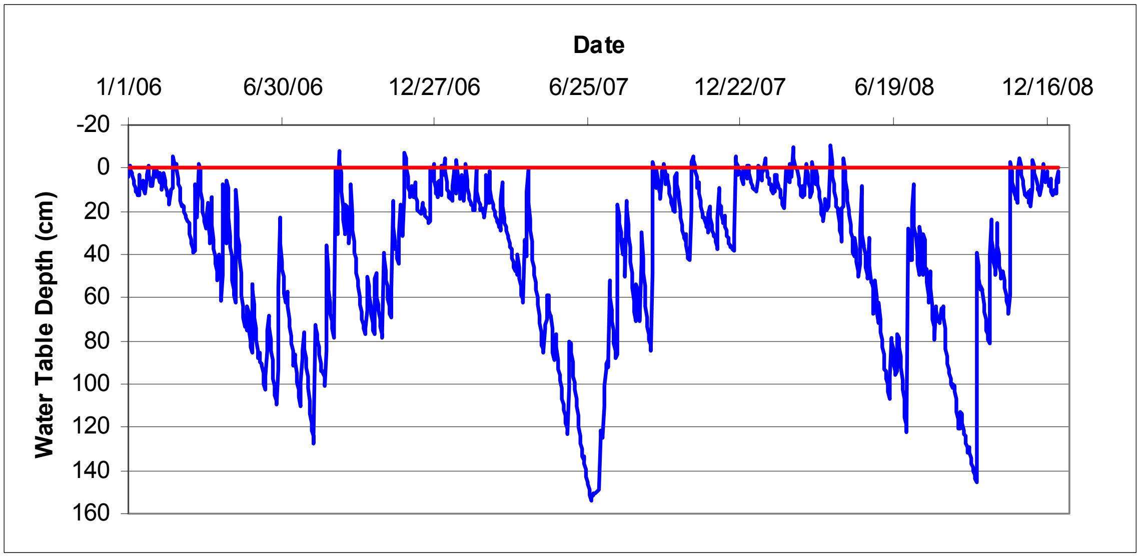

Figure A.3 NR03 water table fluctuations for 2006-2008 (Block 1, PLUG).

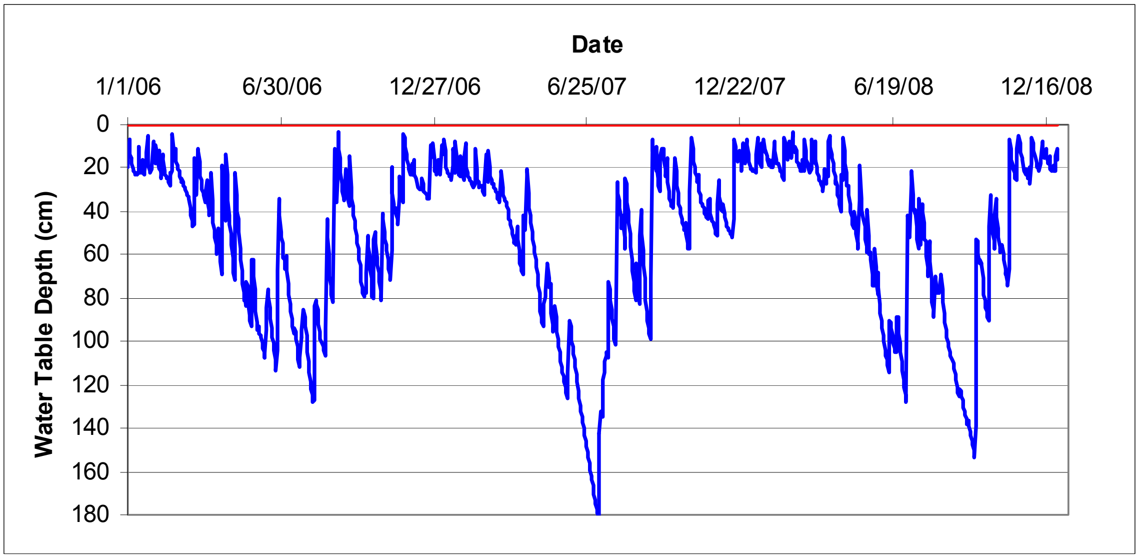

Figure A.4 NR04 water table fluctuations for 2006-2008 (Block 1, PLUG).

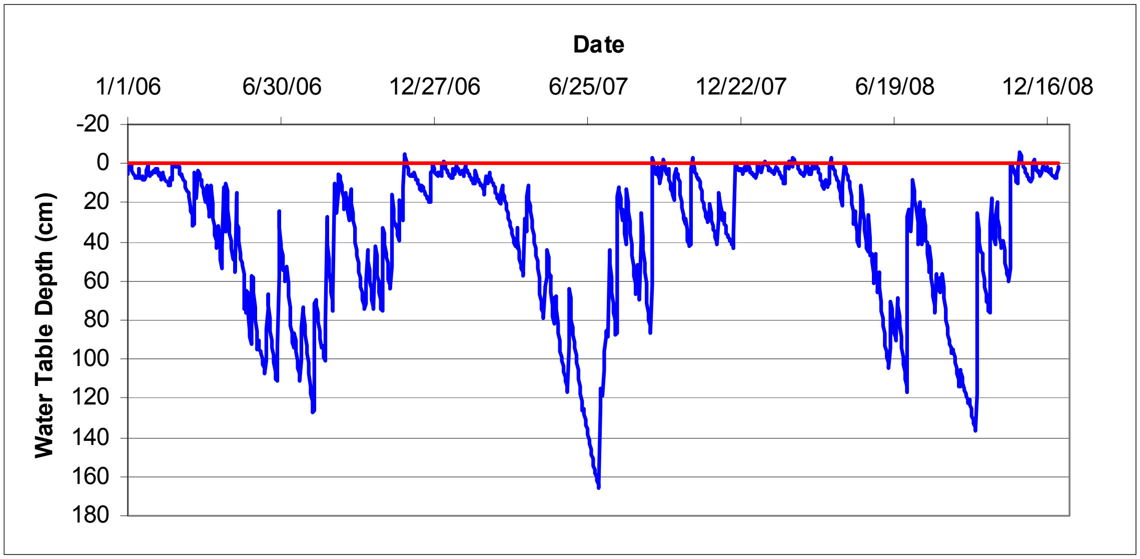

Figure A.5 NR05 water table fluctuations for 2006-2008 (Block 1, CR).

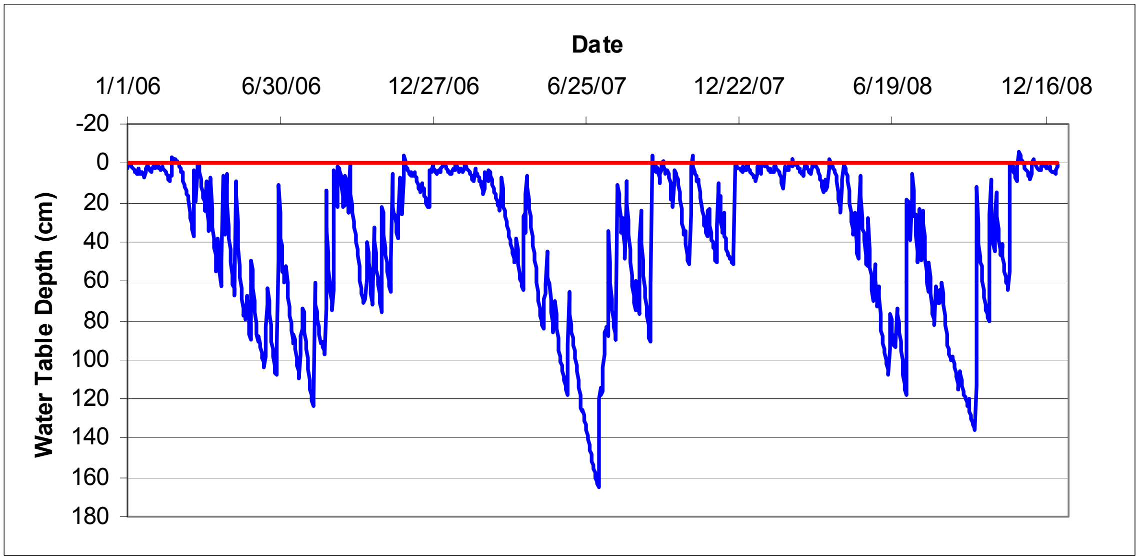

Figure A.6 NR06 water table fluctuations for 2006-2008 (Block 1, CR).

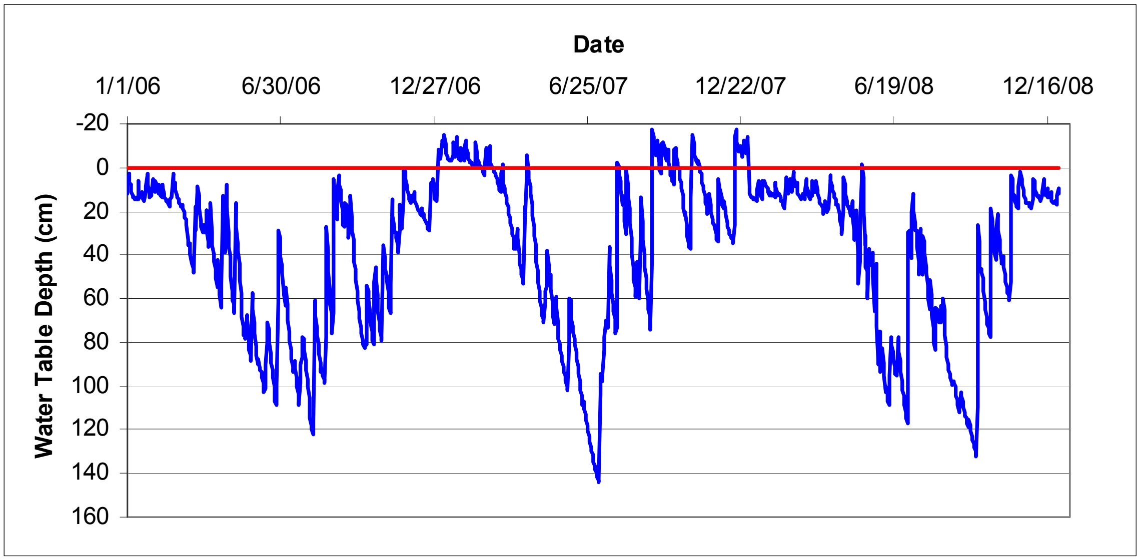

Figure A.7 NR07 water table fluctuations for 2006-2008 (Block 2, CONT).

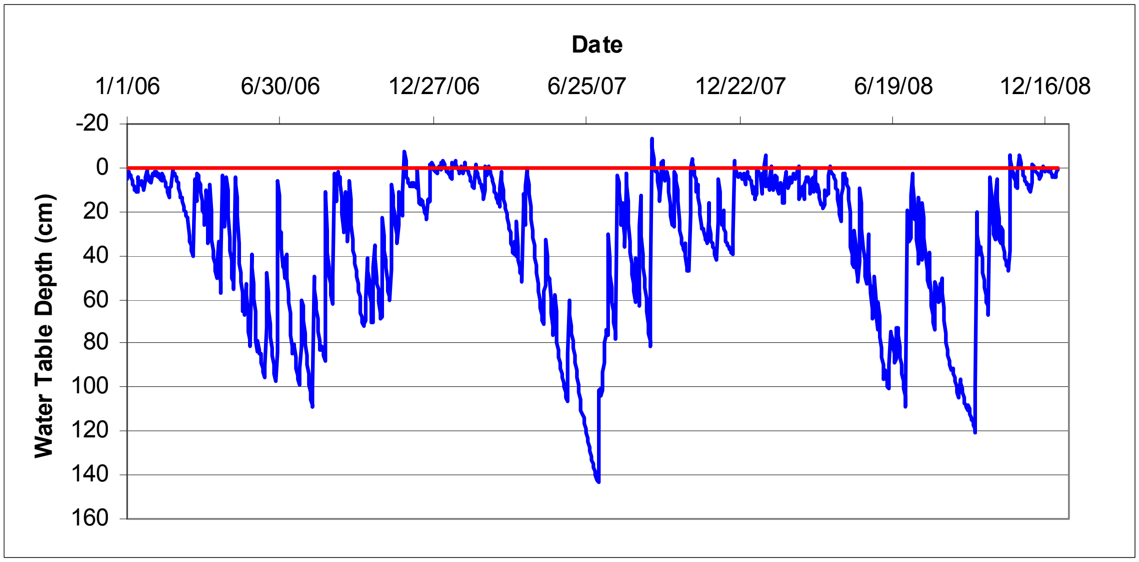

Figure A.8 NR08 water table fluctuations for 2006-2008 (Block 2, CONT).

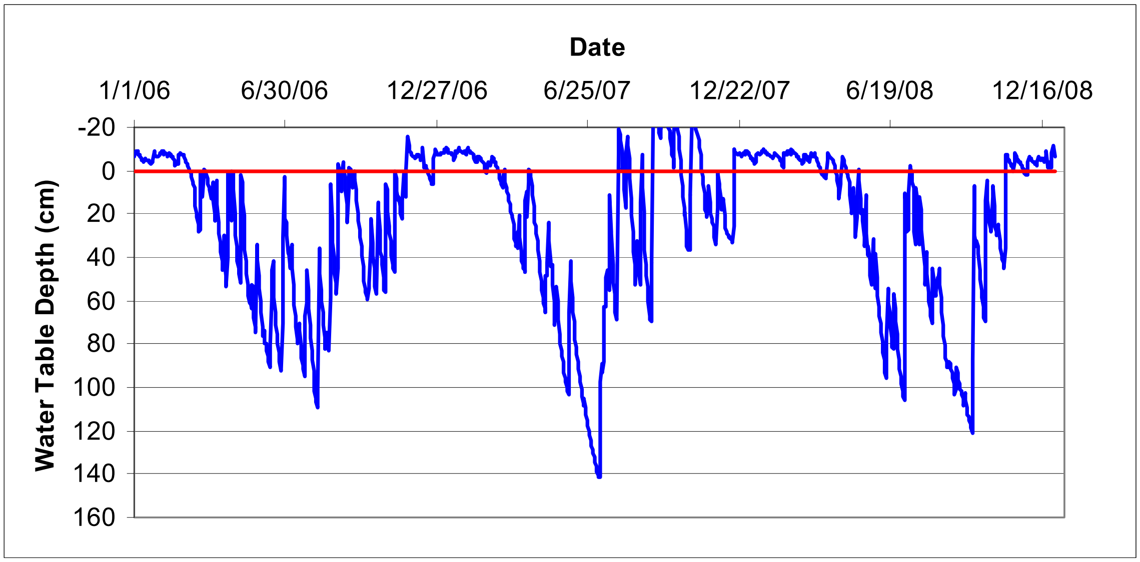

Figure A.9 NR09 water table fluctuations for 2006-2008 (Block 2, CR).

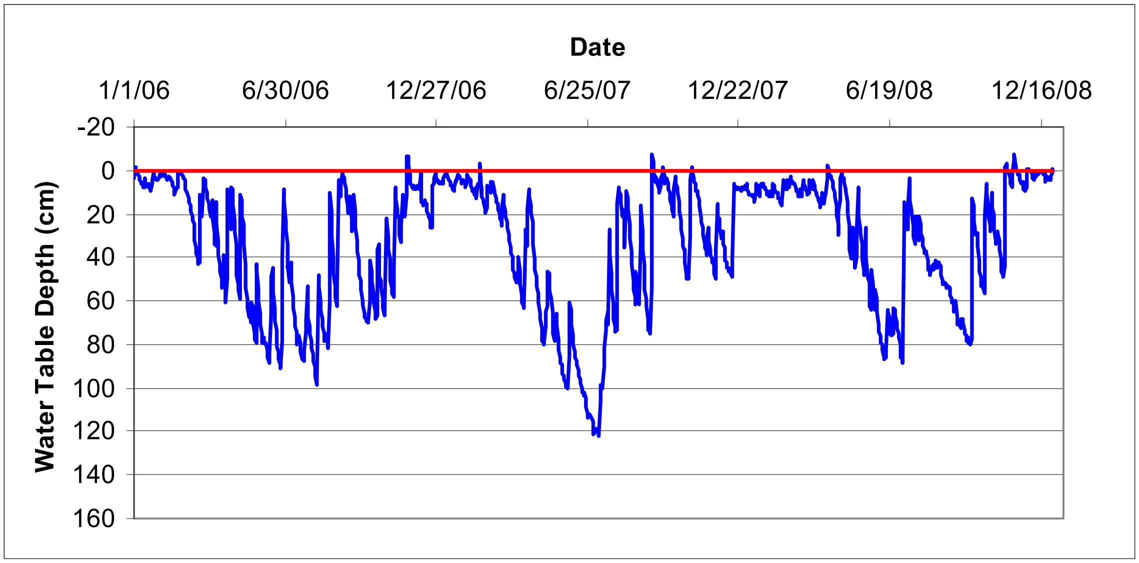

Figure A.10 NR10 water table fluctuations for 2006-2008 (Block 2, CR).

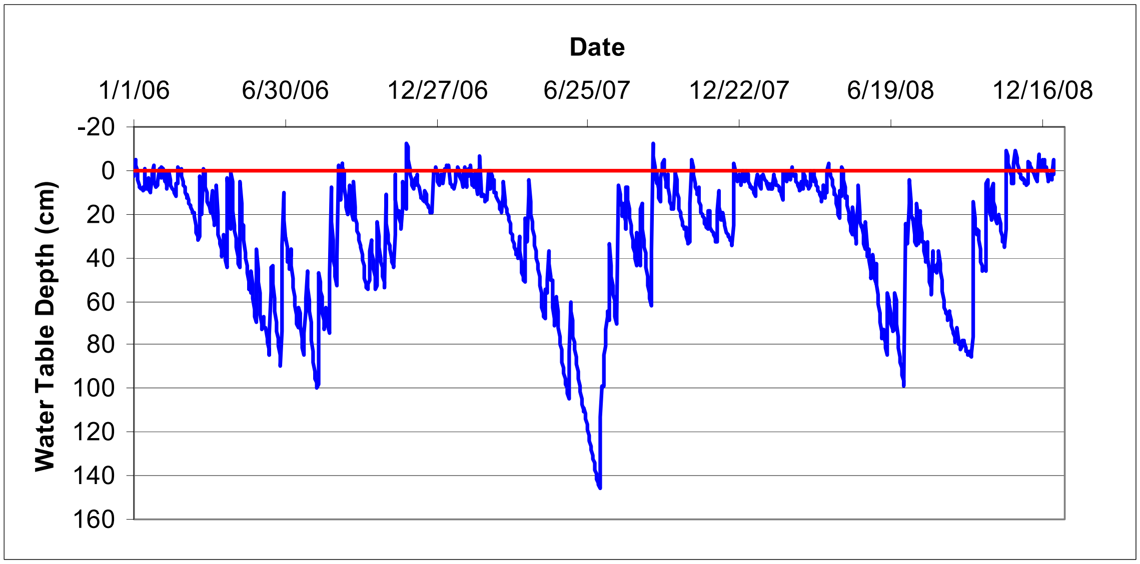

Figure A.11 NR11 water table fluctuations for 2006-2008 (Block 2, PLUG).

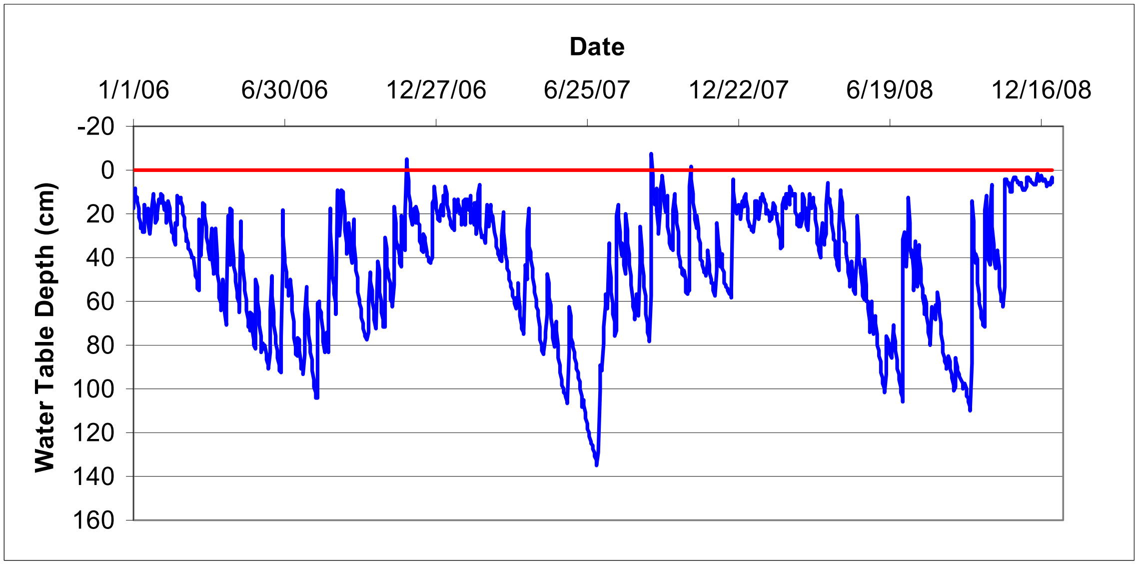

Figure A.12 NR12 Water table fluctuations for 2006-2008 (Block 2, PLUG).

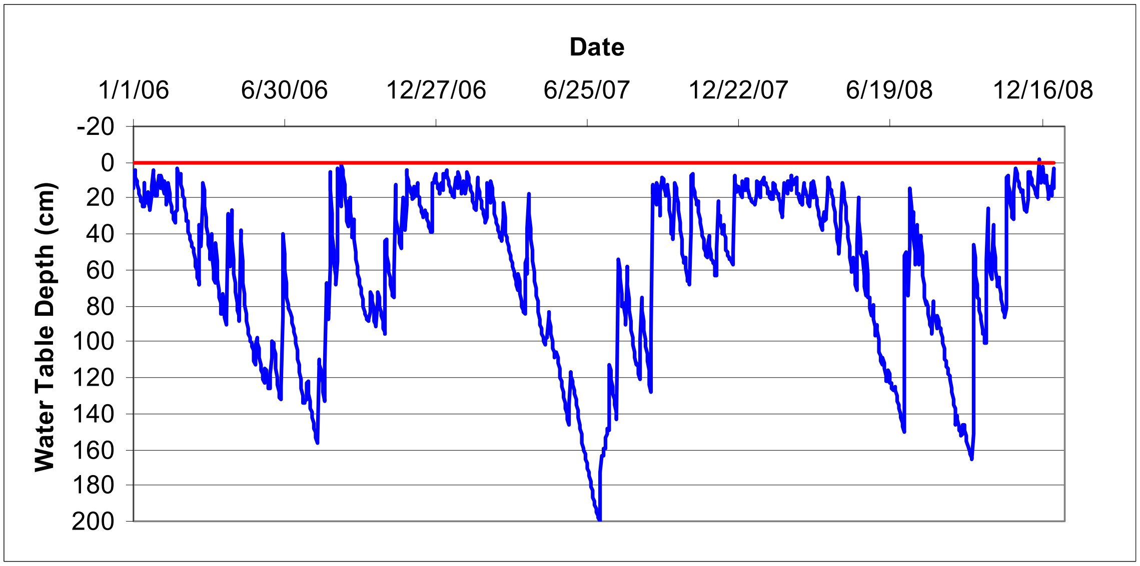

Figure A.13 NR13 water table fluctuations for 2006-2008 (Block 3, PLUG).

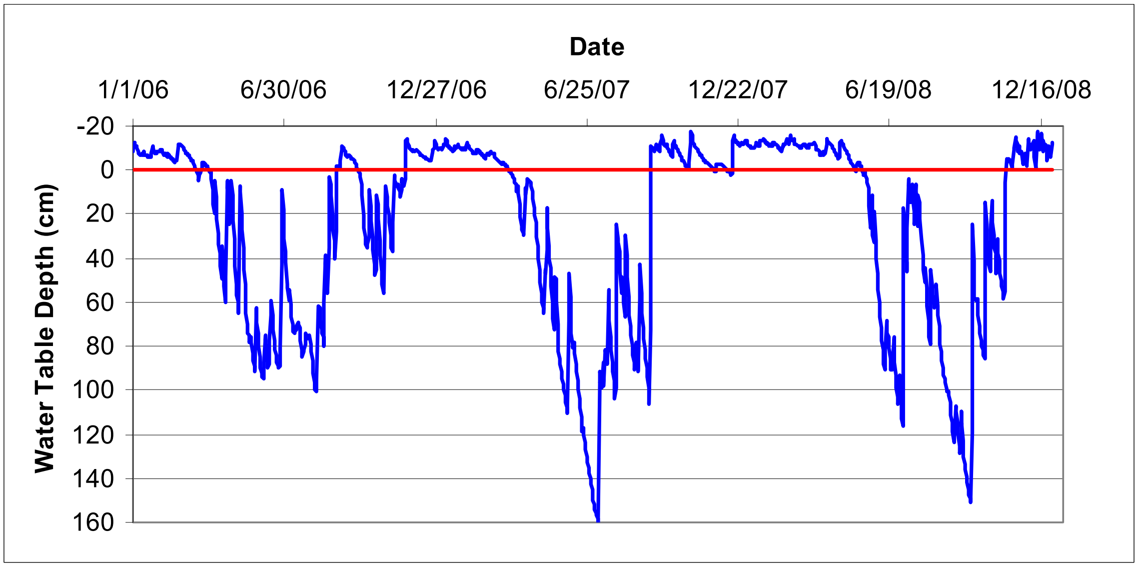

Figure A.14 NR14 water table fluctuations for 2006-2008 (Block 3, PLUG).

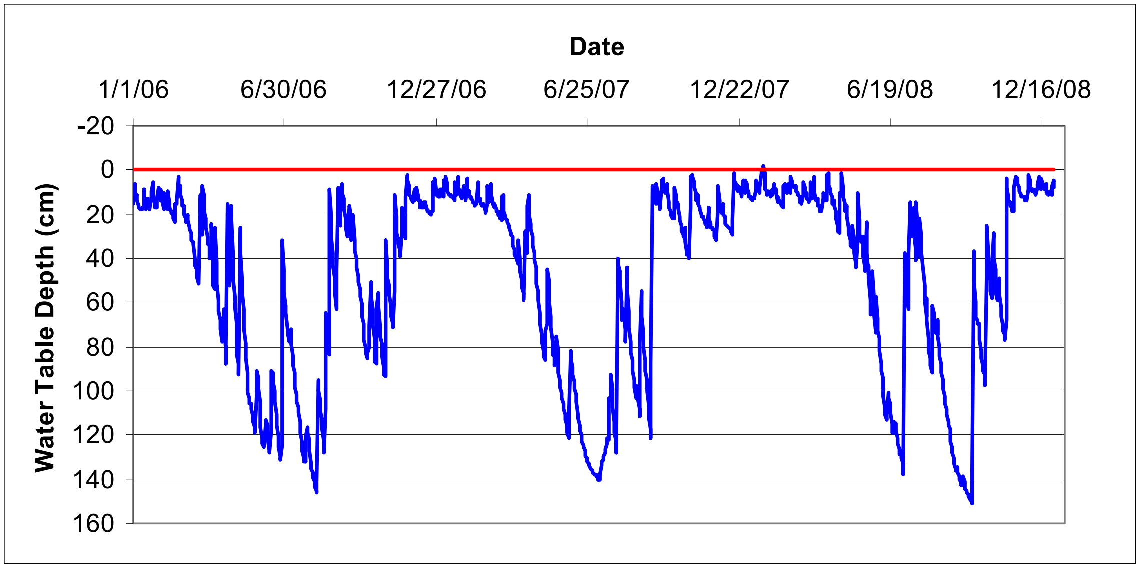

Figure A.15 NR15 water table fluctuations for 2006-2008 (Block 3, CONT).

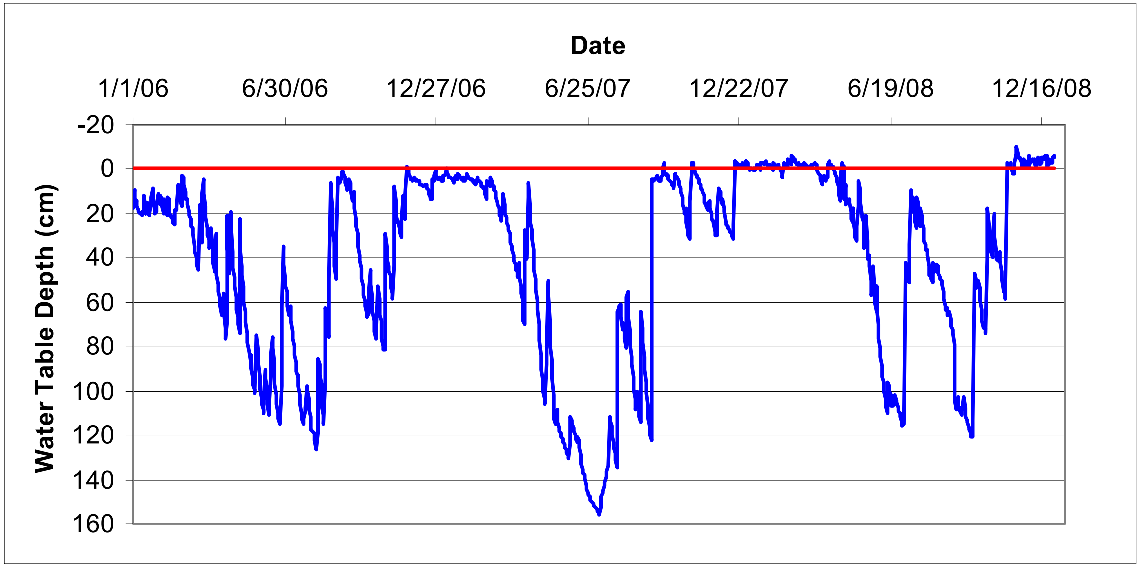

Figure A.16 NR16 water table fluctuations for 2006-2008 (Block 3, CONT).

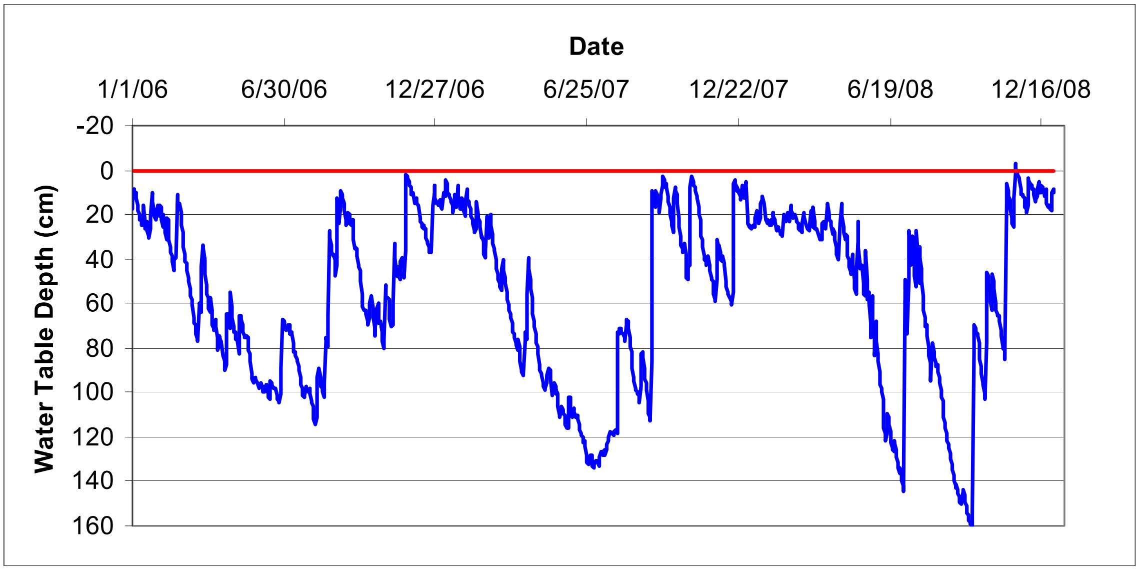

Figure A.17 NR17 water table fluctuations for 2006-2008 (Block 3, CR).

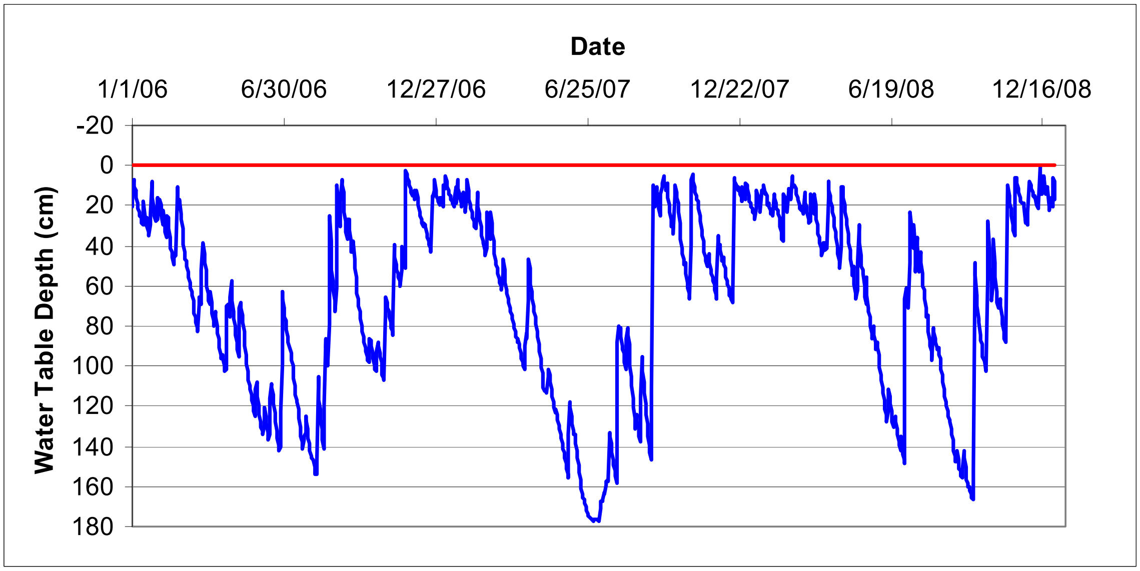

Figure A.18 NR18 water table fluctuations for 2006-2008 (Block 3, CR).

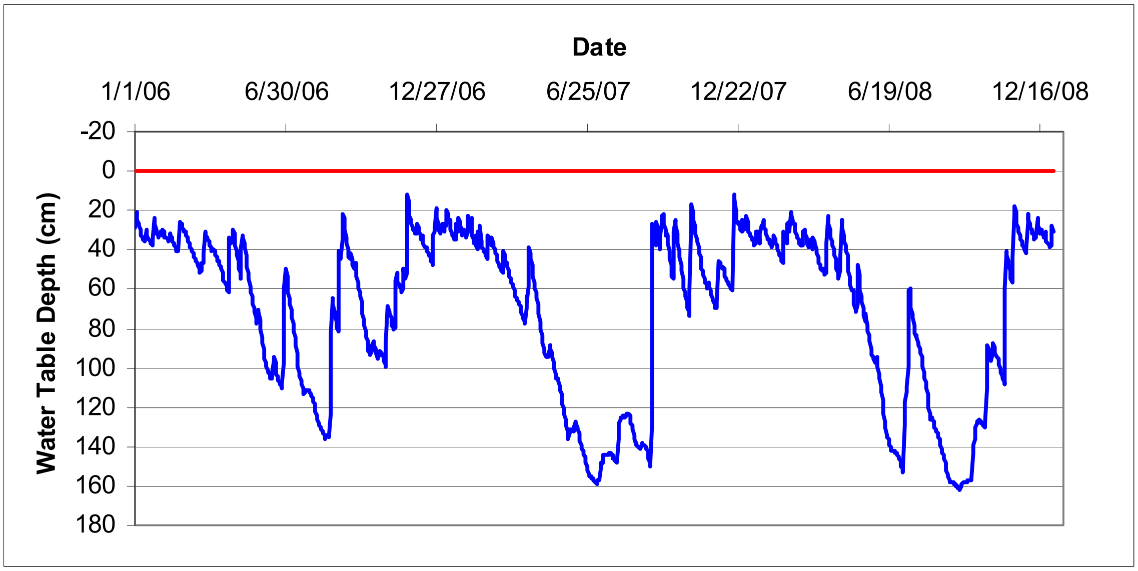

Figure A.19 REF01 water table fluctuations for 2006-2008 (Ref-edge).

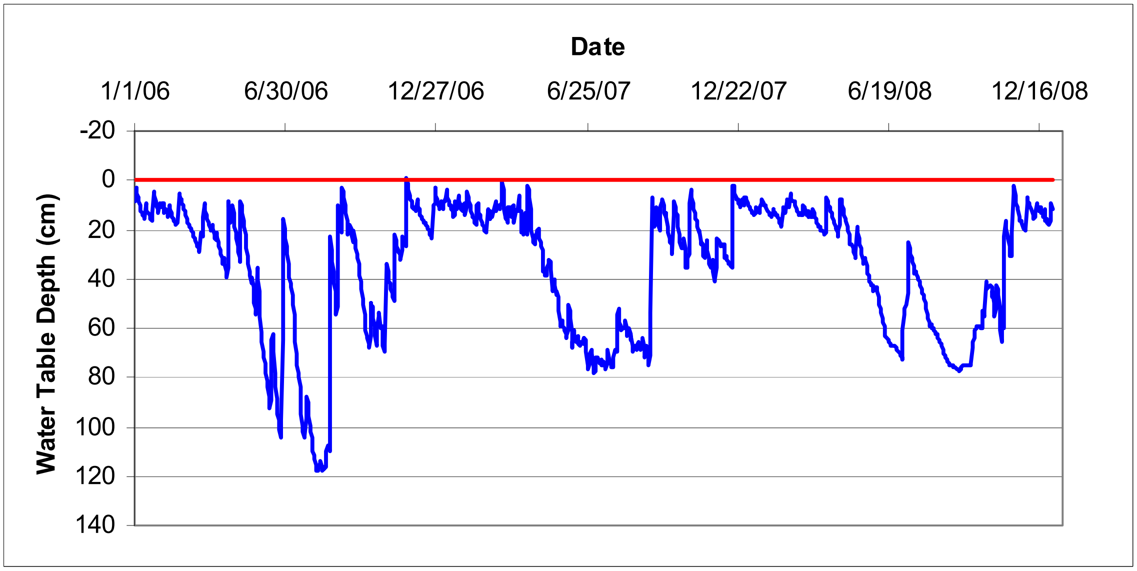

Figure A.20 REF02 water table fluctuations for 2006-2008 (Ref-center).

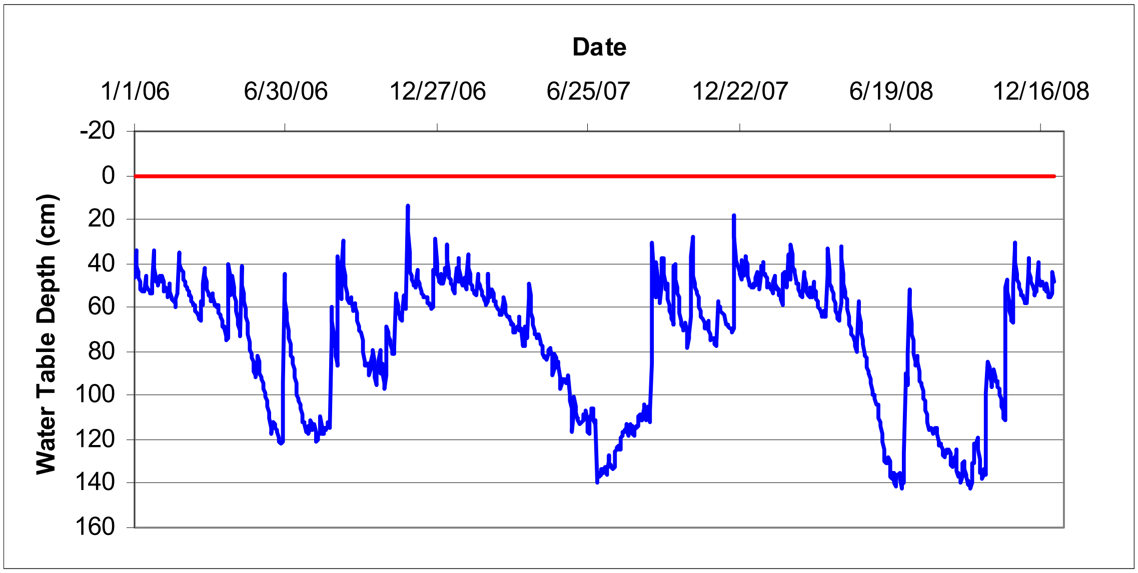

Figure A.21 REF03 water table fluctuations for 2006-2008 (Ref-edge).

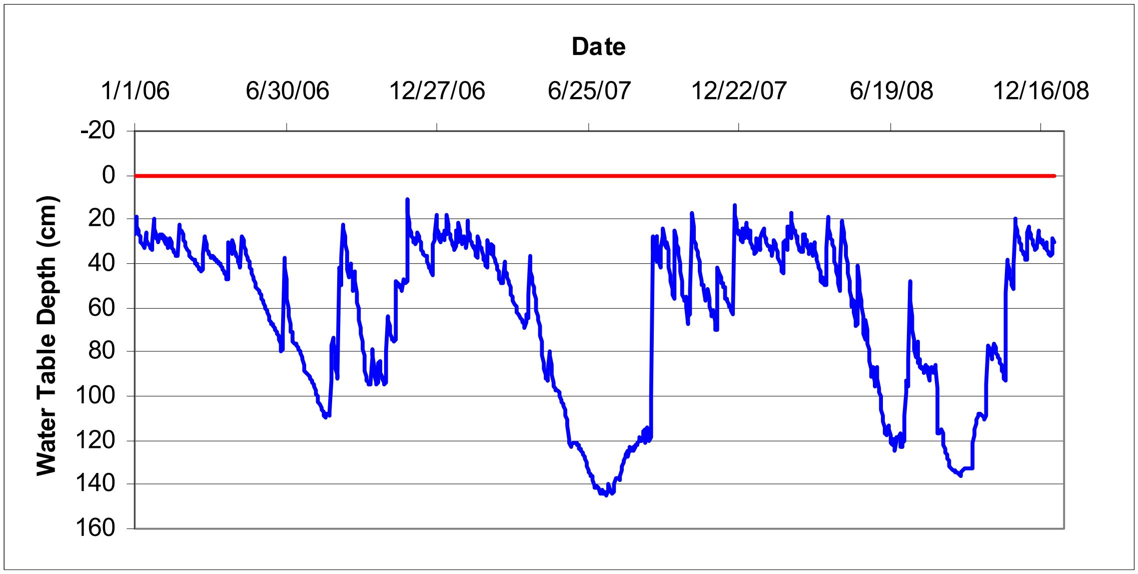

Figure A.22 Ref04 water table fluctuations for 2006-2008 (Ref-edge).

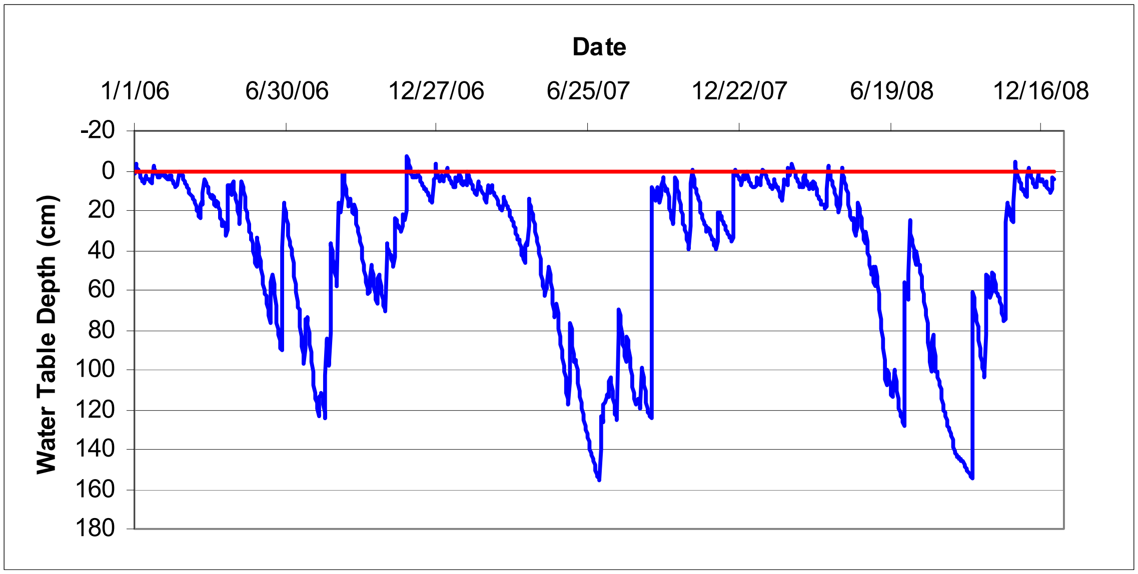

Figure A.23 REF05 water table fluctuations for 2006-2008 (Ref-center).

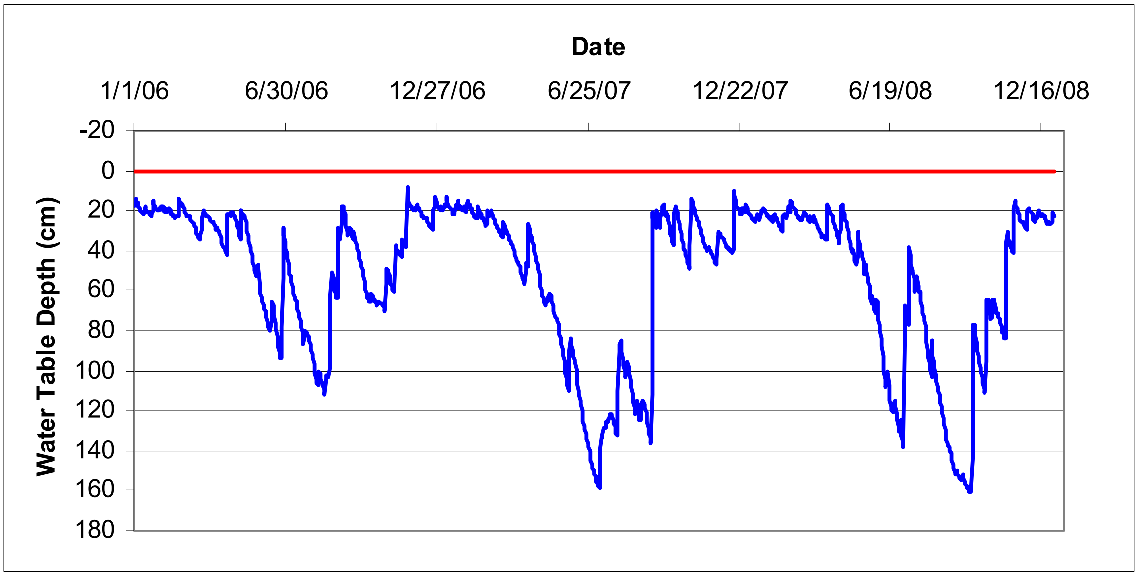

Figure A.24 REF06 water table fluctuations for 2006-2008 (Ref-edge).

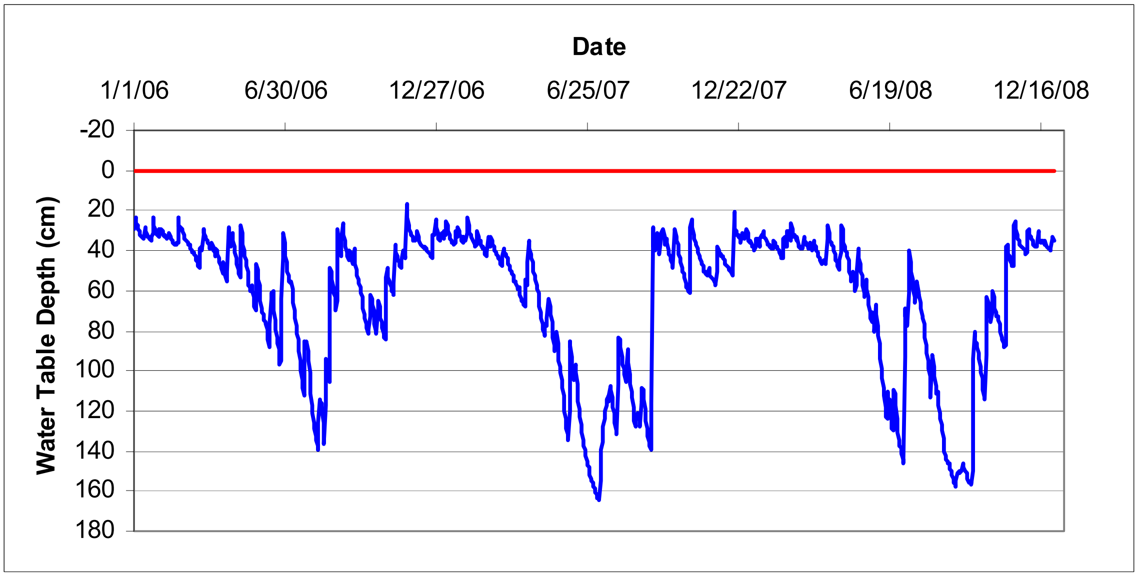

Figure A.25 REF07 water table fluctuations for 2006-2008 (Ref-edge).

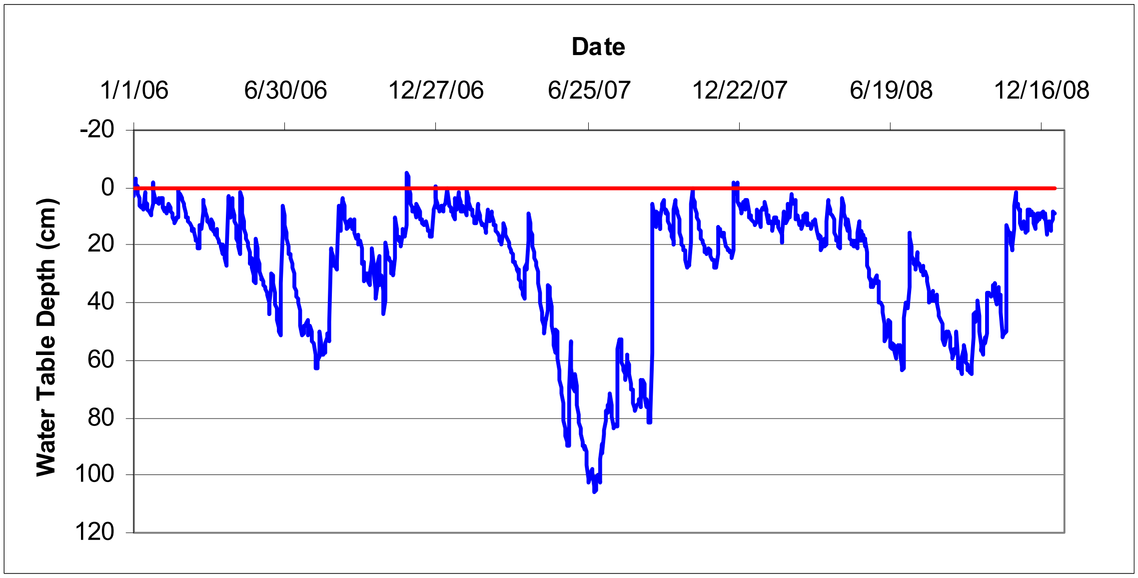

Figure A.26 REF08 water table fluctuations for 2006-2008 (Ref-center).

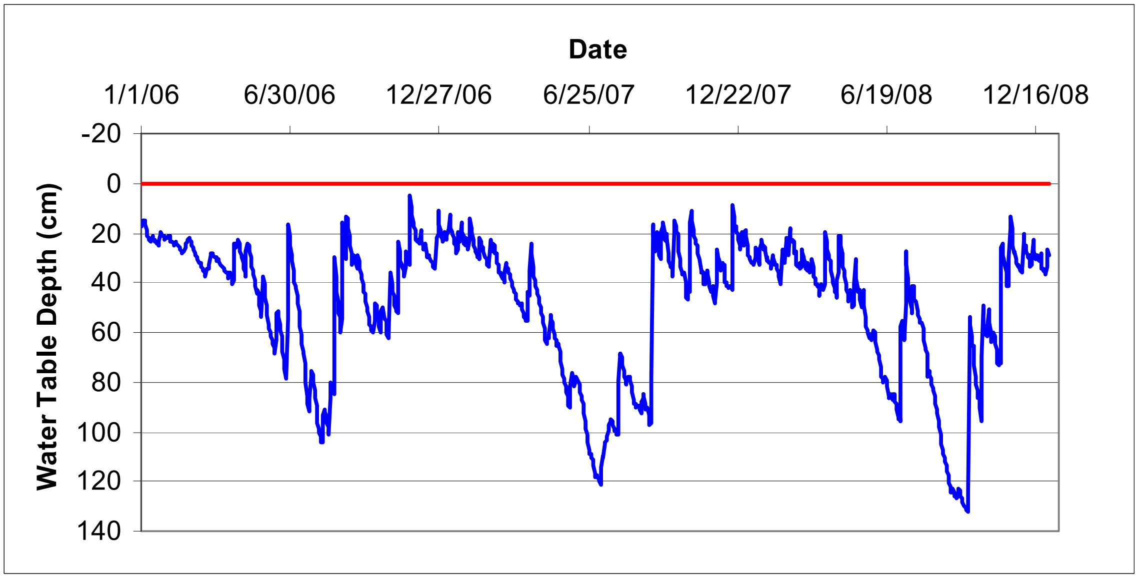

Figure A.27 REF09 water table fluctuations for 2006-2008 (Ref-edge).

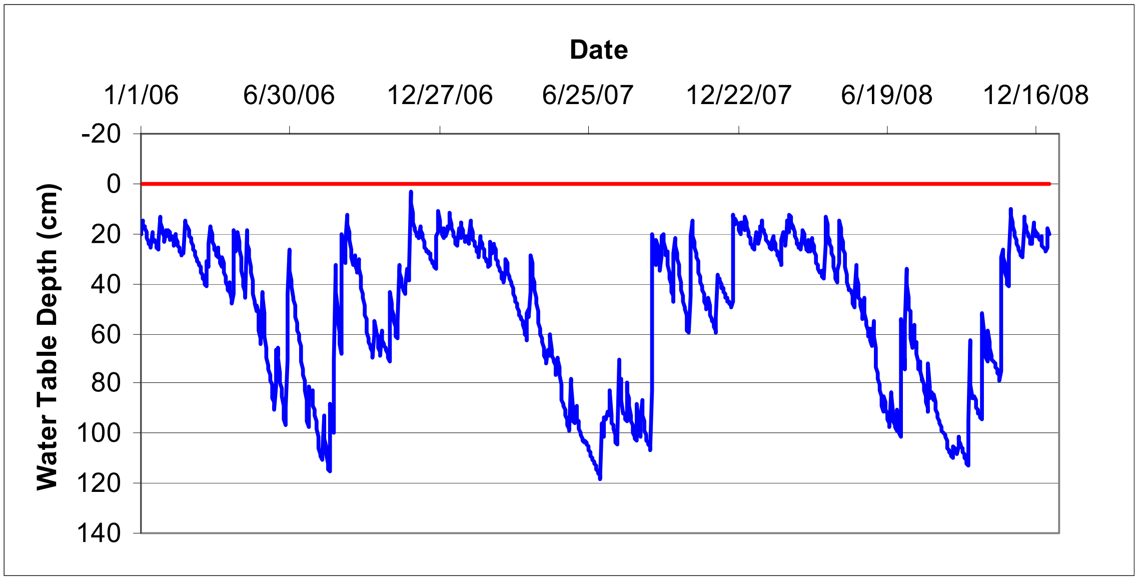

Figure A.28 REF11 water table fluctuations for 2006-2008 (Ref-edge).

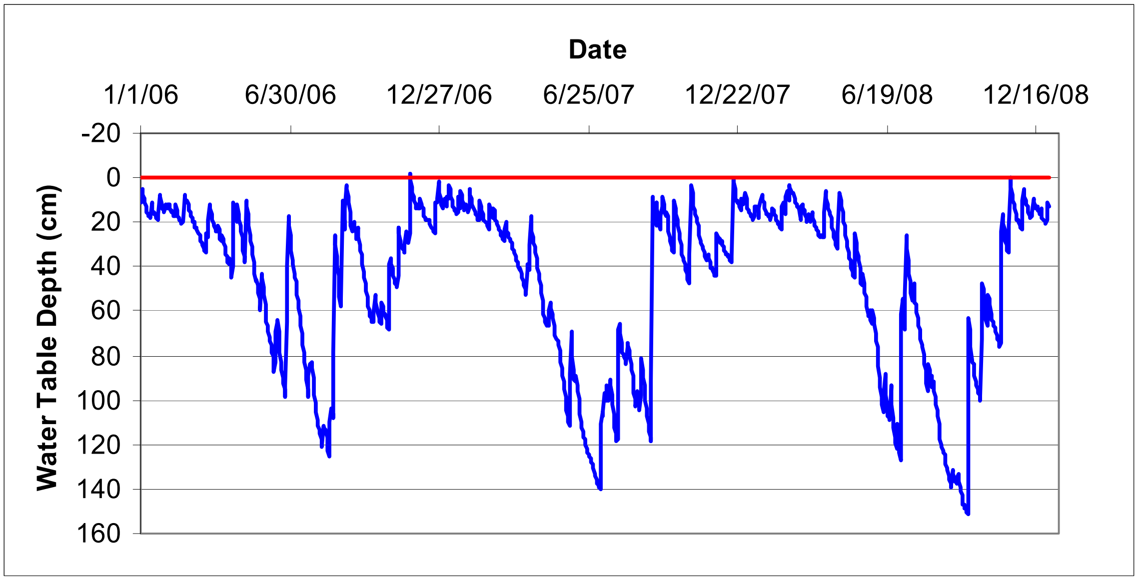

Figure A.29 REF13 water table fluctuations for 2006-2008 (Ref-center).

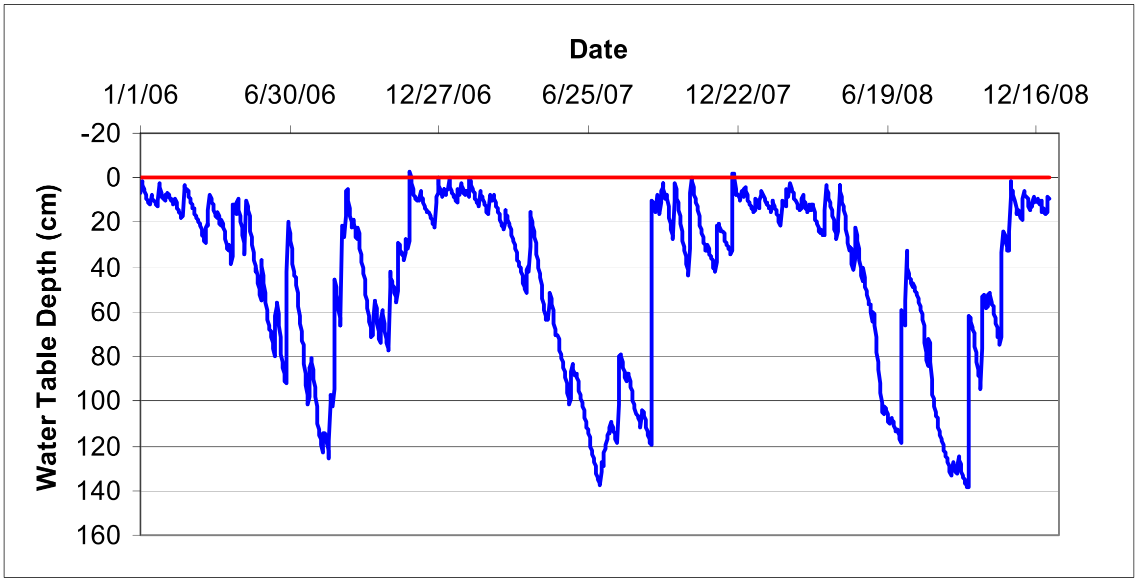

Figure A.30 REF14 water table fluctuations for 2006-2008 (Ref-center).

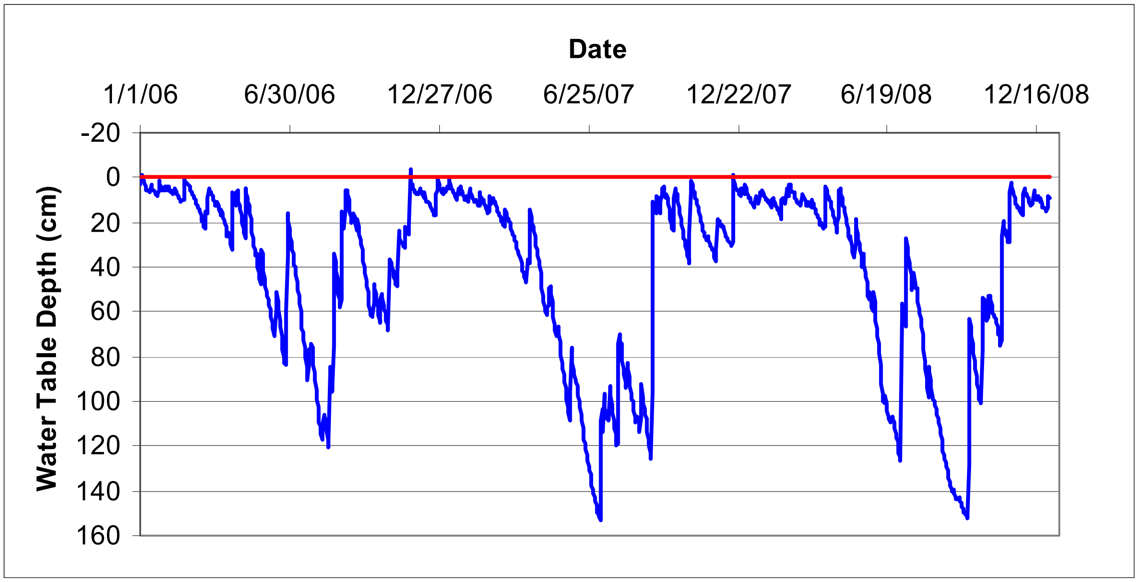

Figure A.31 REF16 water table fluctuations for 2006-2008 (Ref-center).

B. Manual Water Table Readings

Table B.1 Manual water table depths (cm) for block 1, CONT.

	CONT					
Date	1a	NR01	1b	2a	NR02	2b
3/7/2007	23.77	15.37	-2.44	5.79	24.00	13.11
7/31/2007	17.68	15.11	1.83	10.36	26.01	10.06
8/15/2007	60.96	49.76	35.66	41.76	59.77	48.77
9/19/2007	24.99	12.95	-5.18	3.66	27.31	15.54
10/10/2007	19.51	9.75	-5.18	2.44	22.48	10.97
11/14/2007	44.81	33.07	7.32	22.56	42.72	32.61
12/17/2007	5.79	3.25	2.44	4.88	13.08	-4.57
1/23/2008	9.75	4.60	-8.53	0.91	16.33	0.30
3/4/2008	20.42	11.33	-6.10	3.05	20.83	9.45
4/2/2008	28.65	20.65	-1.52	7.32	31.06	15.24
4/30/2008	36.58	26.21	-1.52	11.89	36.40	25.30
5/28/2008	81.69	75.87	60.05	67.67	89.54	75.90
7/9/2008	58.22	48.26	28.35	38.10	56.44	46.94
8/20/2008	98.15	91.24	74.98	85.04	62.89	89.92
10/8/2008	92.05	85.70	70.71	78.64	81.03	84.43

Table B.2 Manual water table depths (cm) for block 1, PLUG.

	PLUG					
Date	3a	NR03	3b	4a	NR04	4b
3/7/2007	19.81	18.49	3.96	0.91	26.97	30.18
7/31/2007	11.58	16.66	12.80	5.79	19.91	24.99
8/15/2007	52.73	43.10	24.38	22.56	53.04	57.30
9/19/2007	25.30	13.59	-0.91	-1.83	30.84	35.36
10/10/2007	18.90	9.12	2.13	0.30	31.22	34.75
11/14/2007	40.84	31.12	10.06	12.50	45.09	49.68
12/17/2007	7.62	2.29	10.36	1.83	10.57	14.33
1/23/2008	4.88	3.61	2.13	-3.96	13.89	20.73
3/4/2008	13.11	12.95	4.27	0.30	20.83	27.74
4/2/2008	21.03	20.09	9.45	4.57	28.14	34.75
4/30/2008	35.97	32.05	9.75	4.27	38.18	43.89
5/28/2008	82.30	71.42	52.12	51.51	78.79	89.61
7/9/2008	51.21	40.41	22.86	23.77	49.81	56.08
8/20/2008	95.40	83.26	71.63	98.76	91.26	94.18
10/8/2008	90.83	77.34	65.53	61.26	86.66	94.18

Table B.3 Manual water table depths (cm) for block 1, CR.

	CR					
Date	5a	NR05	5b	6a	NR06	6b
3/7/2007	13.11	10.67	9.14	7.01	10.54	13.72
7/31/2007	10.36	8.13	11.28	11.28	5.46	11.28
8/15/2007	35.36	38.02	38.40	35.97	45.49	52.73
9/19/2007	10.67	9.60	5.18	8.23	9.91	9.45
10/10/2007	11.58	8.10	10.36	6.40	8.61	10.67
11/14/2007	32.31	31.50	30.78	31.09	36.93	44.81
12/17/2007	6.10	0.00	7.92	2.44	0.30	9.14
1/23/2008	8.23	1.17	7.32	4.88	1.65	8.84
3/4/2008	9.75	5.46	7.01	6.10	5.00	11.89
4/2/2008	16.15	12.22	10.97	10.06	13.77	21.64
4/30/2008	18.59	17.30	14.94	13.41	21.44	21.64
5/28/2008	70.71	65.18	66.45	65.53	74.50	81.08
7/9/2008	33.53	32.59	39.93	40.23	36.12	42.06
8/20/2008	84.12	79.30	87.17	85.95	81.84	86.87
10/8/2008	79.55	72.36	80.47	78.94	76.73	82.60

Table B.4 Manual water table depths (cm) for block 2, CONT.

	CONT					
Date	7a	NR07	7b	8a	NR08	8b
3/7/2007	21.64	18.47	-3.66	5.79	5.56	11.28
7/31/2007	14.02	10.16	-8.23	-0.30	0.81	7.01
8/15/2007	54.86	46.08	19.20	26.82	36.65	36.27
9/19/2007	20.73	20.70	-0.30	8.23	15.60	16.15
10/10/2007	18.29	18.77	-1.52	4.88	11.43	13.41
11/14/2007	50.90	40.41	5.79	30.18	36.50	41.45
12/17/2007	12.50	6.73	-10.97	21.85	1.14	7.92
1/23/2008	14.63	9.73	-3.96	3.35	7.65	5.79
3/4/2008	18.59	13.54	-3.96	5.79	21.84	9.75
4/2/2008	27.74	20.52	-2.74	8.53	13.11	15.54
4/30/2008	32.61	21.41	4.88	17.07	20.04	27.13
5/28/2008	86.56	63.70	46.33	57.30	73.15	75.59
7/9/2008	49.07	37.44	11.58	16.15	29.31	37.80
8/20/2008	92.35	81.79	57.61	65.84	74.83	90.22
10/8/2008	88.39	73.33	45.72	54.56	63.58	81.99

Table B.5 Manual water table depths (cm) for block 2, CR.

	CR					
Date	9a	NR09	9b	10a	NR10	10b
3/7/2007	-11.89	-4.55	20.73	10.97	9.17	27.13
7/31/2007	1.52	-8.43	17.37	12.50	5.51	24.38
8/15/2007	-3.05	12.55	43.89	26.21	32.94	88.70
9/19/2007	-10.67	-15.27	24.99	9.75	10.39	24.08
10/10/2007	-18.29	-5.49	21.64	7.92	7.29	24.08
11/14/2007	-2.44	22.33	62.18	33.53	39.07	60.05
12/17/2007	10.67	-8.86	13.41	12.19	-2.11	30.48
1/23/2008	-16.76	-8.59	13.11	0.91	8.38	22.86
3/4/2008	-13.11	-4.50	17.37	9.75	11.86	24.38
4/2/2008	-7.32	3.20	23.47	11.89	5.13	29.57
4/30/2008	-6.71	1.09	36.27	17.07	19.51	30.18
5/28/2008	52.12	56.41	71.93	67.67	67.28	92.05
7/9/2008	17.07	23.75	56.08	39.01	28.40	46.33
8/20/2008	59.44	69.98	87.17	79.86	48.44	96.32
10/8/2008	52.73	65.56	81.08	71.02	52.71	89.61

Table B.6 Manual water table depths (cm) for block 2, PLUG.

	PLUG					
Date	11a	NR11	11b	12a	NR12	12b
3/7/2007	28.35	9.63	3.96	-0.61	27.94	33.53
7/31/2007	10.67	1.96	4.27	-4.88	36.93	8.84
8/15/2007	54.25	29.49	14.63	3.96	42.90	55.17
9/19/2007	33.83	15.57	-0.61	1.22	31.17	35.36
10/10/2007	30.18	12.01	4.57	0.00	25.12	30.18
11/14/2007	58.22	28.83	20.42	5.79	48.06	64.31
12/17/2007	10.67	-0.30	1.83	-8.23	10.54	8.53
1/23/2008	16.46	4.42	2.13	-1.22	13.92	8.23
3/4/2008	25.60	8.46	1.52	-1.52	25.68	36.58
4/2/2008	-27.13	12.98	6.10	4.57	34.77	38.40
4/30/2008	41.45	21.34	9.14	6.10	42.98	52.12
5/28/2008	90.53	53.19	56.08	57.91	76.15	92.35
7/9/2008	57.30	31.52	35.97	22.56	43.18	53.04
8/20/2008	93.27	54.31	65.23	68.28	74.90	88.70
10/8/2008	90.22	44.48	58.22	54.86	69.11	84.12

Table B.7 Manual water table depths (cm) for block 3, PLUG.

	PLUG					
Date	13a	NR13	13b	14a	NR14	14b
3/7/2007	17.37	27.58	4.27	-10.06	-8.08	10.06
7/31/2007	42.98	37.87	22.56	20.42	16.92	39.93
8/15/2007	75.59	88.21	65.23	49.07	64.69	82.30
9/19/2007	10.97	23.44	3.05	-10.06	-8.51	16.46
10/10/2007	12.19	23.55	0.91	-16.15	-10.26	6.71
11/14/2007	48.77	53.04	4.27	-6.40	-3.61	12.50
12/17/2007	-1.22	11.28	2.44	-13.72	-14.68	1.52
1/23/2008	1.83	12.62	1.83	-14.02	-12.34	6.40
3/4/2008	9.14	23.95	4.27	-13.11	-10.82	8.53
4/2/2008	18.59	33.88	0.91	-9.45	-7.44	9.14
4/30/2008	36.27	41.88	3.66	5.18	-7.72	10.97
5/28/2008	85.95	85.04	43.28	1.22	30.96	60.96
7/9/2008	62.79	65.28	49.99	32.00	40.64	61.87
8/20/2008	98.45	109.83	78.94	62.48	83.13	103.33
10/8/2008	91.74	105.66	79.25	66.75	81.53	103.94

Table B.8 Manual water table depths (cm) for block 3, CONT.

	CONT					
Date	15a	NR15	15b	16a	NR16	16b
3/7/2007	7.32	14.88	5.49	7.01	10.26	2.44
7/31/2007	34.44	26.82	17.07	44.81	57.18	61.26
8/15/2007	74.37	77.09	54.25	72.85	77.62	71.32
9/19/2007	3.96	17.07	2.74	3.05	5.94	-4.57
10/10/2007	5.49	17.30	2.74	3.66	4.19	-3.66
11/14/2007	13.11	26.24	13.41	14.63	18.52	6.71
12/17/2007	7.01	6.22	8.84	6.10	-3.68	8.23
1/23/2008	3.96	8.33	1.83	2.44	-2.90	-4.27
3/4/2008	6.10	13.46	6.10	3.66	-1.50	-4.27
4/2/2008	10.67	13.94	2.13	5.79	5.56	-1.52
4/30/2008	17.07	26.44	5.18	10.36	15.27	0.00
5/28/2008	64.31	65.15	46.33	47.85	53.49	58.22
7/9/2008	54.86	56.41	46.94	48.77	48.08	41.76
8/20/2008	96.32	95.55	75.29	84.12	56.11	87.17
10/8/2008	96.93	93.37	75.59	81.08	71.07	74.37

Table B.9 Manual water table depths (cm) for block 3, CR.

	CR					
Date	17a	NR17	17b	18a	NR18	18b
3/7/2007	19.51	35.05	42.37	41.45	42.82	42.06
7/31/2007	48.16	70.00	89.92	83.52	72.49	54.56
8/15/2007	77.11	75.90	93.57	91.44	99.47	93.88
9/19/2007	-4.27	15.37	17.37	16.46	19.18	14.94
10/10/2007	-3.35	12.80	17.98	17.07	20.09	15.85
11/14/2007	25.30	41.94	48.77	47.24	49.48	47.85
12/17/2007	-9.45	4.39	9.75	9.75	7.14	5.79
1/23/2008	-0.30	22.05	18.29	14.94	15.24	13.72
3/4/2008	4.57	26.01	21.95	20.73	21.06	17.98
4/2/2008	14.63	25.73	41.76	40.84	42.49	39.93
4/30/2008	18.29	38.35	40.54	38.71	39.85	39.32
5/28/2008	73.15	73.36	88.70	87.17	82.78	91.14
7/9/2008	51.82	68.91	74.37	71.32	74.88	68.28
8/20/2008	92.35	105.00	92.96	93.57	108.00	94.18
10/8/2008	83.52	96.80	92.66	92.35	96.57	94.49

C. Surface Outflow

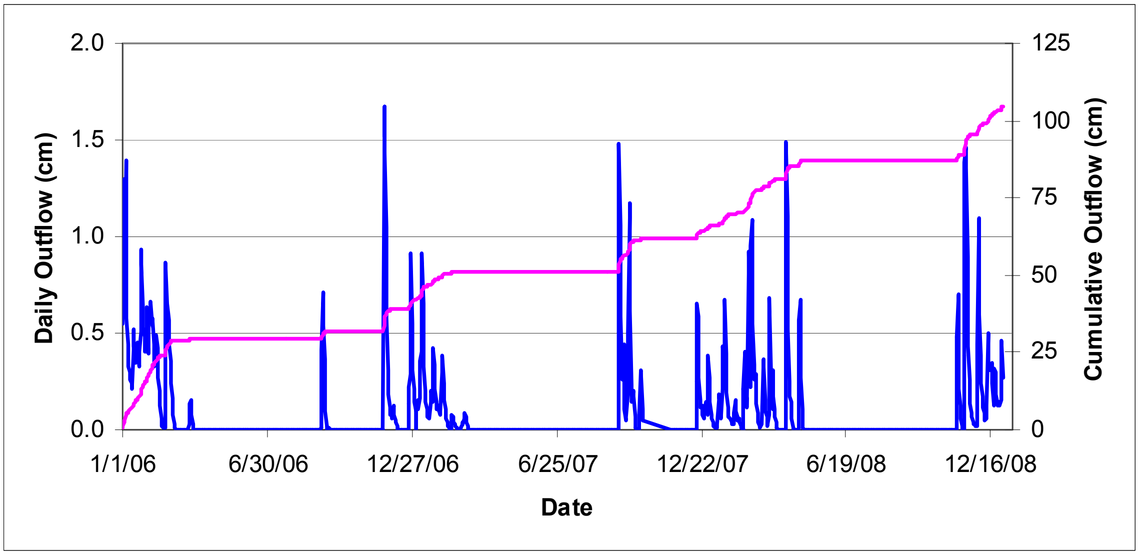

Figure C.1 Daily and cumulative outflow from NRWC01 (Block 1, CONT).

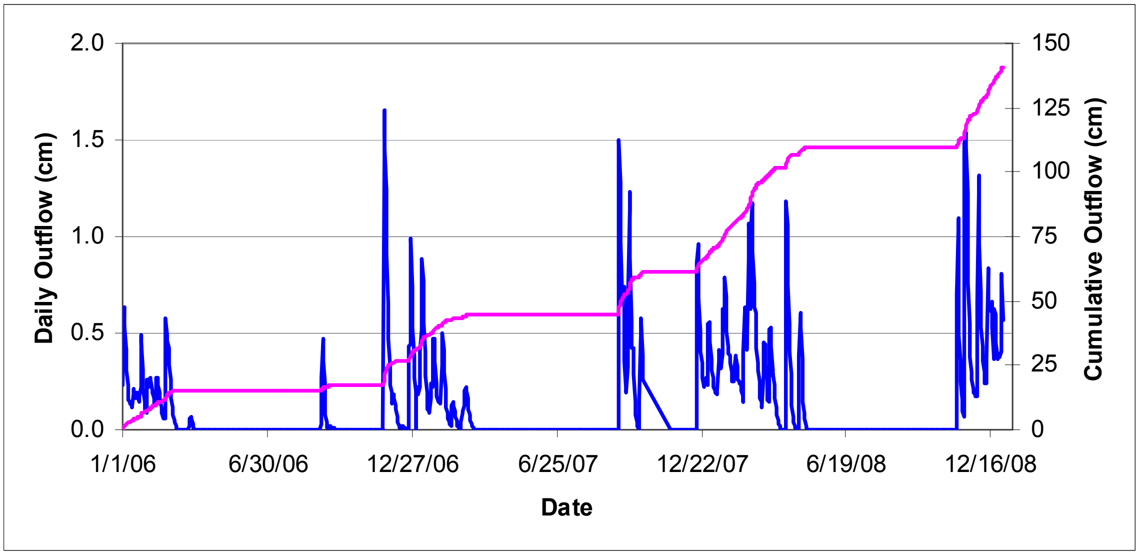

Figure C.2 Daily and cumulative outflow from NRWC02 (Block 1, PLUG).

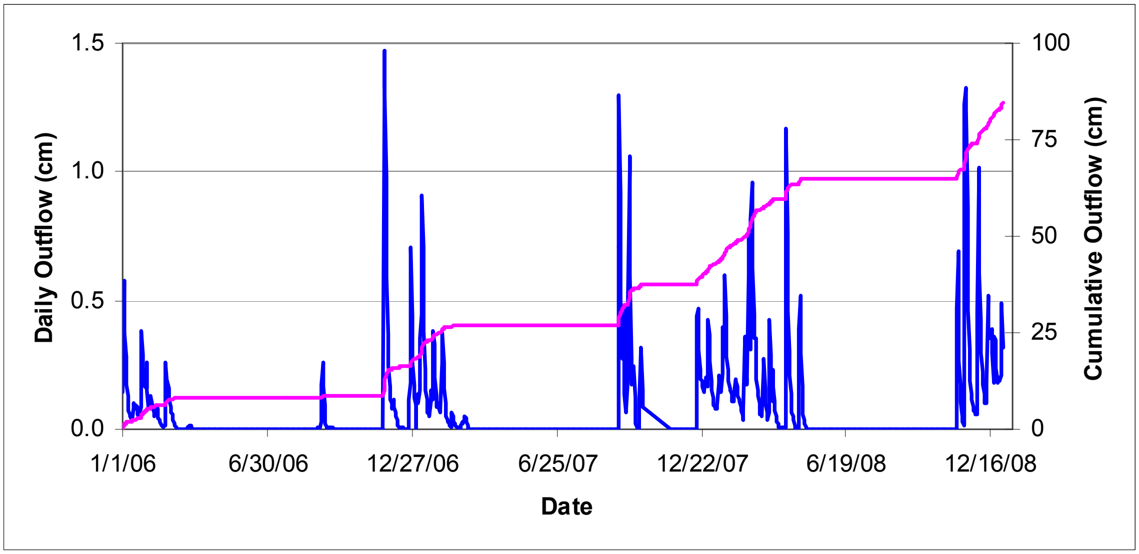

Figure C.3 Daily and cumulative outflow from NRWC03 (Block 1, CR).

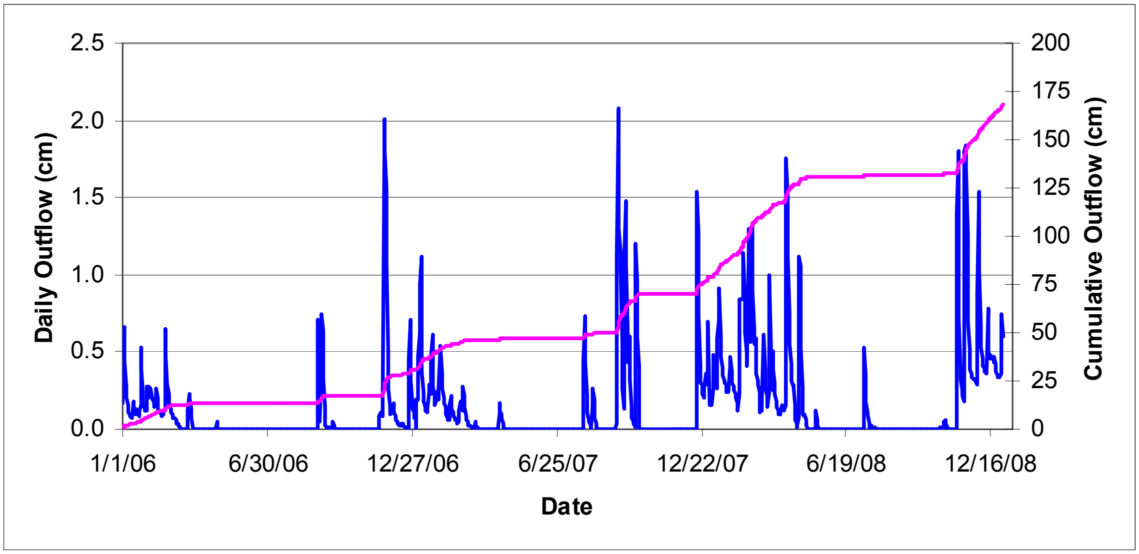

Figure C.4 Daily and cumulative outflow from NRWC04 (Block 2, CONT).

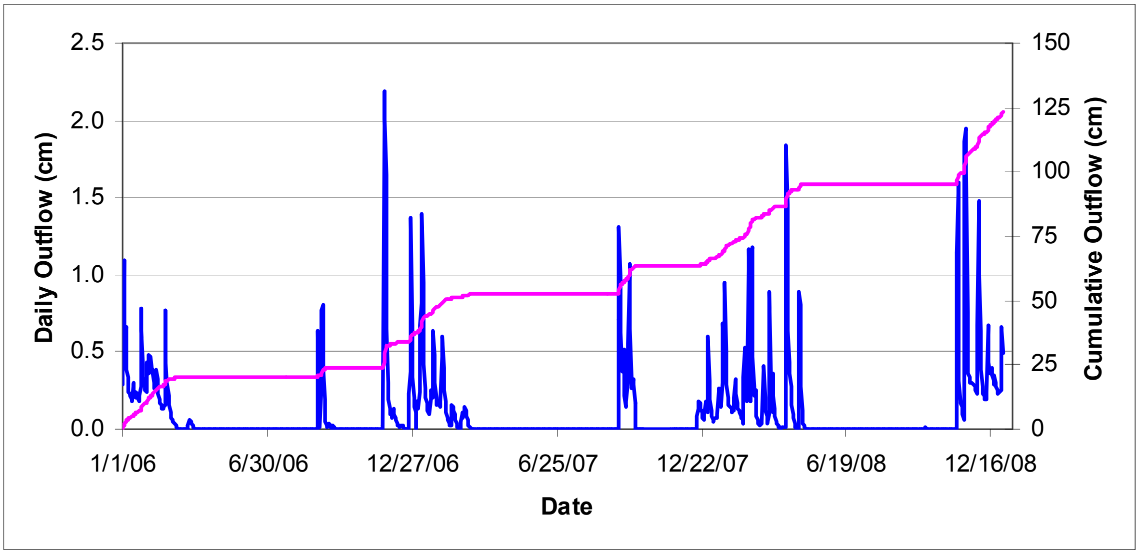

Figure C.5 Daily and cumulative outflow from NRWC05 (Block 2, CR).

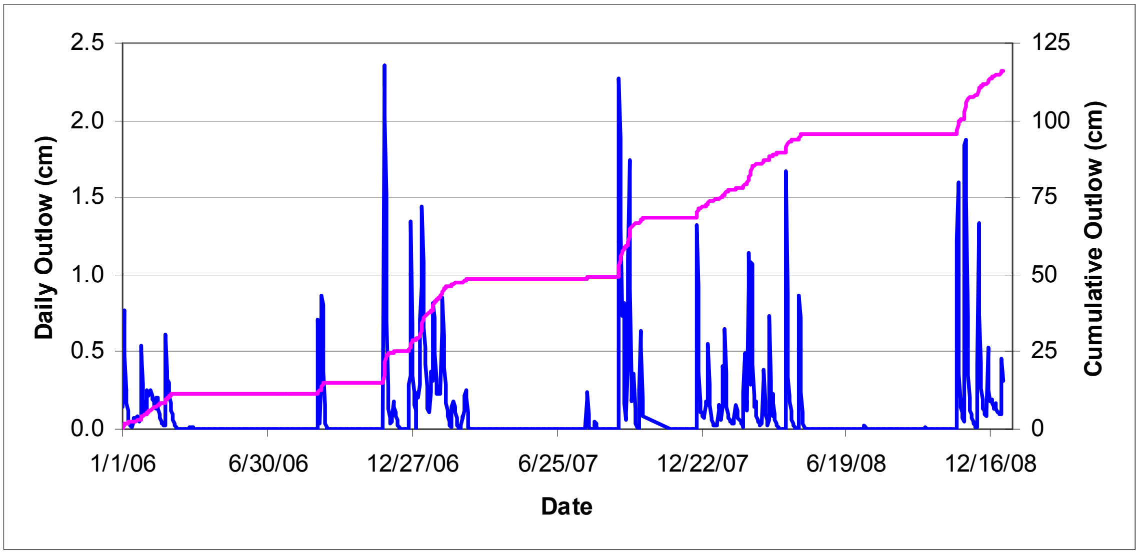

Figure C.6 Daily and cumulative outflow from NRWC06 (Block 2, PLUG).

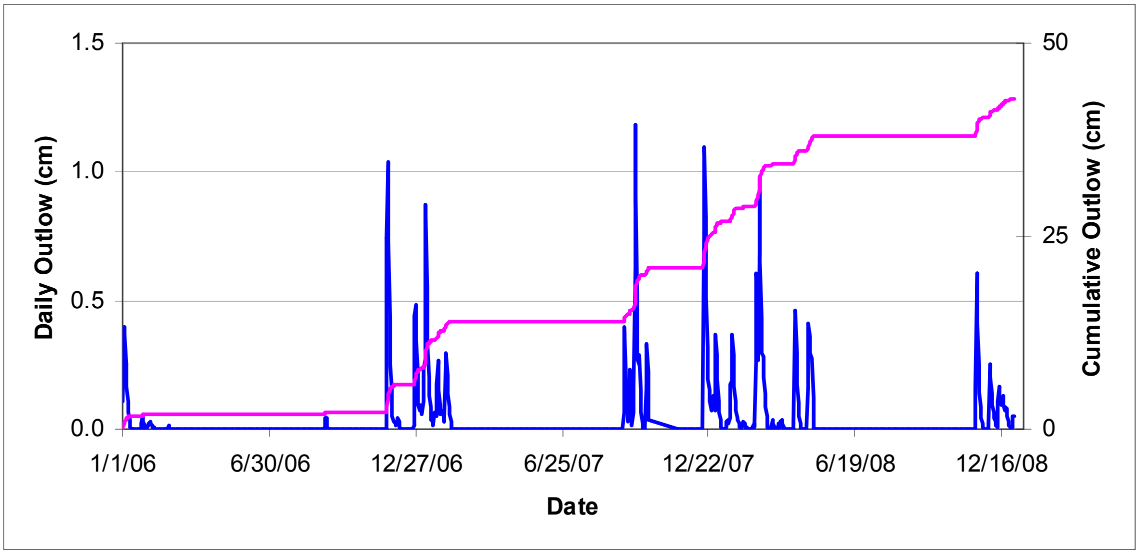

Figure C.7 Daily and cumulative outflow from NRWC07 (Block 3, PLUG).

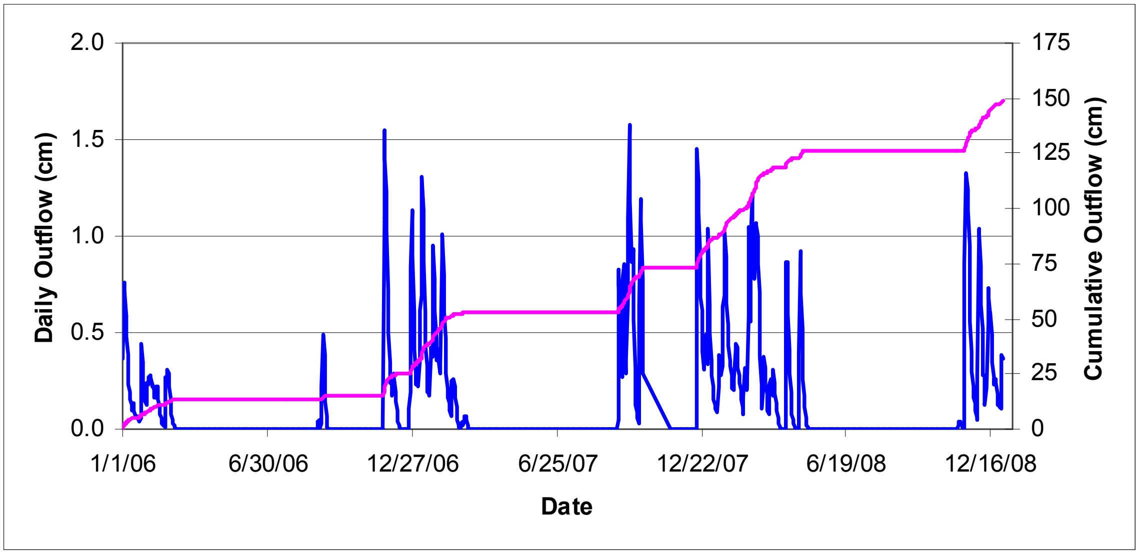

Figure C.8 Daily and cumulative outflow from NRWC08 (Block 3, CONT).

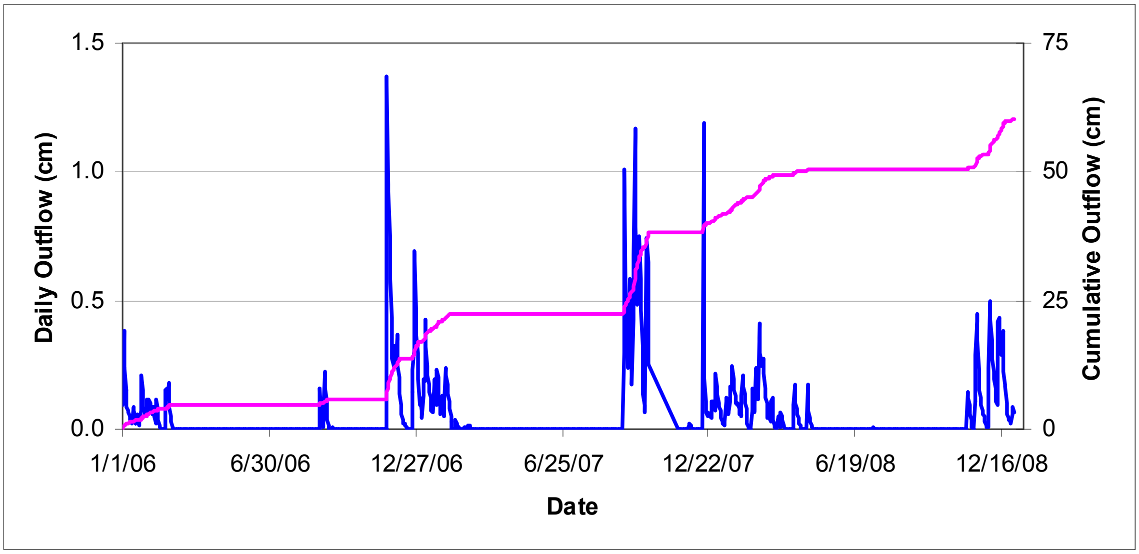

Figure C.9 Daily and cumulative outflow from NRWC09 (Block 3, CR).

Chapter 3 Appendices

D. DRAINMOD Inputs

Soil Water Characteristic

Theta	Head
0.4670	0.00
0.4560	-7.60
0.4550	-11.50
0.4390	-18.10
0.4060	-37.60
0.3590	-67.60
0.3300	-107.40
0.2960	-210.30
0.2690	-406.20
0.2530	-611.70
0.2450	-749.10
0.2067	-15000.00

Water Table	Volume Drained	Upward Flux
0.0000	0.0000	1.0000
10.0000	0.2500	0.7500
15.0000	0.3750	0.5000
30.0000	1.7250	0.2567
40.0000	2.6250	0.0133
50.0000	4.1255	0.0108
60.0000	5.6250	0.0023
70.0000	7.1250	0.0010
80.0000	8.6250	0.0008
90.0000	10.1250	0.0001
100.0000	11.6250	0.0001
110.0000	13.1250	0.0001
120.0000	14.6250	0.0001
130.0000	16.1250	0.0001
140.0000	17.6250	0.0001
150.0000	19.1250	0.0001
160.0000	20.6250	0.0001
170.0000	22.1250	0.0001
180.0000	23.6250	0.0001
190.0000	25.1250	0.0000
200.0000	26.6250	0.0000

Green Ampt Parameters

Water Table	A	B
0.00	0 .00	0.00
25.00	0.50	7.40
50.00	0.50	5.20
250.00	0.70	2.00
500.00	1.00	2.00
1000.00	1.00	2.00

Bottom Depth	Lat Sat Conductivity
15	30
115	15
300	5

Figure D.1 Soil inputs for wetland model.

Soil Water Characteristic

Theta	Head
0.4670	0.00
0.4560	-7.60
0.4550	-11.50
0.4390	-18.10
0.4060	-37.60
0.3590	-67.60
0.3300	-107.40
0.2960	-210.30
0.2690	-406.20
0.2530	-611.70
0.2450	-749.10
0.2067	-15000.00

Water Table	Volume Drained	Upward Flux
0.0000	0.0000	1.0000
10.0000	0.2500	0.7500
15.0000	0.3750	0.5000
30.0000	1.7250	0.2567
40.0000	2.6250	0.0133
50.0000	4.1255	0.0108
60.0000	5.6250	0.0023
70.0000	7.1250	0.0010
80.0000	8.6250	0.0008
90.0000	10.1250	0.0001
100.0000	11.6250	0.0001
110.0000	13.1250	0.0001
120.0000	14.6250	0.0001
130.0000	16.1250	0.0001
140.0000	17.6250	0.0001
150.0000	19.1250	0.0001
160.0000	20.6250	0.0001
170.0000	22.1250	0.0001
180.0000	23.6250	0.0001
190.0000	25.1250	0.0000
200.0000	26.6250	0.0000

Green Ampt Parameters

Water Table	A	B
0.00	0 .00	0.00
25.00	0.50	7.40
50.00	0.50	5.20
250.00	0.70	2.00
500.00	1.00	2.00
1000.00	1.00	2.00

Bottom Depth	Lat Sat Conductivity
15	30
115	15
300	5

Figure D.2 Soil inputs for agricultural model.

Table D.1 Drainage system inputs for wetland model.

Drain Depth (cm)	90
Drain Spacing (cm)	10000
Effective Radius (cm)	40
Drainage Coefficient (cm)	2
Max Surface Storage (cm)	50
Kirkham's Depth	2
Weir Depth (cm)	30

Table D.2 Drainage system inputs for agricultural model

Drain Depth (cm)	90
Drain Spacing (cm)	10000
Effective Radius (cm)	40
Drainage Coefficient (cm)	2.5
Max Surface Storage (cm)	1.5
Kirkham's Depth	0.75
Weir Depth (cm)	-

Table D.3 Monthly PET correctional factors for wetland model.

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

Table D.4 Monthly PET correctional factors for agricultural model.

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

Table D.5 Rooting depths for wetland model.

Month	Day	Depth (cm)
1	1	40
12	31	40

Table D.6 Rooting depths for agricultural model.

Month	Day	Depth (cm)
1	1	3
2	30	3
3	20	20
4	30	25
5	30	25
6	30	25
7	15	25
8	15	25
9	2	15
10	15	10
11	19	5
12	31	3