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Final Report

Methodology to Assess Soil, Hydrologic, and Site Parameters that Affect Wetland Restoration

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16. Abstract

Juniper Bay is a 750 acre Carolina Bay that was purchased by the NC Department of Transportation for wetland restoration. This report summarizes the current condition of the site and reviews its history, geology, hydrology, soils, and also provides data on the target or reference areas that the Bay will be restored to. Juniper Bay was converted to agriculture in the 1970's when its timber was removed and the area was ditched, drained, and fertilized for row crop production. The fertilization increased the levels of plant nutrients in the upper 12 in. of soil to levels approximately five times greater than those found in the original soil. Despite the fertile nature of the soils, nutrient levels in drainage waters were low. A water budget indicated that ground water could comprise between 10 and 35% of the total water input to the Bay. A more precise estimate will require better estimates of evapotranspiration. Evaluation of restoration methodologies indicated that in order for the site to meet the 12.5% criterion the ditches would have to be plugged, field crowns removed, and surface roughness increased. This scenario was developed assuming that ground water inflow did not have a significant impact on water table levels. Examination of vegetation soils in natural bays indicated that pond pine woodland is the most appropriate target community for the existing soils in Juniper Bay. Subsidence of the organic soil surface by up to 2 ft. precludes high pocosin or bay forest plant communities for Juniper Bay.

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SUMMARY

Juniper Bay is a 750 acre Carolina Bay that was purchased by the NC Department of Transportation for wetland restoration. This report summarizes the current condition of the site and reviews its history, geology, hydrology, soils, and also provides data on the target or reference areas that the Bay will be restored to.

Juniper Bay lies on the Middle Atlantic Coastal Plain. Below its surface are alternating layers of sands and clays to a depth of over 50 ft. A clay layer at approximately 20 ft. lies beneath the entire Bay. In its natural state, the Bay probably supported plant communities that are described as pond pine woodland, bay forest, and high pocosin.

Juniper Bay was converted to agriculture in the 1970's when its timber was removed and the area was ditched, drained, and fertilized for row crop production. The fertilization increased the levels of plant nutrients in the upper 12 in. of soil to levels approximately five times greater than those found in the original soil. Despite the fertile nature of the soils, nutrient levels in drainage waters were low. Organic soils cover approximately one-half the Bay. As a result of land clearing operations and drainage, the surface of the organic soil has subsided approximately 24 in. over the previous 30 yr.

The shallowest clay layer varied in depth from 20 in. to 10 ft. across the site and had an average depth of 60 in. This layer is probably not a single, continuous layer, but consists of overlapping clay layers of varying thicknesses. In the southeast corner of the Bay, no clay layer was detected in an area 8 acres in size to a depth of 15 ft. This could be a point of leakage or groundwater inflow.

Measurements of hydraulic gradients across the Bay showed that ground water was entering the Bay to the east and west. It was leaving the Bay to the north and south. Most groundwater movement appeared to occur between a depth of 10 to 20 ft. This was generally below the depth of the lateral ditches. However, it did appear some ground water was moving toward the surface of the Bay in some sections and may be entering ditches. A water budget indicated that ground water could comprise between 10 and 35% of the total water input to the Bay. A more precise estimate will require better estimates of evapotranspiration.

Long-term simulations using the hydrologic model DRAINMOD indicated that under current conditions the six sites monitored within Juniper Bay do not satisfy the hydrologic criterion for wetland if the duration is based on 12.5% of the growing season. Evaluation of restoration methodologies indicated that in order for the site to meet the 12.5% criterion the ditches would have to be plugged, field crowns removed, and surface roughness increased. This scenario was developed assuming that ground water inflow did not have a significant impact on water table levels.

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Chapter 1

INTRODUCTION

Many wetland restoration efforts in North Carolina have failed to meet the relatively limited restoration goals imposed by US Army Corps of Engineers (Corps) permits. On such sites that have been reviewed by the principal investigators, it is obvious that failures result from multiple shortcomings in site assessment, identification of potential functions, methodologies to restore wetland functions, and effective assessment of the progress of functional restoration. The research proposed here is designed to address those shortcomings in a study of restoration success in Juniper Bay, a converted Carolina Bay depressional wetland in Robeson County, NC.

Juniper Bay was developed for agriculture several decades ago and currently has about 300 ha of drained and intensively managed agricultural land that is not jurisdictional wetland due to its status as prior converted agricultural land. The drainage system in Juniper Bay not only removes excess surface and ground water, but it directs runoff to a different location in the watershed than under previous natural conditions. The overall goal of the research is to evaluate the strategy and performance of the restoration of wetland functions in Juniper Bay and to test alternative restoration methods. The restoration efforts will include:

- Plugging or filling the drainage ditches as necessary to restore historical hydrologic functions and the directions and rates of surface and subsurface runoff
- Re-establishing the forest community in accordance with community types located in the reference ecosystem
- Soil management as needed to assist in hydrologic function restoration, forest community establishment, and nutrient cycling processes.

This research will evaluate whether these strategies are sufficient to restore appropriate wetland functions in Juniper Bay, and will identify other factors and methods that must be addressed in implementing wetland restoration in depressional wetlands that have been converted to agriculture.

BACKGROUND

A. *Wetland Restoration Requirements* – Wetland mitigation as practiced by the North Carolina Department of Transportation (NCDOT) is the restoration of wetlands to replace those altered or destroyed in the course of road construction and maintenance. The type of wetland ecosystem that must be replaced is specified by the Corps permit that authorized wetland alteration in a particular road project in accordance with Section 404 of the Clean Water Act. To get full credit for wetland restoration efforts, Corps permits usually specify that wetland hydrology, hydric soils, and a plant community similar to the reference ecosystem be restored. The reference ecosystem is a functioning wetland located in the vicinity of the restoration site that has minimal alteration and that is judged to represent the prior natural condition of the restoration site. However, most wetlands have key hydrologic and soil characteristics, such that if the hydrology is restored to cause key soil processes to occur, then it is likely that the most important wetland functions will be restored.

B. *Reasons Restoration Efforts can Fail* **–** All of the principal investigators have been involved with creating and restoring wetlands in both the southeastern and midwestern U.S. While restoration is simple in concept, it can be difficult to implement for a variety of reasons. These include:

1. **Variability in Soils and Sediments**: In most of the natural wet flat, organic flat, and depressional wetlands in North Carolina, slowly permeable soil or sediment layers near the surface that limit vertical or lateral drainage are instrumental in the maintenance of wetland hydrology. Drainage ditches often penetrate such layers and provide subsurface flow connections to geologic sediments consisting of layers of sand or gravel. Such connections can cause water ponded in a wetland to leak out. This causes the wetland to be drier than normal, and in extreme cases can limit establishment and growth of wetland plants and the development of hydric soils. The locations and depths of both permeable and impermeable layers must be known prior to beginning restoration, and hydrologic restoration methods on the site must restore the functional impact of slowly permeable layers.

2. **Regional Alteration of Hydrology**: If ground water levels in areas outside the restoration site have been lowered by ditching or pumping, then these modified levels will often affect the ground water levels within the restoration site. Regional subsurface hydraulic gradients that are much higher than historical ones can subvert restoration of wetland hydrology by contributing to relatively high rates of subsurface lateral flow in near-surface soil layers with relatively high hydraulic conductivity. Simply filling ditches within the site itself may not restore wetland hydrology if water is able to leak out the wetland's bottom or subsurface perimeter. Therefore, regional hydrology must be assessed and restoration methods must account for restoration of historical regional surface and subsurface hydraulic gradients.

3. **Excessive Levels of Soil Nutrients**: While all plants need certain nutrients to grow, the natural plant communities of Carolina Bays are adapted to soils that are acidic and contain few nutrients. Fields used for agriculture were fertilized and limed regularly, so the nutrient levels in the soils are high and the acidity low. When wetlands are created in fields used for agriculture, the high levels of nutrients can cause undesired plants to flourish at the expense of the desired plants of the reference ecosystem. Conversely, restored areas of bottomland hardwood forest fail to grow adequately when grading and soil alteration leave soils at the surface that contain inadequate nutrient levels.

4. **Alteration of Soil Physical Properties**: Wetland restoration often requires extensive grading of the soil surface. For example, the typical restoration procedure for drained agricultural land includes filling the ditches by pushing soil from the inter-ditch fields into the ditches. That process destroys the soil profile. Top soil is pushed into the ditches, subsoil remains at the surface, and the structure of the soil at the surface is severely degraded by the soil movement and compaction that occurs. The soil remaining

at the surface has much lower site quality potential for plant community restoration than the previous agricultural field. Restoration methods must be developed (and approved by the Corps) that can restore hydrology while minimizing such adverse impacts on the soil.

Successful restoration will require that potential limiting conditions such as those described above be identified in the planning process. Then the site will have to be managed during the construction phase and establishment phases to prevent limiting conditions and or apply management practices that ameliorate them.

PROBLEM NEED AND DEFINITION

Restored wetlands must perform the hydrologic, biogeochemical, and plant community functions that are found in natural wetlands. Limited assessment of those functions is normally conducted in accordance with Corps permits that specify monitoring of certain parameters of hydrology, hydric soil indicators, and plant community structure. While wetlands may perform many ecological functions, the likelihood of their occurrence can be estimated by monitoring key soil and hydrologic properties. In current wetland restoration practice, there is often a lack of detailed pre- and post-restoration monitoring and assessment that documents the progress of the recovery of wetland functions on restoration sites. This leads to conflicts between agencies creating wetlands and those regulating them, and delays issuance of permits until the regulatory agencies are certain the restoration efforts will be successful.

RESEARCH OBJECTIVES

1. Document the variability in the properties of soils and sediments and the water table regime across Juniper Bay and the reference bay that will affect restoration success.

2. Determine current groundwater flow paths and water table regime both inside and outside Juniper Bay, and identify a strategy for hydrologic restoration.

3. Assess the recovery rate of key hydrologic, biogeochemical, and plant community functions that are necessary for a sustainable wetland ecosystem.

4. Assess the usefulness of reference ecosystems for defining required hydrologic and soils factors and target vegetation composition necessary for long-term restoration success.

5. Identify soil chemical and physical properties and hydrologic requirements for optimum growth of Carolina Bay vegetation.

6. Determine the effect of tree species type and diversity for achieving sustainable growth of desired vegetation and soil characteristics in the restored Carolina Bay.

7. Test different restoration methodologies.

LITERATURE REVIEW

Geographic Extent

Carolina Bays are oval, NW-SE oriented depressions with sand rims that are located in upland landscapes in the southeastern Coastal Plain and occasionally in the lower Piedmont in certain areas. They range in size from a few acres to more than 7000 acres. Though most numerous in North and South Carolina, Carolina Bays have been identified as far south as north Georgia and as far north as Maryland and Delaware (Melton, 1938; Frey, 1950; Prouty, 1952; and Bliley and Pettry, 1979;). Prouty (1952) estimated the total number of Carolina Bays at 500,000 with about 80% of that number occurring in the Carolinas. In North Carolina, bays are most numerous in the southern portion of the middle Coastal Plain, including the counties of Bladen, Columbus, Cumberland, Hoke, Robeson, Sampson, and Scotland. However, they occur in most of the counties of the southern and central Coastal Plain and occasionally in the northeastern Coastal Plain.

Character of Soils

The bay floor may have organic soils or poorly drained or very poorly drained sandy to clayey mineral soils that are also found in irregularly shaped wet areas outside the bays (Table 1). The northwest ends of many bays merge imperceptibly with the surrounding upland, but the northeast, southeast, and part of the southwest rims are moderately to distinctly prominent landscape features. The prominent, nearly white, sandy rims with Kureb or Wakulla soils on the southeast ends commonly rise 1-3 m above the bay bottom and usually are eolian (wind transported and deposited) sand. The rims on the northeast and southwest sides are sandy, but many of the sands are the result of normal soil development on materials of the uplands as well as from eolian materials (Daniels et al., 1999).

Table 1. Major soils in the Carolina Bay System (Daniels et al., 1999)

Textural Family	Drainage Class				
	Well	**Moderately well**	**Poorly**	**Very poorly**	**Organic soils**
Bay Interiors					
Fine			Coxville McColl	Byars	
Fine-loamy	Norfolk Noboco	Goldsboro	Rains	Pantego	
Coarse-loamy			Woodington	Torhunta	
Sandy			Lynn Haven	Murville Rutlege	Mattamuskeet Pamlico
Rims					
Loamy	Wagram Autryville	Bonneau			
Sandy	Wakulla Lakeland Cainhoy Rimini Kershaw Kureb Centenary	Chipley Pactolus			

Hydrology

The hydroperiod of Carolina Bays ranges from permanently flooded to seasonally saturated. Due to the topographic gradient in bays, there is a soil drainage class gradient from excessively drained on the highest portions of the sandy rims to poorly drained or very poorly drained in the lowest elevation portions. Most have significant areas of jurisdictional wetlands, though some of the driest bays may have wetland in the lower elevation portion surrounded by nonwetland area. Many Carolina Bays contain natural lakes, the largest located in Columbus and Bladen Counties, NC. Bays vary significantly in types of connections to surface waters. Few have surface flow input, a notable exception being Lake Waccamaw in Columbus County. Some bays have surface runoff outlets, but the majority likely do not. The types of surface outlets range from dispersed overland flow during large rainfall events to well-developed stream channels.

Hydrologists have long theorized that the hydrology of Carolina Bays is influenced by subsurface flow inputs and fine-textured soil or parent material layers that restrict downward flux of stored water in the bay. Early limited studies of Carolina Bay hydroperiods showed that the hydroperiod was dominated by rainfall inputs and evaporation outputs (Sharitz and Gibbons, 1982). Only relatively recently, however, have detailed hydrology studies begun to elucidate the complex hydrology of Carolina

Bays and shown the complex subsurface interactions with the surrounding area (Knight et al., 1989; Newman and Schalles, 1990; Lide et al., 1995; O'ney et al., 1999). In the bays studied by these authors, there was local depressional hydrology superimposed on the regional subsuface hydraulic gradients of the landscape in which the bay occurred. Both Lide et al. (1995) and O'ney et al. (1999) found that the topography of subsurface layers was similar to the surface topography. Sedimentary layers sloped downward from the surrounding uplands to lows under the lower elevation portions of the bay. Hydraulic gradients into the bays resulted in subsurface flows along sandy layers overlying fine-textured layers with upward gradients into the bays during the wet season. In both bays, water accumulated in the bay during the wet season of the year and then was depleted during the dry season. Lide et al. (1995) concluded that Thunder Bay in Barnwell County, SC provided significant ground water recharge during the drying period of late spring/early summer. O'ney et al. (1999) concluded that Chapel Bay in Bamberg County, SC likely provided some recharge but that drying was dominated by evaporation losses.

Geomorphology

Stratigraphy of the lacustrine bay-fill sediment and the fossil pollen in the sediment indicates water levels have fluctuated in the past. In most bays a series of alternating organic and inorganic zones can be identified, and most bays were more lake-like at one time (Whitehead, 1965). Inorganic sediments consist of sandy or clayey loam, lenses of gravel, sand, or iron-cemented sand, and marl and clay. The clay and silt zones represent lacustrine depositional periods after bay formation, and as such did not influence water levels early in bay history. Original bay water levels probably reflected regional hydrology. Surface water levels have decreased in time because bays are infilling with sediment and peat and surrounding groundwater levels are decreasing because of local stream excision (Schalles et al., 1989). Ditching and channelization, for primarily agricultural drainage, have also lowered groundwater levels in their vicinity.

Some bays contain extensive organic deposits, while others are clay based. Significant peat reflects a more stable hydrology with almost continuous groundwater recharge. Chemistry of water and soils in clay-based Carolina bays indicates a rainwater-dominated system characteristic of perched-water settings (Schalles et al., 1989). Water levels are related to precipitation, but variable responses are common.

Sediments on the coastal plain were deposited by both coastal and fluvial processes (and surfaces have been reworked by wind). Consequently, coastal plain stratigraphic units can consist of sands, silts, or clays, reflecting the energy present in the environment at the time of their deposition. Surficial sands often overlie clay layers; these finer-textured sediments perch water and may be important to maintaining the bays.

The original surface of these coastal plain sediments was most likely undulating. Water tables on broad interfluves would have been high; as stream incision progressed, water tables would become lower near interfluve edges. Undulations in the region where water could pond because of poor surface or subsurface drainage resulted in bays (Kaczorowski, 1977).

Bays have been reported to form on saprolite and clayey Coastal Plain sediments (Bliley and Burney, 1988), over impervious humate (Thom, 1970; Kaczorowski, 1977), clay (Gamble et al., 1977; Schalles et al., 1989), and in poorly drained depressions in sandy surficial sediments (Bliley and Pettry, 1979). Landscape position, water table fluctuations, and impervious layers interact to produce differences in individual bay hydrology and response to rainwater inputs. Bays are likely both recharge and discharge features depending on bay water levels in relation to the regional water table (Schalles, 1979). Understanding the hydrology of a particular bay requires an understanding of the nature, continuity, and depth of underlying sediments and their interactions with local hydrology.

Vegetation

The vegetative communities of Carolina Bays in the Carolinas are diverse among bays and usually complex within bays (Sharitz and Gibbons, 1982; Schafale and Weakley, 1990). That diversity and complexity is related to topography, soils, hydrology, and disturbance history. Schafale and Weakley recognize nine natural community types that commonly occur in Carolina Bays in North Carolina: low pocosin, high pocosin, small depression pocosin, pond pine woodland, peatland Atlantic white cedar forest, bay forest, cypress savanna, small depression pond, and natural lake shoreline. However, examples of most common forest or emergent wetland vegetation types that occur in the Coastal Plain may be found in the complex vegetation mixes of Carolina Bays. All bays have a vegetation gradient from the xeric communities of the sandy rims to the wetland or aquatic communities of the lowest elevation area of the bay, usually in the southeastern quadrant (Sharitz and Gibbons, 1982).

The long-term success of the Juniper Bay restoration project will be determined partly by the similarity of the species composition and structure of its future stable plant community to that at reference Carolina bay sites. Certain key wetland functions at Juniper Bay should also be compared with functions at reference sites. In the early years following restoration at Juniper Bay, before a stable community is attained, successional changes in the community structure and wetland functions should be monitored to try to determine if they are progressing toward their desired future states. Clearly, determining the success of the Juniper Bay restoration requires characterization of reference sites.

Carolina bay lengths range from 50 m to 8 km (Frey, 1949). There appears to be no consistent relationship with particular geological formations or topography (Prouty, 1952). Some bays remain dry nearly all of the time; some contain permanent water; others are seasonally inundated (Sharitz and Gibbons, 1982). Many bays have been disturbed by forestry or agricultural practices while some remain in relatively pristine condition. Fire is a natural disturbance that has probably affected all bays, but to varying extents.

Against the background of extremely heterogeneous environmental influences, it is not surprising that plant community types vary widely among Carolina bays. Major community types previously reported at bays include pine forests, herbaceous marshes, shrub bogs, deciduous forests, evergreen bay forests, pond cypress swamps, prairies, and submerged aquatic beds (Buell, 1946; Penfound, 1952; Whitehead and Tan, 1969; Porcher, 1966; Wharton, 1978; Schalles and Shure, 1989). This vegetation variation suggests that the stable community type that will eventually develop at Juniper Bay is difficult to predict, and that several reference sites should be selected. These sites should be located close to Juniper Bay and have soils, hydrology, and disturbance histories similar to those at Juniper Bay prior to its conversion to agriculture. It is expected that the plant community types and wetland functions will vary among these reference sites. The range of structural and functional variability in the plant communities of these reference sites is the target for Juniper Bay.

Wetland Soils or Hydric Soils

Hydric soils are defined as those that are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part. Hydric soils must be anaerobic. Many water quality functions that wetlands perform occur because the soils have become anaerobic and chemically reduced.

Wetland restoration efforts are successful when the soils in the restored wetlands become anaerobic for extended periods of time. Development of anaerobic conditions can be monitored by analyzing water chemistry or by measuring the oxidation-reduction potential, which is also called the redox potential (Ponnamperuma, 1972). Water chemistry measurements are used to determine concentrations of reduced chemical species such as NH_4^+, and Fe(II). The presence of Fe(II) is considered proof that the soils are anaerobic.

Redox potential measurements are electrical measurements that determine the voltage developed between a Pt wire and a reference electrode buried in the soil. (Patrick et al., 1996). They are used to determine whether soils are developing the anaerobic conditions necessary for them to be considered as hydric soils. Redox potential measurements are probably the single most important measurements to be made on soils to confirm that a wetland restoration has been successful.

The time required to restore wetland functions is site specific. However, it has been found that some soils regain their hydric soil processes within years of construction (Vepraskas et al., 1999). In a study of created wetlands in the midwestern U.S., Vepraskas et al. found that hydric soil field indicators developed within 3 yrs of wetland creation, and appeared to reach full development within 5 yrs. To develop the necessary low redox potential required for anaerobic conditions, soil organic matter levels apparently had to exceed 4% in the midwestern U.S. The hydric soil field indicators adopted for use throughout the U.S. have been presented in USDA-NRCS (1998).

ORGANIZATION OF THE REPORT

The following chapters summarize the principal findings of the research done to date. Each chapter covers a separate topic and was written by the researchers involved. The chapters were written to be "self-contained" and can be read without referring to other chapters. This format was selected to make reading of the report easier.

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Chapter 2

SURFICIAL GEOLOGY OF SOUTHERN NORTH CAROLINA AND JUNIPER BAY

C.W. Zanner

INTRODUCTION

This chapter reviews the geologic history of the Juniper Bay and Bladen Lakes region, and then fits the Juniper Bay core stratigraphy into the stratigraphy of that region. The subaerial (emerged) portion of the Atlantic Coastal Plain extends from Long Island, NY to Florida. About 45% of the state of North Carolina is on the Coastal Plain (Daniels et al., 1999). Juniper Bay is in Robeson County NC, in an upland area of the Middle Coastal Plain. Robeson County is bordered by South Carolina to the SW and Bladen County NC to the NE. The Bladen Lakes reference bays are in the Cape Fear River Valley in Bladen County.

The basement rock below the coastal plain sediments consists of a series of arches and embayments that dip to the east. The Coastal Plain is thus a wedge of marine and near shore deposits that thicken to the east. Coastal Plain sediments are thicker in the embayments, but thinner and less complete over the arches, with major unconformities. The area of the bays has been under water many times during and since the Cretaceous (Table 1 shows the portion of the geologic time column that is relevant to this discussion). Juniper Bay is located on the Cape Fear Arch, just south of the hinge. The reference bays are on the arch north of the hinge.

Sediments on the coastal plain were deposited by both coastal and fluvial processes. Figure 1 is a generalized model of the Cretaceous delta to shelf lithofacies developed by Sohl and Owens (1991) for the Carolinas. Although this model was developed to explain the Cretaceous stratigraphy, transgressions and regressions after the Cretaceous reproduced Sohl and Owens' relationships along this part of the Atlantic Coast. Consequently, there is considerable lateral and vertical variation. Laterally, coastal plain stratigraphic units consist of sands, silts, or clays, reflecting the energy present in the environment at the time of their deposition. Vertically, surface sands often overlie clay layers. The finer-textured sediments perch water and are likely an important factor in bay formation. The most recent surface sands have been reworked by wind. At any one place on the Coastal Plain, the stratigraphy of the below ground sediments reflects its former location from under deep water when the shore was to the west to subaerial when the shore was to the east. See Gohn (1988) and Sohl and Owens (1991) for location of the Late Mesozoic and early Cenozoic coasts. See Ward et al. (1991) for the Pliocene and Early Pleistocene coasts.

Sediments covering the Cape Fear Arch show drainage patterns and deeply incised river courses that were influenced by the lowering of sea level associated with glaciations. Sea level decreased 120-135 m (394-443 ft) during the most recent

Pleistocene glaciation which ended about 20,000 years ago (Mitrovica, 2003; Peltier, 2002; Yokoyama et al., 2000). At 18,000 years ago, the great volumes of water tied up in glacial ice caused the coast to move 100-150 km (62-93 mi) east of where it is now (Riggs and Belknap, 1988). Older glacial advances that reached Kansas and Nebraska in North America (Andersen and Borns, 1997) suggest that in these older periods sea levels were also lower than at present. Elevation of sea level was also controlled by geologic events such as continued uplift of the Cape Fear Arch through the Quaternary (Owens, 1988), and changes in ocean basin volume and general upwarping of the eastern North American continent (Colquhoun et al., 1991). Changes in sea level, plus possible increases in effective moisture during glacial periods, marked periods of major incision. Major fluctuations in sea level inundated and reexposed the area, with inundations filing in the previously incised landscape. Sea level lowering was associated with periods of weathering, erosion, and incision. Even those transgressive/regressive sequences that did not reach the elevation of the bays changed base level of the local rivers and streams, which then incised or backfilled depending on proximity to the ocean.

GEOLOGY IN THE AREA OF JUNIPER BAY AND THE REFERENCE BAYSys

Walker and Coleman (1987) estimated Coastal Plain sediments to be 17% Cretaceous, 27% lower Tertiary, 26% upper Tertiary, and 30% Quaternary. In southern North Carolina, Cretaceous deposits are more predominant, approaching to within 100 k (62 miles) of the ocean. Figure 2A shows geology, primarily of the Cretaceous units, of the Juniper Bay and reference bays areas (North Carolina Geologic Survey, 1991). The more detailed map (Figure 2B from Owens,1989) shows that most of the Cretaceous units are covered with more recent Pliocene sediments. Tables 2A and B provide a key to the units shown on each map. Most surfaces have been extensively reworked by wind and in places buried by fluvial deposits, especially in the Cape Fear Valley.

Formations discussed here are summarized in Table 3 which shows the formation name, age, description, and the environment of deposition. Table 3 and the following discussion are based on material presented in Gohn (1988), Sohl and Owens (1991), Soller (1988), Soller and Mills (1991), Ward et al., (1991).

Cretaceous units of North Carolina formed in deltaic and shelf environments, with rapid facies changes (Owens and Sohl, 1989). Figure 1 is a generalized model for the depositional environments of the Cretaceous units in the Carolinas (Sohl and Owens, 1991). Within the Cretaceous section, there are a number of cycles of sedimentation separated by unconformities. These sediments are Upper Cretaceous in southern North Carolina (see Table 1). The oldest part of the section, the Cape Fear Formation (Table 3), is mainly visible in river systems. The Middendorf Formation covers the Cape Fear Arch. Both of these units occur northwest of Juniper Bay at higher elevations. Middendorf is at or close to the surface ~75 km (47 mi)northwest of Juniper Bay (Owens, 1989). These units are likely represented in the subsurface of the Juniper Bay Project research area, but deeper than what we cored. The Middendorf consists of light-colored iron-stained sands and variably colored clays. Coarse-grained sands and pebbles are common.

The Black Creek Group is above the Middendorf. The Black Creek is a group divisible from younger to older into the Donoho Creek Formation, the Bladen Formation, and the Tar Heel Formation (Sohl and Owens, 1991). Each younger formation of the Black Creek is found closer to the present ocean. In the region of Juniper Bay, Figure 3 (from Sohl and Owens, 1991, page 201) suggests Juniper Bay and the Reference Bays occur in the area mapped as Bladen Formation, near the boundary with the Tar Heel Formation, which extends farther inland. The Black Creek Formation consists of marine sediments of onshore, nearshore, and offshore origin with some deltaic deposits exposed on the Cape Fear Arch. Deltaic deposits are not surprisingly more common near river systems. Uplift of the Cape Fear arch may have contributed to erosion and dissection of the Black Creek and other Pre-Pliocene surfaces. Figure 3 also shows the depositional environments associated with the Cape Fear. Note that expression of the delta of the Cape Fear has persisted since Cretaceous time. Figure 1 shows a more detailed model of delta to shelf facies that were deposited at any time when the river mouth was stable for an extended period.

The Black Creek generally consists of bedded black clay and micaceous sands. Donoho Creek is more massively bedded with abraded shells. Bladen Formation beds are more thinly bedded without fossils. Tar Heel is thinly bedded, carbonaceous, and micaceous, without fossils. Owens and Sohl (1989) described the Tar Heel Formation as horizontal beds of thin black clay and light-colored micaceous sand.

The PeeDee Formation overlies the Donoho Creek Formation, but it does not extend inland to the Bay area. No Eocene, Oligocene, or Miocene sediments are found in the area of the bays (Harris and Zullo, 1991; Snyder et al., 1991).

Dissected Cretaceous sediments were filled in by later transgressions. The Late Pliocene Duplin Formation was deposited over the Upper Cretaceous strata over much of the Cape Fear Arch (Ward et al., 1991). This formation was deposited 3.0-3.5 million years ago (Cronin, 1991). Subsequent transgressions inundated smaller areas (see Ward et al., 1991). Current practice is to call this stratigraphic unit the Duplin-Yorktown Formation in North Carolina (Kathleen Farrell, North Carolina Geological Survey, personal communication, 2003). The Yorktown Formation of Virginia and the Duplin Formations are stratigraphically equivalent but have different fossil assemblages. Three members of the Yorktown that were recognized in Virginia can be traced into North Carolina (Ward and Blackwelder, 1980). The Sunken Meadow member is not traceable south of the Neuse (Ward et al., 1991). The Rushmere and Morgarts Beach members are not distinct south of the Neuse (Ward et al., 1991). At the Tarheel locality (Bladen County NC) described by Ward et al., (1991) the sediment underlying the Duplin-Yorktown Formation is the deeply burrowed eroded surface of the Black Creek Group. Common mollusks in the Rushmere and Morgarts Beach members are *Mulinia* sp. and *Chesapecten* sp. Although *Chesapecten* sp. occurs in other Members and Formations (Raysor, Chowan, Bear Bluff) discussed by Ward et al. (1991), *Mulinia* does not (see tables on pages 285-288 in this reference). Duplin beds are composed of medium to coarse sand, sandy and silty clays, and shelly fossiliferous sands. Grayish-blue sandy clay with a low diversity fossil assemblage buries the oldest Duplin deposits, and, in turn, is buried by 3-m (16 ft.) thick quartz sand containing an open marine molluscan assemblage.

The reference bays occur in an area between the Black River and the Cape Fear Rivers. The area has been extensively reworked, as the Cape Fear, which once flowed in the area where the Black now flows, deflected to the southwest. This deflection persisted through the Pleistocene, preserving increasingly older terraces to the northeast. Distinct terrace breaks suggest changes in base level and climate. The effects of this ongoing southerly migration can be seen in the steep bluffs on the south side of the river when compared to the north side. The more detailed maps of Owens (1988; 1989) and the publication of Soller (1988) shows that the broad area between the present location of the Cape Fear River and the Black River is a series of five terraces that are 2.75 million to 10,000 years old. The reference bays are on the Penholoway Formation Terrace that is 750,000 years old. This reworked surface was covered by a mixture of flood plain deposits from sands to clays, reflecting energy of the system at the time of deposition. Wind has since extensively reworked and spread out the sandier deposits over most of these terrace surfaces. The Black Creek and PeeDee Formations are exposed in the valley. A few areas of Duplin and Waccamaw Formations covering the Black Creek are also exposed.

SURFICIAL GEOLOGY

The stepped character of the Coastal Plain (a series of terraces and scarps decreasing in elevation towards the Atlantic) is attributed to a downward trend in sea level through Quaternary time (Colquhoun et al., 1991).

Elevation in and outside Juniper Bay ranges from 35-41 m (115-134 ft.). This places Juniper Bay on the Sunderland Terrace, which has an elevation of 30-47 m (100-155 ft), and is bounded by the Surrey Scarp to the southeast (Fig. 2B). The Orangeburg Scarp to the northwest (Fig. 2B) is equivalent to the Coats Scarp of Daniels at al. (1999) and was created by the transgression that left the Duplin Formation sediments (Dowsett and Cronin, 1990). According to Soller and Mills (1991), the Duplin surface lies at less than 40 m (131 ft) in southern North Carolina. The Duplin surface should thus be at or near the surface in the area of Juniper Bay.

The closest cross-section of Owens (1989) in the vicinity of Juniper Bay (~24 km (14 mi) distant) shows 15-20 m (50-66 ft) (of Duplin Formation below the surface. Tar Heel Formation is below the Duplin south of the Bay, Bladen Formation north of the Bay. The Bear Bluff Formation mapped by Owens (1989) shows Juniper Bay situated less than 3 km (2 mi) from the high stand of this transgression. Retreat after high stands left surfaces covered with sandy beach and barrier deposits that then could be reworked by wind. Juniper Bay occurs between parallel NE-SW ridges that are obvious in the Robeson County Soil Survey (McCachren, 1978), in U.S.G.S. digital orthophotography (Figure 4), and in Digital Elevation Models (Figure 5). These ridges are remnants of the coastal system that was once in this area.

JUNIPER BAY CORES AND THE LOCAL GEOLOGY

Table 4 gives a brief summary of 12 cores collected inside the bay. Core locations are shown in Figure 6. Stratigraphy of Cores 1, 2, 3, 6, 8, and 9 is shown in Figure 7. The uppermost sediments were subaerial during at least four geologic periods. Wood fragments recovered from 1.8-2.4 m (6-8 ft.) depths have Holocene ages: Core 4--3720 +/- 90 years before present, Core 10--8320 +/- 100 YBP, Core 6--8460 +/- 100 YBP. Other wood fragments from 2.4-3 m (8-10 ft) deep have Late Pleistocene ages: Core 12: 35200 +/- 590 YBP, Core 5: 39600 +/- 1760 YBP and Core 16: 43880 +/- 1660 YBP. Each of these ages reflects a time when Juniper Bay was dry enough for trees to have become established. The presence of former surfaces, recognizable because of color and structure, also indicate dry periods when soils could form. The trees that left this older wood behind were growing in the Duplin-Yorktown Pliocene age sediments that are 3.0-3.4 million years old.

Cores that were collected to ~6 m (20 ft.) are grounded in this Duplin-Yorktown Formation. This determination is based on the description of Duplin-Yorktown Formation beds as being medium to coarse sands interbedded with thin gray clays and often fossiliferous. Core 9 was noticeable because of the large number of mollusk shells found between 3.8 m (14 ft) and 5.3 m (20 ft). These shells have been tentatively identified as *Mulinia* and *Chesapecten*. Ward et al. (1991) describe these as two of the common genera in the Rushmere and Morgarts Beach Members of the Duplin-Yorktown Formation. The rest of the Duplin fauna reflect a high energy, that is, not a deepwater environment, associated with shallower water over the Cape Fear Arch. Core 9 has well preserved although somewhat broken shells. Core 20 has shell ghosts at 2.4 m (8 ft), Core 22 at 5.5 m (18 ft), and Core 27 at 1.5 m (6 ft). The absence of these fossils and/or ghosts in the other cores is further indication of differential erosion and or deposition. Figure 7 and Table 4 shows the upper sediments are a mix of sands and clays. Although the surface elevations vary by only ~0.5 m (Figure 8A), the depth to the uppermost clay textures (Figure 8B) shows more variation. Cores 3 and 8 also indicate that over the distance of the bay there was considerable variation in depositional environments and/or variations in erosion patterns across the area of the Bay.

Below ~6 m (20 ft), rhythmites become common, finer textures and black colors become more dominant. Finer textured rhythmites are separated by thin sand laminations. Sands are micaceous. Shells found lower in the section are extremely abraded. This description is consistent with these sediments being part of the Black Creek Group. Core 19 outside the Bay has a shell hash at 14.5 m (48 ft) suggesting that this represents the lower part of the Donoho Creek (Table 3). Sohl and Owens' map (1991) shows the Bladen Formation of the Black Creek Group in the Juniper Bay Area. If thin beds and no fossils are enough to distinguish between group members, sediments under the Bay itself are more likely those of the Bladen Formation. This description is consistent with what was observed: 1-2 cm (0.5 in) thick rhythmites separated by sands, very dark, with a high organic content, suggesting deposition in a back bay setting with some tidal influence. However, Core 8 is clay almost to the surface and is massive, matching more closely the Donoho Creek description.

Figure 9 shows coarse sand percentages for selected cores inside and outside the bay. The top of Core 3 may be affected by spoil created when the ditches were installed. However, a slight coarsening is seen near the surface of all the cores, suggesting the increase in coarse sand may be relative, and reflect wind or water winnowing. The cores show an unconformity, most likely an erosional lag, 2-4 m (7-13 ft) below the surface. In some cases, this lag corresponds to a buried soil. This is consistent with the suggestion made above that the Bay experienced dry periods and suggests the sediment above this point represents bay fill. Core 28 is from the dune form to the southeast of the Bay that can be seen in the DEM and aerial photos. The 10 m (33 ft) of sand above the contact at 28 m (32 ft) consistent with the interpretation that this is a dune form. Cores 8 and 28 show increases and decreases in coarse sand that one would expect in an environment where there were shifts in energy of deposition.

Figures 10A and 10B show clay percentages for cores inside and outside the bay. As is the case with the presence/absence of mollusk shells, the presence/absence of buried soils, the depth of erosional lags, and the depth to the uppermost clayey sediments, these figures point to a variety of depositional and erosional environments in and around Juniper Bay. These figures have been projected to show their respective elevations, with the hope that when corrected for elevation one could find it easier to project a surface across the Bay that can be proposed as a surface of the same age. As stated in the introduction to this piece, there is considerable lateral and vertical variation, even within an area the size of Juniper Bay. Core 17 has very low clay but Cores 6 and 10 are up to 60% clay. The presence of sand over an area with clayey sediment that can perch water close to the surface would be a logical requirement for the formation of a bay (and Core 22 taken in the unnamed bay to the north also meets that). Core 17 seems to violate this hypothesis, but note that there was particularly poor recovery in this core. Cores 11 and 14, which indicate some but a minor clay increase also experienced poor recovery. The most likely explanation for poor recovery is that a thin but important clay layer was underlain by saturated sand, and the core tip once filled with >20% clay just pushed the denser clay out of the way into the saturated sand. With better recovery, we might have seen a more continuous clay layer across the bay.

CONCLUSIONS

Juniper Bay formed in 5-8 m (16-26 ft) of Pliocene aged Duplin-Yorktown Formation sediments that are underlain by Cretaceous aged Donoho Creek and Bladen Formations of the Black Creek Group. Most of the underlying sediment seems to be part of the Bladen Creek Formation, with Donoho Creek possibly remaining at Core 8. The topography at the top of each of the subsurface sediments is irregular, with the newer sediment filling in erosional channels as it was deposited and then in turn was itself eroded after deposition. These irregular surfaces, along with coarse sand lags, buried soils, and radiocarbon dated wood, all indicate that cycles of exposure and burial have been occurring in this landscape since the Cretaceous. The sands of the last transgression filled in incised eroded surfaces as beaches moved to the east until they reached their present location. Wind scour of these sand filled low areas created a series of “bays” of varying sizes. Depth and thus size of any one bay was limited by depth to fine textured sediments. Climate driven increases and decreases in water table levels resulted in periods with wet bays (rise in water tables) or dry basins (lowering of water tables). Larger deeper bays produced waves with higher energy. During wet periods, wave action helped bays to grow and capture adjacent basins, analogous to stream capture. The horizontal distance between less erodible finer textured sediments controlled the ultimate size of any bay.

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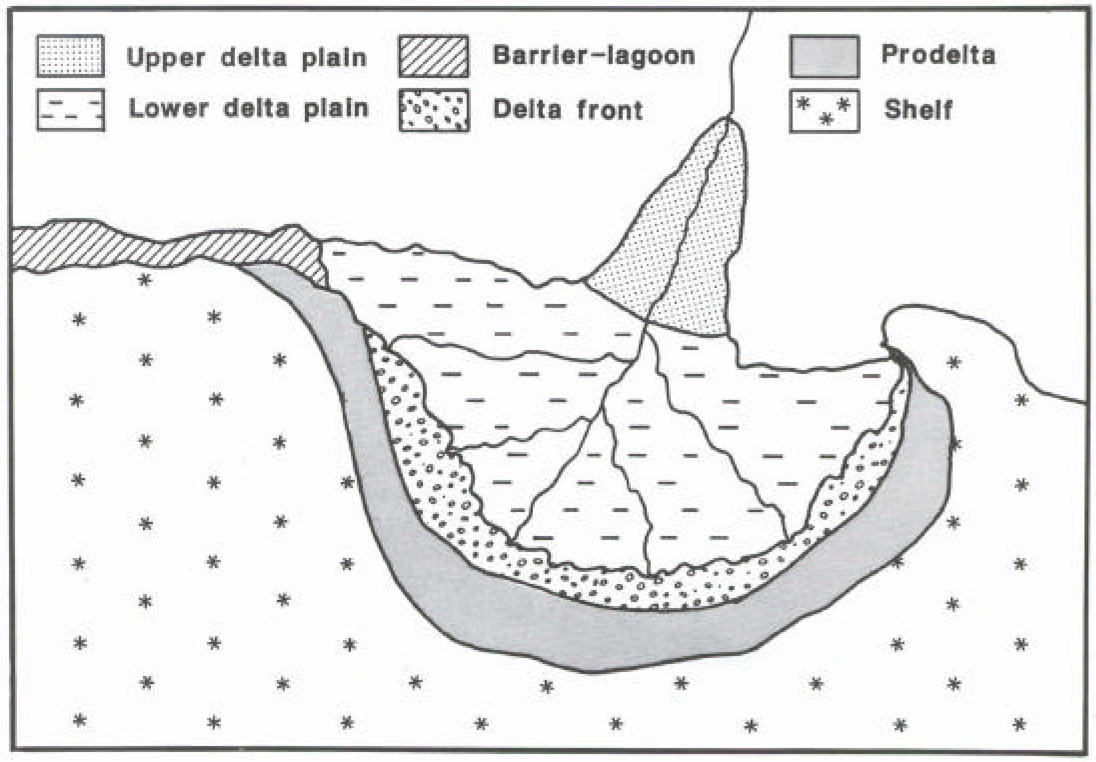

Figure 1. Generalized model of the delta to shelf lithofacies developed by Sohl and Owens (1991) for the Cretaceous of the Carolinas.

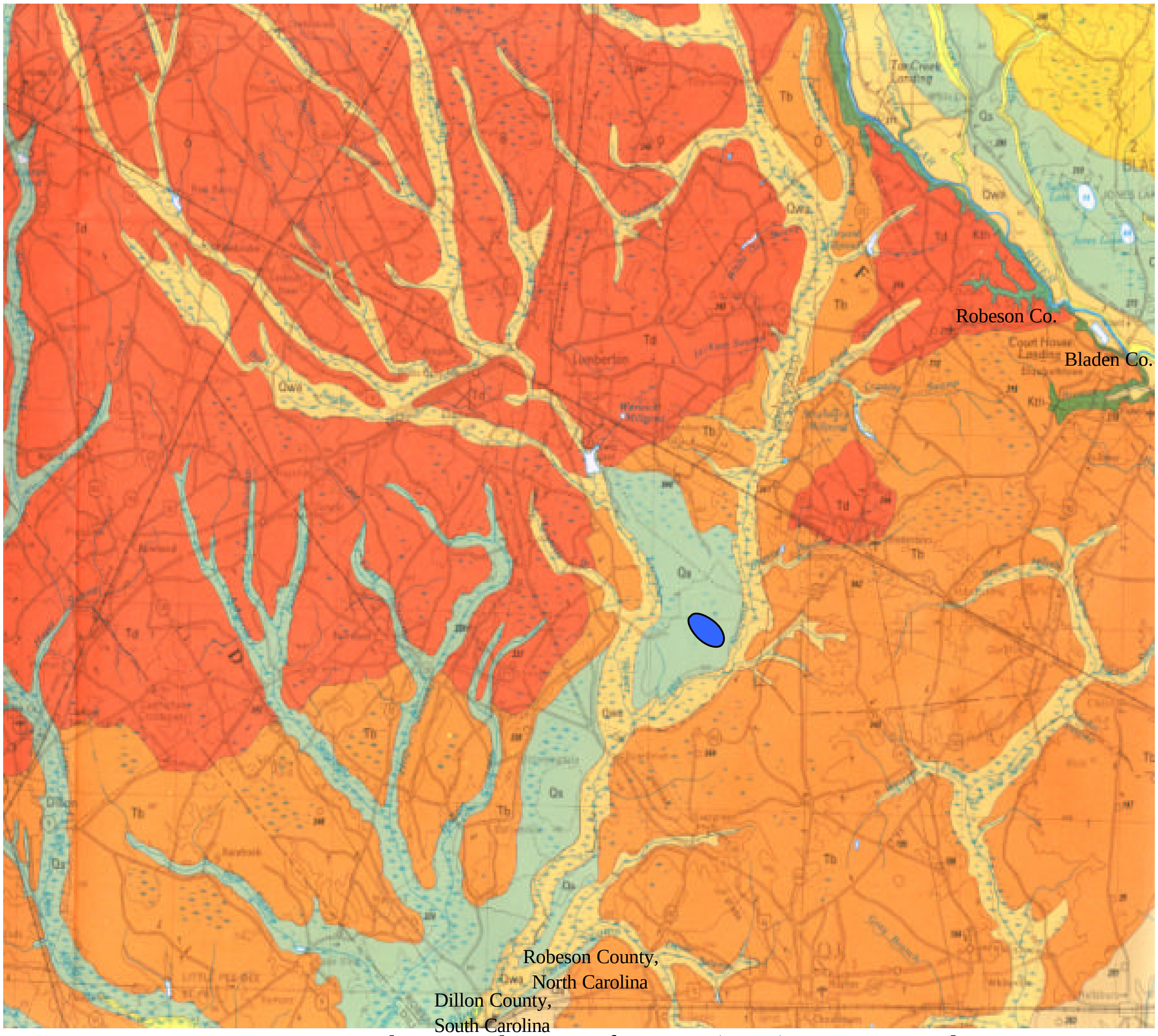

Figure 2A. Juniper Bay area as shown in the map of Owens (1989). Juniper Bay location is shown by the blue oval. See Table 2A for key to geologic units.

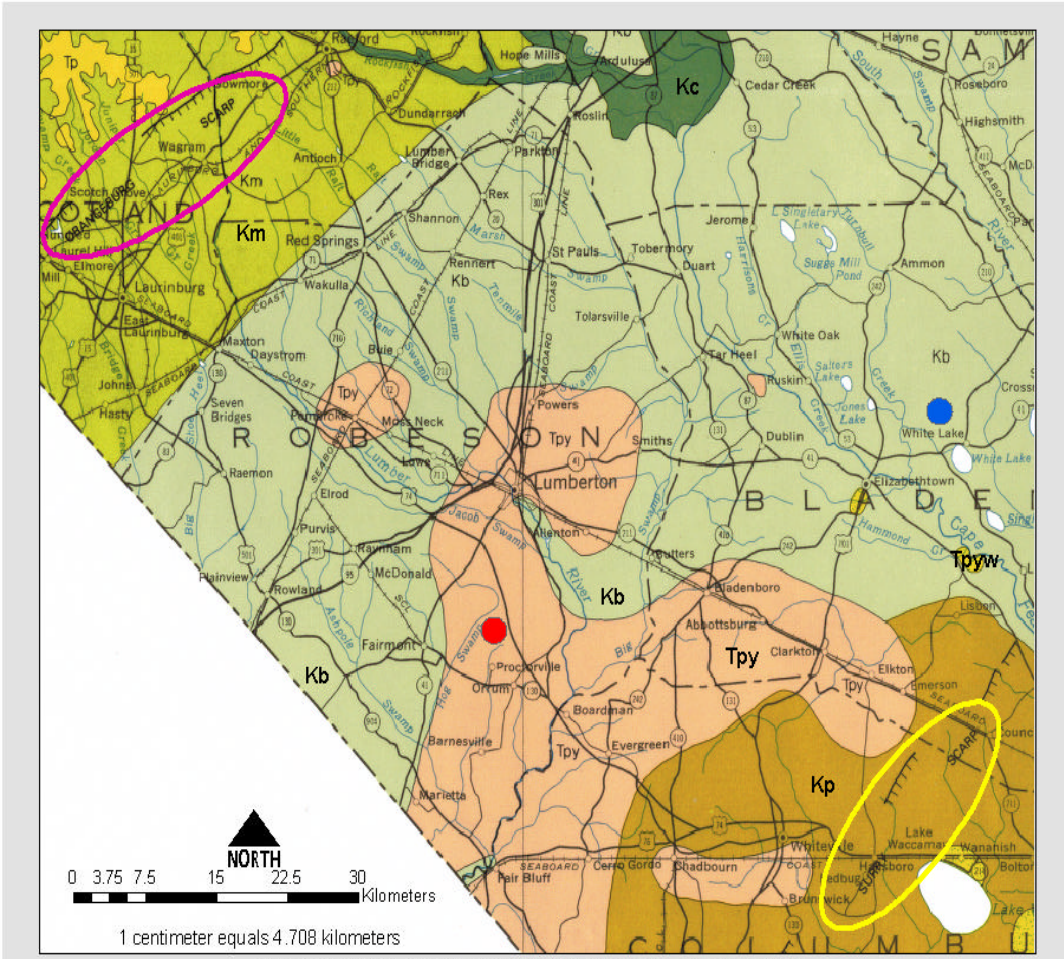

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Figure 2B. Surficial geology of Robeson and Bladen Counties, NC. Blue closed oval is approximate location of the reference bays. Red closed oval is approximate location of Juniper Bay. Note location of Surry Scarp, lower right (yellow open oval) and Orangeburg Scarp, upper left (lavendar open oval).

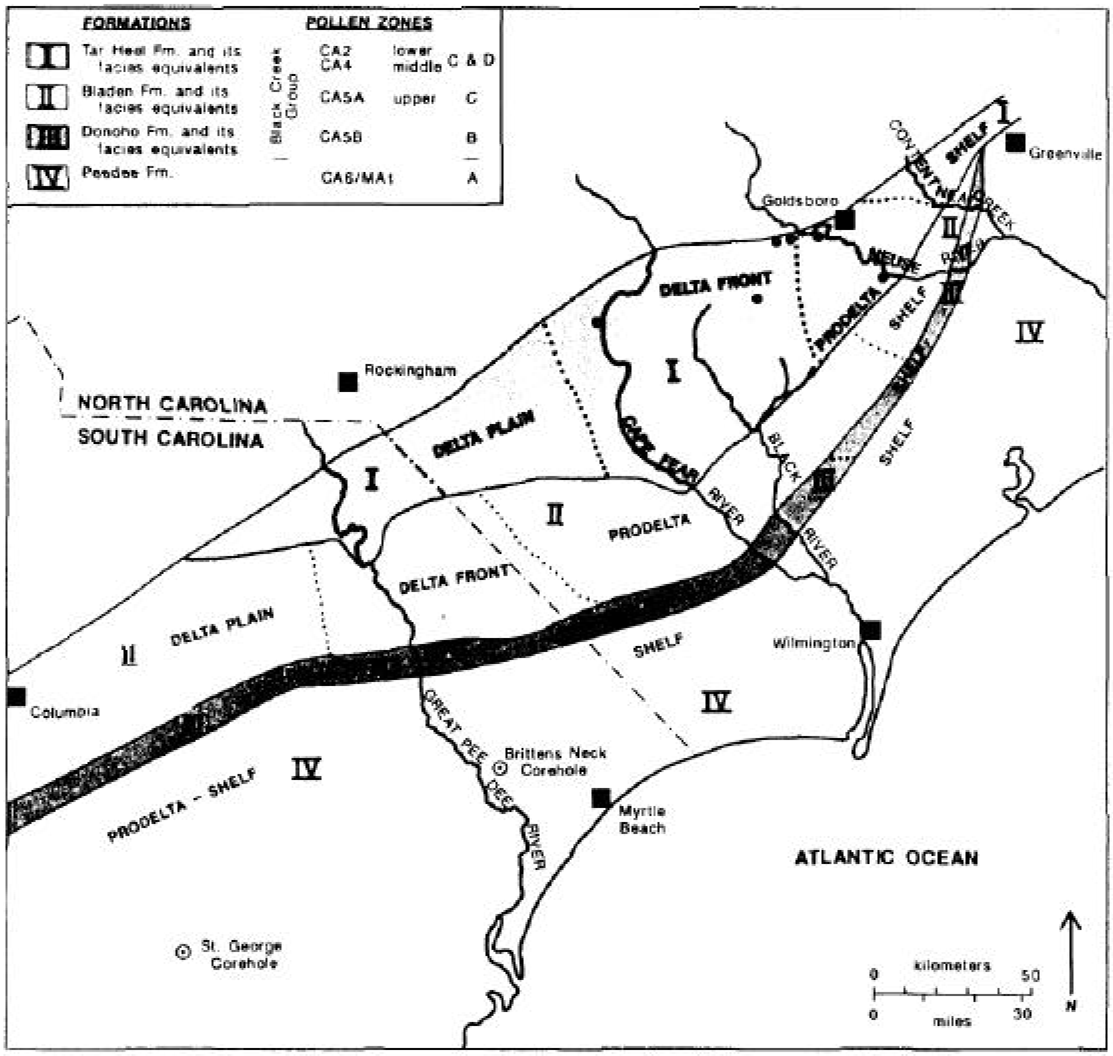


Figure 3. Outcrop distribution of the lithofacies of the formations in the Black Creek Group and the Peedee Formation. (Sohl and Owens, 1991.)

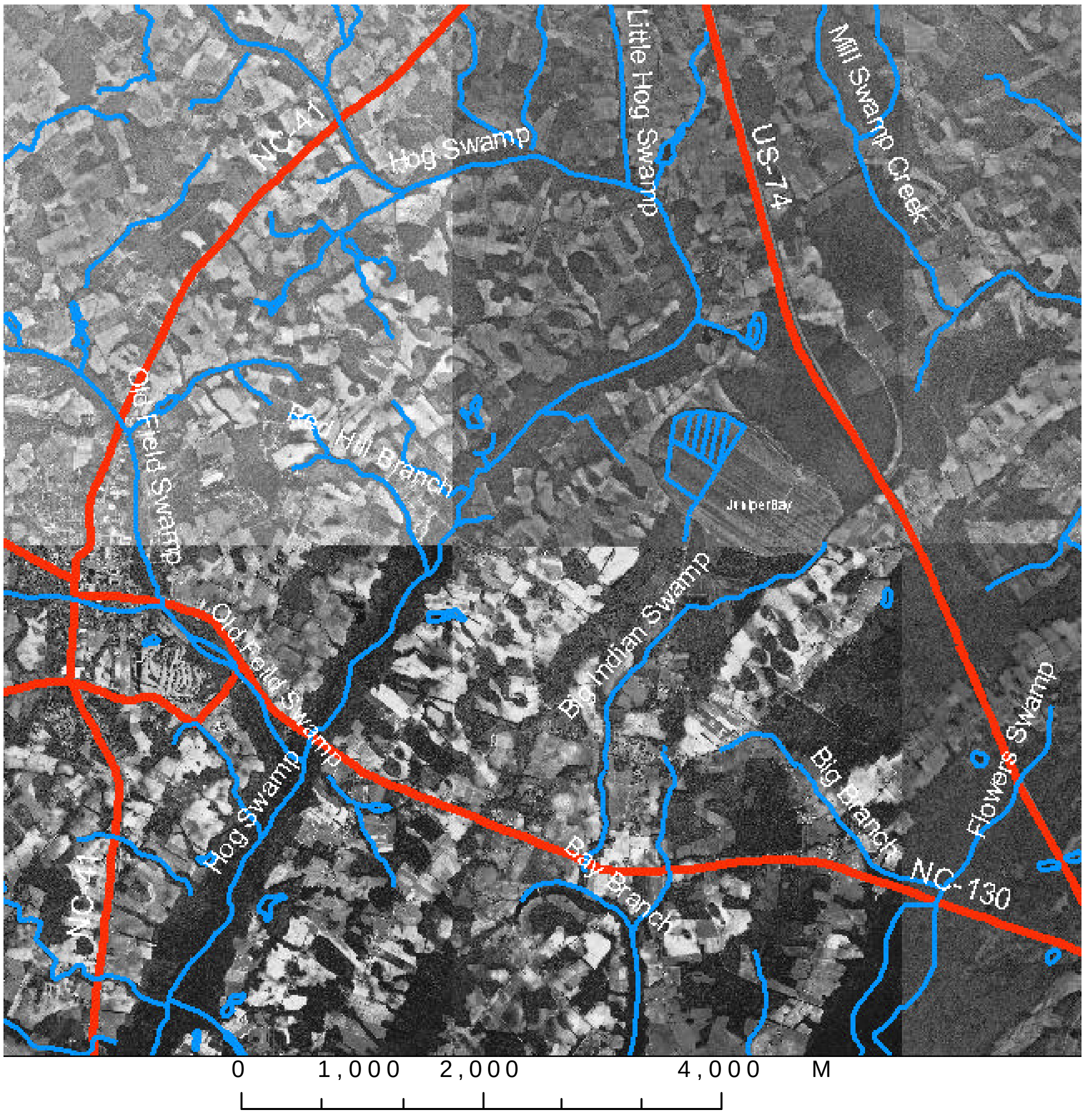


Figure 4. DOQQs of the area around Juniper Bay showing the NE-SW trending features suggesting old coastal dune systems.

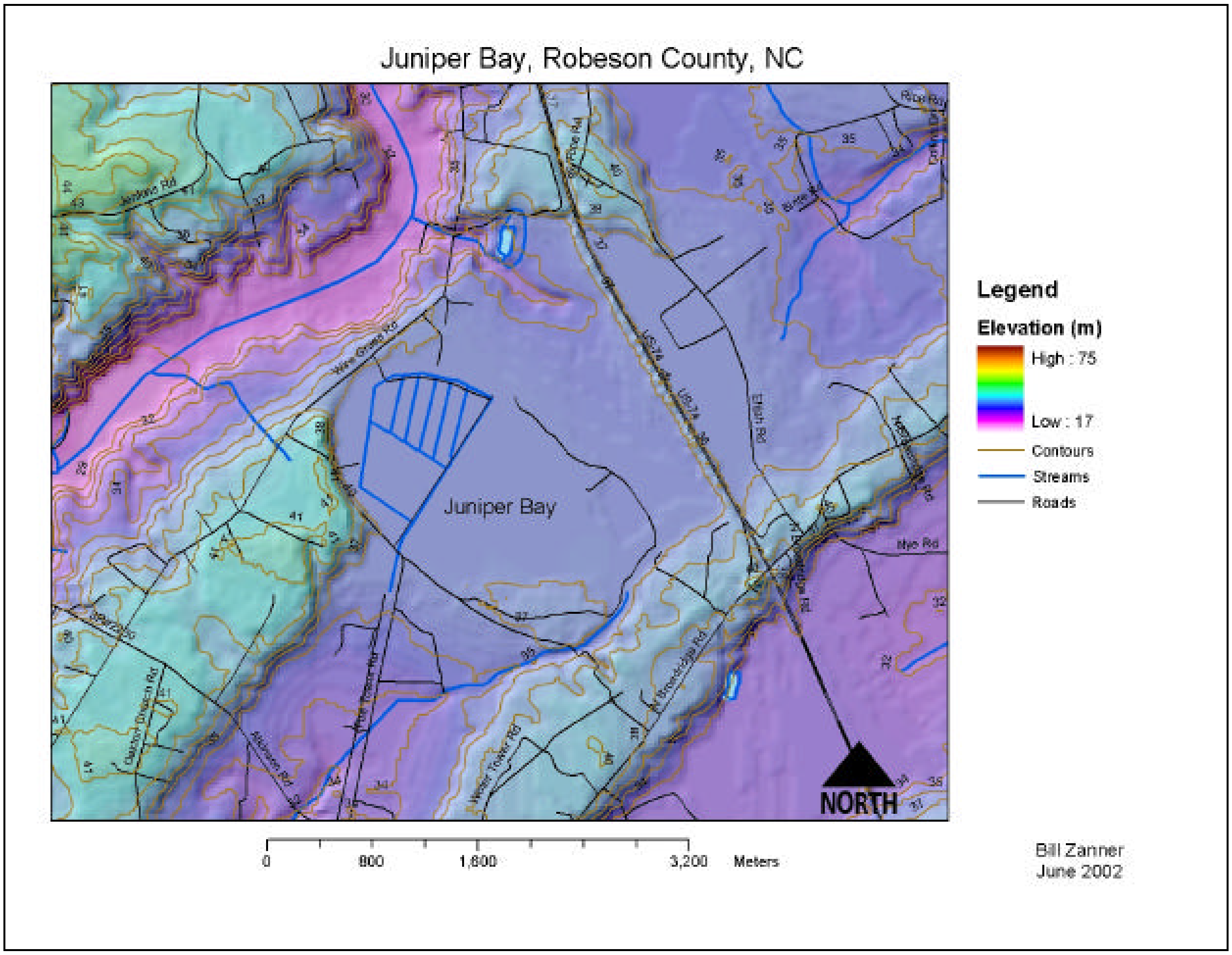


Figure 5. Digital Elevation Model of the setting of Juniper Bay (data from http://www.precisionag.ncsu.edu/data/usgs/dem/nad83m/robeson.zip, 10X exaggeration).

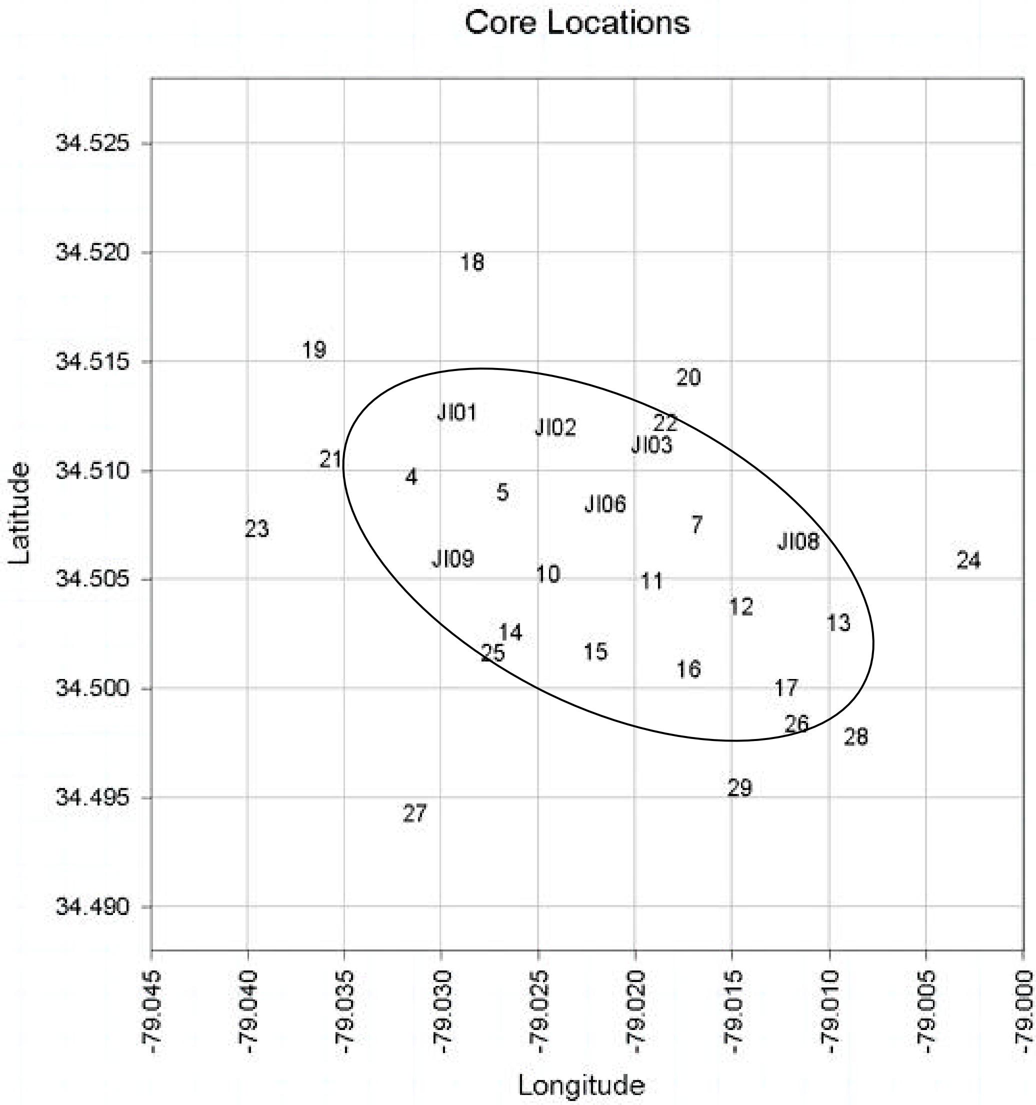


Figure 6. Locations of the 29 cores collected at Juniper Bay in August 2000. Bay rim indicated approximately by the oval line. Cores discussed in the text are marked as JI01, JI02, JI03, JI06, JI08, and JI09; other cores are indicated just by number.

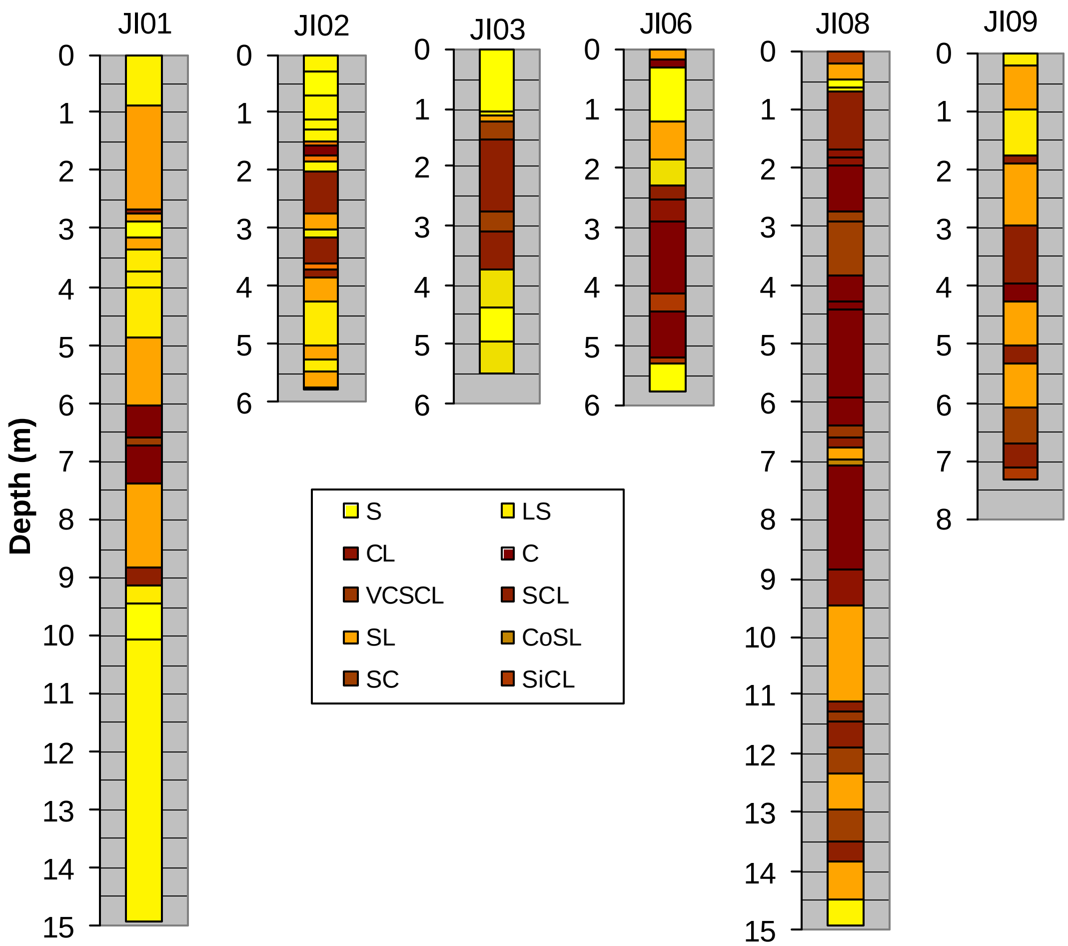
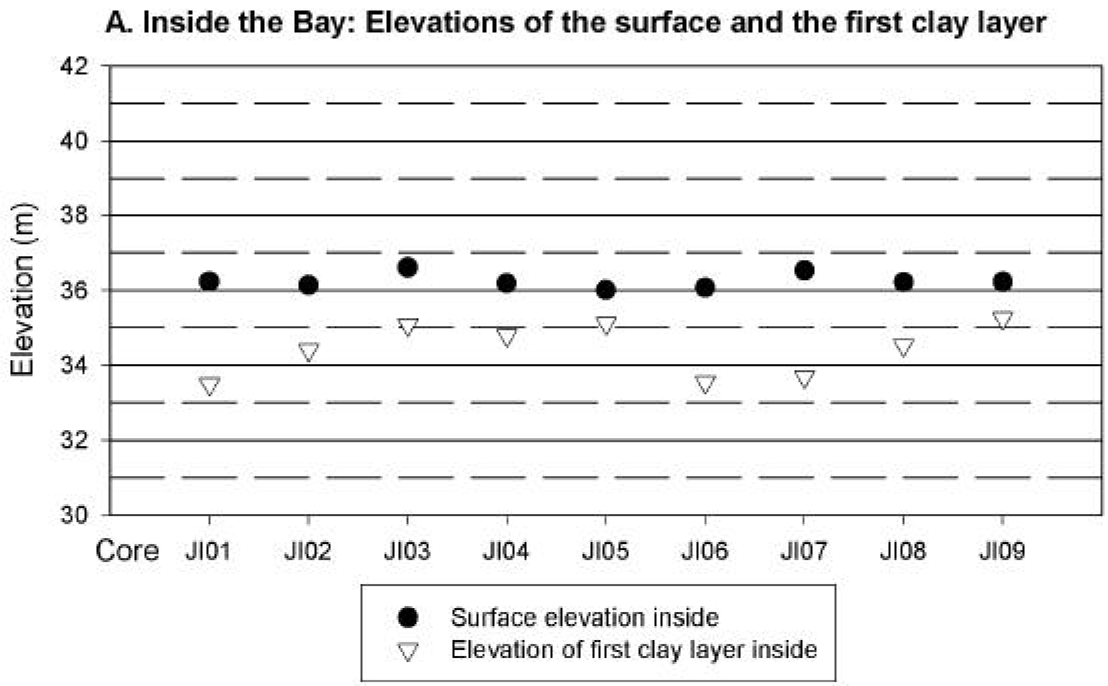


Figure 7. Core stratigraphy. S = sand; LS = Loamy sand; C = Clay; CL = Clay loam; SCL = Sandy clay loam; VCSCL = Very coarse sandy clay loam; SL = Sandy loam; CoSL = Coarse sandy loam; SC = Sandy clay; SiCL = Silty clay loam.



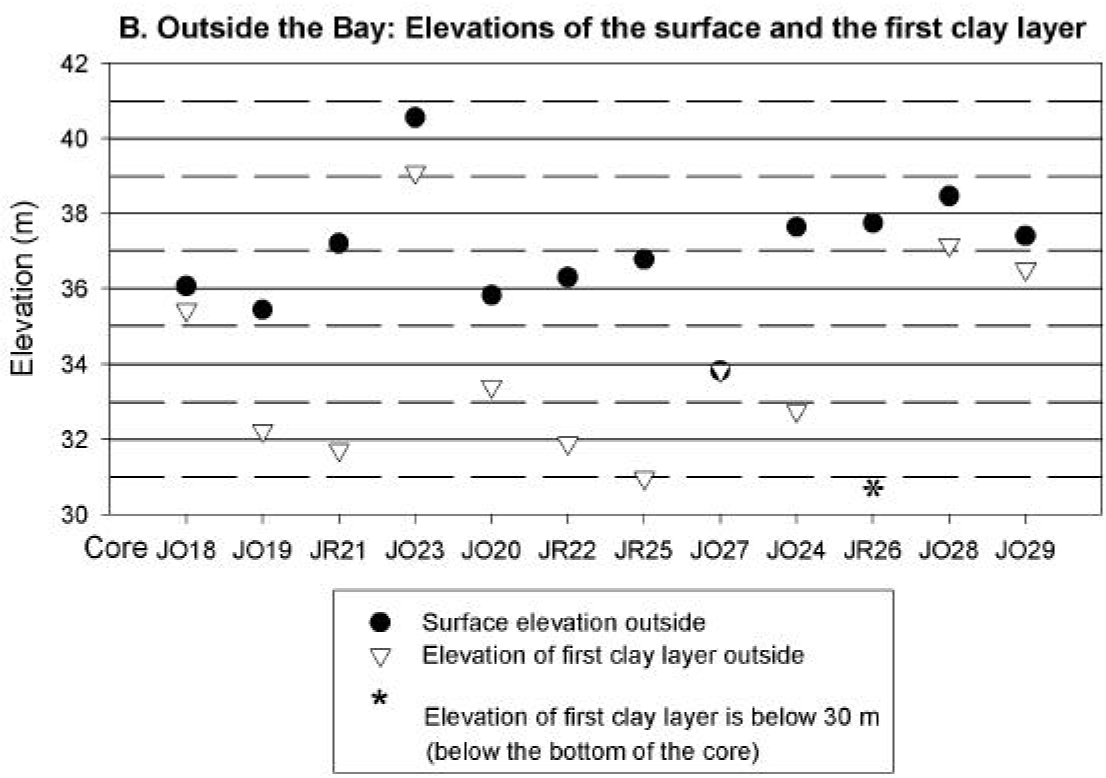


Figure 8. Elevation of the first clay layer inside (A) and outside (B) the bay.

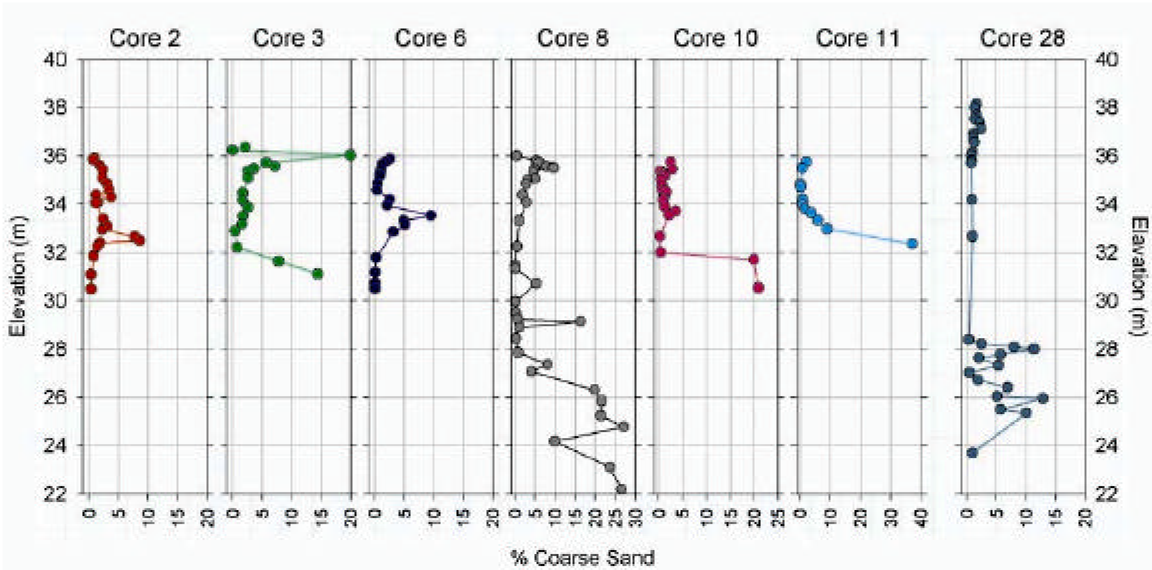


Figure 9. Coarse sand in six cores inside the bay compared to Core 28 outside the bay.

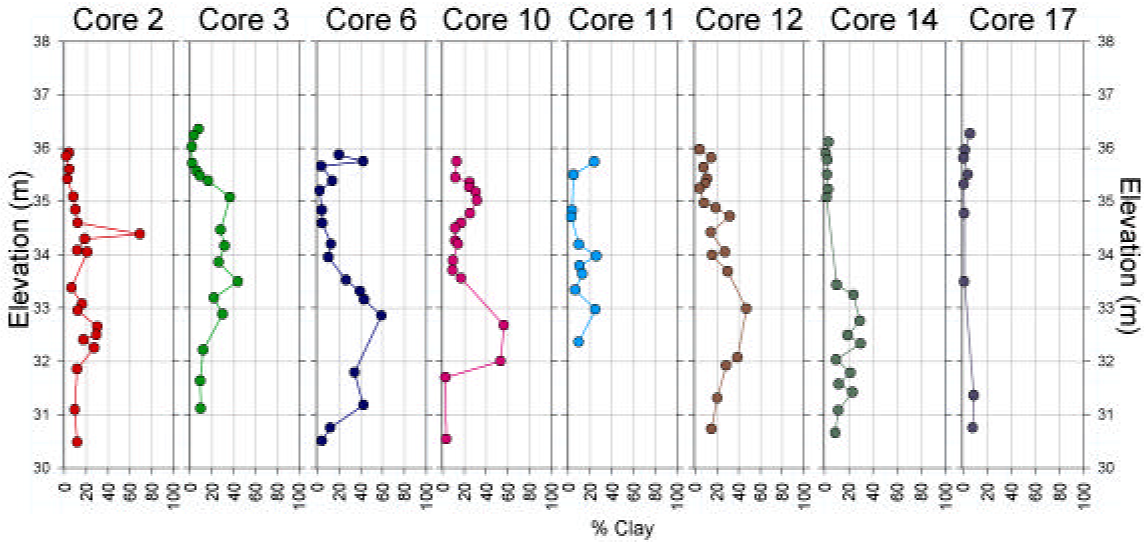


Figure 10A. Clay content of nine cores inside Juniper Bay.

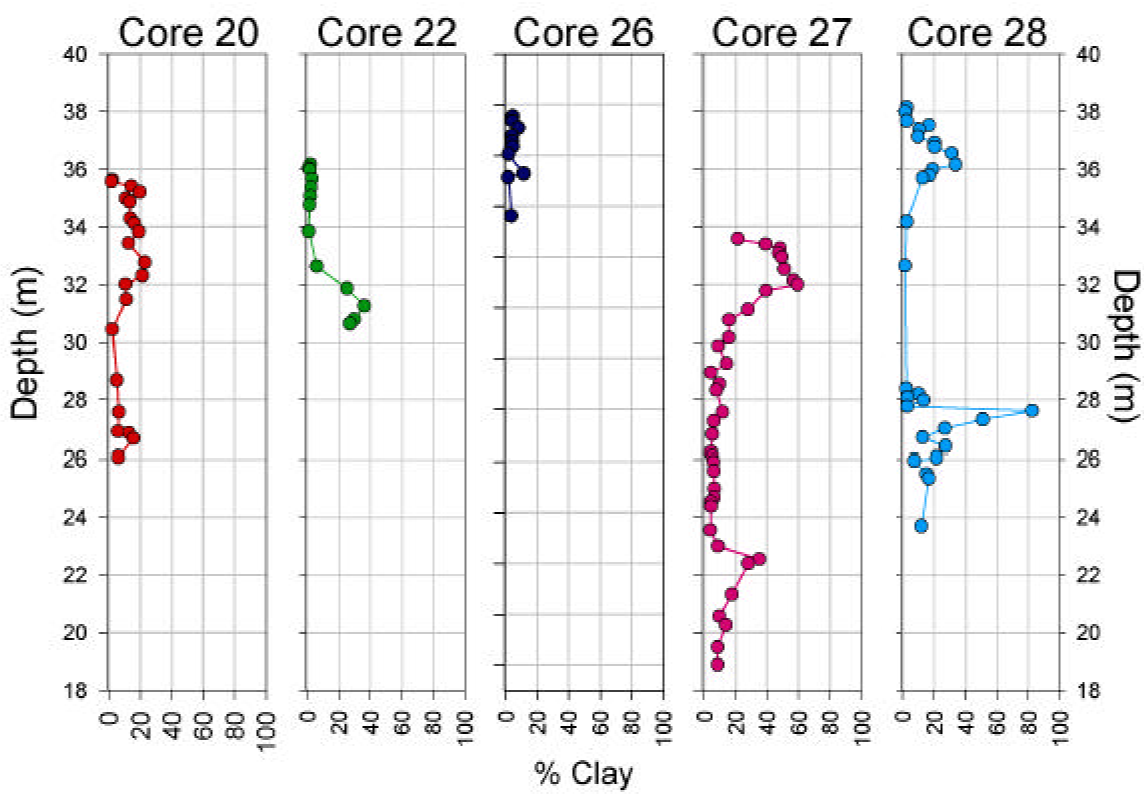


Figure 10B. Clay content of five cores outside Juniper Bay.

Table 1. Portion of the geologic time scale important to Juniper Bay geology (from Rename et al., 2001).

Geologic Time Scale Subdivisions					ESTIMATED AGE (YRS X 10^6)
Eon	**Era**	**Period**	**Epoch**		
Phanerozoic	Cenozoic	Quaternary	Holocene		0-0.01
			Pleistocene		0.01-2
		Tertiary	Pliocene		2-5
			Miocene		5-24
			Oligocene		24-38
			Eocene		34-55
			Paleocene		55-66
	Mesozoic	Cretaceous	Late	Maastrichtian	66-71
				Campanian	71-84
				Santonian	84-86
				Coniacian	86-89
				Turonian, Cenomanian	89-99
			Early		99-142
		Jurassic			138-205
		Triassic			205-250

Table 2A. Key to Figure 2A. North Carolina Geologic Survey: general geology of North Carolina near Juniper Bay and the reference bays (North Carolina Geological Survey, 1991).

Key to Geologic Units	Period	**Epoch**	**Formation**
Tpyw	Tertiary	Plio-Pleistocene	Waccamaw
Tpy	Tertiary	Pliocene	Yorktown and Duplin, undivided (Duplin south of the Neuse River)
Tp	Tertiary	Upper Miocene	Pinehurst
Kp	Cretaceous	Upper Cretaceous-Maastrichtian	PeeDee
Kb	Cretaceous	Upper Cretaceous, Maastrichtian-Campanian	Black Creek
Km	Cretaceous	Upper Cretaceous, Santonian	Middendorf
Kc	Cretaceous	Upper Cretaceous, Santonian	Cape Fear

Table 2B. Key to Figure 2B; Owens (1989) map of the detailed geology of the Cape Fear Region, scan of the portion showing mapping units around Juniper Bay.

Key to Geologic Units	**Period**	**Epoch**	**Formation**
Qwa	Quaternary	Upper Pleistocene	Wando
Qs	Quaternary	Upper Pleistocene	Socastee
Qph	Quaternary	Lower Pleistocene	Penholoway
Qw	Quaternary	Lower Pleistocene	Waccamaw
Tb	Tertiary	Upper Pliocene	Bear Bluff
Td	Tertiary	Lower Pliocene	Duplin

Table 3. Stratigraphy of southeastern North Carolina, with geologic age of each unit, unit name, description, and environment of deposition. Developed from information in Owens (1988, 1989) and Sohl and Owens (1991), and Dowsett and Poore (1991).

Formation		Age	Description	**Depositional environment**
Contemporary flood plain		Holocene, <10,000 ybp	Active flood plain	Fluvial, no Carolina Bays
Wando Formation		Upper Pleistocene, ~90,000 ybp	Terrace	Fluvial, no Carolina Bays
Socastee Formation		Upper Pleistocene, ~200,000 ybp	Terrace	Fluvial, dune fields, Carolina Bays
Penholoway Formation (fluvial facies in the Cape Fear River Valley—also in the uplands below 21 m elevation, 40 km SE of Juniper Bay)		Lower Pleistocene, >760,000 ybp	Terrace, Sand--15 m thick	Fluvial, dune fields, Carolina Bays
Waccamaw Formation		Lower Pleistocene, ~1,750,000 ybp	Terrace, sand with basal gravels; ~14 m thick. Locally, *Mulinia* fossil beds	Fluvial, dune fields, Carolina Bays
Bear Bluff Formation		Very late Pliocene-very early Pleistocene, 2,40,000-1,800,000 ybp	Terrace, sands and calcareous silts, overlies upper Cretaceous units, aragonite mollusks	Fluvial, shallow marine, poorly preserved Carolina Bays
Yorktown Formation/Duplin Formation		Early Pliocene, 3,000,000-3,400,000 ybp	Shelly, medium- to coarse-grained sand, sandy marl, bluish gray. Up dip, interbedded thin gray clay and silt and yellow sand. Lack of weathering in upper part of the Duplin indicates extensive erosion. Some sands are thicker, gravelly, cross-bedded. Some are burrowed. Often fossiliferous; fossil beds are up to 3 m thick near Lumberton, fills channels cut into underlying Cretaceous formations.	Complex marginal marine environment with interfingered marine and non-marine sands. Abundant Carolina Bays.
PeeDee Formation		Upper Cretaceous-Maastrichtian	Massive. Dark greenish-gray to gray fine sand, sparingly micaceous, glauconitic, with few marine clay beds. Calcareous. Fragmented shells. Common burrows. Irregular surface due to post-depositional erosion.	Shelf
Black Creek Group	Donoho Creek Formation	Upper Cretaceous-Lower Maastrichtian	More massively bedded in general, black clay and micaceous sand, fossils deeper in the section, glauconitic. Abraded shells. Reworked sands, bones, and teeth at bottom.	Delta front-prodelta to shelf up section. Very eroded surface. Much has been stripped from the Cape Fear arch area.
	Bladen Formation	Late Campanian	Thin laminated black clays with laminae of light colored very micaceous sands; with incised channels. No marine fossils, lignitized wood fragments.	Shelf (deeper water than the Tar Heel)
	Tar Heel Formation	Lower Campanian	Thin black carbonaceous beds of clay with cross-bedded light colored micaceous sand; pyritized wood fragments; marine bones and sharks' teeth, no bivalve fossils	In Cape Fear River area, delta front with minor marine influence
Middendorf		Cretaceous-Santonian	Interbedded black clay and sand	Delta front
Cape Fear		Cretaceous-Coniacian	Sand and clay beds of varying thickness, scattered mica	Upper delta plain

Table 4. Core observations inside the bay. JI01, 02, 03, 06, 08, and 09 stratigraphy is shown in Figure 7. The lower part of the table shows details notes in additional cores.

Cores from Fig 7	**Depth (m)**	**Observations and measurements**
JI01	0-5.8	Sandy textures with one thin (9 cm) SCL layer; rhythmites at 3.4 m
	>5.8	Grey/black colors; silty clay 5.8-7.4 ; coarser sand below 7.4 m
	6.7-8.8	Rhythmites: fines separated by thin sand lenses
JI02	0-5.8	Sandy textures with three (10, 40, 20 cm) SCL layers; Buried A at 1.1 m
JI03	0-5.8	Sandy textures with Clay/SCL between 1.2-3.7 m
	3.7	Wood fragments
JI06	0-5.8	Buried A at 1.9; wood fragments at 1.9, 2.5, 4.3, 5.5 m; sand 0-2.1 and 5.1-5.8; Clayey textures 2.1-5.1
JI08	0-7.1	0-0.7 sandy, 0.7-6.7 clayey textures; 6.7-7.1 sandy textures
	3.8-5.9	Granular structure, shell ghosts, burrows, root channels
	5.9-6.6	Rhythmites (sand lenses)
	7.1	Pebbles, 25% coarse sand
	7.1-14.9	Rhythmites; clayey 7.1-9.1, 11-13; sandy 9.1-11, 13.1-14.9
	11.9-13.4	Abundant mica
	>9.1	Coarse sand
JI09	0-7.3	0-3 m sandy; 3-4.3 clayey; 4.3-6.1 sandy; 6.1-7.3 clayey
	2.0	Buried A
	3.8-5.3	Shells (*Mulinia, Chesapecten*), shell ghosts
	3.8-7.3	Reaction to HCl
	11-13	Abundant mica
Other cores		
JI04	0-7.4	Sandy to 2.8 m with 20 cm of SCL at 1.4 m, SC 2.3-2.6 m 2.8-7.4 clayey textures with sandier textures at very bottom.
	5.8	Rhythmites
JI05	0-5.8	Buried A at 2.5 m; wood fragments at 1.8, 2.5, 4.1, 5.5 m. Sandy with clayey textures 0.9-2.1 m and 2.3-3 m.
JI07	0-5.8	Sandy to 2.8 m; clayey textures to 5.7 with sand at very bottom; Buried A at 0.7, 2.4, and 3.4 m
	3.4 –5	Clay with vertical seams of sand
JI10	0-5.8	Sandy textures with SiCL between 0.75 and 1 m and clayey textures 2.5-4 m; very coarse sand at 4.3 m
	5.5	Rhythmites (sand lenses)
JI11	0-5.8	Buried A at 1.2 m; shell ghosts at 3.3 m; sandy textures with loam: 30 cm at 1.7 and 40 cm at 2.6 (with root fragments).
JI13	0-7.3	Sandy with clayey textures 1.2-2.5 m and 6.6-7.3 m
	> 6.6	Black clayey textures
	4-5.9	Rhythmites

Chapter 3

HISTORICAL RECORDS OF AGRICULTURAL PRACTICES THAT AFFECTED HYDROLOGY AND SOILS AT JUNIPER BAY

J.M. Ewing, M.J. Vepraskas, and C.W. Zanner

INTRODUCTION

Wetland restoration is being conducted on an increasing scale throughout the U.S. In the southeastern U.S., wetlands that were cleared and drained for agriculture in the 1930's or later, are now having their ditches plugged to restore the original hydrology and wetland trees are also being planted to restore the original vegetation. Such restoration is expensive and any information that increases the likelihood of success is of value. We are involved in a current restoration of a Carolina Bay wetland in North Carolina. As part of this effort we assembled a record of historical data on land use that provided additional insight into practices that have affected both the soils and hydrology.

In our experience, historical data on land use is frequently not used in planning restoration activities. Water sources such as surface inflows and outflows can affect restoration and should be know before hydrologic alterations are designed. Existence of perennial natural lakes suggest groundwater inflow is an important contribution to a wetland's hydrology. However, small lakes or ponds may not appear on all soil maps, especially if the area has been drained for agriculture. Many construction or demolition projects, land clearing, mining and farming can leave the landscape looking unaltered, but examinations below the surface can show dramatic soil variability due to human activities. For example, soils developed from mine spoils have been shown to be more variable between 1 to 10 m depths than natural soil (Shafer, 1979). In soil research studies it is important to have a grasp on the variability of the soil so that the correct number of samples can be taken. In areas known to be altered by human activity, it can be beneficial to collect historical land use data to document where and when alterations occurred that could explain variation.

The North Carolina Department of Transportation (NCDOT) bought 750 ac (256 ha) of drained agricultural land in 1999, near Lumberton, North Carolina. This land was purchased with the intent of returning it to its natural state so that the NCDOT would gain wetland mitigation credits. The NCDOT awarded a seven-year grant to North Carolina State University, Soil Science Department, in 2000, to evaluate and help develop methods of restoration that will insure success. The Carolina Bay being restored is called Juniper Bay. Since one of the hopeful outcomes of this project is the restoration of soils typically found in Carolina Bays we had to describe the soils as they were after drainage and agriculture production and to examine soils of undrained Carolina bay soils. This Carolina bay wetland was altered thought ditching and other to allow agriculture production to occur. However former land owners also reported other activities that had occurred that may have altered soil properties.

The purpose of this study was to assemble an historical record of land use spanning the last 80 years to find potential sites of human induced variability and discuss implications on wetland restoration.

MATERIALS AND METHODS

Site Description

Carolina bays are elliptical depressions in the landscape that are orientated along the long axis SE to NW (Prouty, 1952). They range in size from 40 ft (10 m) to >2.5miles (4 km) along the long axis. The bays are usually surrounded by a sandy rim and have a high amount of organic matter within the depression (Johnson, 1942). The extent of these bays range from Northern Florida to Delaware with the highest concentration in North and South Carolina. Estimates on the number of these bays are as high as 500,000 (Johnson, 1942), but the actual number maybe less than 100,000 (Nifong, 1998). Many theories for bay formation have been proposed, from the most popular, meteor impact (Johnson, 1936), artesian springs (Prouty, 1952; LeGrand, 1952), whale wallows (Grant 1945), and ice flows (Bliley and Burney, 1988). Currently the most plausible explanation is that originally there was a slight depression in the landscape with a shallow aquitard that allowed the water table to be held above the surface. Prevailing winds then shaped the depression into the now familiar orientated shape (Thom, 1970; Odum, 1952). During the past century agricultural and community development have led to the drainage and use of these bays. It is estimated that 50% of all Carolina bays were drained and developed in some manner in Bladen County, NC by 1982 (Weakley and Scott, 1982). This figure would be higher if other management practices such as logging were included. As these bays are used for agriculture and other activities, their defining characteristics of sand rims and organic surfaces, become blurred into the surrounding landscape.

The Carolina bay in question is called Juniper Bay and is located approximately 7 miles (10km) south of Lumberton, North Carolina. The soil survey of Robeson County (Fig.1), shows Juniper Bay with areas of Ponzer (Loamy, mixed, dysic, thermic Terric Haplosaprists), Leon (Sandy siliceous, thermic Aeric Alaquods), Pantego (Fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults), Rutlege (Sandy, siliceous, thermic, Typic Humaquepts) (McCachren, 1978). An earlier soil survey (Hearn, 1909) identified the soils in Juniper Bay as Portsmouth fine sandy loam.

Sources of Information

There were several sources of information that we used to conduct the historical land use search. They included aerial photos from the United States Aerial Photography Service Office, the former landowner, Mr. Robert Freeman, courthouse documents and the National Railway Historical Society (NRHS). Aerial photos were available from 1938, 1952, 1961, 1966, 1972, 1981, 1991, and 1997, and were obtained from the USDA-FSA Aerial Photography Field Office, 2222 W 2300 S, Salt Lake City, UT 84119-7619. Mr. Freeman provided a wealth of information about Juniper Bay before it was drained.

He was also the person who drained and placed Juniper Bay into agricultural production. Documents found from the Robeson County courthouse provided a history of ownership and use. The NRHS provided information concerning a railroad that ran through Juniper bay and how the tracks were constructed.

RESULTS AND DISCUSSION

1911-1938: Railroad Years

A Robeson County road map found at the county court house, dated 1922, showed a creek flowing out of Juniper Bay that was initially unnoticed in the aerial photos. This creek flowed out of the NE corner and was originally the head water of Little Indian swamp which flowed south into Big Indian Swamp which fed into Ashpole river and finally into the Lumber River which is an important river in the area. A faint outline of this creek was discovered in a few of the older aerial photos upon close examination. The 1938 aerial photo (Fig. 2) shows that Juniper Bay was heavily forested. The vegetation supported abundant wildlife. Mr. Freeman told of seeing deer, black bear, beavers, bobcats, snakes, foxes, otters, and hundreds of geese and ducks when he hunted there before draining Juniper Bay. The densely forested bay contained large Atlantic White Cedars, Bald Cyprus, Tupelos, and various Bay trees.

While virtually undeveloped, the site did have a railroad line running through it in a north-south direction. Mr. Freeman remembered stories about how his father would hop the train in Fairmont and ride it10 miles into Lumberton to conduct business. A map of the Seaboard Airline Railway (SAL RY) in 1911 (Prince, 1966) showed a route running from Lumberton through Ashpole (Fairmount) and to Pee Dee (just NE of Marion S.C.). This route would run through Juniper Bay and is identified (Fig. 3) in the 1909 soil survey of Robeson County (Hearn, 1909). The company that built and owned the railroad that ran between Lumberton and Marion, South Carolina, was The Raleigh-Charleston Railroad Company. The Raleigh & Charleston Railroad (R&C) was formed in December of 1905 (Carriker, 1985a). SAL RY bought controlling stock of the R&C in November 1911 (Cariker, 1985b), and in 1933, 23 miles of its line between Lumberton, N. C. and Lakeview, S.C. in 1933, and the remainder into Marion in 1946 (Prince, 1966).

The railroad bed was 4 to 5 feet (~1.5m) above the surrounding terrain. Mr. Freeman recalled that there was one ditch that ran along the track, and that it appeared the railroad bed was mostly fill material from the ditch. With the assistance from the NRHS, literature was found that supported the Mr. Freeman's description of the construction of the railroad bed in Juniper Bay. During the time of R & C, the common construction practice was to dig a ditch and use the spoil for the railroad bed (Kirkman, 1904). The ditch supplied fill for the bed, and was not dug for drainage or long-term bed stability. Clay was brought to the site to stabilize sections of the bed at a later date. We estimate that the railroad bed in Juniper bay was elevated to match the surrounding areas, resulting in a bed elevation of 3 to 5 ft (~1-1.5m) above the surface inside the bay. This bed was also estimated to have been approximately 10 ft (~3m) wide with an adjacent ditch on one or both sides of the bed. Ditch depth probably ranged from 5 to 10 ft (~2-3 m), but an exact depth could not be determined. It is still possible to see where the location of the old railroad in current aerial photos. In addition, a slight crest across the bay where the bed used to be can still be seen when in the field. We have also found several rusted railroad spikes along the old railroad transect during our field studies.

While the railroad's tracks are visible in the 1938 photograph, it was apparently abandoned by that time. It is uncertain if the tracks were removed by 1938. During our soil sampling, pits placed where the old railroad bed was did have evidence of disturbance by excavation and filling to a depth of one meter (Fig. 4). This disturbance could be traced along the railroad line, and was considered to be of small extent.

1938-1966: Forest Harvest

Aerial photos from 1958 showed little change in Juniper Bay since 1938, but by 1966 some major changes had occurred. M. Carr Gibson of Canal Industries bought the land from Lawrence Ballard in the mid 1960's to harvest trees. The 1966 aerial photo (Fig 5) shows an outline through the vegetation where drainage ditches will be located, and also shows that some of the vegetation has been thinned. One ditch runs parallel, possibly adjacent to the old railroad bed. Another ditch will run SW to NE and with another perpendicular ditch to run SE to NW. Canal Industries harvested timber from the entire the bay except for the area around the center of the bay that contained a shallow lake and parts of this lake can be seen in the 1966 photo.

By the time Canal Industries sold Juniper Bay to Robert Freeman Sr., a drainage system on the NW side of Juniper Bay had been constructed (Fig. 1). This drainage system included a perimeter drainage ditch surrounding the NW end of the bay, five lateral drainage ditches running parallel to the railroad bed on the north side of the NW/SE ditch, and one ditch that ran the width of the bay. It is uncertain if the railroad bed had been leveled at this time but the drainage ditch along the old railroad bed probably still served as a collector to the main outlet. During the time Canal Industries owned Juniper Bay, the Robeson Co Soil Survey was being conducted. Willie Spruill, a soil surveyor who helped with the survey, has stated that often Carolina bays were so thick with vegetation that it was impossible to conduct a thorough survey through the bay itself. Often the Carolina bays were mapped extrapolating soil map units into the Carolina bays from adjacent lands. Vegetation patterns visible on aerial photos were used to estimate map unit boundaries within the bays (Soil Survey Manuel, 1993, Buol et al., 1997). Mr. Spruill could not recall if this is how Juniper Bay was mapped and it is uncertain how accessible Juniper Bay was at the time of mapping, however, the 1966 and the 1971 aerial photographs show that the soil delineations follow vegetation patterns fairly well.

1975-1981: Clearing and Cultivation

Mr. Freeman's father purchased Juniper bay in October 1975 and drainage of the bay for agriculture began during a dry summer in 1979. This was no small operation, and over 15 individuals were employed to operate 10 bulldozers, 3 trackhoes, and a dragline.

Over a period of 9 months in 1979, the railroad bed was leveled and the parallel ditches were filled. Mr. Freeman said that when he was ditching the bay, there were many creosote crossties that remained, but no rails. Lines where the lateral, main and perimeter ditches were to be located, evenly spaced, were cut with handheld equipment including chainsaws, machetes, and bush-axes because the soils were too wet to support heavy equipment. While cutting over 30 miles (48 km) of trails for the ditches, workers would climb up in the trees to escape the stifling heat and mosquitoes during lunch and work breaks.

Once trails for the ditches were cut, a trencher was used to excavate the ditches inside the bay. Workers had to lay logs and other debris ahead of the trencher so it had a "solid surface" to work on. A dragline was used to dig the perimeter ditch on the sandy rim of the bay. During the ditching and clearing operations, many preserved trees, logs and roots were pulled from the muck with tree rakes (Fig 6). For years after the clearing occurred, any time the fields were tilled, wagonloads of roots and debris had to be removed. During our sampling of soils in 2001 we did find buried roots of trees in many pits.

After enough drainage had occurred to allow the soils to support the weight of heavy equipment, debris was windrowed with bulldozers into piles 40 to 50 ft wide (~15-20m), that ran the length of the bay (Fig. 7). The debris was then burned, with some piles burning for 2 to 3 years. The debris fires ignited the peat that lined the bay floor, and in some areas burned the surface was lowered 2 to 3 ft (50-90cm) to either a mineral layer or the water table. This created a depression that filled with water and was inaccessible with any equipment (Fig. 8). To drain the depressions, an additional ditch had to be dug or the depression had to be filled. Fill material would come from another ditch, located near the depression. This is why the lateral ditches do not match up across the length of the bay, the cuts are of uneven size, and the distance between cuts decreased. After the ditches were in place and sufficient drainage had occurred, spoil from the ditches were used to shape all the fields such that the center of the field was approximately 18 inches (45cm) higher than the edges to increase surface runoff. This practice is locally called "crowing" or "turtle backing."

1981-2000: Agriculture Production

The aerial photo from 1981 (Fig.9) shows almost all of the bay completely drained and in agricultural use except for a small corner in the NE section. This was and is the wettest and lowest area in the bay. This was re-emphasized when a landowner adjacent to Juniper Bay on the NE cleared and ditched a small parcel of land and tied into Juniper Bay's drainage system. Unfortunately for this farmer, his land was lower than the main outlet of Juniper Bay, and thus his new field became a semi-permanent pond. That landowner eventually disconnected from Juniper Bay's drainage system. The NE corner of Juniper bay was cleared and drained in 1986, and put into production the following year.

Currently, 2003, Juniper Bay is drained though one outlet point (Fig.10). There is a perimeter ditch around the whole bay, and two main ditches that run SW/NE and one that runs SE/NW, which are approximately 9 feet (3m) deep and 20 feet (6m) wide. Perpendicular to the SW/NE main ditches are lateral drainage ditches that are approximately 3 ft (1m) deep and 5ft (1.5m) across. Mr. Freeman stated that ditches were maintained as needed yearly. Every 5 or 6 years all ditches were cleaned using a piece of equipment, called a Dondi ditcher (Fig. 11), that dredged out the ditch and slung the spoil out over the field, where it was disked in.

Mr. Freeman maintained excellent records and has soil test results dating back to 1976 giving us an idea of what the chemical variability was. The 1976 soil test analysis of the plow layer from various (unknown) locations across the bay, conducted by Brookside Farms Laboratory Association, Inc., showed that pH ranged between 3.6 and 4.8, cation exchange capacity 2.76-14.04 meq $100g^{-1}$, 2.7 to 11.5 % organic matter, 145 – 2240 lb/ac P, 279-698 lb/ac Ca, 26-363 lb/ac K, and 31-51 % base saturation. Soil test reports from 1978 and 1979, by A & L Eastern Agricultural Laboratories, Inc., of Richmond, Virginia, show approximately the same values. Mr. Freeman estimated that 15 to 20 cumulative tons per acre of lime have been applied over the years in addition to the yearly-recommended fertilizer rate. Crops grown in Juniper Bay included; soybeans, corn, tobacco, cotton, oats, millet, wheat, and vegetable crops like lettuce and okra. One year, a leasing farmer raised winter wheat and burned the stubble off leaving a blanket of ash that looked like snow. Of course this re-ignited some of the peat, burning some areas down to the water table, most notably in the NE corner.

Use of Historical Data

Historical information has provided insight into spatial heterogeneity of the soils and hydrology that we have at Juniper Bay. Successful restoration depends on a returning the site's hydrology to what it was prior to ditching. The historical record has given us a glimpse of the past hydrology. The 1922 Robeson, County map documented the creek on the NE side of the bay that was historically a source of surface water removal. The aerial photos and personal accounts indicated the existence of a natural lake in the center of the organic soils. This was unexpected because none of the neighboring bays have lakes or even organic soils. This suggests that Juniper Bay was receiving subsurface inputs of water, unlike the neighboring bays, which may have been rain-fed. Our hydrologic measurements are confirming that groundwater upflow (discharge) does appear to be occurring on the north side of the organic soils.

The historical record has also shown that human activities have affected soil variability in Juniper Bay. We were able to document processes that affect organic soil subsidence, and estimate that 2 to 3 ft (50-90cm) of subsidence has occurred. It is well known that organic soils subside following drainage (Everett, 1983). Processes responsible for this include a rapid settling of material as it loses the buoyant force provided by water after drainage (primary subsidence), oxidation of organic matter, and shrinkage of the organic material on drying (both termed secondary subsidence). The historical record shows that the primary subsidence can be increased by compaction from the heavy equipment used to clear the land. More importantly, fire increases oxidation rate of organic matter. The historical record has shown that fire events have occurred in Juniper Bay more than once and one fire burned for 2 years. We found evidence of fire, including charcoal and ash, in several soil profiles throughout Juniper Bay. We have dated charcoal and other buried vegetation to 8400 and 3100 years before present (Zanner, 2001 personal communication). The burning also explains why some of the wettest areas in the bay were devoid of organic soils. Estimating the amount of subsidence that has occurred is useful to predict the elevation of the original water table, and the potential elevation after restoration.

Construction of the railroad and the current and previous ditching systems has altered the soils to depths of 1 m and more. Historical aerial photos provided approximate dates showed where the ditching occurred. We were able show how the fill from the railroad bed changed the soil profile, which allowed us to factor in similar areas during studies of the soils and hydrology. The present soil material at the surface is not necessarily a product of the original soils owing to the spreading of dredge material during canal construction. The surface of Juniper Bay has been shaped several times since drainage to promote surface drainage, and ditch maintenance brought subsurface material to the surface and broadcast it over the field.

Our historical records also included the dating of agricultural development including application of lime and fertilizer. Leaching of agricultural chemicals, notably phosphorus, to the groundwater is currently of great interest because it reduces quality of surface waters. The historical record provided specific dates for when chemical additions began. This information is being used to evaluate the rate and depth of chemical movement through the soil profile over 15, 20, and 30 years of agricultural additions across the bay.

By establishing the presence of spatial variability prior to drainage evaluation of restoration efforts should not expect uniform results over the entire area. Although many early soil surveys identified wetland areas only as swamps, marshes, etc., important soil properties were not identified or spatially mapped. Many of the soil properties appear related to underlying hydrology that will again influence restoration results.

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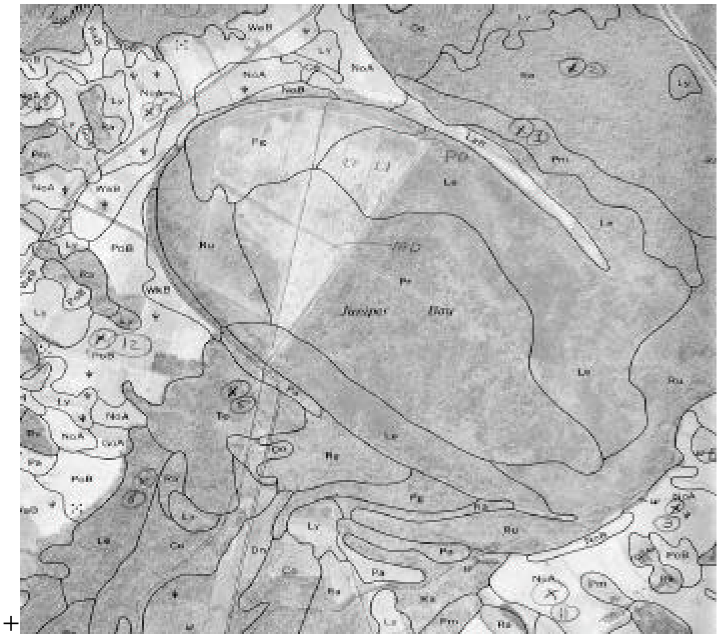


Legend

Co- Coxville loam
Dn- Dunbar sandy loam
LaB- Lakeland sand 0-6%
Le- Leon sand
Ly- Lynchburg sandy loam
GoA- Goldsboro loamy sand, 0-2%
NoA- Norfolk sandy loam, 0-2%
NoB- Norfolk sandy loam, 2-6%
Pg- Pantego fine sandy loam
Pm- Plummer and Osier
PoB- Pocalla loamy sand, 0-3%
Pr- Ponzer muck
Ra- Rains sandy loam
Ru- Rutledge loamy sand
To- Torhunta loam
WaB- Wagram loamy sand, 0-6%
WkB- Wakulla sand, 0-6%

Figure 1. Aerial photo 1972 and Soil Survey map of Juniper Bay, Sheet 61 (USDA-SCS,1978).

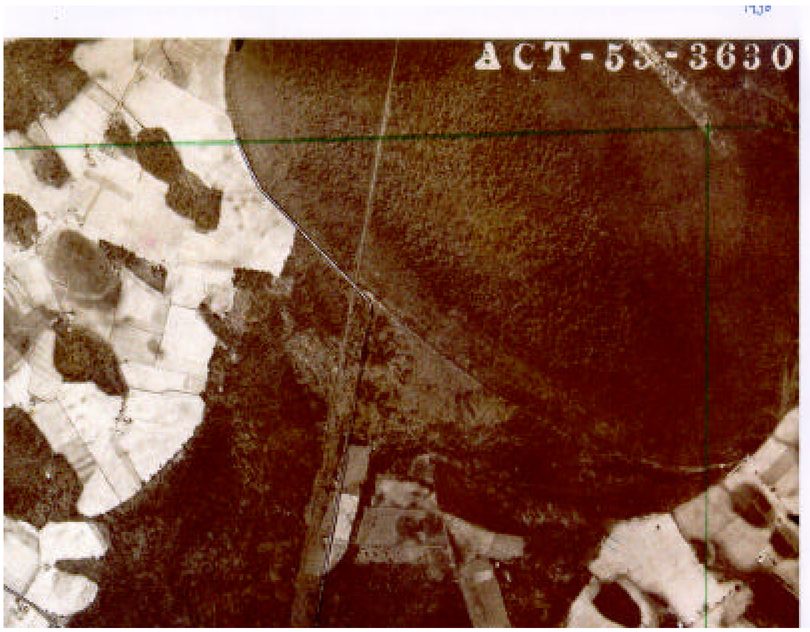
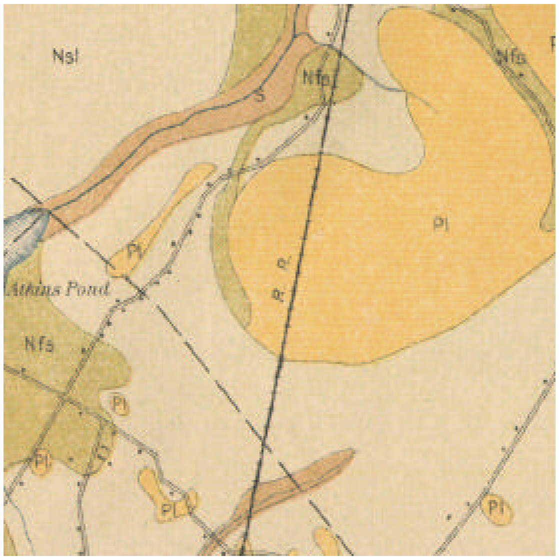


Figure 2. Aerial photo of Juniper Bay in 1938 (National Archives and Records Administration).



Legend

Nsl- Norfolk fine sandy loam
Nfs- Norfolk fine sand
Pl- Portsmouth fine sandy loam
S- Swamp

Figure 3. The 1909 Soil Survey of Robeson County (Hearn, 1909) shows the Raleigh & Charleston Railroad going through Juniper Bay. The “R.R.” on the map is located inside the boundaries of Juniper Bay.

Figure 4. Soil profile showing a prior ditch and subsequent fill material from the railroad transect. Arrow points to the interface between undisturbed soil and ditch fill. Scale is in cm.

Figure 5. Aerial photo from 1966(USDA-FSA).

Figure 6. Log-rake pulling log from the soil in the Blacklands of North Carolina (with permission S.W. Buol).

Figure 7. Debris from clearing piled into windrows in the Blacklands of North Carolina (with permission S.W. Buol).

 a. 

b

Figure 8. a). Windrows burning down to mineral. The white areas are ashes from the most intense fire and the black areas to the right are areas of largely unburned organic soil. b). Loss of approximately 30 miles (48km) organic soil after a wild fire in the Blacklands of North Carolina (with permission S.W. Buol).

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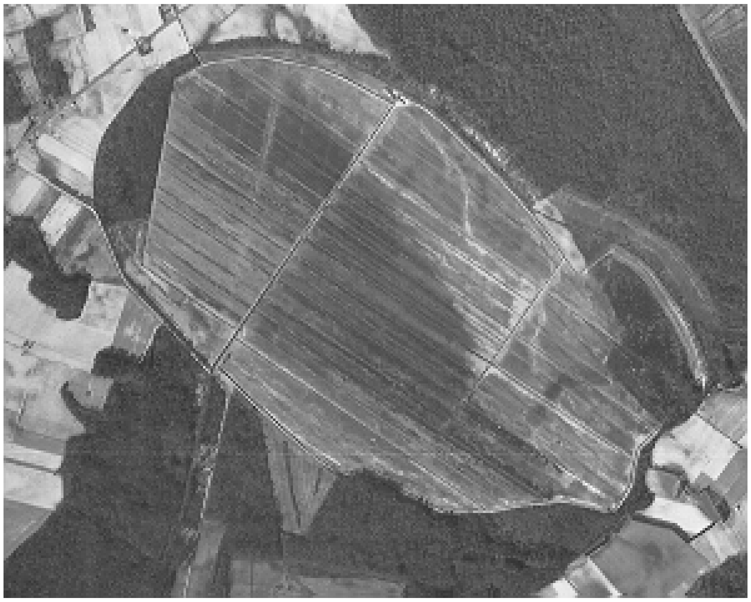

Figure 9. Aerial photo of Juniper Bay from 1981(USDA-FSA).

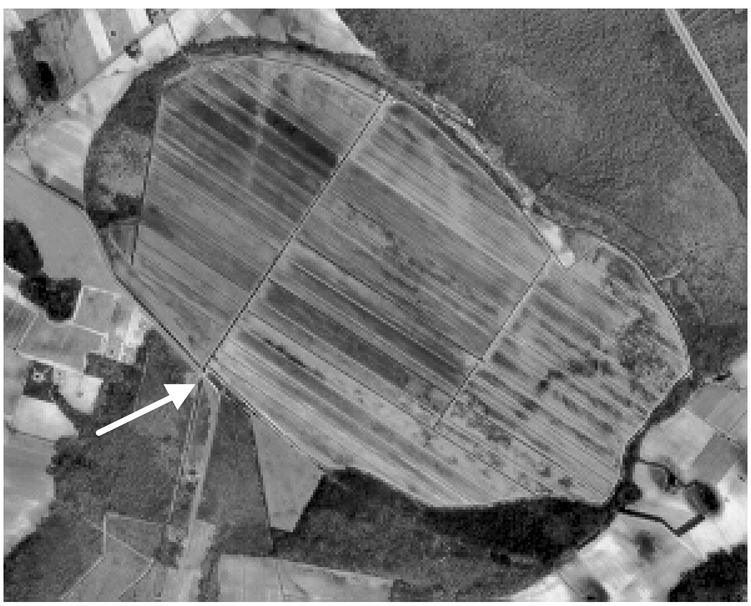

Figure 10. Aerial photo of Juniper Bay from 1993 (USDA-FSA) Arrow indicates drainage outlet.

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Figure 11. Ditch maintenance with a Dondi ditcher.

Chapter 4

VEGETATION OF THREE REFERENCE CAROLINA BAYS IN RELATIION TO SOILS AND HYDROLOGY

B. Lees, J. M. Stucky, M. J. Vepraskas,
and T.R. Wentworth

INTRODUCTION

Carolina Bays are unique ovoid depressions distributed throughout the Atlantic Coastal Plain from Florida to Virginia. An estimated 13,000 Carolina Bays exist in North Carolina and South Carolina alone. Unaltered Carolina Bays are consistently elliptical, oriented along a northwest to southeast axis, exhibit a sand rim along the eastern side of the depression, range in size from less than 50m to 8km (5 miles) across, and contain deepwater or depressional wetland habitat (Sharitz and Gibbons, 1982). Prouty's (1952) estimate of 400,000 - 500,000 total Carolina Bays is now considered a gross overestimate and is thought to have led to a low conservation priority and, consequently, a high exploitation rate (Nifong, 1998). Humans have cleared the native vegetation from and altered the hydrology in 79% of the Carolina Bays that have been identified (Nifong 1998). Collectively, unaltered bays function as wildlife habitat for several endangered animals (Clark et al., 1985; Zevelof, 1983), provide habitat for several rare plant species (Weakley, 1982), support an array of unique plant communities (Weakley, 1982), provide stormwater storage on a landscape level, and act as carbon sinks (Richardson et al., 1981; Bridgham et al., 1991). Therefore, it is important to understand the structural attributes (vegetation), physical settings (geomorphology), hydrologic regimes, and soil chemistry that compose the Carolina Bay ecosystem of this area so that we can preserve, manage, and restore these bays to their maximum functional capacities.

There is relatively little known about the relationship between soils, hydrology, and distribution of plant community types in Carolina Bays (Sharitz and Gibbons, 1982; Nifong, 1998; Reese and Moorhead, 1996). Although other peatland wetland systems, such as fens and mires, have been studied extensively, the hydrology, substrate, and vegetation in these ecosystems tend to be distinctly more homogenous than in Carolina Bays (Schalles and Shure, 1989; Malmer, 1986; Vitt and Chee, 1990; Bridgham and Richardson, 1993). Variation in soil chemistry and water table regime in Carolina Bays is associated with an array of distinct plant communities that are typically found in concentric patterns between the rim and center of individual bays (Reese and Moorhead, 1996).

The North Carolina Department of Transportation (DOT) currently is restoring a depressional wetland in a 750 acre Carolina Bay located in Robeson County, NC. This Carolina Bay was ditched, drained, and converted to agricultural land in the early 1970s. The success of the restoration project will be determined in the future by comparing characteristics of the restored ecosystem at the mitigation site to those of reference sites. While previous research presented general descriptions of Carolina Bay vegetation communities and their distribution patterns, the information they provided was not applicable reference data due to the absence of quantitative and comparable measurements necessary for determining the success of vegetation community restoration on a given soil type. Kologiski (1977), in a thorough analysis of the Green Swamp Natural Area in Brunswick County, North Carolina, described several peatland communities. His research built on previous descriptive studies by including a quantitative analysis of the vegetation communities correlated with soil series. However, his quantifications were used in ordination techniques in order to delineate community types based on soil depth, hydroperiod, and frequency of fire. The quantifications were not included in his publication. Therefore we were not given the necessary structural or compositional quantities necessary for measuring the establishment of a specified community type at a restoration site, for which our study is intended. In addition, our research focuses on Carolina Bay systems, and Kologiski performed his study in a coastal plain wetland complex. Although inferences can be made regarding between the two systems, our reference data is from Carolina Bays and suitable therefore suitable for the purposes of Carolina Bay ecosystem restoration. Schafale and Weakley (1990 and 1991) classified and described pocosin vegetation and associated communities and Nifong (1998) described Carolina Bay vegetation community composition across the entire geographic range of Carolina Bays. These studies provided important descriptive information but lack quantitative data necessary for measuring or gauging the success of restoration activities. In addition, previous studies did not provide values that indicate the range of vegetation communities and/or their rate of occurrence on a given soil type. Our study provides data that allows site stewards to determine restoration success based on a range of potential communities that could be established on varying depths of organic material.

The research reported here was conducted in three unaltered Carolina Bays that serve as reference sites for the proposed mitigation project. The objectives of this research project were to 1) describe the species composition and structure of the plant communities; 2) describe associations of the plant community types with soil properties and water table regimes; 3) determine soil and/or hydrology factors that dictate vegetation community distribution; and 4) develop objectives relating to plant community type, soil type, soil phosphorus content, and water table depth applicable to the long term monitoring of Carolina Bay restoration projects in this region.

REFERENCE SITES

The study was conducted in three unaltered "reference" Carolina Bays in Bladen County, North Carolina: Causeway Bay, Charlie Long Bay, and Tatum Millpond. The DOT restoration site, Juniper Bay, was located approximately 30 miles southwest of the reference bays in Robeson County, North Carolina. Reference bays were chosen based on preliminary observations of typical Carolina Bay vegetation communities, lack of indication of recent logging or draining, soil mapping units similar to those of restoration site, proximity to the restoration site, accessibility, and property owner cooperation. The southeastern middle Coastal Plain of North Carolina is warm temperate, with a mean annual temperature of 63°F and average annual precipitation of 46" (Elizabethton, North Carolina, Weather Station, Lock 2).

The three reference bays were vegetated throughout, containing no open water zones. They collectively exhibited a total of four vegetation communities: pond pine woodland, non-riverine swamp forest, bay forest, and high pocosin. These vegetation communities were distinguished based on dominance and/or abundance of dominant tree species and classified according to Schafale and Weakley's (1990) community descriptions.

The soils in the reference bays exhibited an accumulation of organic material from the periphery to the center of a bay, grading from mineral soil (0-20cm depth of organic material) into organic soils that could be divided into three categories: histic (20-40cm organic depth), shallow organic (40-80cm organic depth), and deep organic (>80cm organic depth). The soils in all three bays were mapped as Pamlico (Terric Medisapist) in the interior, a very poorly drained series containing variable depths of highly decomposed organic material over a sandy sediment. In Causeway Bay and Charlie Long Bay, the Pamilco soils of the interior graded into Lynn Haven series (Typic Haplaquod) on the bay periphery, a poorly drained soil overlaying sandy sediment. In Tatum Millpond, soils graded outwardly from Pamlico to Croatan (Terric Medisaprist) to Torhunta (Typic Humaquept), both very poorly drained soils overlaying a loamy sediment, and eventually into Lynn Haven at the bay periphery. All four soil series were typical of the Carolina Bays in this region (Leab, 1983; Stolt and Rabenhorst, 1987).

The reference bays were depressional wetlands that receive hydrology from rainwater, surface water runoff, and possibly groundwater inputs. All three bays maintained a water table depth shallower than 30cm below the soil surface for at least 2 weeks during the growing season (March 16 – November 14; dates correspond to 50% probability that temperatures will drop below 28°) (Leab, 1990). Average yearly rainfall between 1957 and 1979 was recorded at 115cm (Leab, 1990). However, the North Carolina drought summary report (www.hprcc.unl.edu/Nebraska/drought-summary2002.htm/#top) indicated that rainfall was below normal in 2002. These reference bays were positioned at an elevation of approximately 7m above sea level, while the surrounding landscape is between 8 and 12m above sea level (USGS Topographic Map, Elizabethtown Quadrangle, 1984). In addition to rainwater and surface water runoff, these depressions may have acted as flow-through wetlands where groundwater input is a major factor in their hydrology. All three bays are located in the Cape Fear River watershed.

Causeway Bay was a 600 acre wetland located on private property approximately 10 miles north east of Elizabethtown (34°29'N, 78°24'W). Although in the past, Carolina Bays typically experienced wildfire every 20-50 years (Christenson et al. 1988), historical aerial photographs reveal no wildfire events within the last 65 years in Causeway Bay. Similarly, these photographs indicate that the study area was not logged within the same historical time span.

Charlie Long Bay, a 500 acre bay, was located on Bladen Lakes State Forest property (34°36'N, 78°33'W). According to retired forest service workmen, the bay was never logged (Carson Tatum and J.B. Johnson, personal communication). Likewise, no wildfire events have occurred in the past 65 years, according to review of historical aerial photographs. This bay had a surface water outlet in the northwest corner, which was dammed in the late 1960's for farming operations.

Tatum Millpond, approximately 1400 acres, was located 2 miles south of Charlie Long Bay on Bladen Lakes State Forest property (34°42'N, 78°33'W). This bay was logged selectively for pond pine and Atlantic White Cedar under forest service supervision between 1938 and 1954. In 1954, Hurricane Hazel damaged the majority of the desirable/valuable trees in Tatum Millpond, and therefore, logging operations ceased following this storm event (Carson Tatum and J.B. Johnson, personal communication).

MATERIALS AND METHODS

During the summer of 2001, NCSU students/technicians established a transect from the periphery (wetland boundary) toward the center of each reference bay. Transects began at a point along either the northeast or southwest side of the bay (depending on accessibility), and extended into the center of the bay at an azimuth that formed a right angle to the tangent along the bay periphery. Sampling vegetation, hydrology, and soil along these transects took place during the summer of 2002.

Sample Plots

5X5 m plots were established every 30 meters along the left side of each transect beginning 6m from the bay periphery. The plots were distributed along each transect until the depth of organic material began to level. Causeway Bay and Charlie Long Bay contained 15 sample plots each, reaching 456m from the periphery toward the center of each bay. Tatum Millpond contained 20 sample plots, reaching 606m from the periphery toward the center of the bay (Figures 1, 2, and 3). In March 2002, the peripheral vegetation of Tatum Millpond was clear-cut by the Forest Service. This portion (first 36m; first 2 sample plots) of the transect was relocated further southeast within the bay in an area where vegetation and soils appeared similar to that portion of the original transect.

Vegetation Assessment

Vegetation sampling consisted of a plant inventory, species' aerial cover determination, shrub stem counts, and determination of tree species' density and basal area. The species inventory, cover determination, and stem counts took place within the 5X5m plots. Identification of all species found within each plot occurred *via* meander search, and a cover value was assigned to each species based on the percentage of the 5X5m surface area shadowed by the projection of all parts of a given species (percentages recorded to the nearest 5%; values less than 5% were assigned a real number, 1 to 4%, based on estimated cover).

Shrub stems were counted within 2 two-dimensional planar bands along the north side of each 5 X 5m plot. Tallying total number of stems that passed through a horizontal

5m (long) X 20cm (deep) band along the soil surface of a plot resulted in an approximated $1m^2$ vertical stem count for a given plot. Assessment of horizontal structure was accomplished using the same 20cm planar band, only erecting it vertically and tallying all vegetation parts that passed through the 3m(high) X 20cm(deep) plane at 1m increments along the 5m side.

The Bitterlich method (resulting in variable plot size) was implemented through the use of a cruise angle for determining tree basal area from a given plot (Grosenbaugh 1952). Basal area data was recorded by species from each plot, and then summed to determine total basal area for each plot. The distance between the plots and the relatively small diametered trees encountered in this study ensured that trees could not be tallied twice from two separate plots.

Soil Analysis

Soil samples were collected from a 90cm core at each 5X5m vegetation plot. Samples were collected from the 0-15cm, 25-40cm, 60-75cm, and 75-90cm depth intervals. Samples were dried, ground, and shipped to the North Carolina Department of Agriculture, Agronomic Division, for analysis. Using a mehlich-3 extraction/mehlich buffer acidity (Mehlich 1984), quantities of available phosphorous, potassium, calcium, magnesium, sodium, manganese, zinc, and copper were determined for each sample (4 samples/plot by depth). In addition, each sample was analyzed for pH, base saturation, humic matter content, cation exchange capacity, and weight/volume. We conducted the soil texture analysis using a standard hydrometer procedure (Ketter et al., 2001). The North Carolina State University Analytical Service Laboratory completed the percent carbon analysis utilizing continuous flow isotope ratio mass spectrometry (Goodman, 1998). In addition, a complete soil profile description was recorded at each plot. This included field identification of soil texture, color, and the observed depth of organic material.

Water Table Monitoring

A total of 12 wells were distributed along the sampling transects within the bays, resulting in hydrology monitoring of four soil categories: mineral soils (0-20cm depth of organic material), soils exhibiting a histic epipedon (20-40cm depth of organic material), shallow organic soils (40-80cm depth of organic material), and deep organic soils (>80cm depth of organic material) (Figures 1, 2, and 3). The wells recorded water table depths on an hourly basis and allowed for the generation of seasonal watertable/hydrographs (Fig. 4).

Data Analysis

The plant community in each plot was classified as pond pine woodland, nonriverine swamp forest, bay forest, or high pocosin according to the system of Schafale and Weakley (1990) (Table 1; Figures 1, 2, and 3). Plots maintaining a dominance of pond pine (*Pinus serotina* Michx.) (basal area between 40 and $60ft^2$/acre) were classified as pond pine woodland. Plots maintaining a dominance of swamp gum (*Nyssa bifora*

Walt.) (basal area between 60 and 140ft^2/acre) were classified as nonriverine swamp forest. Plots exhibiting a dominance of loblolly and sweet bay (*Gordonia lasianthus* (L.) Ellis and *Magnolia virginiana* L.) (combined basal area between 20 and 50ft^2/acre) were classified as bay forest. Plots with fewer pond pine trees (less than 30ft^2/acre) were classified as high pocosin.

Soil type (mineral, histic, shallow organic, or deep organic) of each plot was determined based on percent organic matter at a given depth. Plots were classified based on our field texture assessment, and verified using % organic carbon (OC) values. Plots located on soils containing <20% OC at a depth of 20-40cm were classified as mineral soils. If soils contained >20% OC at a depth of 20-40cm, but <20% at a depth of >40cm, the plot was considered to be located on a histic epipedon. Plots with soils containing >20% OC at 40-80cm depths but <20% organic matter at depths >80cm were classified as shallow organic . Plots with deep organic soils maintained an organic matter percentage of >20% at depths >80cm (Fig. 1, 2, and 3). Because the amount of clay particles present in these soils was insignificant (<10% consistently), it was not necessary to consider the % clay values when determining whether the plot was located on mineral or histic soils (USDA-NRCS 1998).

Subsequent to classifying the plant community and soil of each plot, the 50 plots were grouped by soil type and plant community type. Data were analyzed with plant community type as the independent variable and then again with soil type as the independent variable. Analyses involved determining average vegetation, soil, and water table variables associated with each plant community and soil class. The sampling design employed here was limited by the thick, tangled, jungle-like, impenetrable vegetation that comprise the communities found in Carolina Bays of the North Carolina coastal plain. Therefore, although our sample size was limited and our sampling strategy represented pseudo-replication (non-random replication, therefore statistically dependent treatments), we ran several single factor analysis of variance tests (ANOVAs) in order to infer potential significant differences between soil types or between community types, completely aware of the weakness in our sampling strategy for applying these tests (Hulbert 1984). We also tested the independence of community type to soil type utilizing contingency table analyses and chi-squared tests to determine potential dependence of community type to soil type, aiming to reject the hypothesis that these community types are randomly distributed in Carolina Bays.

RESULTS

Associations of Plant Community Types and Soil Types

Of the 50 plots, 13 were found on mineral soil, 13 on soils containing a histic epipedon, 6 on shallow organic soil, and 18 on deep organic soil. Of these same plots, 21 were found to exhibit a pond pine woodland community, 8 exhibited nonriverine swamp forest, 5 exhibited bay forest, and 16 exhibited a high pocosin community (Table 1). Table 2 indicates that mineral soil supported almost exclusively pond pine woodland, deep organics supported nearly exclusively bay forest and high pocosin, shallow organics supported pond pine woodland and swamp forest, and histic soils supported a variety of community types.

We conducted a contingency table analysis for determining the interdependence of community type on soil type. The actual values (Table 2) were compared to expected values using a chi-squared test. Our The chi-squared test of independence for each community type across all soil types resulted in a values ranging between 0.08 to 0.001 with 3 degrees of freedom and tabulated *p*-values all greater than 0.25.

Vegetation

Six tree species were identified in the reference bays: red maple (*Acer rubrum* L.), Atlantic white cedar (*Chamaecyparis thyoides* (L.) B.S.P.), loblolly bay, sweetbay, swamp gum, and pond pine. Mineral and hsitic soils exhibited relatively similar total basal areas (71 and 73 ft^2/acre). Shallow organic soils exhibited highest total basal area (100 ft^2/acre), and deep organic soils maintained the lowest total basal area (28 ft^2/acre) (Table 3).

Although red maple basal area was evenly distributed (5-13 ft^2/acre) between soil types, pond pine basal area was higher on soils with shallower organic material (54 and 40 ft^2/acre), swamp gum basal area was highest in shallow organic soils (70 ft^2/acre), and the basal area of bay trees combined (loblolly and sweet bay) was highest in deep organic soils (10 ft^2/acre). Atlantic white cedar was a minor component of the canopy on deep organic soils (Table 3).

Pond pine basal area was highest in pond pine woodland (40 - 80 ft^2/acre). Plots classified as high pocosin contained only scattered pond pine trees (less than 30 ft^2/acre). Swamp gum basal area was highest in swamp forest (60 -140 ft^2/acre). The combined basal area of loblolly bay and sweet bay was greatest in bay forest (20 - 50 ft^2/acre). Red maple basal area was evenly distributed across community types (8-15 ft^2/acre) with the exception of high pocosin (2 ft^2/acre). Atlantic white cedar was a minor component of the canopy in the bay forest community (Table 4).

Table 5 combines the information obtained by grouping the plots into soil and community classes. This table includes the average basal areas of dominant tree species found on different soil types within different community types. For example, based on our sampling strategy and averaging analyses, pond pine woodland on mineral soil was comprised of 58 ft^2/acre pond pine, 14 ft^2/acre red maple, and 3 ft^2/acre bay trees. These values can be used for comparison between the same community type found on different soil types as well as for comparison between the same soil type that exhibits different plant communities. By summing species' basal area across community types within a given soil type, we generated average basal area figures for a given community of a specified soil type. Nonriverine swamp forest maintained the highest average total basal area on shallow organic soils (118 ft^2/acre), whereas pond pine woodland maintained the highest average total basal area on histic soils (82 ft^2/acre). High pocosin on mineral soil was found to have higher average total basal area (30 ft^2/acre) than pond pine woodland found on deep organic soils (15 ft^2/acre).

A total of 31 shrub species were identified in the reference bays. The 11 most common species (occurring in greater than 50% of the plots identified as a specific community type, with an absolute cover value of >5%) included giant cane (*Arundinaria gigantea* (Walt.) Muhl.), coastal sweetpepper bush (*Clethra alnifolia* L.), blue huckleberry (*Gaylussacia frondosa* (L.) Torr. and Gray ex Torr.), large gallberry (*Ilex coriacea* (Pursh) Chapman), smooth winterberry (*Ilex laevigata* Pursh) Gray), coastal doghobble (*Leucothoe axillaris* (Lam.) D. Don), swamp doghobble (*Leucothoe racemosa* (L.) Gray), fetterbush lyonia (*Lyonia lucida* (Lam.) K. Koch), red bay (*Persea palustris* (Raf.) Sarg.), laurel greenbriar (*Smilax laurifolia* L.), and highbush blueberry (*Vaccinium corymbosum* L.). Table 6 provides average aerial cover values for all dominant shrub species in all combinations of soil type and plant community type encountered in this study. For example, in pond pine communities on mineral soil, fetterbush lyonia averaged 24% of the shrub coverage; however, fetterbush lyonia increased to an average 37% cover when found in pond pine communities on shallow organic soil. Likewise, fetterbush lyonia cover increased to 57% of the total cover in bay forest communities, which are only found on deep organic soils.

The average stem densities of different plant community types are shown on Table 7. Pond pine woodland, nonriverine swamp forest, and bay forest exhibited similar average vertical stem counts per m^2 (35, 36, and 33 counts, respectively). High pocosin exhibited the highest average number of vertical stem counts per m^2 (52 counts). On a horizontal plane, pond pine woodland and nonriverine swamp forest exhibited fewer stem counts (121 and 127 counts, respectively) in a one m^2 by 3m high area than bay forest and high pocosin (85 and 183, respectively). For comparison purposes between communities, we ran single factor analyses of variance (ANOVA) to determine significant differences between the structures of the four community types. The ANOVA resulted in a *p*-value of 0.015 when analyzing the vertical stem counts, indicating significant structural. However, the horizontal stem counts did not result in a *p*-value that indicated significance between community types (p-value>0.05). Unlike the structural density numbers resulting from a between community comparison, the structural density of vegetation between soil types resulted in similar numbers across the four soil types. Likewise, a single factor ANOVA test using the soil classification scheme resulted in no significant difference (p-value>0.05).

Soils

Tables 8, 9, and 10 present average values for phosphorous, potassium, calcium, magnesium, sodium, manganese, zinc, and copper for plots on different soil types within different community types. There was no data available for the one plot found on mineral soil and in a high pocosin community because the test results for the samples from this plot were extremely high, and therefore, thrown out. Although our sample size was limited and our sampling strategy represented pseudo-replication, we ran several single factor ANOVAs in order to infer potential significant differences in phosphorous levels between soil types and community types, completely aware of the weakness in our sampling strategy for applying these tests (Hulbert 1984). We performed single factor ANOVAs to test the null hypothesis that the mean available phosphorous found between the four soil and community types are equal. All tests (i.e. available phosphorous between soil types across bays, between soil types within individual bays, between community types across bays, between community types within individual bays) resulted in insignificant differences (p-value<0.05) except when testing variance of the mean phosphorous levels between the four soil types in Tatum Millpond (p-value=0.007).

Other than depth of organic material, no trends or significant relationships were detected between soil type and community when examining the other soil properties analyzed for this study. Cation exchange capacity fell between 8.3 and 11.1 meq/100cm^3 across soil types; soil pH across soil types was between 3.5 and 3.9; and base saturation was between 6.3% to 9.9%. Additional information regarding soil properties analyzed by depth for the purposes of this study is available from the authors.

Hydrology

Although our hydrology monitoring did not yield testable results for the purposes of scientific analyses, it did provide information useful in making inferences that support current theories regarding the relationship between depth of organic material and hydrologic regime. Figure 3 illustrates the water table depths in Tatum Millpond between March 6, 2001, and August 8 2001, across all four soil categories, as an example of variations in hydrologic regime between the soil types found in the reference bays. It is expected that mineral soils exhibit a deeper water table than histic soils, but shallower than the organic soils (Mitch and Gosselink, 1993). According to Figure 3, the water table remained at or near the soil surface for most of March and April. With the onset of summer and evapotranspiration activity increasing, the water table continues to drop below the soil surface as the growing season begins, and remains below the soil surface through out the remainder of the season, with occasional replenishment by storm events. In mineral soils, the water table dropped to nearly 60cm below the soil surface, but averaged –33.7cm across the growing season. The watertable sampled in histic soils dropped to 45cm below the soil surface, and averaged –19.7cm across the growing season. The watertable in shallow organic soils fell slightly shallower (-40cm) than the water table exhibited in histic soils, and averaged –17.9cm across the growing season. The watertable in deep organic soils dropped to 45cm below the soil surface, and averaged 24.9cm across the growing season. Addition to water table depths, the hydrographs shown illustrated the storm events across the four soil types. They indicate that as the depth of organic material increases, stormwater is retained for a longer period of time, resulting in a more highly curved hydrograph rather than the sharp rises and falls in water table depth as seen in mineral and histic soils.

DISCUSSION

Carolina Bays are considered nutrient poor systems, with deficiencies in nitrogen and phosphorous limiting productivity (Waldbridge, 1991; Richardson and

Vaithiyanathan, 1995; Walbridge and Richardson, 1991). Nutrient availability in soils is correlated with hydrologic regime. Relative to drier soils, saturated and inundated soils are anaerobic for extended periods and this slows the decomposition of organic material and results in a nutrient poor rhizosphere. Therefore, saturated and inundated systems are prone to organic material accumulation due to the decreased rate of decomposition. Likewise, nutrient availability decreases with an increase in organic material accumulation associated with longer hydroperiods and shallower water table depths (Daniel, 1982; Mitsch and Gosselink, 1993; Cronk and Fennessey, 2001). Decreased nutrient availability would result in lower primary productivity, restraining the growth of vegetation and potentially dictating vegetation community change as available nutrients decrease with increased organic material accumulation (Bridgham et al., 1995; Reader and Stewart, 1972; Bridgham et al., 1991). Over the course of this study, we sought to determine if there was a detectable association between available nutrient amount and plant community distribution in Carolina Bays in order to identify target communities for restoration at the NCDOT – Juniper Bay wetland mitigation site. In general, we found no significant differences in nutrient availability between soil types or between soils that supported different plant community types. The soils in Tatum Millpond were the exception to this general result. At this site there were significant differences in available phosphorous across soil types and community types. This result was due to the fact that Tatum Millpond was the only reference bay that contained non-riverine swamp forest, a community comprised of deciduous species which return greater amounts of nutrients in leaf litter than do evergreen species. This greater nutrient return resulted in higher nutrient concentrations in the organic soils of the swamp plant community than in the other soils of this site. In addition, our ANOVA's were based on a limited sample size and pseudo-replication. Therefore, the results are useful for gleaning preliminary insight into ecological trends. Likewise, it should be noted that the values obtained from the reference bays for available phosphorous and other major and minor elements all represented extremely low quantities when compared to more eutrophic systems.

The data obtained from the reference bays can be applied to the restoration of disturbed Carolina Bay systems in the North Carolina coastal plain based on soil types similar to those in the reference bays. The chi-squared test of independence was used to determine significant associations between community type and soil type. The test was applied to contingency tables of expected number of plots verses actual number of plots exhibiting a particular community type across soil types. We generated expected values tables based on the ratio of the product of row totals and column totals to the grand total. We used the chi-squared test to generate a statistical value that can be tabulated to formulate a probability value that indicates significance. The chi-squared test was applied to each community type across soil types, and each resulted in an insignificant *p*-value (>0.25). An insignificant difference between the actual data and the expected data implies our observed values are similar to expected values. Therefore, we can infer that the community types identified in this study are not randomly distributed across soil types.

This reference data will be useful in long-term monitoring of plant community development at restoration sites. Restoration site monitoring should note whether or not the restored plant communities on a particular soil type meet the descriptions of the reference communities on comparable soil types. To facilitate the application of the reference data for monitoring purposes, we first describe the community types, the underlying soil and water table parameters that contribute to the maintenance of these communities, and other possible variables that may influence the distribution of these communities in the reference bays. Secondly, we apply this information to the NCDOT – Juniper Bay wetland mitigation project in order to construct recommendations for the planting plan and long-term monitoring of this and other potential Carolina Bay restoration projects in the North Carolina coastal plain.

Plant Community Type Descriptions

The four plant community types identified in this study include pond pine woodland, non-riverine swamp forest, bay forest, and high pocosin. These communities differ in canopy species composition, canopy basal area, shrub stem density, and composition and/or abundance of some shrub understory species. Community types are described below.

Pond pine woodland was found in all three reference bays, predominantly on the wet mineral soil of the bay periphery and well represented on histic soil adjacent and transitioning to more substantial depths of organic accumulation (Tables 1 and 2). The water table associated with this soil type exhibited a maximum depth of –45cm, and experienced sharp rises and quick drainage during storm events. This hydroperiod minimizes the length of saturation and/or inundation through out the rooting zone, optimizing nutrient availability for plant uptake. In the reference bays, this community type exhibited an average basal area of pond pine of 58 ft^2/acre on mineral soils and 68 ft^2/acre on histic soils (Table 5). The understory was dominated by large gallberry and fetterbush lyonia (Table 6). The shrub layer was approximately 3m tall, exhibiting a density of an average 35 vertical stems/m^2 and 121 horizontal stems/m^2X3m high (Table 7). The vertical density is similar to that found in the nonriverine swamp forest and bay forest communities, but significantly different than the structure exhibited by thehigh pocosin community. The horizontal density is similar to that of nonriverine swamp forest, but somewhat less than bay forest and high pocosin structural architecture. These distinguishing features of the pond pine woodland community type identified in the reference bays fit the description provided by Shafale and Weakley's (1990). The mineral soils contained an average of 13.0-13.8 mg/dm^3 phosphorous within a 0-90cm depth (Table 8).

The typical pond pine woodland community is sustained by fire (Schafale and Weakley, 1990). Pond pine reproduction occurs via seed germination following fire, which is required by their serotinous cones for triggering seed release. Likewise, fire returns nutrients to the soil and maintains a relatively open understory. Because the reference bays have not been burned in at least the past 60 years, the identified pond pine woodland communities most likely contained denser, taller shrubby vegetation than what would be expected of bays that have experienced wildfire once every 20-50 years, the historically natural fire frequency period for Carolina Bays of this area (Richardson, 1991).

Nonriverine swamp forest was found in Tatum Millpond on histic and shallow organic soils, but was absent from the other reference bays (Tables 1 and 2). This community type is known to occur on peatlands with seasonally saturated or inundated soils, as evidenced in the hydrographs (Fig. 3). .The community identified in Tatum Millpond was selectively logged for Atlantic white cedar prior to 1954. Nonriverine swamp forest is known to occur in a mosaic with Atlantic white cedar forest (Schafale and Weakley, 1990). The removal of the Atlantic white cedar trees from this system could have allowed nonriverine swamp forest to dominate. The reduction of Atlantic white cedar in the canopy and absence of fire enhanced the establishment of swamp gum and impeded the reestablishment/regeneration of the cedar (Levy and Walker, 1979; Wells and Whitford, 1976). The nonriverine swamp forest identified in Tatum Millpond contained a closed canopy of swamp gum (87-105 ft^2/acre basal area) with no co-dominant canopy species (Table 5). The understory was dominated by coastal sweetpepper bush (RIV 36%) and highbush blueberry (RIV 16%). The shrub layer also contained fetterbush lyonia (RIV 8%) and red bay (RIV 7%) (Table 6). The understory exhibited an average stem density of 36 vertical stems/m^2 and 127 horizontal stems/m^2 x 3m high (Table 7). The vertical density is similar to that found in the nonriverine swamp forest and bay forest communities, but significantly different than that exhibited by the high pocosin community. The horizontal density is similar to that of nonriverine swamp forest, but somewhat less than bay forest and high pocosin structural architecture. This nonriverine swamp forest adheres to the description given by Schafale and Weakley (1990). The histic and shallow organic soils contained an average of 14.9-19.9 mg/dm^3 phosphorous within a 0-90cm depth (Table 8).

Historically, this community is not maintained by fire. However it is believed that these systems receive mineral input from groundwater or surface water sources (Schafale and Weakley, 1990). Aerial photographs did not indicate a major source or hydrologic discharge point for surface water input or output at Tatum Millpond, and our study does not investigate hydrology dynamics. Therefore, further research is necessary in order to determine the hydrologic parameters necessary for maintaining this community at Tatum Millpond.

A bay forest community was identified in Tatum Millpond, but was absent from the other reference bays (Tables 1 and 2). This community type was found solely on deep organic soils in the interior of the bay, where the water table exhibited long-time retention of storm water and a watertable no deeper than 45cm below the soil surface. The canopy is dominated by bay trees (loblolly bay and sweet bay), exhibiting a combined basal area of 34 ft^2/acre (Table 5). The understory was fetterbush lyonia (RIV 57%), laurel greenbriar (RIV19%), and large gallberry (RIV 12%). No herbaceous layer was present (Table 6). The understory exhibited a stem density of 33 vertical stems/m^2 and 185 horizontal stems/m^2X3m high (Table 7). The vertical density is similar to that found in the pond pine woodland and nonriverine swamp forest communities, but significantly different than that exhibited by the high pocosin community. However, the horizontal density is high, more closely resembling the figures of a high pocosin community. This indicates that the structural architecture of a bay forest community is more highly branched on a horizontal plane, but maintains a similar vertical stem density when compared to pond pine woodland and nonriverine swamp forest. The observed community adheres to the description given by Schafale and Weakley (1990). The histic and shallow organic soils contained an average of 12.1 mg/dm^3 phosphorous within a 0-90cm depth (Table 8).

Bay forests are a component of the successional stages in peatland community development. However, the circumstances under which a bay forest develops are agreeably unclear. A combination of fire suppression, relatively higher nutrient availability (relative to pocosins), absence of disturbance, and presence of deep organic material accumulation (deeper than a nonriverine swamp forest) are the parameters that may give rise to a bay forest community (Richardson, 1991; Otte, 1981; Buell and Cain, 1943). In Tatum Millpond, the bay forest is found at the most centralized point in the bay along the sampling transect. High pocosin is found between nonriverine swamp forest and bay forest; however, this is possibly due to tree falls within the identified high pocosin community associated with hurricane winds (Figure 3).

High pocosin was identified in all three reference bays, predominantly on deep organic soils where the water table exhibited long-time retention of storm water and a water table at or above 45cm below the soil surface (Tables 1 and 2). This community was characterized by scattered pond pines (7-20 ft^2/acre) (Table 5), with a thick/dense shrub layer growing up to approximately 3m in height and exhibiting a stem vertical density of 52 stems/m^2 and 183 horizontal stems/m^2 x 3m high (Table 7). The vertical density is significantly different than that of pond pine woodland, nonriverine swamp forest, and bay forest communities. The horizontal density is high, similar to that exhibited in the bay forest. The understory was dominated by fetterbush lyonia (RIV 27%), highbush blueberry (RIV 15%), and large gallberry (RIV 13%) (Table 6). These distinguishing features fit the description of high pocosin provided by Shafale and Weakley (1990). The deep organic soils contained an average of 8.3 mg/dm^3 phosphorous within a 0-90cm depth (Table 8).

Although the reference bays have not experienced a wildfire in over 60 years, this community type is typically maintained by periodic fire (every 20-50 years). Fire returns nutrients to the soil, encouraging high productivity and a quick reestablishment of the shrub layer. In addition, fire reduces the density and height of shrubby vegetation, maintaining a low pocosin community (Richardson, 1991). It is possible that the high pocosin communities encountered in the reference bays may indeed represent a historic low pocosin community that has experienced fire suppression.

Planting Recommendations and Long-Term Monitoring

The NCDOT – Juniper Bay wetland mitigation site is currently a retired agricultural field that was cleared of vegetation, ditched, and drained in the early 1970s.

The bay was then farmed in row crop for the subsequent 30 years. Currently, this bay contains wet mineral soil, histic soil, and shallow organic soil. For the purposes of this study, we will assume the water table will be restored to the appropriate depths for maintaining the existing soil types. Due to erosion, subsidence, and a lowered water table resulting from the initial conversion of Juniper Bay from wetland to farmland, much of the organic material accumulation that once made Juniper Bay a peat filled bay has disappeared. The process of organic material accumulation will be reestablished with a restored water table. Saturation and/or inundation of the rooting zone will result in slower decomposition rates, nutrient deficiencies, and accumulation of organic material.

Ecological factors identified in association with the community types described from the three reference bays are outlined in Table 11. Based on this reference data, we recommend planting the mitigation site in pond pine woodland (Fig. 4). Pond pine woodland dominated mineral soils and was well represented on histic soils in the reference bays. Although nonriverine swamp forest dominated the shallow organic soils, this community type would not be appropriate for restoration at Juniper Bay due to 1) the unknown nature of the hydrologic regime necessary for maintaining its species structure and composition; and 2) its uncommon occurrence as a dominant community type without the typical Atlantic white cedar forest community mosaic dynamic. Because we have no reference data that includes this natural mosaic pattern, we are limited to simply excluding nonriverine swamp forest from the recommended planting plan. Both bay forest and high pocosin would not be appropriate for restoration at Juniper Bay due to their preference/requirement for deep organic soils that are not present at Juniper Bay. It is likely that over time, the pond pine woodland established on shallow organic soils will accumulate organic material due to an elevated water table, resulting in decrease in nutrient availability. Consequentially, primary productivity would reduce resulting in stunted shrub growth and a decreased pond pine basal area, developing into a high pocosin community (Richardson 1991). With a prescribed fire (every 20-50 years), the high pocosin would eventually succeed into low pocosin (Otte 1981).

Long-term vegetation monitoring should consist of a canopy and understory species inventory, with the understanding of the types of communities that may evolve from the planted community over time. Likewise, shrub stem density and basal area should be estimated. In addition, soil properties should be monitored to determine success of nutrient level restoration to values at or near those of reference bays. In addition, continued hydrology monitoring in the reference bays and the mitigation bay is recommended.

CONCLUSION

Because of the extremely dense structure of bay vegetation, we stumbled upon many sampling constraints over the course of this study. Randomly sampling throughout the reference bays was precluded by the extreme density of the vegetation. Therefore, this research resulted in a general description of bay plant communities and the associated soil and water table properties that probably contribute to their development and maintenance. This baseline data will be useful to those working in the field of wetland restoration in Carolina Bays of the North Carolina coastal plain. In addition, this research can easily be expanded upon by closer, more in depth studies pertaining specifically to hydrologic parameters that are, most likely, the ultimate dictator of soil properties, which are, in turn, influenced by the various vegetation communities that cycle nutrients through the rooting zone. Likewise, detailed studies comparing common disturbance regimes (flooding, fire, logging, tree fall, etc.) in this region may also result in significant findings pertaining to vegetation community distribution in Carolina Bays. At a regional level, these bays are valuable resources for stormwater retention, carbon storage, and provision of unique floral habitat for wildlife. They also represent a large fraction of the intact natural areas found across a highly developed/agricultural landscape (Richardson et al. 1981). Therefore, further studies are necessary for better understanding the means by which restoration of these increasingly uncommon bay wetlands can be achieved successfully.

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Table 1. Number of plots found on each soil type and within each community type by bay.

Soil/Community Type	Reference Bays: Causeway Bay	Charlie Long Bay	Tatum Millpond	Total no. of plots
Mineral (<20cm OM)	4	7	2	13
Histic (20-40cm OM)	2	7	4	13
Shallow organic (40-80cm OM)	1	1	4	6
Deep organic (>80cm OM)	8	0	10	18
Pond Pine Woodland[a]	5	13	3	21
Nonriverine Swamp Forest	0	0	8	8
Bay Forest	0	0	5	5
High Pocosin	10	2	4	16
Total # of plots	15	15	20	50

[a]Schafele and Weakley (1990).

Table 2. Percentage (absolute values in parentheses) of total plots found in pond pine woodland, nonriverine swamp forest, bay forest, and high pocosin communities on the specified soil types.

	Community type			
Soil Type	Pond Pine Woodland	Nonriverine Swamp Forest	Bay Forest	High Pocosin
	------------------------------------%------------------------------------			
Mineral (N=13)[a]	92 (12)[b]	0	0	8 (1)
Histic (N=13)	54 (7)	23 (3)	0	23 (3)
Shallow Organic (N=6)	33 (2)	67 (4)	0	0
Deep Organic (N=18)	0	6 (1)	27 (5)	67 (12)

[a] Number of plots sampled.
[b] Values indicate the specified communities are found *independently* on a particular soil type; not to be interpreted that community types are found intermingled on a particular soil type.

Table 3. Average absolute basal area (ft^2/acre) and average relative basal area (in parentheses, ft^2/acre) of dominant tree species within the specified soil types.

	Soil Type			
Species	Mineral (N=13)[a]	Histic (N=13)	Shallow Organic (N=6)	Deep Organic (N=18)
Red Maple	13 ± 9[b] (18) min=0 max=30	12 ± 10 (16) min=0 max=30	12 ± 8 (12) min=0 max=20	5 ± 7 (18) min=0 max=30
Atlantic white cedar	0	1 ± 3 (1) min=0 max=10	0	2 ± 7 (6) min=0 max=20
Loblolly bay	3 ± 5 (4) min=0 max=10	1 ± 1 (1) min=0 max=5	0	7 ± 15 (26) min=0 max=50
Sweet bay	0	0	2 ± 4 (2) min=0 max=10	3 ± 6 (12) min=0 max=20
Swamp gum	0	20 ± 38 (27) min=0 max=90	70 ± 57 (70) min=0 max=140	7 ± 15 (23) min=0 max=60
Pond Pine	54 ± 17 (77) min=20 max=70	40 ± 29 (54) min=0 max=80	17 ± 26 (17) min=0 max=50	4 ± 9 (16) min=0 max=30
Average Total	71	73	100	28

[a] Number of plots sampled.
[b] Standard deviation.

Table 4. Average absolute basal area (ft^2/acre) and average relative basal area (in parentheses, ft^2/acre) of dominant tree species within the specified community types.

	Community Type			
Species	Pond Pine Woodland (N=21)[a]	Nonriverine Swamp Forest (N=8)	Bay Forest (N=5)	High Pocosin (N=16)
Red maple	15 ± 8[b] (20) min=0 max=30	8 ± 7 (7) min=0 max=20	12 ± 8 (23) min=0 max=20	2 ± 3 (13) min=0 max=10
Atlantic white cedar	5 ± 2 (1) min=0 max=10	0	6 ± 13 (12) min=0 max=30	0
Loblolly bay	3 ± 3 (2) min=0 max=10	0	26 ± 19 (50) min=0 max=50	1 ± 3 (6) min=0 max=10
Sweet bay	0	1 ± 4 (1) min=0 max=10	8 ± 8 (15) min=0 max=20	1 ± 3 (8) min=0 max=10
Swamp gum	0	93 ± 24 (87) min=60 max=140	0	4 ± 7 (21) min=0 max=20
Pond Pine	59 ± 13 (77) min=40 max=80	5 ± 10 (5) min=0 max=30	0	9 ± 10 (53) min=0 max=30
Total Average	76	106	52	17

[a] Number of plots sampled.
[b] Standard deviation

Table 5. Average basal area (ft^2/acre) of Red maple (RM), Swamp gum (SG), Pond pine (PP), and the bay trees (BT) across mineral, histic, shallow organic, and deep organic soil types within pond pine woodland, nonriverine swamp forest, bay forest, and high pocosin community types.

	Community Types															
	Pond Pine Woodland				Nonriverine Swamp Forest				Bay Forest				High Pocosin			
Soil Type	RM	SG	PP	BT	RM	SG	PP	BT	RM	SG	PP	BT	RM	SG	PP	BT
Mineral (N=13)[a]	14	0	58	3	--	--	--	--	--	--	--	--	0	0	20	10
Histic (N=13)	19	0	63	0	3	87	13	0	--	--	--	--	0	0	20	2
Shallow Organic (N=6)	15	0	50	0	10	105	0	3	--	--	--	--	--	--	--	--
Deep Organic (N=18)	--	--	--	--	10	60	0	0	12	0	0	34	2	5	7	2

[a] Number of plots sampled

Table 6. Average absolute vegetation cover (% cover) of all common shrub species (RIV in parentheses) across mineral, histic, shallow organic, and deep organic soil types within pond pine woodland, nonriverine swamp forest, bay forest, and high pocosin community types.

	Community Types			
Soil Type	Pond Pine Woodland	Nonriverine Swamp Forest	Bay Forest	High Pocosin
Mineral				
Giant cane	6 (7)	--	--	1 (1)
Coastal sweetpepper	7 (3)	--	--	1 (1)
Blue huckleberry	8 (7)	--	--	10 (11)
Large gallberry	30 (32)	--	--	30 (32)
Smooth winterberry	3 (3)	--	--	0
Coastal doghobble	0	--	--	0
Swamp doghobble	0	--	--	0
Fetterbush lyonia	17 (24)	--	--	40 (44)
Red bay	1 (1)	--	--	0
Laurel greenbriar	3 (3)	--	--	0
Highbush blueberry	10 (11)	--	--	10 (11)
Histic				
Giant cane	13 (21)	0 (0)	--	7 (6)
Coastal sweetpepper	6 (8)	10 (3)	--	7 (6)
Blue huckleberry	1 (1)	1 (1)	--	17 (17)
Large gallberry	27 (27)	15 (13)	--	25 (15)
Smooth winterberry	4 (4)	2 (2)	--	5 (5)
Coastal doghobble	0	0	--	0
Swamp doghobble	0	1 (1)	--	0
Fetterbush lyonia	16 (25)	31 (53)	--	18 (17)
Red bay	1 (1)	5 (7)	--	1 (1)
Laurel greenbriar	2 (3)	3 (3)	--	3 (3)
Highbush blueberry	6 (8)	14 (16)	--	17 (15)
Shallow Organic				
Giant cane	2 (2)	0	--	--
Coastal sweetpepper	5 (7)	30 (36)	--	--
Blue huckleberry	4 (4)	0	--	--
Large gallberry	22 (24)	0	--	--
Smooth winterberry	8 (9)	2 (2)	--	--
Coastal doghobble	0	5 (6)	--	--
Swamp doghobble	0	10 (11)	--	--
Fetterbush lyonia	28 (37)	9 (8)	--	--
Red bay	2 (2)	8 (7)	--	--
Laurel greenbriar	1 (2)	5 (6)	--	--
Highbush blueberry	15 (16)	14 (16)	--	--

Deep Organic				
Giant cane	--	0	0	6 (5)
Coastal sweetpepper	--	10 (11)	5 (4)	9 (8)
Blue huckleberry	--	0	0	12 (7)
Large gallberry	--	0	14 (12)	18 (13)
Smooth winterberry	--	0	0	1 (1)
Coastal doghobble	--	10 (11)	0	0
Swamp doghobble	--	10 (11)	0	0
Fetterbush lyonia	--	5 (6)	69 (57)	35 (27)
Red bay	--	4 (4)	5 (4)	3 (3)
Laurel greenbriar	--	0	23 (19)	15 (3)
Highbush blueberry	--	25 (53)	0	22 (15)

Table 7. Average structural density by community type based on counts derived from number of times vegetation (leaf, twig, branch…) passes through a 3-D vertical and horizontal 20cm band along a 5m transect.

Community Type	Vertical Stem Counts	Horizontal Stem Counts
Pond Pine Woodland	35	121
Nonriverine Swamp Forest	36	127
Bay Forest	33	185
High Pocosin	52	183

Table 8. Average measured quantities of *phosphorous* (mg/dm^3) at a 0-90cm depth across Mineral, Histic, Shallow Organic, and Deep Organic soil types within Pond Pine Woodland, Nonriverine Swamp Forest, Bay Forest, and High Pocosin communities.

	Community Types			
Soil Type	Pond Pine Woodland	Nonriverine Swamp Forest	Bay Forest	High Pocosin
Mineral	13.0	--	--	--
Histic	13.8	14.9	--	4.3
Shallow Organic	10.0	19.9	--	--
Deep Organic	--	15.9	12.1	8.3

Table 9. Average measured quantities (meq/dm^3) of potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) at a 0-90cm depth across Mineral, Histic, Shallow Organic, and Deep Organic soil types within Pond Pine Woodland, Nonriverine Swamp Forest, Bay Forest, and High Pocosin communities.

	Community Types															
	Pond Pine Woodland				Nonriverine Swamp Forest				Bay Forest				High Pocosin			
Soil Type	K	Ca	Mg	Na	K	Ca	Mg	Na	K	Ca	Mg	Na	K	Ca	Mg	Na
Mineral	0.07	0.29	0.19	0.05	--	--	--	--	--	--	--	--	--	--	--	--
Histic	0.09	0.20	0.23	0.09	0.12	0.23	0.22	0.17	--	--	--	--	0.15	0.23	0.51	0.09
Shallow Organic	0.11	0.27	0.21	0.09	0.12	0.22	0.24	0.36	--	--	--	--	--	--	--	--
Deep Organic	--	--	--	--	0.10	0.18	0.23	0.25	0.15	0.22	0.77	0.32	0.12	0.21	0.54	0.15

Table 10. Average measured quantities (meq/dm^3) of manganese (Mn), zinc (Zn), and copper (Cu) at a 0-90cm depth across mineral, histic, shallow organic, and deep organic soil types within pond pine woodland, nonriverine swamp forest, bay forest, and high pocosin community types.

	Community Types											
	Pond Pine Woodland			Nonriverine Swamp Forest			Bay Forest			High Pocosin		
Soil Type	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn	Cu
Mineral	1.21	0.78	0.11	--	--	--	--	--	--	--	--	--
Histic	1.15	1.74	0.06	1.17	2.16	0.14	--	--	--	0.79	1.89	0.05
Shallow Organic	0.98	1.48	0.06	1.14	2.76	0.10	--	--	--	--	--	--
Deep Organic	--	--	--	0.93	3.00	0.03	1.11	4.13	0.11	1.06	5.79	0.05

Table 11. Suggested ecological parameters for monitoring purposes in the establishment and/or restoration of pond pine woodland, nonriverine swamp forest, bay forest, and high pocosin communities in Carolina Bay ecosystems, based on the ecological parameters exhibited by the three reference Carolina Bays sampled over the course of this study.

Ecological Parameters	Pond Pine Woodland	Nonriverine Swamp Forest	Bay Forest	High Pocosin
Dominant Canopy Species and Basal Area	Pond Pine 58-68 ft^2/acre	Swamp Gum 87-105 ft^2/acre	Bay Trees 34 ft^2/acre	Pond Pine 7-20 ft^2/acre
Dominant Understory Composition	large gallberry fetterbush lyonia,	coastal sweetpepper bush highbush blueberry	fetterbush lyonia laurel greenbriar large gallberry	fetterbush lyonia highbush blueberry large gallberry
Vertical Density (Understory Stems)	35/m^2	36/m^2	33/m^2	52/m^2
Horizontal Density (Understory Stems)	121/m^2 X 3m high	127/m^2 X 3m high	185/m^2 X 3m high	183/m^2 X 3m high
Soil Type	Mineral Histic	Histic Shallow Organic	Deep Organic	Deep Organic
Available Phosphorous	13.0-13.8 mg/dm^3	14.9-19.9 mg/dm^3	12.1 mg/dm^3	8.3 mg/dm^3
Average Water Table Depth	-33.7cm	-19.7cm	-17.9cm	-24.9cm

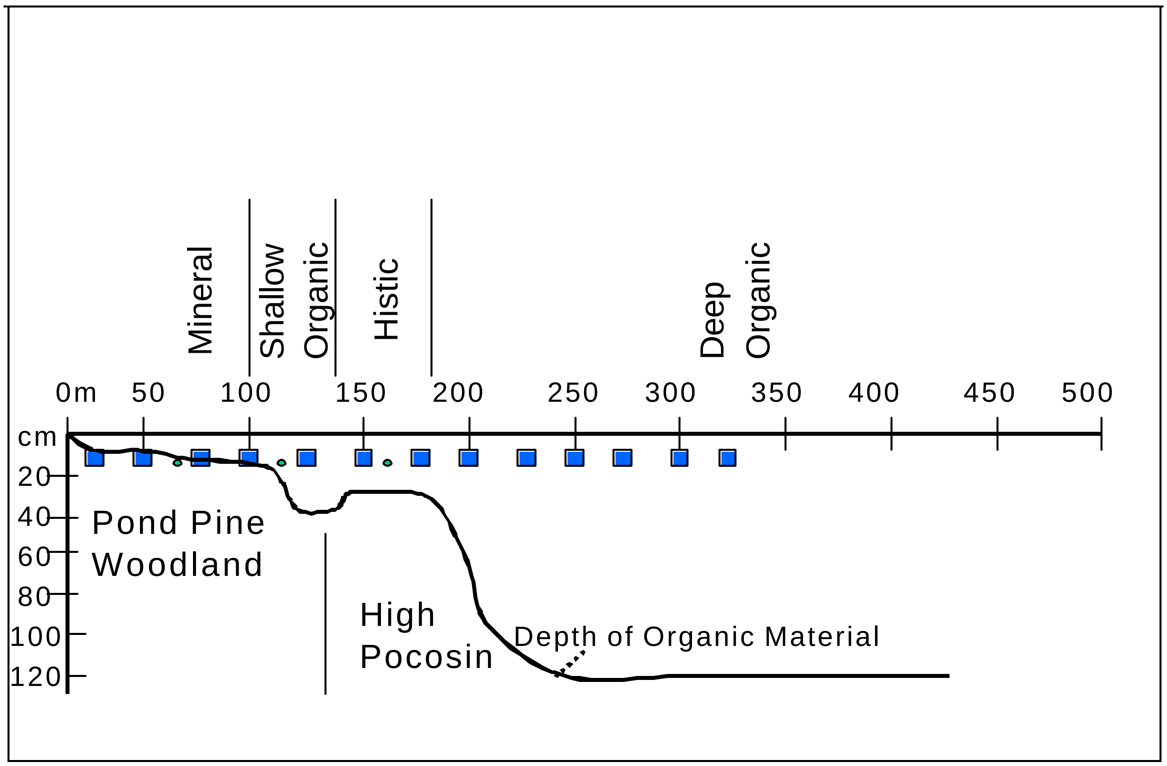

Figure 1. Plot layout along transect at Causeway Bay from periphery (0m) to center (500m) of the bay. ■ = plot; • = hydrology monitoring well.

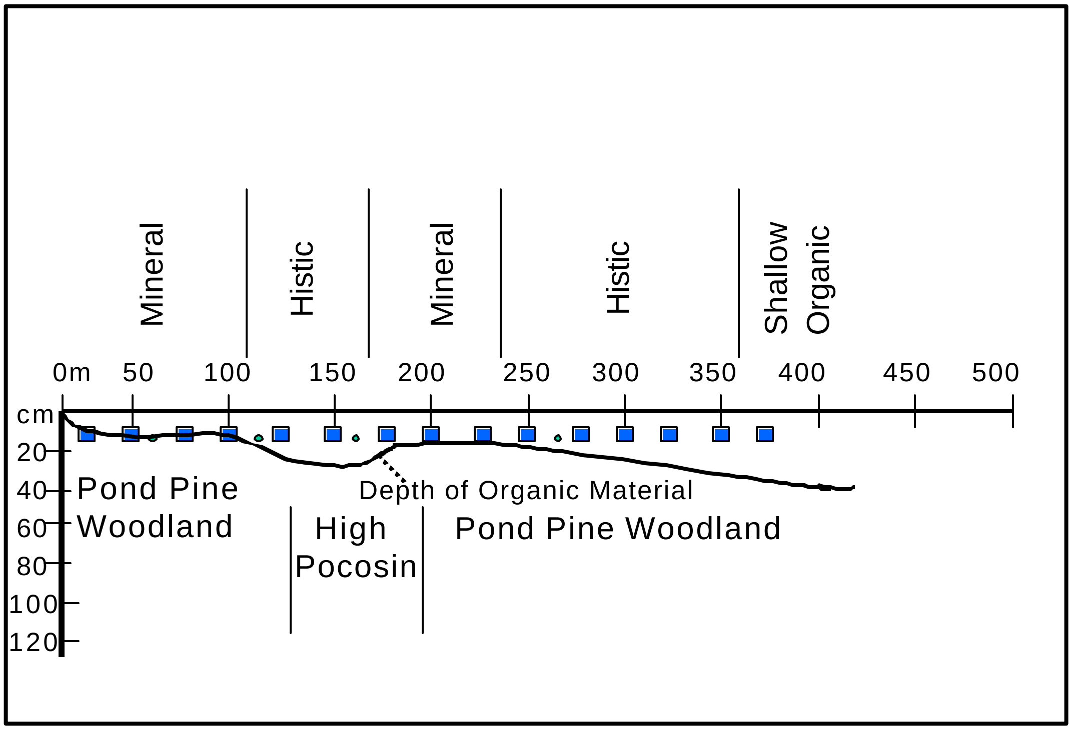

Figure 2. Plot layout along transect at Charlie Long Bay from periphery (0m) to center (500m) of the bay. = plot; ● = hydrology monitoring well.

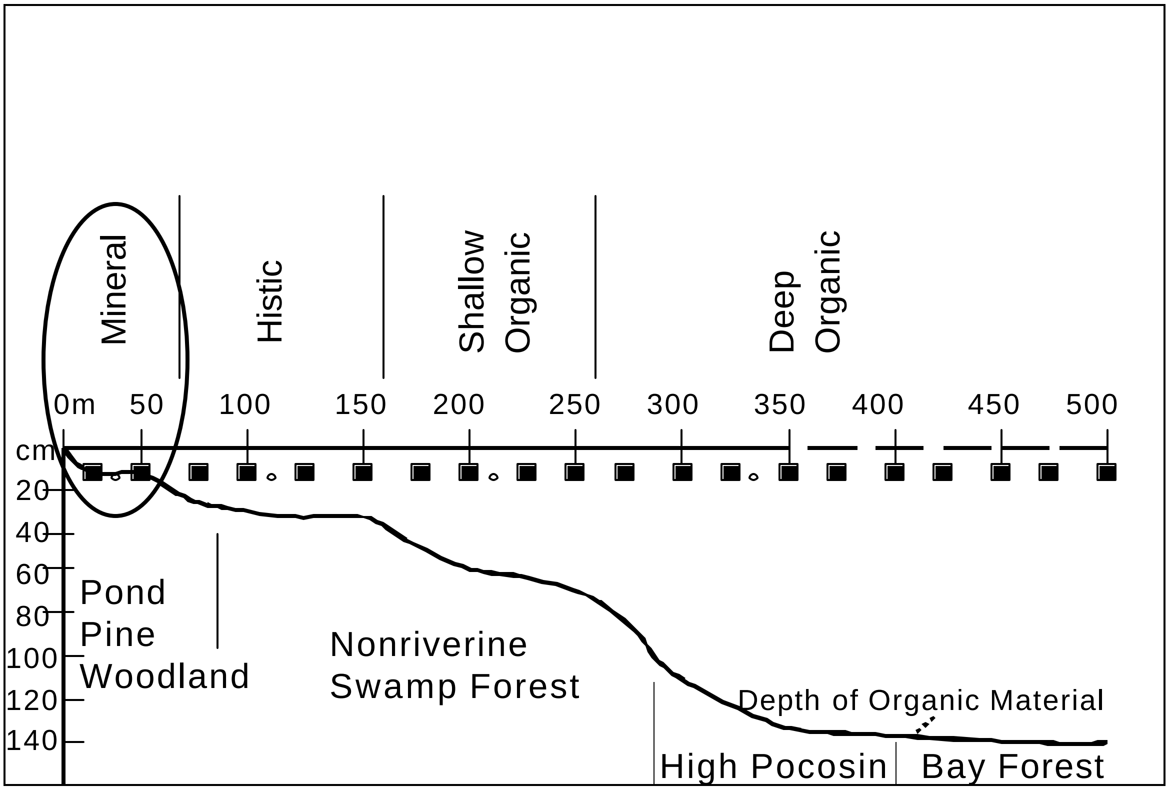

Figure 3. Plot layout along transect at Tatum Millpond from periphery (0m) toward the center of the bay. Circled area indicates portion of transect relocated due to clear-cutting of original transect in those areas. ■ = plot; • = hydrology monitoring well.

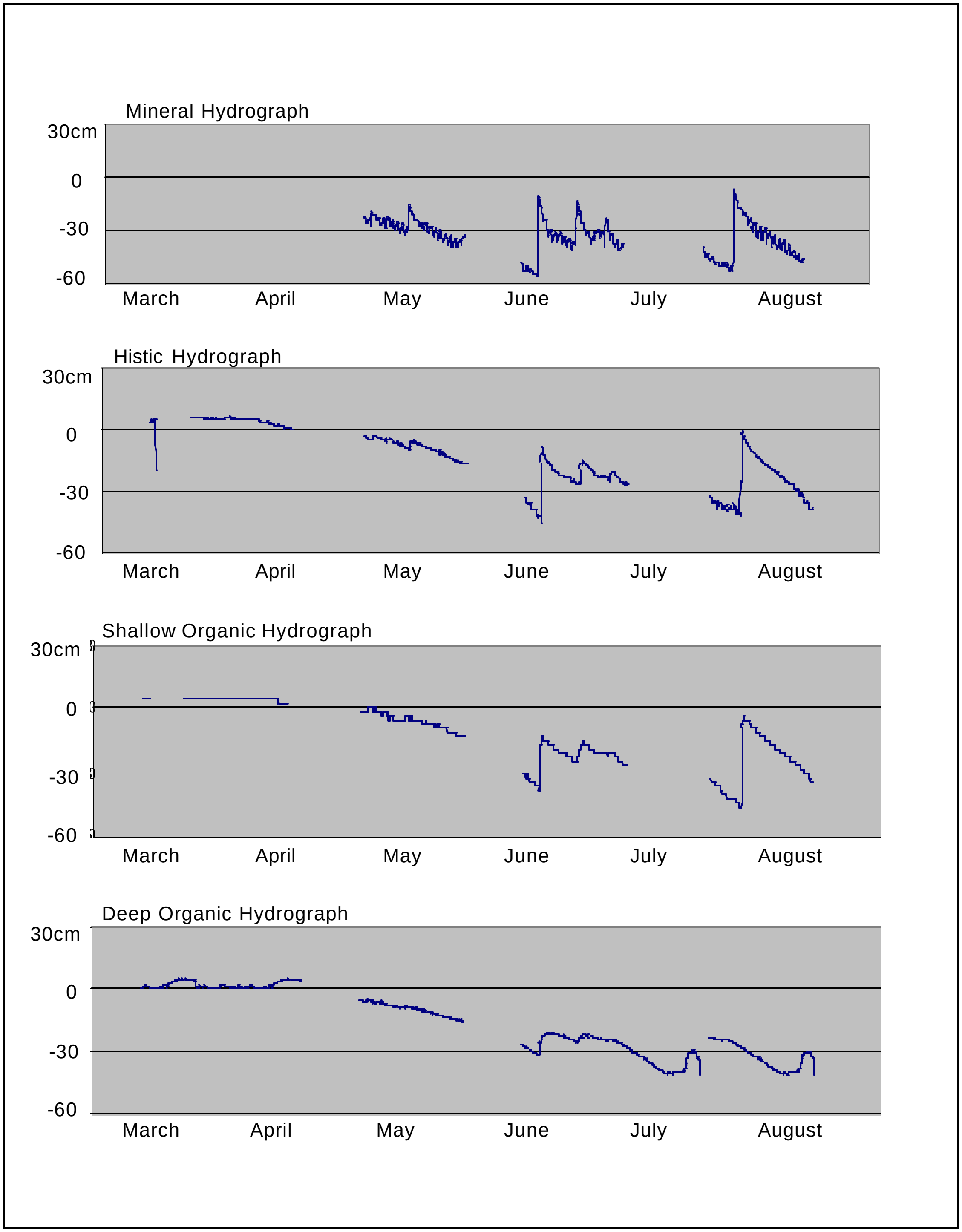

Figure 4. Hydrographs for March 6, 2001 through August 9, 2001 from mineral, histic, shallow organic, and deep organic soils in Tatum Millpond.

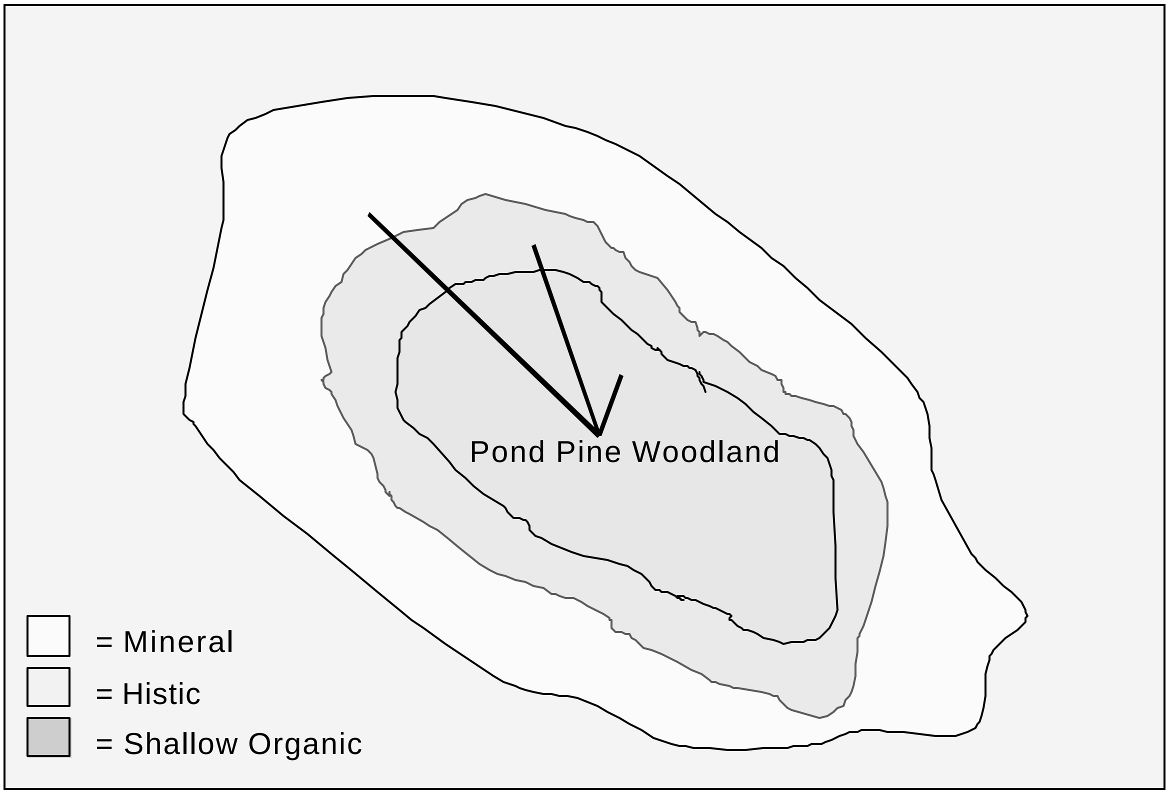

Figure 5. Recommended planting plan for specified soil types at the Juniper Bay DOT mitigation/restoration site

Chapter 5

CHEMICAL SOIL PROPERITES OF JUNIPER BAY AFTER 15, 20, AND 30 YEARS OF DRAINAGE AND AGRICULTURAL PRODUCTION

J.M. Ewing and M.J. Vepraskas

INTRODUCTION

Section 404 of the Clean Water Act (1977) requires the replacement, or mitigation, of destroyed wetlands. Wetland mitigation includes, enhancement and preservation of current wetlands, creation of new wetlands, or the restoration of prior wetlands (USCOE, 2002). Success of such mitigation projects has been mixed. Erwin (1991) found that of 40 mitigation projects in south Florida 60% were judged incomplete or failures, Wilson and Mitsch (1996) found that only 38% of the desired wetland was established at mitigation sites in Ohio, and Gallihugh and Rogner, (1998) found that 99 ha of 128 mitigation sites involving 144 ha, were found to have unsatisfactory hydrology. The probability of success should be greater in an area that once supported wetland hydrology, hydric soils, and hydrophytic vegetation.

Drained Carolina bays found along the Atlantic Coast in the southeastern U.S., are being utilized for wetland restoration. Carolina bays are elliptical depressions in the landscape that are orientated along the long axis SE to NW. They range in size from 10 m to >4 km along the long axis. The bays are usually surrounded by a light colored sandy rim and have a dark colored depression resulting from high amounts of organic matter (Johnson, 1942). The extent of these bays range from Northern Florida to Delaware with the highest concentration in North and South Carolina. Estimates on the number of these bays are as high as 500,000 (Johnson, 1942), but the actual number maybe less than 100,000 (Nifong, 1998). Many theories for bay formation have been proposed, from the most popular, meteor impact (Johnson, 1936), artesian springs (Prouty, 1952; LeGrand, 1952), whale wallows (Grant 1945), and ice flows (Bliley and Burney, 1988). Currently the most plausible explanation is that originally there were shallow depressions in the landscape with an aquitard that allowed the water table to be held above the surface. Prevailing winds then shaped the depression into the now familiar orientated shape (Thom, 1970; Odum, 1952). During the past century agricultural and community development have led to the drainage and use of these bays. It is estimated that 50% of all Carolina bays were drained and developed in some manner in Bladen County, NC by 1982 (Weakley and Scott, 1982). This figure would be higher if other management practices such as logging were included. As these bays are used for agriculture and other activities, their defining characteristics of sand rims and organic surfaces, become blurred into the surrounding landscape.

Plant communities typically found in undrained Carolina bays include non-riverine swamp forest, low pocosin, high pocosin, pond pine woodland, peatland Atlantic White Cedar forest, and Bay forest (Schafale and Weakly, 1990). These plant communities are found in nutrient poor soils that maybe organic soil or mineral soils. Variability in these plant communities depends on depth of organic matter, seasonal water table depths, fire and mineral input if any (Schafale and Weakly, 1990). Soil series associated with theses plant communities (Croatan, Pamlico, Ponzer, Lynn Haven, Torhunta, Rutlege, and Pantego) are very strongly acidic (4.5-5.0) to ultra acidic (<3.5). Cation exchange capacity tends to be very low ranging from 1 to 30 cmol kg^{-1}, but can be as high as 100 cmol kg^{-1} in the surface layers. Exchangeable phosphorus has found to be strongly limiting to plant production in High Pocosin plant communities (Schafale and Weakly, 1990).

The North Carolina Department of Transportation (NCDOT) purchased a 256 ha drained Carolina bay in 1999, near Lumberton, North Carolina. This land was purchased with the intent of earning wetland mitigation credits. The Carolina bay being restored by the NCDOT is called Juniper Bay. Juniper Bay was drained, cleared, and put into agricultural production incrementally in 1971, 1981 and 1986. A review of the history of the clearing process was described by Ewing et al. (2003). Agricultural practices in the organic soils include the addition of lime to achieve a pH of 5.5 to 5.0 (Lilly and Baird, 1993). To reach this target pH up to 13470 kg ha^{-1} may have to be applied to overcome the large reserve of acidic cations present in organic soils (Lilly, 1981). The North Carolina Cooperative Extension Service recommends the application of 135-180 kg N ha^{-1}, 35-55 kg P_2O_5 ha^{-1}, and 90-115 kg K ha^{-1} for corn production (Crozer, 2000). Organic soils in North Carolina have been shown to leach nitrogen and phosphorus and have to be applied yearly (Lilly, 1981). Crop cultivation, depending on the crop, can include the use of chisel plows, moleboard plows, disks, and subsoilers. The overall objective of the Juniper bay project is to restore Juniper bay back to an ecosystem that is typical of Carolina bays. This includes restoration of hydrology, vegetation, and soils typically found in Carolina bays.

The objective of this study was to evaluate the changes in soil chemical properties created by agricultural practices in Juniper Bay. Changes resulted from the addition of fertilizer and lime over 30 years as well as tillage and drainage of the area.

MATERIALS AND METHODS

Juniper Bay is located 10 km southeast of Lumberton, North Carolina in Robeson County (34^{o}30’30”N 79^{o}01’30”E). The Bay was logged, drained, and put into agricultural production in three stages. The western third of Juniper Bay was drained by ditches in 1971, the central third and most of the eastern third was drained in 1981, the area to the north in the eastern third was drained in 1986. A perimeter ditch was dug in 1971 around the entire bay, two main drainage ditches that run NE to SW and many lateral ditches that run NW to SE. The perimeter ditch and the main ditches were approximately 7 m wide and 4 m deep. The lateral ditches were roughly 1.5 m wide and 1m deep. Areas that are enclosed by ditches are called ‘cuts’. There was only one outlet in Juniper Bay and it is located at the SW end of the main ditch on the western side. A soil survey of Juniper Bay indicated three broad groups of soil that are based on the thickness of the organic layer. They were mineral (<20cm organic material), histic epipedon (20-40 cm organic material), and organic (>40 cm organic material).

Sampling locations were chosen by randomly placing an equilateral triangle grid over a map of Juniper Bay. Grid points were spaced far enough apart to allow 24 sampling points to be within the site boarded by the perimeter ditch, with ten located in organic soil, eight in mineral soil, and six in soils with a histic epipedon. Those points were found in the field using GPS. Using the location point from the grid as a reference, we dug a 1 to 1.5 m pit at the center of a field cut and a pit near the closest lateral ditch, resulting in a pair of pits at each location. Soil profiles were described and bulk samples for laboratory analysis were taken from each horizon.

Three reference bays were selected in Bladen County, North Carolina based on their similarity of soils to Juniper Bay, lack of drainage or agricultural applications, and ownership cooperation. Three reference sites were named Charlie Long-Millpond Bay (34^{o}46'00"N 78^{o}33'30"E), and Tatum Millpond Bay (34^{o}43'00"N 78^{o}33'00"E), both located in the Bladen Lakes State Park and Causeway Bay (34^{o}39'45"N 78^{o}25'45"E), which was located 10 km N of White Lake, N.C. A trail from the rim of each bay to the center was cut through the dense vegetation. The three broad soil groups described in Juniper Bay, mineral, histic, and organic, were also found in all three reference bays. Plots were marked off at 50m intervals along the transect. Plots to be sampled were then randomly selected in each soil. There were a total of eight sampling plots in each reference bay, two in the mineral and histic soils, and four in the organic soils. Soil profiles in the selected plot were described from samples extracted with a McCauley peat sampler and an open bucket auger. Bulk samples were taken for laboratory analysis from each horizon.

Bulk samples from Juniper Bay and the reference bays were air dried and ground with an electric grinder to pass through a 2-mm sieve. Extractable K, Ca, Na, Mg, Mn, Zn, and Cu were determined by running Mehlich III extract (Mehlich, 1984) through an inductively coupled plasma emission spectrograph. Cation exchange capacity and sum of base cations were also determined (Mehlich, 1976). The pH was determined using a 1:1 soil to water ratio. Organic carbon and total nitrogen were determined through dry combustion with a Perkin-Elmer PE2400 CHN Elemental Analyzer (Culmo, 1988).

Soil types, organic, histic, and mineral, were analyzed separately using the SAS procedure PROC MIXED (SAS, 1985), with an AR(1) covariance structure to compare years since drainage and proximity to a ditch. The number of locations for a given soil type and years in agricultural production can be seen in Table 6. Each location had paired pits with one located at the crest of the cut and one near the ditch. The horizon type and depth present at each location varied and were evaluated as a spatially repeated measure. The data were not balanced so least square means (LSMEANS) were used to obtain estimated means. Comparisons among crest and near ditch pits were made with $p>0.1$ being significant.

The comparisons between the reference bays and Juniper Bay were analyzed separately depending on, soil type, organic, histic, and mineral, using the SAS procedure PROC MIXED (SAS, 2000), with an AR(1) covariance structure. Data from the crest locations in Juniper Bay were used in this analysis after determining that differences in crest and ditch locations were minimal. Organic, histic, and mineral soils were combined into one data set among the three reference bays, resulting in 12 organic, six histic, and six mineral locations. Horizons varied depending on location and pit and were evaluated as a spatially repeated measure. The reference Carolina bays were considered random variables so results could be inferred to natural Carolina bays as a whole. Soils from the reference bays were assumed to be equal to the Juniper Bay soils prior to drainage and chemical application. Data were not balanced so LSMEANS were used to obtain estimated means. Comparisons among Juniper Bay and the reference bays and time since drainage were made with $p>0.1$ being significant.

RESULTS AND DISCUSSION

Typical profile descriptions for organic, histic, and mineral soils from Juniper Bay and the reference bays are given in Table 1. The soils in Juniper Bay have been affected by tillage and drainage. The surface horizons do not have an organic mat, Oi or Oe horizons that are typically found in undrained Carolina bays. The surface horizons in JB have moderate to strong structure while the RB have weakly developed structure. Drainage has allowed the deeper organic soil in JB to develop structure while similar soil in the RB is massive. The agriculture producer who owned the land prior to the NCDOT had soil fertilizer records from 1976, which showed one to three tons/ac of dolomitic lime, 50 to 200 lb P_2O_5, and 200 to 300 lb K/ ac was applied. Mr. Freeman also indicated that fertilizer recommendations were followed yearly.

ORGANIC SOILS

Juniper Bay vs. Reference Bays

There were significant differences in organic carbon, extractable K, Ca, Mn, BS, CEC, and total N between the organic soils of Juniper Bay and the organic soils of the reference bays (Table 2). The organic soils in the reference bays had 8.4 g kg^{-1} more OC at the surface than in Juniper Bay (Fig. 2a). The RB soils decreased in OC content with depth, 37.6 g kg^{-1} at the surface to 3.7 g kg^{-1} at 175 cm. The change from organic soil to mineral soil in the RB occurred around 150 cm. The OC increased in JB from 29.2 g kg^{-1} at the surface to 35.2 g kg^{-1} at 32 cm, and then decreased with depth to 2.5 g kg^{-1} at 108 cm. This shows that oxidization at the surface was reducing the soil OC content, but below the plow layer the rate of oxidation was slower and OC was similar to that of the RB. The change from organic soil to mineral soil in JB occurred at approximately 75 cm. Total nitrogen followed a similar trend as OC and was higher through the profile in RB. Total N content in general, corresponds with the amount of organic matter in the soil, however it does not relate to the amount available to plants (Tonapa, 1974). Nitrogen levels in JB were 0.87 g kg^{-1} at the surface, decreasing to 0.5 g kg^{-1} at 108 cm, and in RB they decreased from 1.46 g kg^{-1} at the surface to 0.07 g kg^{-1} at 173 cm.

Organic soils have very high CEC's, which in general increases as OM increases (Kamprath, and Welch, 1962). Such is the case in JB where the CEC is lower throughout the profile ranging from 24.0 $cmol_c\ kg^{-1}$ at the surface to 4.0 $cmol_c\ kg^{-1}$ at 108 cm while in the RB it ranged from 46.6 $cmol_c\ kg^{-1}$ at the surface to 6.6 $cmol_c\ kg^{-1}$ at 171cm. This means higher amounts of lime are required to change pH values because of the large reserves of acidic cations (Juno and Kamprath, 1979) and the ability to adsorb large amounts of basic cations from lime (Evans and Kamprath, 1970). Such was the case in Juniper Bay where agricultural producers added several tons of lime per ha each to increase and maintain an elevated pH (Freeman, 2000 personal interview). The pH in JB was 0.72 to 0.24 units higher through the profile than in RB. The pH in both decreased with depth through the organic material and then increased when mineral material was encountered. Due to the high amounts of lime applied extractable Ca was higher in the surface soils of JB and decreased with depth to a level found in RB (Fig 2b). Extractable Ca was 4.5 cmol Ca kg^{-1} higher at the surface in JB and continued to be elevated over levels in the RB to a depth of 88cm. There was a similar trend with extractable Mn was 6.83 mg kg^{-1} higher at the surface in JB and continued to be elevated over RB levels to a depth of 75 cm. Histosols contain no or very little K-supplying or K-fixing silicate minerals and essentially all the K present is held on the OM exchange complex and is readily avaible (Lilly, 1981). It would be expected that JB have equal or higher amounts of K due to fertilizer additions, however, extractable K was higher in the upper 20cm of the RB, 1.10 cmol K kg^{-1} compared to JB 0.33 cmol K kg^{-1}. This might be because crops had remove the readily avaible K. As a result of the decreased CEC and increased level of base cations, base saturation in JB was consistently higher than the RB (Fig 2c). The RB had a BS of 12.0% at the surface and decreased with depth while at JB it was 61.4% at the surface decreasing to 15.4% at 84cm, then increased slightly to 20.0% at 108cm.

It was expected that levels of extractable P would show signs of leaching through the profile in Juniper Bay because organic soils are low in Al and Fe oxides will not hold inorganic P, and can be leached from pure organic soils or quartz sand. Fox and Kamprath, 1971; Larson et al., 1959). However extractable P, as well as Mg and Zn, were not significantly different but had some notable trends. Extractable P and Mg followed a familiar trend of having higher levels in JB and decreasing with depth to levels found in the RB, but the opposite was true for extractable Zn, which had higher values at the surface in the RB. The ability of organic soils to hold P will increase with time as subsidence, ditch spoil, and lime increase the mineral content in the root zone (Larson et al., 1958), and may be the case in Juniper Bay.

Time in Agricultural Production

Nutrient levels, pH and base saturation have been reported to increase in Carolina bay soils when under agricultural production (Ewing, 2002; Hanchey et al., 2000). Increased periods of time in agricultural production resulted in significant increases of BS and extractable Ca. (Fig. 3) in the organic soils of Juniper Bay. Base saturation increases reflect combined impacts of Ca, Mg, Na and K. Depths of apparent leaching of Ca also increased with time in agricultural production. Calcium levels were increased over these in the RB down to depths of approximately 40, 70, and 90 cm after 15, 20, and 30 years in production. This results in an estimated leaching rate of 2.5, 3.4, and 2.9 cm yr^{-1} for 15, 20, and 30 years of agricultural production.

Crest vs. Ditch

There was a significant difference in the amount of zinc between the crest and ditch locations (Fig. 1). Extractable Zn was higher at the crest than the ditch, 10.40 and 5.6 mg kg^{-1} in the surface 15 cm respectively and decreased with depth to 0.38 and 0.22 mg kg^{-1} at depths of 107 and 110cm. Levels of Zn reached a low constant level below 1.00 mg kg^{-1} at 48cm at the ditch and 74cm at the crest.

Although there were no differences found in extractable P, K, Ca, Mg, Mn, CEC, BS, and pH for the organic soil there was a similar depth trend of higher levels in the surface 15cm at the crest relative to the ditch and tended to be elevated through the profile at the crest compared to the ditches. For example, extractable P was 81.0 mg kg^{-1}, at the crest and 59.0 mg kg^{-1} at the ditch. Organic carbon was above 12 g kg^{-1} from 0-74 cm at the crest and 0-48cm at the ditch. The trends seem to indicate that there is more oxidation of the organic soil near the ditch due to better drainage. The trends in nutrients indicate a continued overlap during application of fertilizer and lime, or that nutrients have been remove near the ditch through drainage or surface runoff.

HISTIC SOILS

Juniper Bay vs. Reference Bays

LSMEANS estimates comparing Juniper Bay and the reference bays for histic soil types can be seen in Table 3. The general trend for both JB and RB is to have the highest amount of constituent at the surface and decrease with depth. There were two different trends, one, like extractable P (Fig. 5a), had higher levels the upper 30cm at JB and then decreased to levels found in the RB, and the other, like extractable K (Fig. 5b) had higher levels in the upper 30 cm at the RB.

Base saturation, extractable Ca, Mg, Zn, followed the trend illustrated by extractable P.   Extractable P levels at the surface for JB were 96.4 mg kg^{-1} and decreased with depth to levels found in RB. There was 36.6 mg kg^{-1} of ex. P in the surface 20cm at the RB and decreased to 9.5 mg kg^{-1} at 32cm and remained constant through the rest of the profile. Extractable Ca in the surface 20cm at JB was 3.88 cmol Ca kg^{-1} and 0.43 cmol Ca kg^{-1} at RB. Extractable Mn at the surface in JB was 8.05 mg kg^{-1} and of 3.37 mg kg^{-1} at the RB. Extractable Mg at JB was 1.54 cmol Mg kg^{-1} in the surface 20cm at JB and 0.86 cmol Mg kg^{-1}, at the RB. Base saturation in the surface 20cm is 63.0% at JB and 9.6% in the RB.

Organic carbon, total N, and CEC followed the trends illustrated by extractable K. Extractable K was higher in the surface 20cm at the RB 0.71 cmol K kg^{-1}, compared to JB 0.28 cmol K kg^{-1}. Levels below 20 cm were similar for both locations and decreased with depth. The histic soils in JB had lower amounts of OC (17.0%) at the surface 20cm compared to the histic soils at the RB (30.5%). This is reversed at 30 cm with 24.7% OC at JB and 13.5% at RB. Below 40 cm the OC levels decrease with depth for JB and RB. The organic mineral boundary in JB was at 30cm and 32cm in RB. Total N was 1.08% at the surface in the RB and 0.51 in JB. CEC in JB is 33.05 $cmol_c\ kg^{-1}$ in the surface 20cm and decreased with depth, RB is highest at the surface, 17.83 $cmol_c\ kg^{-1}$.

Although not significant the pH in JB was highest in the surface horizon 4.29, and ranged to a low of 3.81, while at the RB the high pH, 4.37 was in the C horizon and ranged to 3.51 near the surface.

Time in Agricultural Production

Differences based on the amount of time since drainage were significant for percent organic carbon, CEC, base saturation, and extractable Ca, and Mn. The amount of organic carbon after 0, 15 and 20 years of drainage, in the surface 18cm was 30.5, 20.2, and 13.4% respectively and decreased with depth (Fig. 6a). However, areas drained for 30 years first increased to 39.2% at 32cm, then decreased. Extractable Ca was highest, 5.08 cmol Ca kg^{-1} in the surface 20 cm in the areas under agricultural production for 20 years, followed by 2.69 cmol Ca kg^{-1} in the areas under production for 15 years. Time zero had 0.43 cmol Ca kg^{-1} or less extractable Ca throughout the profile. The 15year areas decreased with depth and reached low levels (<0.20 cmol Ca kg^{-1}) found in the RB at 52cm, and the 20 year areas reached RB levels at 104cm. This means that Ca move through the soil 2.0 and 3.6 cm yr^{-1} for 15 and 20 years of agricultural production. Extractable Mn followed the same trend as extractable Ca and had 10.38 mg Mn kg^{-1} in the surface 20 cm in the areas under agricultural production for 20 years, and 5.71 mg kg^{-1} in the areas under production for 15 years with 3.37 mg kg^{-1} at time zero. Extractable Mg move through the soil 2.0 and 3.6 cm yr^{-1} for 15 and 20 years of agricultural production. CEC at time zero was higher than 15 or 20 years in the upper 50cm due to higher amounts of organic matter, but lower below 50cm because of lower amounts clay (Fig 6b). CEC in the RB was 33.05 $cmol_c\ kg^{-1}$ in the surface 16cm, areas in production for 20 years had 19.36 $cmol_c\ kg^{-1}$ in the surface 19cm. Base saturation was highest through the profile after 20 years of production, followed by areas in production for 15 years (Fig 6c). Base saturation at time zero were never above 9.6%, but ranged from 52.4 to 12.9 for areas drained for 15 years and from 73.4 to 12.5% for areas drained 20 years.

Crest vs. Ditch

There were significant differences between crest and ditch for extractable P, Mg, Mn, and Zn, and base saturation. Extractable P levels at the crest were 48 to 25 mg kg^{-1} higher at the crest compared to the ditch in the upper 30 cm (Fig 4). Extractable P levels for both crest and ditch dropped to low (<3.5 mg kg^{-1}) levels below 40 cm. The same trend of higher levels in the surface 30cm at the crest decreasing to similar low levels is evident in extractable Mg, Mn, and Zn and BS. The surface soils in the histic soil type had 6.38 and 4.07 mg kg^{-1} extractable Zn at the crest and ditch. Extractable Mn was higher in the surface horizon at the crest 8.07 mg kg^{-1} than the ditch 4.07 mg kg^{-1}. Extractable Mg was higher at the crest 1.58 cmol Mg kg^{-1} in the surface horizon compared to the ditch 0.77 cmol Mg kg^{-1}. The base saturation was higher in the upper 30cm crest surface soil by 23-11% when compared to the ditch.

Although not significant the trends of CEC, extractable K and Ca looked like that of extractable P and tended to be higher in the surface 30 cm at the crest position and decrease to similar low levels. The pH was similar a both locations with highest at the surface and ranged from 3.80 to 4.88 at the crest and 4.07 to 4.68 at the ditch. Organic carbon was above 12% in the surface 30cm at both positions. Organic carbon increased from 15cm to 30 cm before decreasing below 12%. The lower levels of OC at the surface could be due to increased oxidation or addition of ditch spoil.

MINERAL SOILS

Juniper Bay vs. Reference Bays

LSMEANS estimates comparing Juniper Bay and the reference bays for mineral soil types can be seen in Table 5. Levels of base saturation, pH, extractable Ca, P, and Zn had higher levels in the surface 30cm in JB then decreased with depth to levels found in the RB. This trend is illustrated with extractable P (Fig. 8a). Levels of extractable P are 0.33 and 87.1 mg kg^{-1} in the surface 10cm at the RB and JB respectively. Extractable P decreases rapidly to 16.0 mg kg^{-1} at 44cm in JB, and remained near levels found in the RB for the remaining of the profile. Base saturation was highest in the upper 10cm, 16.3%, at the RB and 74.6% in JB, and then decreased with depth. Extractable Ca in the surface 10cm was 1.15 cmol Ca kg^{-1} in the RB and 3.34 cmol Ca kg^{-1} in JB. Zinc levels were 12.4 and 5.96 mg kg^{-1} in the surface 10 cm in JB and the RB respectively. The pH in JB in the surface 30cm was approximately 5.0 and decreased to around 4.3 below 62cm while in the RB the pH was approximately 3.65 in the upper 25 cm increasing to 4.1 below 52cm. Organic carbon, total N, CEC, extractable K and Mg had the opposite trend with higher levels in the surface layers in the RB decreasing to levels that are similar to those in JB. This trend is illustrated with extractable K in Fig 8b. Extractable K levels in the surface horizon were 0.26 and 0.75 cmol K kg^{-1} at JB and RB respectively. JB decreased to 0.04 cmol K kg^{-1} at 24cm and the RB decreased to 0.14. Below this depth extractable K remained around 0.04 cmol K kg^{-1} for the rest of the profile in JB, but continued to decrease to 0.01 cmol K kg^{-1} in the RB. Organic carbon in the surface 10cm of the RB is 24.9% and 7.64% in JB. The high OC in the RB is due to an accumulation of leaf litter at the surface. Total nitrogen in the surface 10cm was higher in the RB, 0.73% than in JB, 0.19%. CEC levels in the RB were highest in the surface horizon, 32.62 $cmol_c$ kg^{-1}, and decreased with depth to 8.67 $cmol_c$ kg^{-1} at 22cm. Juniper Bay soils had a CEC of 12.71 $cmol_c$ kg^{-1} in the surface horizon, decreased with depth to 2.63 $cmol_c$ kg^{-1} at 126cm. Extractable Mg in the surface horizon for JB was 1.12 cmol Mg kg^{-1} and 1.23 cmol Mg kg^{-1} for the RB. There were no significant differences between JB and the RB for extractable Mn, however it did follow the trend of having higher levels at the surface in JB and decreasing to levels found in the RB.

Time of Drainage

Significant effects due to the time of drainage and agricultural production were found in base saturation (Fig. 9). Time zero, the reference bays, had a BS of 16.3% at the surface and decreased with depth to 4.98 at 82cm. After 25 years of agricultural production the BS in the surface 10 cm was 76.48% and decreased with depth to 27.08% at 120cm. After 30 years of agricultural production BS in the surface 10 cm was 72.76% decreased rapidly to 46.79% 23cm, and continued to decrease with depth to 25.08% at 57cm before increasing to 37.43% at 132cm.

Although not significant extractable Ca, Mg, P, Mn, and Zn followed the same trend with areas drained for 30 years having higher levels in the surface soils, closely followed by areas drained for 20 years, followed by time zero levels. Levels of these constituents, from either drainage time, decreased with depth to levels found in the RB. In areas drained for 20 years the pH levels were higher than areas drained for 30 years, and both drainage areas were generally higher than pH from the RB. The surface horizon at time zero was above 12% organic carbon and was 10 cm thick. The area drained for 30 years had 10.5 and 13.0% organic carbon in the surface two horizons or 23cm. These values may indicate that this location may use to have been a histic or organic horizon. The organic carbon in the areas drained for 20 years is less than 5% through out the profile.

Crest vs. Ditch

Although not significant extractable P and CEC followed the trend of having higher levels in the surface horizons at the crest and decreasing with depth to levels similar to that of the ditch (Table 4). Organic carbon and total nitrogen were very similar at both locations with the highest level being at the surface and decreasing with depth.

Levels of extractable Ca, K, Mg, Mn, and Zn, pH and BS in the surface horizon were significantly higher at the crest compared to the ditch. All of these variables decrease with increasing depth down to 30-50 cm where the values reach a relatively constant equilibrium (Fig. 7). Extractable Ca was twice as high at the crest compared to the ditch in the surface horizon, then decreased to similar levels by 30cm and continued to decrease through the profile. Extractable K was 0.206 cmol K kg^{-1} at the crest and 0.071 cmol K kg^{-1} at the ditch in the surface horizon. Extractable Mg was 0.66 cmol kg^{-1} higher in the surface horizon at the crest but decreased to similar levels found in the ditch profile by 50cm. Extractable Mn and Zn were 3.65 mg kg^{-1} and 6.77 mg kg^{-1} higher at the crest in the surface horizon. The pH in the surface horizon at the crest was 5.04 then decreased to 4.47 at 50cm then varied between 4.47 and 4.23 for the remained of the profile. At the ditch pH was 4.68 in the surface horizon, then increased to 4.76 at 50cm, and then decreases to 4.23 at 125cm. Because of the elevation in Ca and Mn, base saturation is 22.4% higher at the crest compared to the ditch.

CONCLUSIONS

Three reference bays were used to estimate the original conditions of the soils at Juniper Bay prior to agricultural practices being imposes. In general, soils of the reference bays had higher nutrient levels at the surface due to biocycling, however, those levels were significantly less than those found at the surface in Juniper Bay. The organic soils at Juniper Bay have increased levels of extractable K, Ca, Mn, and base saturation, and decreased levels of organic carbon and total nitrogen in the surface 75 cm as compared to the reference bays. The increases in nutrient levels and base saturation are a result of fertilizer and lime applications from agricultural practices. The decreases in organic carbon, total nitrogen and CEC are due to oxidation of the organic soil. The histic soils in Juniper Bay are higher in extractable Ca, Mg, P, Mn, and base saturation in the surface 30 to 50cm compared to the RB as a result of agricultural additions. Extractable K, organic carbon, total nitrogen and CEC are lower in Juniper bay due to oxidization of organic matter and crop up take. The mineral soils at Juniper bay had higher levels of Extractable Ca, Mg, P, Zn, base saturation, and pH compared to the reference bays because of agricultural additions. There were lower levels of extractable K, organic carbon, total nitrogen, and CEC in Juniper bay because of the loss of a litter layer and plant up take.

The differences in the soils at Juniper bay when evaluated at crest and ditch locations showed that Extractable Zn was higher at the crest in organic soils. Extractable Mg, P, Mn, Zn and base saturation were higher at the crest in the histic soils. Extractable K, Ca, Mg, Mn, and Zn were higher at the crest in the mineral soils. The increased levels at the center of the field may be due to over a continual practice of overlapping application passes due to the spacing of the cuts. Additionally, nutrients at the ditch may have been lost through surface runoff or diluted by additions of spoil from ditch maintenance. While differences exist between crest and ditch locations in each soil, they both are well above levels found in the reference bays and could be managed in a similar fashion.

When looking at changes over time, the trend for all the soils is for higher nutrient levels, base saturation and pH and lower organic carbon, CEC, and total nitrogen the longer the soil has been drained and in agricultural production. However, only extractable Ca and base saturation were shown to be affected in this manner in the organic soils. The histic soils had more extractable Ca, Mn, base saturation, and lower CEC and organic carbon after 20 years of production compared 15 years of production, which had higher levels than time zero. In the mineral soils, base saturation and CEC were the only variable that shows a correlation to the length of time in production with base saturation increasing over time and CEC decreasing. The length of time influenced the depth to which there were differences, i.e. the longer in production the deeper the differences occur.

The changes in soil chemical properties due to agricultural production are large. We believe that the increases in nutrient levels and pH will negatively influence the establishment of plant communities typical of Carolina bays, which thrive under acidic and nutrient poor conditions. Invasive plant species will thrive and out compete species that are planted for restoration purposes for nutrients and light resources. To better understand how these differences will affect the establishment of desired species, and to find soil management practices that facilitate the re-vegetation efforts, further studies should be conducted.

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Table 1. Example profile descriptions of organic, histic, and mineral soils from the reference bays and Juniper Bay.

Horizon	**Depth**	Description
	cm	Reference bay Mineral
Oi	0-10	Brown (7.5YR 3/4) fibric organic material, root mat and leaf litter. Weak medium platy structure. Clear boundary.
A	10-20	Black (10YR 2/1) sandy loam. Weak fine granular structure. Clear boundary.
E	20-40	Gray (10YR 6/1) sand. Single grain structure. Clear boundary.
Bh1	40-70	Black (10YR 2/1) sandy loam. Weak medium sub-angular blocky structure. Clear boundary.
Bh2	70-100	Very dark grayish brown (10YR 3/2) loamy sand. Weak coarse sub-angular blocky structure.
		JB17C Core17: Mineral
Ap	0-20	Black (10YR 2/1) loamy sand with 95% organically coated sand grains. Weak medium (2-5mm) granular structure. Abrupt boundary.
E	20-47	20-47cm. Gray (N 6/0) loamy sand with 12% A horizon material in root channels. Single grain structure. Clear boundary.
Bhir1	47-70	Very dark brown (10YR 2/2) sandy loam with 25% E material in upper half of horizon. Massive structure. Clear boundary.
Bhir2	70-92	Black (10YR 2/1) and dark brown (10YR 3/3) sandy loam in alternating layers 2-7cm thick. Massive structure. Abrupt boundary.

Bh	92-120	Black (10YR 2/1) sandy loam with 10% gray (10YR 6/1) sandy grains. Massive structure. Firm and slightly brittle.
		Reference bay Histic
Oi	0-15	Very dark brown (10YR 2/1) hemic muck. Weak medium platy structure. Clear boundary. Root mat.
Oa	15-36	Black (N 2.5/0) sapric muck. Massive structure. Clear boundary.
OC	36-65	Black (N 2.5/0) sandy loam. Massive structure. Gradual boundary.
C	65-100	65-100cm. Very dark brown (10YR 2/2) sand. Single grain structure.
		JB61C: Histic
Ap	0-22	Black (N 2.5/0) mucky sandy loam with 60% organically coated sand grains. Moderate medium granular structure. Clear boundary.
Oa	22-36	Very dark brown (10YR 2/2) sapric muck. Strong coarse granular structure. Clear boundary.
Bw	36-56	Dark brown (10YR 3/3) sandy loam with 2% gray (10YR 6/1) sand. Weak medium sub-angular blocky structure. Clear boundary.
BC	56-74	Dark yellowish brown (10YR 4/6) loamy sand with 2% gray (10YR 6/1) sand. Weak medium sub-angular blocky structure. Gradual boundary.
C	74-108	Brownish yellow (10YR 6/6) with 2% gray (10YR 6/1) sand. Single grain structure.
		Reference bay Organic

Oi	0-20	Black (10YR 2/1) fibric to hemic muck that is part of the root mat. Weak coarse platy structure from layering of plant debris. Gradual boundary.
Oe	20-50	Very dark brown (10YR 2/2) hemic muck. Massive structure with many organic bodies 0.5 to 1.0 cm in diameter. Gradual boundary.
Oa	50-85	Black (10YR 2/1) sapric muck. Massive structure. Gradual boundary.
OC	85-110	Very dark brown (10YR 2/2) mucky loam or mucky sandy loam. Massive structure. Gradual boundary.
2C1	110-140	Very dark brown (10YR 2/2) sandy loam. Massive structure. Gradual boundary.
2C2	140-180	Dark gray (10YR 4/1) sand. Single grain structure.
		JB10C: Organic
Ap	0-10	Very dark brown (10YR 2/2) sandy loam. Moderate medium (3mm) granular structure. Abrupt boundary.
Oa	10-20	Black (N 2.5/0) sapric muck. Moderate fine (2mm) granular to sub-angular blocky structure. Abrupt boundary.
OA1	20-51	Black (10YR 2/1) mucky silt loam. Weak very coarse (20cm) prismatic structure. Clear boundary.
OA2	51-61	Very dark brown (10YR 2/2) mucky silt loam with 25% black (N 2.5/0) charcoal. Weak coarse (10cm) prismatic structure.
OA3	61-68	Dark brown (10YR 3/3) mucky fine sandy loam. Very weak coarse (10cm) prismatic structure. Clear boundary.

Bw	68-107	Yellowish brown (10YR 5/4) very fine sandy clay loam. Weak very coarse (20cm) platy to moderate medium (5cm) sub-angular blocky structure. Clear boundary.
C	107-120	Light brownish yellow (10YR 6/2) sandy clay loam. Strong medium (1cm) angular blocky structure. Faint reaction to alpha-alpha.

Table 2. LSMEANS estimates for Juniper Bay (JB) and the reference bays (RB) in an organic soil. (*) Significant at p<0.1

Horizon	Depth	K*	Ca*	Mg	P	Mn*	Zn	BS*	CEC*	pH	C	N*
	(cm)	---------- (cmol kg^{-1}) ---------			---------- (mg kg^{-1}) -----------			-- (%) --	(cmol$_c$ kg^{-1})		------- (%) -------	
Juniper Bay												
Op	15	0.329	5.16	2.01	76.9	11.44	10.41	61.37	23.97	4.43	29.23	0.83
Oa1	32	0.248	2.6	1.12	32.36	5.06	3.93	34.69	21.45	4.03	35.17	0.75
Oa2	54	0.167	1.41	0.58	12.31	2.91	1.56	21.89	15.63	3.75	21.49	0.5
Oa3	75	0.134	0.82	0.34	7.91	2.25	0.88	15.84	13.26	3.77	16.4	0.37
Bw	87	0.076	0.35	0.14	6.03	0.63	0.28	16.81	6.23	3.88	6.52	0.14
2C	108	0.069	0.23	0.1	4.06	0.53	0.18	20.05	4.01	3.97	2.54	0.05
Error		0.18	0.28	0.37	6.2	0.68	4.9	2.03	6.03	0.07	4.9	0.21
Reference Bays												
Oi	19	1.1	0.62	1.75	70.77	4.61	15.05	11.97	46.6	3.73	37.58	1.46
Oe	48	0.35	0.31	0.5	25.14	2.06	16.48	9.26	23.3	3.51	28.11	0.97
Oa1	88	0.067	0.21	0.28	10.96	1.14	7.46	5.46	17.92	3.5	20.45	0.54
Oa2	123	0.009	0.09	0.07	3.87	0.4	2.56	3.27	10.7	3.87	16.1	0.34
OC	148	0.021	0.14	0.1	2.67	0.65	1.35	3.52	10.48	3.95	13.66	0.27
2C	171	0.051	0.07	0.1	0.1	0.36	0.47	4.41	6.59	3.98	3.77	0.07
Error		0.11	0.23	0.23	5.1	0.58	3.6	2.39	3.88	0.06	3.7	0.14

Table 3. LSMEANS estimates for Juniper Bay (JB) and the reference bays (RB) in a soil with a histic epipedon. (*) Significant at p<0.1

horizon	depth	***K****	***Ca****	***Mg****	P*	***Mn****	***Zn***	BS*	***CEC****	pH	C*	N*
	(cm)	---------- (cmol kg^{-1}) ----------			--------- (mg kg^{-1}) ----------			-- (%) --	(cmol$_c$ kg^{-1})		------- (%) -------	
Juniper Bay												
Ap	18	0.28	3.88	1.54	96.4	8.05	6.34	62.96	17.83	4.9	17	0.51
Oa	30	0.23	1.83	0.83	35.1	3.57	2.16	30.76	16.06	4.02	24.7	0.46
Bw1	51	0.13	0.59	0.37	1.4	1.81	0.46	16.61	10.29	3.83	10.2	0.23
Bw2	65	0.08	0.21	0.1	2.2	0.46	0.28	13.74	9.88	3.81	1	0.06
BC	95	0.07	0.17	0.11	0.2	0.42	0.24	20.18	3.63	3.97	0.8	0.04
C	112	0.06	0.16	0.09	2.7	0.53	0.28	15.1	4.61	3.87	1	0.06
Error		0.08	0.28	0.15	5.8	0.7	1.02	2.75	2.8	0.1	3.1	0.091
Reference bays												
Oi	16	0.71	0.429	0.865	36.6	3.37	6.34	9.57	33.05	3.63	30.5	1.08
Oa	32	0.18	0.165	0.153	9.5	1.23	3.84	7.04	11.02	3.51	13.5	0.47
OC	56	0.08	0.177	0.086	9.6	0.98	1.19	6.05	8.48	3.72	6.5	0.21
2C1	82	0.06	0.104	0.013	3.9	0.26	0.39	6.17	5.2	3.98	3.6	0.1
2C2	118	0.04	0.058	0.024	3.8	0.14	0.87	4.84	3.65	4.37	1.9	0.05
Error		0.08	0.31	0.13	7.4	0.7	1.39	2.61	2.8	0.1	3.3	0.095

Table 4. LSMEANS estimates for mineral soils in a crest vs. ditch comparison. (*) Significant at p<0.1

Horizon	depth	***K****	***Ca****	***Mg****	P	***Mn****	***Zn****	BS*	CEC	pH*	C	N
	(cm)	------ (cmol kg^{-1}) -----				------ (mg kg^{-1}) -----		-- (%) --	($cmol_c$ kg^{-1})		----- (%) -----	
						Crest						
1	15	0.206	3.36	1.07	85.67	8.37	12.02	71.5	12.54	5.04	7.69	0.27
2	31	0.045	1.52	0.52	32.11	2.12	3.99	52.9	7.26	4.93	6.42	0.17
3	48	0.035	0.45	0.24	14.61	0.42	0.56	31.9	4.06	4.47	1.87	0.04
4	67	0.052	0.27	0.18	5.67	0.62	0.22	24.2	4.18	4.29	1.56	0.03
5	92	0.052	0.27	0.16	6.53	0.59	0.37	27.7	3.41	4.30	1.47	0.03
6	107	0.031	0.18	0.10	8.99	0.27	0.17	26.6	2.33	4.47	1.01	0.01
7	122	0.330	0.19	0.08	4.35	0.30	0.05	25.0	2.08	4.23	0.63	0.01
Error		0.028	0.31	0.11	6.17	0.61	0.99	5.50	1.20	0.17	1.80	0.04
						Ditch						
1	15	0.071	1.76	0.39	66.51	4.48	5.25	49.1	8.57	4.68	7.54	0.25
2	32	0.040	1.33	0.33	27.44	2.13	3.54	45.6	7.01	4.75	6.89	0.19
3	49	0.037	0.65	0.18	9.47	0.92	1.09	37.2	4.61	4.76	3.91	0.06
4	70	0.025	0.38	0.18	14.61	0.48	0.29	29.5	4.08	4.5	1.67	0.03
5	89	0.033	0.24	0.13	15.17	0.34	0.21	24.5	2.97	4.38	1.21	0.02
6	107	0.062	0.19	0.09	10.86	0.42	0.31	16.1	3.51	4.11	1.45	0.04
7	125	0.050	0.14	0.07	15.14	0.31	0.45	14.5	3.00	4.04	0.91	0.02
Error		0.028	0.31	0.11	6.17	0.61	0.99	5.5	1.20	0.17	1.70	0.04

Table 5. LSMEANS estimates for Juniper Bay (JB) and the reference bays (RB) in a mineral soil. (*) significant at $p<0.1$

Horizon	Depth	K*	Ca*	Mg*	P*	Mn	Zn*	BS*	CEC*	pH*	C*	N*
	(cm)	------- (cmol kg^{-1}) -------			------- (mg kg^{-1}) ------			--- (%) ---	(cmol$_c$ kg^{-1})		----- (%) -----	
Juniper Bay												
1	10	0.257	3.343	1.12	87.1	9.05	12.44	74.62	12.71	5.1	7.64	0.27
2	27	0.035	1.68	0.66	33.5	2.37	5.23	56.13	7.85	4.91	7.31	0.22
3	44	0.031	0.54	0.31	16	0.09	0.49	35.01	4.7	4.55	2.48	0.06
4	62	0.059	0.34	0.18	7.4	0.54	0.17	27.36	4.23	4.31	1.83	0.04
5	85	0.047	0.34	0.13	8.1	0.64	0.5	30.91	2.96	4.34	1.43	0.03
6	101	0.034	0.28	0.12	10.3	0.27	0.38	31.21	2.63	4.55	0.73	0.01
7	126	0.035	0.26	0.09	5	0.34	0.38	32.25	2.41	4.29	0.19	0
Error		0.07	0.35	0.3	5.6	2.8	1.31	4.52	3.02	0.25	3.1	0.07
Reference bays												
1	10	0.75	1.15	1.23	33.3	8.69	5.96	16.3	32.62	3.74	24.95	0.73
2	22	0.141	0.11	0.16	8.7	1.08	0.97	8.47	8.67	3.62	6.09	0.19
3	52	0.001	0.03	0.04	3.1	0.26	0.49	7.8	1.71	4.07	0.26	0.01
4	82	0.001	0.069	0.06	8	0.27	0.24	4.98	3.58	4.12	0.96	0.02
Error		0.08	0.38	0.23	6.8	1.9	1.37	4.97	3.51	0.21	2.5	0.07

Table 6. Number of locations in relation to general soil type and years of agricultural production.

	15 years	20 years	30 years
Organic Soil	2	2	4
Histic Soil	3	3	
Mineral Soil		5	4

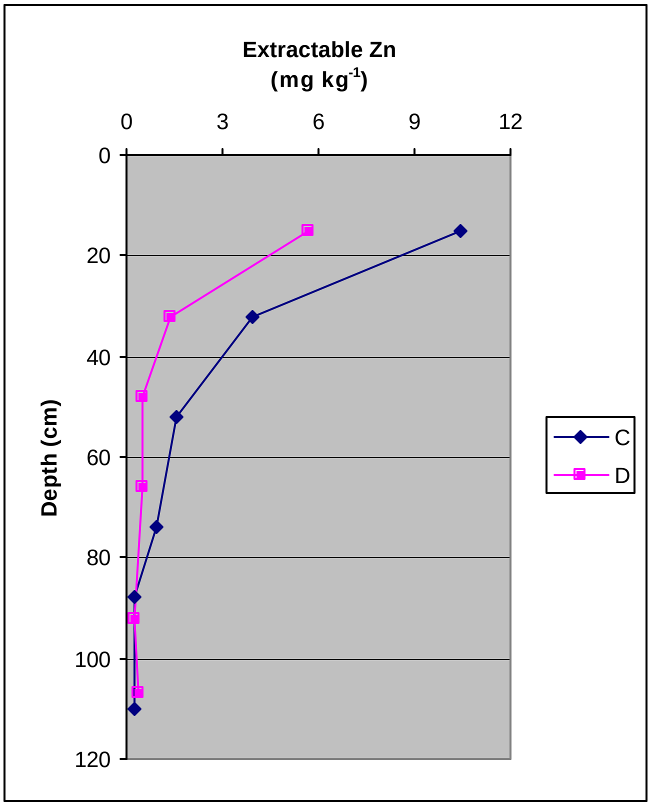
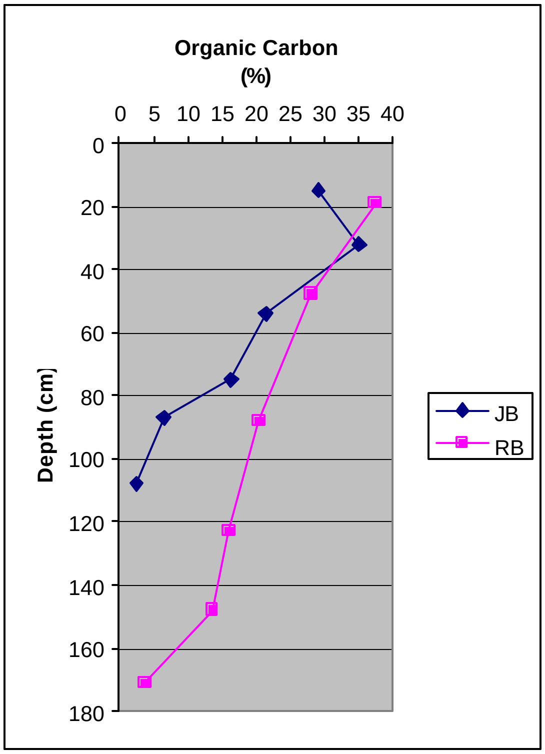
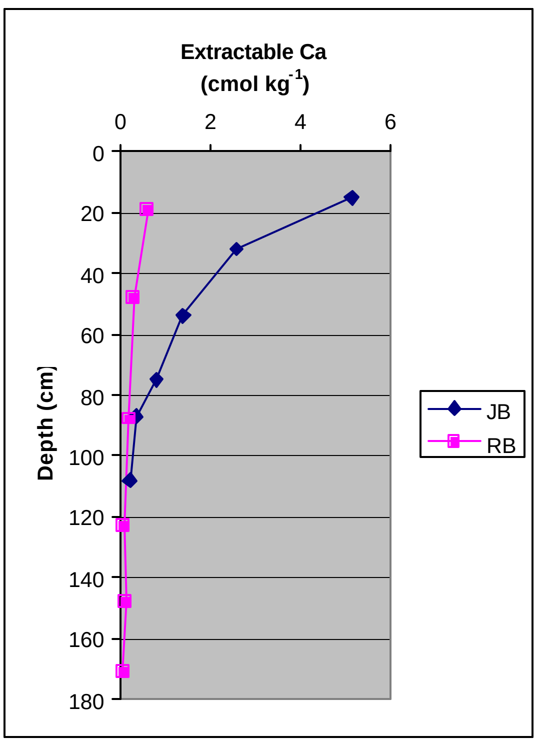


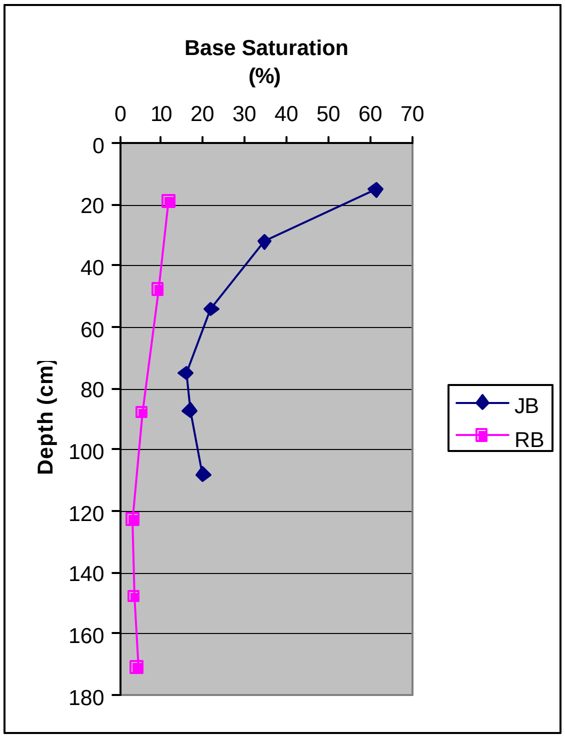
Figure 1. Comparison of extractable Zn at the crest (C) and ditch (D) in organic soils at Juniper Bay.


Organic Carbon
(%)
0 5 10 15 20 25 30 35 40
0 20 40 60 80 100 120 140 160 180
Depth (cm)
JB
RB

a.

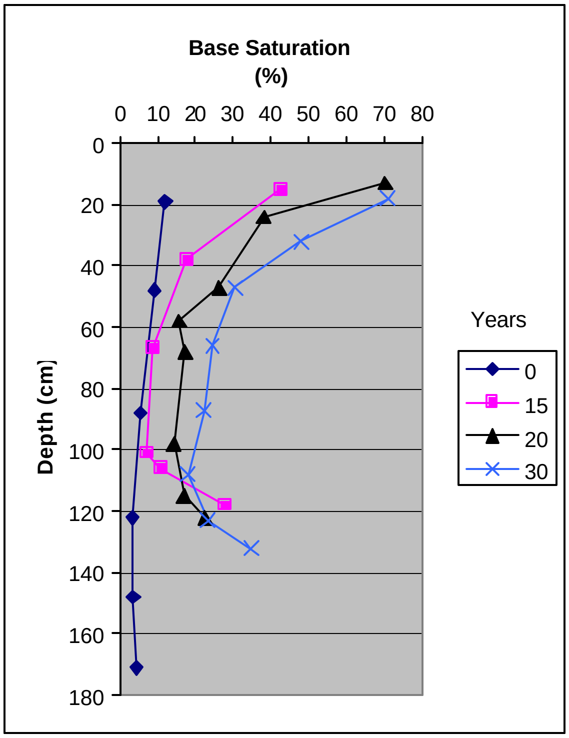

Extractable Ca
(cmol kg-1)
0 2 4 6
0 20 40 60 80 100 120 140 160 180
Depth (cm)
JB
RB

b.

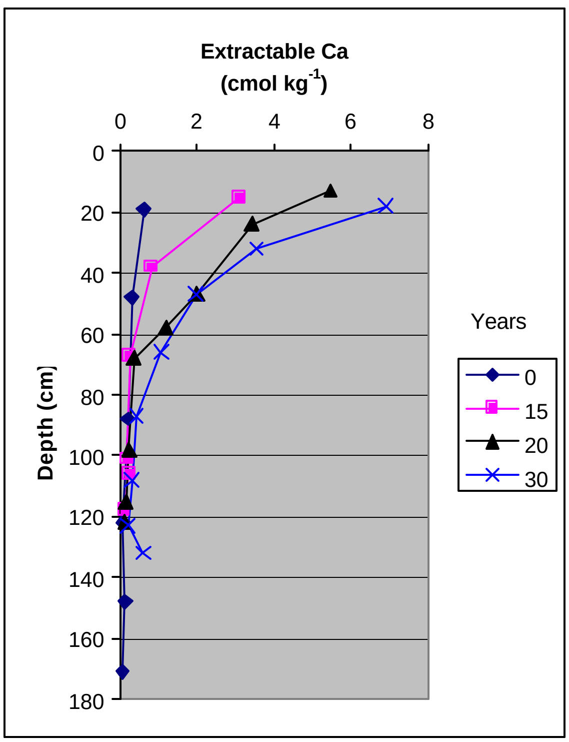


c.

Figure 2. Comparison of organic carbon (a), extractable Ca (b), and base saturation (c), or organic soils from Juniper Bay (JB) and the reference bays (RB).



a



b.

Figure 3. Relation of years in agricultural production on base saturation (a) and extractable Ca (b) in organic soils.

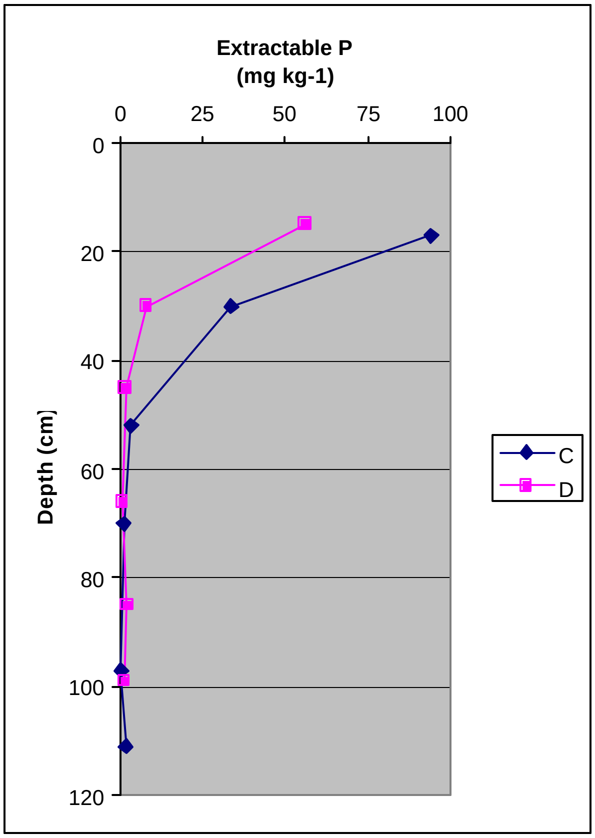
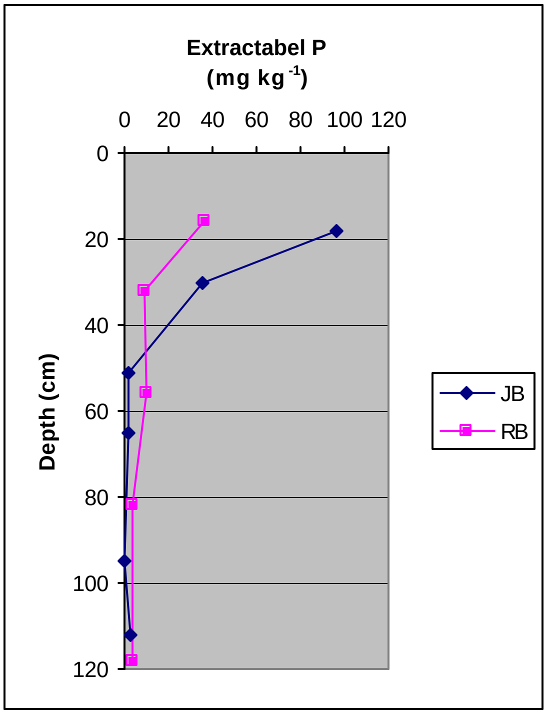


Figure 4. Crest (C) vs. Ditch (D) comparison of extractable P in soils with a histic epipedon at Juniper Bay.



a.

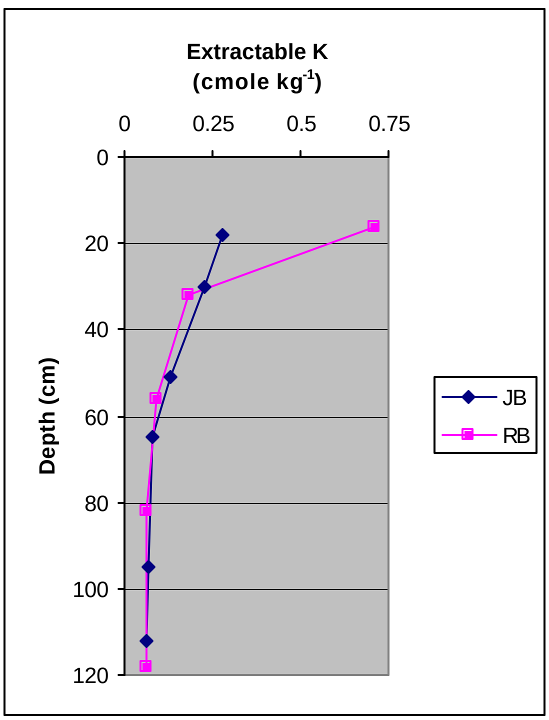
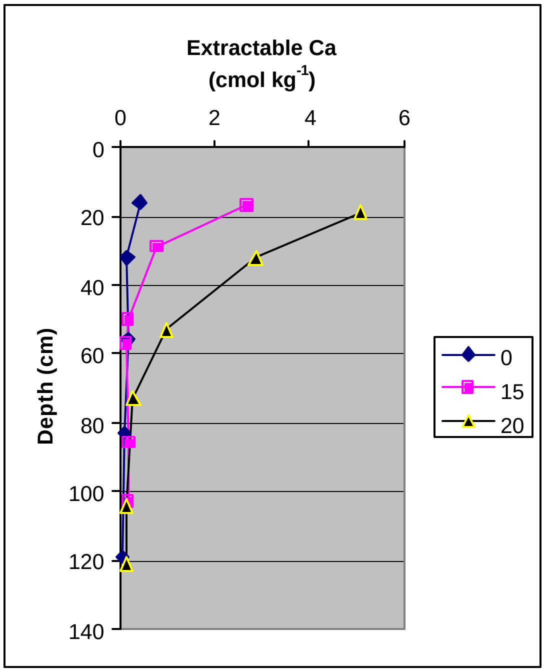
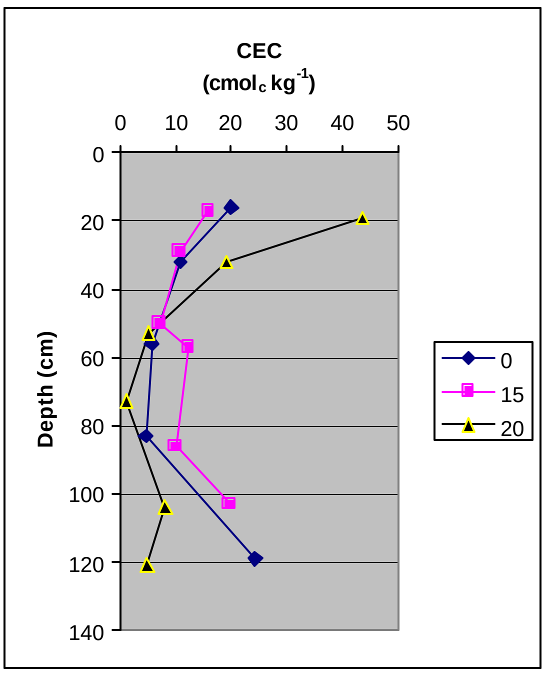


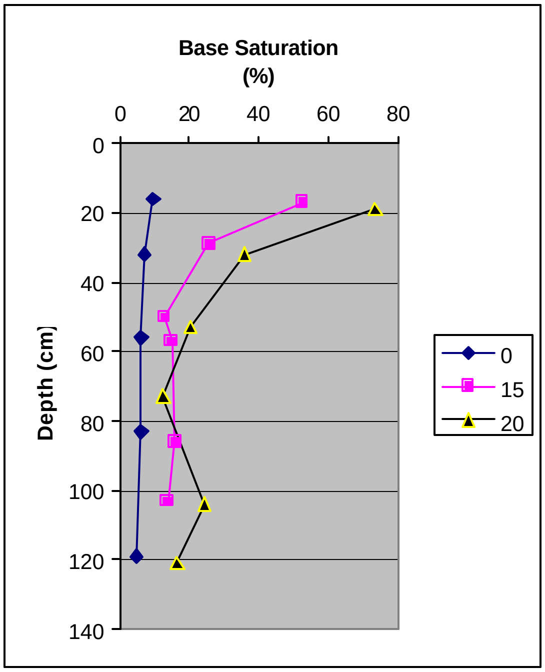
Figure 5. Comparisons of extractable P (a) and K (b) in soils with a histic epipedon at Juniper Bay (JB) and the reference bays (RB).


Extractable Ca
(cmol kg-1)
0
2
4
6
0
20
40
60
80
100
120
140
Depth (cm)
0
15
20

a.


CEC
(cmolc kg-1)
0
10
20
30
40
50
0
20
40
60
80
100
120
140
Depth (cm)
0
15
20

b.



c.

Figure 6. Relationship of time in agriculture on extractable Ca (a), CEC (b), and base saturation (c) in soils with a histic epipedon.

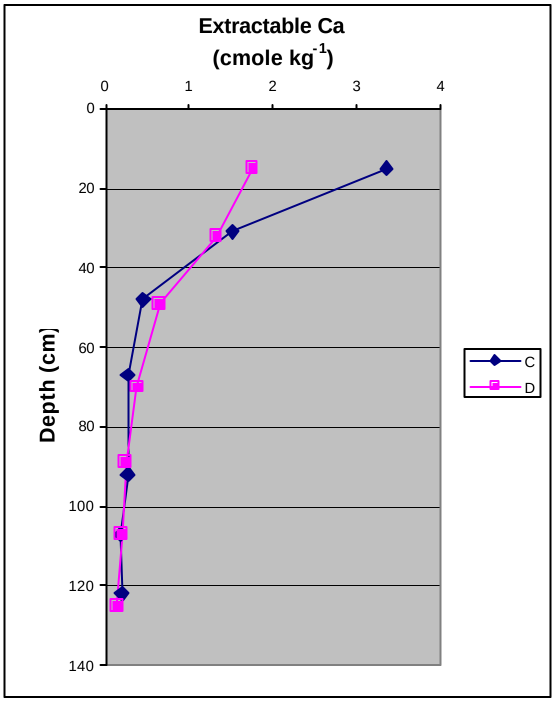
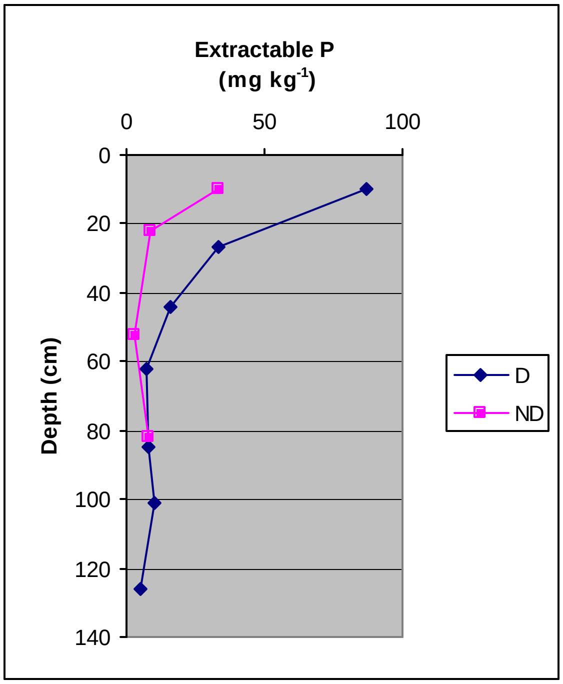
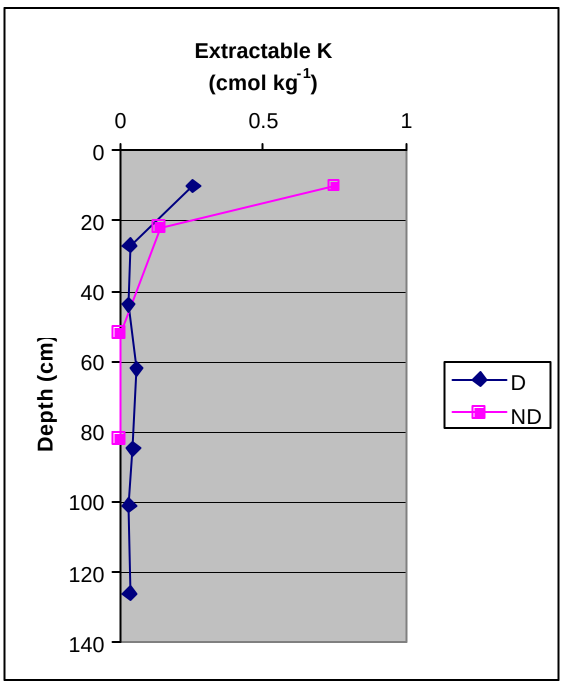


Figure 7. Crest (C) vs. Ditch (D) comparison of extractable Ca in mineral soils of Juniper Bay.



a.



b.

Figure 8. Juniper Bay (JB) verses Reference Bays (RB) on extractable P (a) and K (b) in a mineral soil.

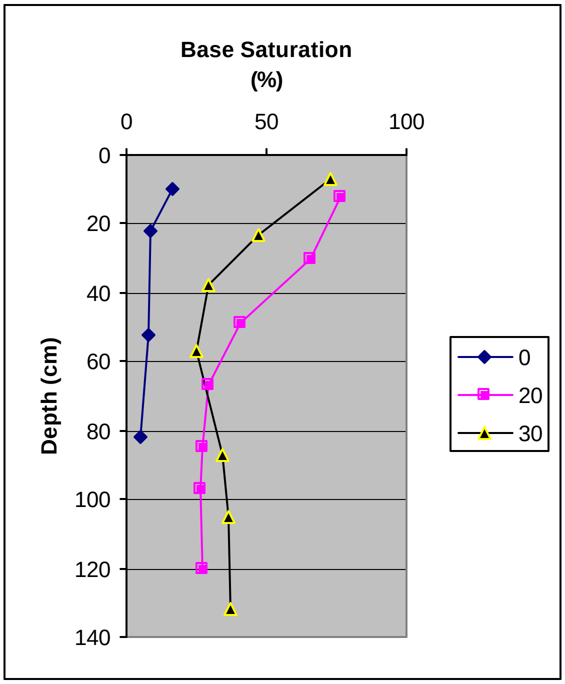


Figure 9. Time of agricultural practices on base saturation in a mineral soil

Chapter 6

PHYSICAL AND MORPHOLOGICAL CHARACTERISTICS OF CAROLINA BAY WETLAND SOILS AFTER 15, 20, AND 30 YEARS OF DRAINAGE AND AGRICULTURAL PRODUCTION

J.M. Ewing and M.J. Vepraskas

INTRODUCTION:

Section 404 of the Clean Water Act (1977) requires the replacement, or mitigation, of destroyed wetlands. Wetland mitigation includes, enhancement and preservation of current wetlands, creation of new wetlands, or the restoration of prior wetlands (USCOE, 2002). Success of such mitigation projects is mixed. Erwin (1991) found that of 40 mitigation projects in south Florida 60% were judged incomplete or failures, Wilson and Mitsch (1996) found that only 38% of the desired wetland was established at mitigation sites in Ohio, and Gallihugh and Rogner, (1998) found that 99 ha of 128 mitigation sites involving 144 ha, were found to have unsatisfactory hydrology. The probability of success should be greater in an area that once supported wetland hydrology, hydric soils, and hydrophytic vegetation.

Drained Carolina bays found along the Atlantic Coast in the southeastern U.S., are being utilized for wetland restoration. Carolina bays are elliptical depressions in the landscape that are orientated along the long axis SE to NW. They range in size from 10 m to >4 km along the long axis. The bays are usually surrounded by a light colored sandy rim and have a dark colored depression resulting from high amounts of organic matter (Johnson, 1942). The extent of these bays range from Northern Florida to Delaware with the highest concentration in North and South Carolina. Estimates on the number of these bays are as high as 500,000 (Johnson, 1942), but the actual number maybe less than 100,000 (Nifong, 1998). Many theories for bay formation have been proposed, from the most popular, meteor impact (Johnson, 1936), artesian springs (Prouty, 1952; LeGrand, 1952), whale wallows (Grant 1945), and ice flows (Bliley and Burney, 1988). Currently the most plausible explanation is that originally there were shallow depressions in the landscape with an aquitard that allowed the water table to be held above the surface. Prevailing winds then shaped the depression into the now familiar orientated shape (Thom, 1970; Odum, 1952). During the past century agricultural and community development have led to the drainage and use of these bays. It is estimated that 50% of all Carolina bays were drained and developed in some manner in Bladen County, NC by 1982 (Weakley and Scott, 1982). This figure would be higher if other management practices such as logging were included. As these bays are used for agriculture and other activities, their defining characteristics of sand rims and organic surfaces, become blurred into the surrounding landscape.

Plant communities typically found in undrained Carolina bays include non-riverine swamp forest, low pocosin, high pocosin, pond pine woodland, peatland Atlantic White Cedar forest, and Bay forest (Schafale and Weakly, 1990). These plant communities are found in nutrient poor soils that maybe organic soil or mineral soils. Variability in these plant communities depends on depth of organic matter, seasonal water table depths, fire and mineral input if any (Schafale and Weakly, 1990). Soil series associated with theses plant communities (Croatan, Pamlico, Ponzer, Lynn Haven, Torhunta, Rutlege, and Pantego) are very strongly acidic (4.5-5.0) to ultra acidic (<3.5). Cation exchange capacity tends to be very low ranging from 1 to 30 cmol kg^{-1}, but can be as high as 100 cmol kg^{-1} in the surface layers. Exchangeable phosphorus has found to be strongly limiting to plant production in High Pocosin plant communities (Schafale and Weakly, 1990).

The North Carolina Department of Transportation (NCDOT) purchased a 256 ha drained Carolina bay in 1999, near Lumberton, North Carolina. This land was purchased with the intent of earning wetland mitigation credits. The Carolina bay being restored by the NCDOT is called Juniper Bay. Juniper Bay was drained, cleared, and put into agricultural production incrementally in 1971, 1981 and 1986. A review of the history of the clearing process was described by Ewing et al. (2003). Agricultural practices in the organic soils include the addition of lime to achieve a pH of 5.5 to 5.0 (Lilly and Baird, 1993). To reach this target pH up to 13470 kg ha^{-1} may have to be applied to overcome the large reserve of acidic cations present in organic soils (Lilly, 1981). The North Carolina Cooperative Extension Service recommends the application of 135-180 kg N ha^{-1}, 35-55 kg P_2O_5 ha^{-1}, and 90-115 kg K ha^{-1} for corn production (Crozer, 2000). Organic soils in North Carolina have been shown to leach nitrogen and phosphorus and have to be applied yearly (Lilly, 1981). Crop cultivation, depending on the crop, can include the use of chisel plows, moldboard plows, disks, and sub-soilers. The overall objective of the Juniper bay project is to restore Juniper bay back to an ecosystem that is typical of Carolina bays. This includes restoration of hydrology, vegetation, and soils typically found in Carolina bays.

The objective of this investigation was to describe and compare the physical and morphological properties found in a natural Carolina bay, and those found in Juniper Bay and discuss the impacts on restoration efforts.

MATERIALS AND METHODS

Juniper Bay (JB) is located approximately 10 km southeast of Lumberton, North Carolina in Robeson County (($34^{o}30'30''$N $79^{o}01'30''$E). Juniper Bay was logged, drained and put into agricultural production in three stages. The western third of Juniper Bay was drained in 1971, the central third and most of the eastern third was drained in 1979, the area to the north in the eastern part was drained in 1986 (Figure 6.1). There is a perimeter ditch around the whole bay, two main drainage ditches that run NE/SW and many lateral ditches that run NW/SE. The perimeter ditch and the main ditches are approximately 7 m across and 4 m deep. The lateral ditches are roughly 1.5 m wide and 1m deep. Areas that are enclosed by ditches are called ‘cuts’. There is only one outlet in Juniper Bay and it is located at the SW end of the main ditch on the western side. Initial survey of Juniper Bay indicated three types of soil based on the thickness of the organic layer. The soils were classified as Aquic Haploarthods (<20cm organic material), Histic

Humaquepts (20-40 cm organic material), and Terric Haplosaprist (>40 cm organic material), and will be referred to as mineral, histic and organic (Fig 1).

Sampling locations were chosen by randomly placing an equilateral triangle grid over the soils map. There were a total of 24 locations inside of Juniper Bay, 10 in organic soil, 8 in mineral soil, and 6 in histic soils. Those points were then found in the field using GPS. Using the point from the grid as a reference, a 1-1.5 m pit was dug at the center of cut and near the closest lateral ditch, resulting in a pair of pits at each location. Figure 2 shows the location of all pits. Soil profiles were described and sampled. Grab samples and Uhland cores (75mm in diameter x 75mm in height) for laboratory analysis were taken from each horizon.

Three reference bays (RB) were selected in Bladen County, North Carolina based on their similarity of soils to Juniper Bay, lack of drainage or agricultural applications, and ownership cooperation. The bays selected were Charlie Long-Millpond Bay (34^{o}46'00"N 78^{o}33'30"E) and Tatum Millpond Bay (34^{o}43'00"N 78^{o}33'00"E), both located in the Bladen Lakes State Park and Causeway Bay (34^{o}39'45"N 78^{o}25'45"E) which is located 10 km N of White Lake, N.C. A trail from the rim of each bay to the center was cut through the vegetation (Fig 3). The general soil types found in Juniper Bay were also found in all three natural bays, mineral, histic, and organic. Plots were marked off and numbered at 50m intervals along the transects. Plots were then randomly selected in each soil to be sampled. There were a total of eight sampling plots in each reference bay, two in both the mineral and histic soils and four in the organic soil. The soil profile in the selected plot was described using a McCauley peat sampler and an open bucket auger. Grab samples were gathered and placed in plastic bags for laboratory analysis. The McCauley auger was also used to take undisturbed samples to determine bulk density and porosity (Soil Survey, 1993). Due to the high water table (10 cm below the surface) we were unable to dig a pit or obtain Uhland core samples. Sampling occurred during the summer of 2002.

Grab samples from Juniper Bay and the reference bays were dried and ground with an electric grinder to pass through a 2mm mesh sieve. Percent organic carbon and total nitrogen were determined through dry combustion with a Perkin-Elmer PE2400 CHN Elemental Analyzer (Culmo, 1988). Uhland cores from Juniper bay were used to determine saturated hydraulic conductivity, soil moisture release curves, bulk density, and porosity. Ten-cm undisturbed samples taken with the McCauley sampler from the reference bays were used to determine porosity and bulk density. Disturbed samples from all horizons were placed in pressure plates to determine water content at 1 and 15 bars in samples from Juniper bay, and 1/3 and 15 bars in samples from the reference bays. Available water was the difference in water content at 1/3 and 15 bars and porosity were calculated from the difference between saturation and oven dry.

Soil types, organic, histic, and mineral, were analyzed separately using the SAS procedure PROC MIXED (SAS, 2000), with an AR(1) covariance structure. There were two locations in the organic soil at Juniper Bay that had been drained 15 and 20 years, and 4 locations that had been drained for 30 years. There were three locations in the histic soil at Juniper Bay that had been drained 15 and 20 years. There were five locations in the mineral soil at Juniper Bay that had been drained 20 years, and four locations that had been drained for 30 years. Each location had paired pits with one located at the crest of the field and one near the ditch. Horizons varied depending on location and pit and were evaluated as a spatially repeated measure. The data were not balanced so LSMEANS were used to obtain estimated means. Comparisons among crest and near ditch pits were made with p>0.1 being significant.

The comparisons between the reference bays and Juniper bay were analyzed separately depending on, soil type: (organic, histic, and mineral), using the SAS procedure PROC MIXED (SAS, 2000), with an AR(1) covariance structure. Data from the crest locations in Juniper Bay were used in this analysis after determining that differences in crest and ditch locations were minimal. Organic, histic, and mineral soils were combined across the three reference bays, resulting in 12 organic, six histic, and six mineral locations. Horizons varied depending on location and pit and were evaluated as a spatially repeated measure. The reference Carolina bays were considered random variables so results could be inferred to other natural bays. Soils from the reference bays were considered as time zero so comparisons could be made as to the effects of time since drainage. The data were not balanced so LSMEANS were used to obtain estimated means. Comparisons among Juniper Bay and the reference bays and time since drainage were made with p>0.1 being significant.

RESULTS AND DISCUSSION

ORGANIC SOILS

Juniper vs. Reference Bays

A typical description of organic soil profiles at the reference bays and a typical profile or organic soil in Juniper Bay are given in Table 1. Reference bay soils included Oi and Oe horizons, which have been recognized in other Carolina bays with natural vegetation (Stager and Cahoon, 1987). The Oi horizon is a fibric woody peat layer about 20 cm thick that is composed of plant debris and roots. The Oe horizon is a hemic or mucky peat layer that is massive and often contains organic bodies and extended to 50cm. These two layers are not present in JB and were probably removed and burned during clearing of the land for agriculture. The organic soil at JB has a surface horizon Oap that is sapric material or muck that has a strong to moderate fine granular to subangular blocky structure. The Oa horizons in the RB are composed of sapric material with massive structure and can extend from 40 to 180cm deep. The Oa horizons in JB have sub-angular blocky to prismatic, and occasionally massive structure. Structural difference between JB and RB is a result of drainage and tillage. Similar changes in structure were described by Lee and Manoch (1974) in which organic soils become granular or subangular blocky in structure in the surface horizons; subsurface horizons become prismatic with secondary blocky characteristics following drainage and pedogenic structure ends where the soil becomes saturated. This structure change should increase saturated hydraulic conductivity. Oa horizons extend to depths of 40 and 70 cm below the surface, much shallower than comparable locations in the RB. The thinner organic horizons in JB is a result of clearing activities and subsidence which, has been estimated to be between 75 and 86 cm in JB (Ewing et al., 2003). Reported thickness of the organic layers in Carolina bays vary from 1cm (Newman and Schalles, 1990) to 4.6 m (Shariz and Gibbons, 1982). There is a thick (25cm) transitional horizon from organic material to mineral material at the RB and the C horizons tend to be sandy loam or sand, while at JB the transition is a clear boundary and the C horizons are loamy sand to sandy clay loam. Saunders and Brown (1992) stated that the subsoil type in Carolina bays are related to their geomorphic surfaces, and could account for the differences in the C horizon material.

The colors of the organic soils at Juniper bay were black to dark brown, (10YR) with an occasional redder hue (7.5YR) but were black at the RB (N 2.5/0). This is somewhat contradictory to what Dolman and Buol (1967) found in organic soils of the Tidewater region of North Carolina and in which, deeper less oxidized organic horizons tended to be a dark reddish brown (5YR 2/2) while shallower more oxidized organic horizons tended to be black (10YR 2/1) to very dark brown (10YR 2/2). Lee and Manoch (1974) found in a Wisconsin marsh in which there was a change in color from a dark reddish brown to a black color after 50 years of drainage. However, the difference in color maybe a result of different soil environments. Lilly (1981) indicates that the dark reddish color of deep organic soils of North Carolina are preserved by being kept continuously anaerobic, while the areas with black organic soils have experienced some oxidization. This suggests that deeper horizons in Juniper Bay's organic soils remained anaerobic for longer periods and the RB formed under anaerobic conditions that fluctuated.

Charcoal fragments were found in several of the profiles in JB, but were not seen in the RB suggesting that fire may have played a role in the development of the soils at JB. However, the profile sites described in the RB were limited in size and may not have provided adequate information for such a discovery. There have been other studies of Carolina bays that have found evidence of fire in the soil profiles (Cohen et al., 1999).

LSMEANS estimates comparing physical characteristics of organic soils at Juniper Bay to the reference bays are in Table 2. There was a significant difference between Juniper Bay and the reference bays in available water. In the surface 20 cm of JB and RB there was the same amount of available water, 0.27 and 0.30 cm^3 cm^{-3}. Available water in RB remained constant through the profile at 0.30 cm^3 cm^{-3}. Available water in JB increases to 0.50 cm^3 cm^{-3} at 54 cm and then decreased back to levels found in RB at 87 cm. Histosols have an extremely high water holding capacity and much of it is in the larger pores (gravitational) or in micropores that is unavailable for plant growth (Boelter and Blake, 1964). Fibric soils, like those in the RB, have large pores and relatively high saturated hydraulic conductivities, while sapric soils have more micropores and have hydraulic conductivities lower than clay-textured sediment (Boelter, 1965). Despite the ability to hold large amounts of water, drained organic soils may dry out quickly and be prone to drought (Lilly, 1981). In addition, water in the small pores in the underlying undeveloped organic soil will not move by capillary conductivity to the larger pores in the developed surface soil, i.e. no recharge from underlying soil resulting in droughty conditions near the surface (Lilly, 1981). Although not significant, there were trends in particle size, bulk density and porosity. There tended to be less sand and clay through the profile in the RB. These trends are probably a result of the geomorphic surface (Saunders and Brown, 1992) or deposition from the surrounding landscape (Preston and Brown, 1964). Bulk density tended to be higher at JB and ranged from 0.48 to 1.23 g cm^{-3} compared to 0.29 to 0.96 g cm^{-3} at the RB. Conversely porosity tended to be higher at JB.

It is unfortunate that we were unable to obtain saturated hydraulic conductivity measurements in the RB. We would of expected higher Ksat values in the Oi and Oe horizons and lower Ksat values in the Oa horizons in the RB than at JB. Unrippened organic material K values of 0.002 to 0.19 cm hr^{-1} and 15-37cm hr^{-1} for a ripened to layer (Skaggs, 1976). Chaston and Siegel (1986) found that the K of decomposed peat can range from 0.1 to 8.0 m day^{-1}, with the large K values caused by discontinuous zones of buried wood and other structural features which can enhance or obstruct water flow. In the upper layers of undisturbed peat K can be as high as 30m d^{-1} (Ingram 1967). The K of geologic materials of low permeability is scale dependent: the greater the size of the flow system, the greater the permeability (Neuzil, 1986).

Time of drainage

There were significant differences in bulk density due to time of drainage in the organic soils (Figure 4). Bulk density in organic soils tends to increase with subsidence and decomposition (Boelter, 1965) and values will vary according to the amount of mineral material and the type of vegetation. Bulk density also increases as traffic of agricultural equipment compacts soil layers near the surface. Bulk density of JB organic soils were consistently higher than RB organic soils and are similar to findings by Ewing et al., (2003b) in which bulk density in a drained Carolina bay is higher than that of an undrained Carolina bay. Bulk density at the surface of RB, was lowest at the surface and increased with depth. Bulk density in the upper 50 cm was similar for all lengths of drainage JB to a depth of 100cm. Below 100cm bulk density was different among time of drainage due to different types of mineral material in the C horizons. Bulk density was higher in the surface 20cm of JB and decreased at 50cm depth, as result of mineral material from ditch spoil, subsidence, and tillage. The increase in bulk density below 50 cm in JB is due to increases of mineral material as the soil changes from organic to mineral. Although not significant porosity tended to be the inverse of bulk density throughout the profile, when bulk density increased porosity decreased, and vise versa.

Crest vs. Ditch

Profiles of organic soils located at the crest of the field and near the ditch varied due to increased drainage and addition of ditch spoil. Figure 5 provides an illustration of the soil at the crest and ditch at location 16, and Table 3 includes the associated profile descriptions. The Oap horizon at the ditch is 24 cm deep and only 11cm deep at the crest, and both have the same strong medium granular structure. However, in the OA1 and

OA2 horizons the structure is massive at the crest while at the ditch there is weak to moderate very coarse prismatic to sub-angular blocky structure, which indicates greater profile development. Both profiles have a dense or cemented layer between 100 and 110cm. This is a characteristic of Carolina bays that has been described by others (Thom, 1970, and Wright et al., 2000), and indicates an accumulation of silica or humate material. There is a 2Bh horizon at the ditch that is not present at the crest. This maybe a result of the increased movement water, and associated organic material, through the soil around the ditch with the organic material accumulating in this horizon.

LSMEANS estimates comparing the crest and ditch locations in the organic soils can be found in table 6.4. There was a significant difference in bulk density and total pores between the crest and ditch in the organic soils. Bulk density near the ditch was 0.16 to 0.46 g cm-1 higher in the upper 70 cm, and can be attributed to the higher amounts of sand deposited from maintaining the ditches. Bulk density for both areas decreased from the surface to 50 cm, and then increased. Porosity was higher throughout the profile at the crest compared to the ditch as a result of the lower bulk density. Particle size, saturated hydraulic conductivity, and available water were not found to be significantly different between the crest and ditch location.

HISTIC SOILS

Juniper Bay vs. Reference Bays

A typical description of histic soil profiles at the RB and a typical profile or histic soil in JB is given in Table 5. The histic soils tend to form a ring around areas of organic soils in both JB and RB. The RB usually has an Oi or Oe horizon of woody peat that consists of accumulated plant debris and roots, with an Oa horizon of massive sapric muck extending to less than 40 cm depth. Below this is an OC horizon where the organic material changes to mineral material, and then a C horizon that is usually sand. There are no Oi or Oe horizons in the histic soils at JB. They have Ap horizons with organically coated sand grains, with an underlying Oa horizon that extends to approximately 40cm and tends to have granular to sub-angular blocky structure. The structure in the Oa horizon is due to agricultural practices and subsidence processes. There is a clear transition in JB to mineral material that is usually sand or loamy sand. The color of the C horizon in JB tends to be lighter in color (10YR 6/4) than in the RB (10YR 2/2), and is a result of local geomorphic surfaces (Saunders and Brown, 1992).

LSMEANS estimates comparing physical properties of the histic soils at Juniper Bay and the reference bays are in Table 6. There was a significant difference in available water and clay between JB and the RB. Juniper Bay tended to have 0.1to 0.3 cm^3 cm^{-3} more available water than the RB. The higher amount of clay in JB, approximately 8 to 25% higher through the profile, can result in higher amounts of available water. In addition, there is the potential that the organic horizons at the RB may contain a greater portion of macropores reducing the amount of available water. There were no significant difference between JB and the RB in percent sand, bulk density and porosity.

Time since drainage

There was a significant time since drainage effect on particle size and available water (Fig. 6). Sand ranged from 72.9% at 32 cm and increased with depth to 92.9% at 119cm at time zero. After 15 years sand ranged from 78.7 to 63.4% and 47.2 to 94.2% after 20 years. Clay was the lowest at time zero ranging from 7.2 to 2.8%. After 15 years of drainage clay ranged from 30.5% in the C horizon to 21.2% at the surface, and after 20 years it ranged from 3.6 to 42.4%. Available water was similar in the upper 20 cm for 0 and 15 years since drainage, 0.37 and 0.33 cm^3 cm^{-3} respectively, but lower 20 years since drainage, 0.21 cm^3 cm^{-3}. All increased as depth increased to 32cm, however 0 and 20 years were similar, 0.42 and 0.43 cm^3 cm^{-3} respectively and 15 year was higher at 0.65 cm^3 cm^{-3}. Below 32cm, 0 year decreased and remained around 0.17 cm^3 cm^{-3} through the rest of the profile. The 15 years since drainage decreased to 0.11 cm^3 cm^{-3} by 85cm and thin increased to 0.22 cm^3 cm^{-3} at 104cm. The area drained for 20 years increased to 0.54 cm^3 cm^{-} at 77cm, then decreased to 0.25 cm^3 cm^{-3} at 122cm.

Crest vs. Ditch

There are some visual differences between soil profiles located at the crest and the ditch through the histic soils. Figure 7 provides an illustration of the soil at the crest and ditch at location 11, and table 6.7 is the associated profile descriptions. There was an Oap horizon at the surface of the crest location with strong medium granular structure, while the ditch location had an Ap horizon with a weak fine granular structure. This suggests that either the organic soil has decomposed to a point that it is no longer organic, or that mineral material from the ditch has been mixed in. The OA horizon at the ditch extends to a depth of 23cm, while at the crest it extends to a depth of 34cm, again indicating a loss of organic material, from oxidization or land shaping. The more defined structure in the OA horizon at the ditch, weak medium sub-angular blocky, compared to the weak coarse prismatic at the crest, indicates drier conditions which results in the formation of better structure in organic soils (Lee and Manoch, 1974). There are some locations in the histic soils where it is histic at the center of the ditch, but is closer to "mineral" near the ditch. Also there are locations near the ditch in which the surface horizon has been influenced by spoil form the ditch maintenance. All organic soils in the, if cultivated long enough, will become mineral soils with dark surface horizons due to the inevitable natural loss of organic matter through oxidization (Lilly, 1981), and this may be the case in the histic soils of Juniper Bay.

There were no physical differences between the crest and ditch positions in the histic soils, however, LSMEANS estimates for the physical properties of the histic soil can be found in table 6.8. However, saturated hydraulic conductivity tended to be higher in soils at the ditch, probably due to increased soil structure.

MINERAL SOILS

Juniper Bay vs. Reference Bay

Mineral soils in RB and JB were relatively similar (Table 9) with differences in the surface horizon being a result of agricultural activities. The mineral soils at the RB had a thin (10cm) Oi horizon consisting of plant debris and roots, which are not present in JB. Below this is an A horizon with weak granular structure. A thick (20cm) E horizon is next, followed by several spodic horizons. There were a few locations in the RB that had an E' and Bh' horizons. The mineral soils in JB had a dark Ap horizon with organically coated sand grains and weak granular structure. There was a thick (20 cm) E horizon, which sometimes was mixed with the Ap horizon, followed by several Bh horizons. There were also C horizons at the bottom of some mineral soil profiles that consisted of sand or cemented sandy clay loam similar to what was described by Ingram et al., (1959), Stager and Cahoon (1987), and Lide et al., (1995).

There were no significant differences in particle size between the mineral soils at Juniper Bay and reference bays (Table 10). We were unable to obtain undisturbed samples from the RB to determine bulk density, porosity and available water. However bulk density at JB ranged from 1.09 g cm^{-3} at the surface and increased to 1.63 g cm^{-3} at 126cm, porosity ranged from 0.42 to 0.52 cm^3 cm^{-3}, and available water ranged from 0.27 to 0.18 cm^3 cm^{-3}.

Time since drainage

We were unable to take intact samples in the RB to determine bulk density, porosity, and available water. The areas drained for 30 years had an available water of 0.23 in the surface 10cm, increased to 0.35 at 23cm, then decreased to 0.18 at 57cm, and then remained close to the values found in the 20 year areas (Fig. 8). Bulk densities in mineral soils at JB were similar after 20 and 30 years of drainage.

Crest vs. Ditch

There are visual differences between soil profiles located at the crest and the ditch. Figure 9 provides an illustration of the soil at the two locations, and Table 11 is the associated profile description of location 3. The Ap horizon is approximately the same thickness and color at both locations, however, there is 10% less organically coated sand grains at the ditch. It appeared that some of the surface material might be from ditch maintenance, and is more evident at other locations. There is an AE horizon at the ditch that is a result of tillage. Such a mixing of A and E horizons occurred at several locations at both the crest and ditch in the mineral soils. The E horizon is 4 cm thicker at the ditch, and the Bhir horizons extend deeper into the profile. There was defined structure in the surface 22cm at the ditch but only the surface 12 cm at the crest. There was a sulfur smell associated with the lowest horizon indicating reduced conditions.

There was a significant difference in the particle size between the crest and ditch positions in the mineral soil (Table 12). There was more than 85% sand throughout the profile in both positions. The crest had 3% more sand in the surface 15 cm, approximately the same at 30 cm and the crest had 7.5% more at 50 cm, and approximately the same for the remainder of the profile, increasing with depth to 95% sand at 125cm. There was 2 to 6% more clay in the surface 50 cm at the ditch position than the crest. Below 50 cm clay content was similar, approximately 3%, for the rest of the profile. There were no significant differences between the crest and ditch for bulk density, porosity, available water, or saturated hydraulic conductivity (Table 12). However , there was a trend for saturated hydraulic conductivity to be higher near the ditch and for available water to be lower. This trend probable reflects the increased development of structure and the associated increase in macropores.

CONCLUSIONS

The organic soils in Juniper bay have under gone the most change since drainage began. There were some differences between crest and ditch locations, however they are relatively small compared to the differences between JB and the RB. Agricultural production caused the removal of surface organic horizons Oi and Oe. The remaining organic soil is thinner due to subsidence and has developed granular structure at the surface due to tillage and desiccation. The loss of the surface horizons and the development of structure have increased hydraulic conductivity, and plant available water. Bulk density has increased since drainage and indicated that the process of oxidation is still ongoing. Restoration efforts may be hampered or influenced by the change in hydraulic properties. For example restoring the water table to pre-drainage levels might result in a water table that is above the soil surface, or the sapric Oa horizon, which perched water originally due to extremely low Ksat, may allow water to move through the profile. Although there were differences in particle size properties in the organic soils, we feel that there is not a large enough difference to influence restoration efforts. The dense layer found beneath the organic soils in Juniper Bay was not encountered in the reference bays. This layer was either deeper in the profile at the reference bays or has formed since drainage at Juniper Bay and is now acting as an aquitard.

Histic soils at Juniper bay were lacking an Oi and Oe horizons and have greater structure development. Other physical properties were similar enough between JB and the RB and should not affect hydraulic properties. However, some histic areas in Juniper Bay show indications that they may have once been organic soils and have subsided to only a histic epipedon. This may result in water tables above the soil surface if hydrology is returned to the pre-drained levels. The effects of ditch maintenance were most evident in the histic soils with an Ap horizon over an Oa horizon at the ditch locations. There were also indications of better structure at the ditch indicating better drainage. Difference between the ditch and crest and differences in particle size data are not enough to justify different management practices.

Mineral soils at all locations were well developed with some differences. These differences include a thin Oi horizon at the RB and a thicker Ap horizon and deeper E horizon as a result of the addition of ditch spoil. The E horizon was thicker at the ditch and the Bh horizons extended deeper into the profile indicating better water movement through the profile. Soil structure was more developed at Juniper Bay. There is little to indicate that the physical properties of the mineral soils in JB are different than those of the RB, and both should behave similarly under the same hydraulic conditions. Differences in sand silt and clay are relatively small and could be attributed to the depositional environments at the time of formation. Areas of JB that are now mineral soils may have had histic epipedons prior to drainage and may result in water tables above the soil surface if hydrology is returned to the pre-drained levels.

The restoration of Juniper Bay soils to those typically found in natural undrained Carolina bay wetlands can be achieved over time. The mineral soils are similar enough already, however, the mineral soils may not support hydrophytic vegetation as well as the histic and mineral soils. Histic soils would require some time to accumulated organic debris to form an Oi and Oe horizons. The organic soils would require a great deal of time to be restored to natural conditions, due to the large amounts of organic material that has been lost since drainage.

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Table 1. Example profile descriptions of organic soils from the reference bays and Juniper Bay.

Horizon	Depth	Description
		Reference bay
Oi	0-20	Black (10YR 2/1) fibric to hemic muck that is part of the root mat; weak coarse platy structure from layering of plant debris; gradual boundary.
Oe	20-50	Very dark brown (10YR 2/2) hemic muck; massive structure with many organic bodies 0.5 to 1.0 cm in diameter; gradual boundary.
Oa	50-85	Black (10YR 2/1) sapric muck; massive structure; gradual boundary.
OC	85-110	Very dark brown (10YR 2/2) mucky loam to mucky sandy loam; massive structure; gradual boundary.
2C1	110-140	Very dark brown (10YR 2/2) sandy loam; massive structure; gradual boundary.
2C2	140-180	Dark gray (10YR 4/1) sand; single grain structure.
		Juniper Bay: JB10C
Ap	0-10	Very dark brown (10YR 2/2) sandy loam; moderate medium (3mm) granular structure; abrupt boundary.
Oa	10-20	Black (N 2.5/0) sapric material; moderate fine (2mm) granular to sub-angular blocky structure; abrupt boundary.
OA1	20-51	Black (10YR 2/1) mucky silt loam, weak very coarse (20cm) prismatic structure; clear boundary.

OA2	51-61	Very dark brown (10YR 2/2) mucky silt loam with 25% black (N 2.5/0) charcoal; weak coarse (10cm) prismatic structure.
OA3	61-68	Dark brown (10YR 3/3) mucky fine sandy loam; very weak coarse (10cm) prismatic structure; clear boundary.
Bw	68-107	Yellowish brown (10YR 5/4) very fine sandy clay loam; weak very coarse (20cm) platy to moderate medium (5cm) sub-angular blocky structure; clear boundary.
C	107-120	Light brownish yellow (10YR 6/2) sandy clay loam; strong medium (1cm) angular blocky structure; faint reaction to alpha-alpha.

Table 2. Comparison of organic soils between Juniper Bay (JB) and Reference bays RB.

Horizon[t]	Depth	Sand	Clay	Bulk Density	Porosity	Available Water*
	(cm)	-------- (%)	-------	(g cm^{-3})	(cm cm^{-3})	(cm cm^{-3})
	Juniper Bay					
1	15	57.5	26.4	0.70	0.60	0.27
2	32	53.8	30.0	0.52	0.64	0.46
3	54	57.1	27.8	0.48	0.67	0.50
4	75	59.5	22.2	0.85	0.62	0.42
5	87	71.1	11.8	0.12	0.58	0.30
6	108	---	---	---	---	---
Error		14.8	6.7	0.17	0.14	0.07
	Reference Bays					
1	19	---	---	---	---	0.30
2	48	40.5	16.2	0.29	0.62	0.29
3	88	44.4	13.6	0.35	0.66	0.26
4	123	55.7	12.0	0.64	0.58	0.27
5	148	53.5	12.9	0.74	0.60	0.32
6	171	63.8	11.2	0.96	0.52	0.19
Error		10.9	4.5	0.15	0.09	0.05

* significant at p>0.1 (---) data not available. [t] Horizons were different between Juniper bay and reference bays and are numbered here to indicate the presence of a distinct horizon.

Table 3. Profile descriptions of crest and ditch in an organic soil at Juniper Bay.

Horizon	Depth	Matrix	Texture	Structure	OC	Comments
	(cm)				(%)	
JB16C						
Oap	0-11	N 2.5/0	sm	Strong Medium Granular	26.2	
OA1	11-31	10YR 2/2	sm	Massive	52.5	10% wood fragments 10% charcoal
OA2	31-52	10YR 2/2	sm	Massive	27.9	10% wood fragments 10% charcoal
2Bw	52-61	5YR 3/3	SL	Moderate Coarse Prismatic	5.5	
2BC	61-78	10YR 5/4	LS	Massive	0.5	10% wood fragments 40% 2.5Y 8/1 depletions
2C1	78-100	10YR 6/4	LS	Massive	0.3	5% wood fragments
2C2	100+	10YR 4/1	LS	Single Grain	0.3	Dense; reacts to alpha, alpha
JB16D						
Oap	0-24	N2.5/0	sm	Strong Moderate Granular	13.4	
OA1	24-41	10YR 2/2	sm	Moderate Very Coarse Subangular Blocky	31.9	20% wood fragments
OA2	41-59	10YR 2/1	sm	Weak Very Coarse Prismatic	19.6	10% wood fragments
2Bw	59-74	10YR 5/4	SL	Very Weak Coarse Subangular Blocky	1.5	20% 10YR 8/2 depletions
2BC	74-110	10YR 6/4	LS	Massive	0.5	10% 10YR 8/2 depletions, slightly brittle
2Bh	110-130	10YR 2/1	SL	Massive	0.5	Cemented, brittle and firm

sm = sapric material, LS = loamy sand, SiL = Silt loam, SL = Sandy loam, mSL = mucky sandy loam

Table 4. Crest vs. Ditch comparison of physical properties of the organic soil in Juniper Bay.

Horizon	Depth	Sand	Clay	Bulk Density*	Ksat	Porosity*	Available Water
	(cm)	-------- (%)	-------	(g cm^{-3})	(cm hr^{-1})	(cm cm^{-3})	(cm cm^{-3})
				Crest			
Oap	15	56.4	27.3	0.69	10.35	0.61	0.17
OA1	32	53.8	30.0	0.53	6.76	0.62	0.35
OA2	52	57.1	27.7	0.47	5.41	0.67	0.41
Bw	74	59.5	22.2	0.83	7.48	0.65	0.33
BC	88	71.1	11.8	1.16	1.49	0.61	0.20
C	110	---	---	---	---	---	---
Error	3	13.8	6.5	0.10	3.20	0.04	0.07
				Ditch			
Oap	15	70.0	17.7	0.85	7.13	0.60	0.15
OA1	32	66.7	18.5	0.69	10.17	0.65	0.26
OA2	48	70.2	17.3	0.87	4.43	0.59	0.24
Bw	66	72.2	13.7	1.29	2.62	0.46	0.34
BC	92	72.4	14.2	1.23	3.22	0.47	0.20
C	107	79.4	10.7	1.61	2.37	0.52	0.47
Error	3	13.8	6.5	0.10	3.20	0.04	0.07

* significant at p>0.1 (---) data not available.

Table 5. Example profile descriptions of histic soils from the Reference bays and Juniper Bay.

Horizon	**Depth**	Description
	(cm)	Reference bay
Oi	0-15	Very dark brown (10YR 2/1) hemic material; weak medium platy Structure; clear boundary; root mat.
Oa	15-36	Black (N 2.5/0) sapric material; massive structure; clear boundary.
OC	36-65	Black (N 2.5/0) sandy loam; massive structure; gradual boundary.
C	65-100	Very dark brown (10YR 2/2) sand; single grain structure.
		Juniper Bay: JB61C
Ap	0-22	Black (N 2.5/0) mucky sandy loam with 60% organically coated sand grains; moderate medium granular structure; clear boundary.
Oa	22-36	Very dark brown (10YR 2/2) sapric material; strong coarse granular structure; clear boundary.
Bw	36-56	Dark brown (10YR 3/3) sandy loam with 2% gray (10YR 6/1) sand; weak medium sub-angular blocky structure; clear boundary.
BC	56-74	Dark yellowish brown (10YR 4/6) loamy sand with 2% gray (10YR 6/1) sand; weak medium sub-angular blocky structure; gradual boundary.
C	74-108	Brownish yellow (10YR 6/6) with 2% gray (10YR 6/1) sand; single grain structure.

Table 6. Comparison of histic soils between Juniper Bay (JB) and Reference bays RB.

Horizon[t]	**Depth**	**Sand**	**Clay***	**Bulk Density**	**Porosity**	**Available Water***
	(cm)	-------- (%)	-------	(g cm^{-3})	(cm cm^{-3})	(cm cm^{-3})
	Juniper Bay					
1	18	70.9	22.0	0.84	0.66	0.27
2	30	57.4	32.0	0.63	0.62	0.54
3	51	64.4	28.6	1.16	0.56	0.41
4	65	81.8	13.7	1.32	0.48	0.46
5	95	82.4	10.4	1.73	0.32	0.22
6	112	75.9	19.6	1.67	0.40	0.23
Error	4.6	8.5	5.6	0.07	0.05	0.13
	Reference Bays					
1	16	---	---	---	---	---
2	32	72.9	7.2	0.6	0.62	0.44
3	56	85.9	3.2	0.61	0.61	0.18
4	82	91.1	2.8	0.47	0.37	0.19
5	118	92.9	2.8	---	---	---
Error	4.4	5.4	3.7	0.11	0.07	0.10

* significant at p>0.1 (---) data not available.

[t] Horizons were different between Juniper bay and reference bays and are numbered here to indicate the presence of a distinct horizon.

Table 7. Profile descriptions of crest and ditch in a histic soil at Juniper Bay.

Horizon	Depth	Matrix	Texture	Structure	OC	Comments
	cm				%	
JB11C						
Oap	0-18	N 2.5/0	sm	Strong Medium Granular	46.4	
OA	18-34	10YR 2/2	sm	Weak Coarse Prismatic	48.8	5% wood fragments
Bw	34-57	10YR 2/2	SiL	Weak Medium Prismatic	6.1	
2BC	57-67	10YR 6/4	LS	Single Grain	0.6	15% 10YR 8/1 depletions
2C1	67-90	10YR 7/6	LS	Single Grain	0.1	20% 10YR 8/1 depletions
2C2	90-110	10YR 6/4	LS	Single Grain	0.2	
JB11D						
Ap	0-10	N2.5/0	SL	Weak Fine Granular	5.2	90% coatings
OA	10-23	N2.5/0	mSL	Weak Medium Subangular Blocky	12.6	80% coatings
Bw1	23-39	10YR 2/2	SL	Weak Fine Prismatic	2.7	20% 10YR 8/1 depletions
Bw2	39-59	10YR 3/4	SL	Very Weak Medium Prismatic	1.0	30% 10YR 8/2 depletions
BC	59-92	10YR 6/6	LS	Single Grain	0.3	
C1	92-111	10YR 5/2	LS	Massive	0.3	1-2cm bands of 10YR 3/1
C2	111-120	10YR 2/1	SL	Massive	0.8	Sulfur smell

sm = sapric material, LS = loamy sand, SiL = Silt loam, SL = Sandy loam, mSL = mucky sandy loam

Table 8. Crest vs. Ditch comparison of physical properties of the histic soils in Juniper Bay.

Horizon	Depth	Sand	Clay	Bulk Density	Ksat	Porosity	Available Water
	(cm)	-------- (%) -------		(g cm^{-3})	(cm hr^{-1})	(cm cm^{-3})	(cm cm^{-3})
Crest							
Oap	17	70.9	22.0	0.82	9.29	0.06	0.19
OA	30	57.4	31.9	0.65	4.39	0.64	0.42
Bw	52	64.4	28.6	1.15	3.22	0.56	0.34
BC	70	81.8	13.7	1.36	2.23	0.47	0.36
C1	97	82.4	10.4	1.67	2.88	0.35	0.16
C2	111	75.9	19.6	1.70	1.33	0.34	0.13
Error		7.56	6.90	0.11	3.10	0.07	0.10
Ditch							
Oap	15	74.8	19.5	0.89	17.16	0.36	0.14
OA	30	66.9	22.1	0.65	10.56	0.73	0.16
Bw	45	77.6	15.2	1.06	5.44	0.57	0.18
BC	66	79.4	13.6	1.40	5.37	0.35	0.45
C1	85	82.6	14.7	1.60	2.06	0.31	0.11
C2	99	79.1	16.9	1.76	0.03	0.40	0.15
Error		7.56	6.90	0.11	2.8	0.07	0.10

* significant at p>0.1

Table 9. Example profile descriptions of mineral soils in reference bays and Juniper Bay.

Horizon	Depth	Description
	(cm)	Reference bay
Oi	0-10	Brown (7.5YR 3/4) fibric organic material, root mat and leaf litter; weak medium platy structure; clear boundary.
A	10-20	Black (10YR 2/1) sandy loam; weak fine granular structure; clear boundary.
E	20-40	Gray (10YR 6/1) sand; single grain structure; clear boundary.
Bh1	40-70	Black (10YR 2/1) sandy loam; weak medium sub-angular blocky Structure; clear boundary.
Bh2	70-100	Very dark grayish brown (10YR 3/2) loamy sand; weak coarse sub-angular blocky structure.
		Juniper Bay: JB17C
Ap	0-20	Black (10YR 2/1) loamy sand with 95% organically coated sand grains; weak medium (2-5mm) granular structure; abrupt
E	20-47	20-47cm. Gray (N 6/0) loamy sand with 12% A horizon material in root channels; single grain structure; clear boundary.
Bhir1	47-70	Very dark brown (10YR 2/2) sandy loam with 25% E material in upper half of horizon; massive structure; clear boundary.
Bhir2	70-92	Black (10YR 2/1) and dark brown (10YR 3/3) sandy loam in alternating layers 2-7cm thick; massive structure; abrupt boundary.
Bh	92-120	Black (10YR 2/1) sandy loam with 10% gray (10YR 6/1) sandy grains; massive structure; firm and slightly brittle.

Table 10. Comparison of mineral soils between Juniper Bay (JB) and Reference bays RB.

Horizon[t]	**Depth**	**Sand**	**Clay**	**Bulk Density**	**Porosity**	**Available Water****
	(cm)	-------- (%)	-------	(g cm^{-3})	(cm cm^{-3})	(cm cm^{-3})
	Juniper Bay					
Ap	10	90.9	7.4	1.09	0.48	0.23
A/E	27	88.1	5.1	1.32	0.46	0.26
E	44	93.8	3.1	1.45	0.49	0.26
Bhir1	62	93.2	3.7	1.49	0.52	0.20
Bhir2	85	94.5	4.3	1.55	0.49	0.23
Bh	101	95.7	2.5	1.59	0.43	0.17
C	126	95.9	2.7	1.63	0.43	0.18
Error	7	3.5	1.1	0.04	0.06	0.07
	Reference Bays					
Oi	10	82.7	4.1	---	---	---
A	22	85.7	3.3	---	---	---
E	52	96.4	1.2	---	---	---
Bh	82	90.4	4.2	---	---	---
Error	6	2.6	0.8	---	---	---

* significant at p>0.1 (---) data not available. [t] Horizons were different between Juniper bay and reference bays and are numbered here to indicate the presence of a distinct horizon.

Table 11. Profile descriptions of crest and ditch in a mineral soil at Juniper Bay.

Horizon	Depth	Matrix	Texture	Structure	OC	Comments
	cm				%	
JB03C						
Ap	0-12	N 2.5/0	LS	Moderate Fine Granular	3.3	90% coated sands
E	12-26	5YR 7/1	LS	Single Grain	0.2	25% Ap material mixed in
Bhir	26-42	5YR 3/1	LS	Massive	1.1	
Bir	42-61	10YR 6/3	LS	Single Grain	1.2	
B'hir	61-75	10YR 5/2	LS	Single Grain	0.4	Accumulation organic material
C	75-85+	10YR5/2	LS	Single Grain	0.9	Sulfur smell
JB03D						
Ap	0-15	N 2.5/0	LS	Moderate Fine Granular	2.3	80% coatings
A/E	15-22	N 2.5/0 2.5Y 7/1	LS	Weak Fine Subangular Blocky	1.7	Mixed Ap and E horizons
E	22-40	2.5Y 7/1	LS	Single Grain	0.1	
Bhir1	40-54	10YR 3/2	LS	Massive	0.8	2 cm bands of 10YR 2/1
Bhir2	57-70	10YR 3/3	LS	Massive	0.8	
Bhir3	70-84	10YR 3/3	LS	Massive	1.5	25% 10YR 2/1 weakly cemented LS
Bhir4	84-100	10YR 2/2	LS	Massive	2.1	Sulfur smell

LS = loamy sand

Table 12. Crest vs. Ditch comparison of physical properties of the mineral soils in Juniper Bay.

Horizon[t]	Depth	Sand*	Clay*	Bulk Density	Ksat	Porosity	Available Water
	(cm)	------ (%) ------		($g\ cm^{-3}$)	($cm\ hr^{-1}$)	($cm\ cm^{-3}$)	($cm\ cm^{-3}$)
Crest							
1	15	90.8	7.45	1.09	18.4	0.05	0.13
2	31	88	5.21	1.31	15.38	0.46	0.16
3	48	93.7	3.21	1.44	9.97	0.48	0.16
4	67	93.1	3.81	1.48	5.42	0.53	0.10
5	92	94.4	4.31	1.54	5.14	0.49	0.12
6	107	95.3	2.99	1.58	5.64	0.43	0.08
7	122	95.5	3.19	1.61	3.32	0.43	0.08
Error		1.52	1.2	0.05	4.06	0.04	0.03
Ditch							
1	15	87.7	10.24	1.19	19.01	0.45	0.14
2	32	89.1	8.13	1.27	26.12	0.43	0.11
3	49	85.6	9.34	1.47	21.52	0.35	0.08
4	70	90.7	3.79	1.51	6.71	0.43	0.12
5	89	93.1	4.28	1.49	6.65	0.44	0.13
6	107	94.0	4.18	1.52	4.27	0.39	0.13
7	125	95.1	3.14	1.54	2.7	0.38	0.14
Error		1.52	1.2	0.05	4.06	0.04	0.03

* significant at $p>0.1$ [t] Horizons were different between Juniper bay and reference bays and are numbered here to indicate the presence of a distinct horizon.

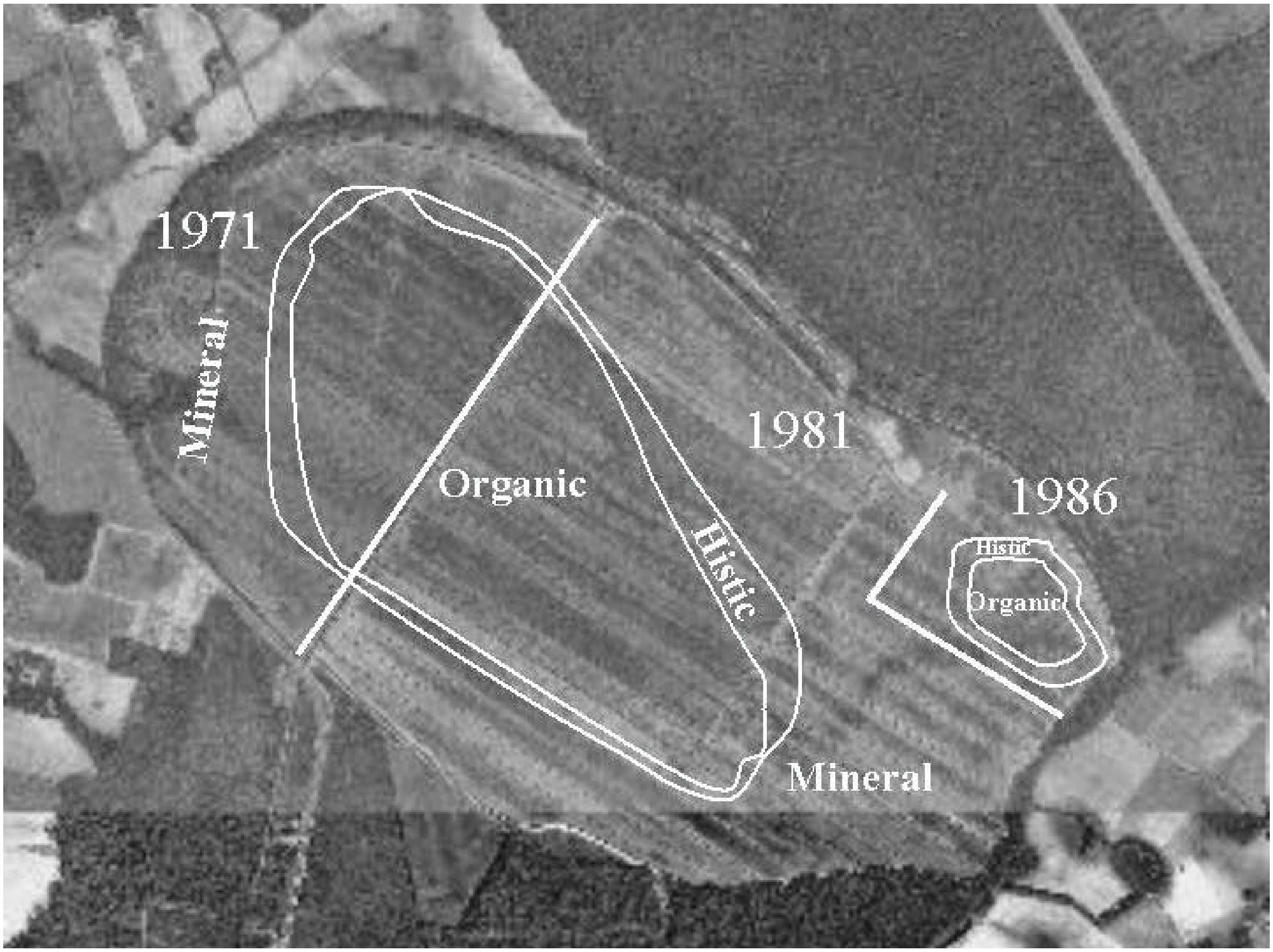


Figure 1. Aerial photo of Juniper Bay (2.4 x 1.6 km) showing the time of drainage and areas where organic, histic, and mineral soils are located.

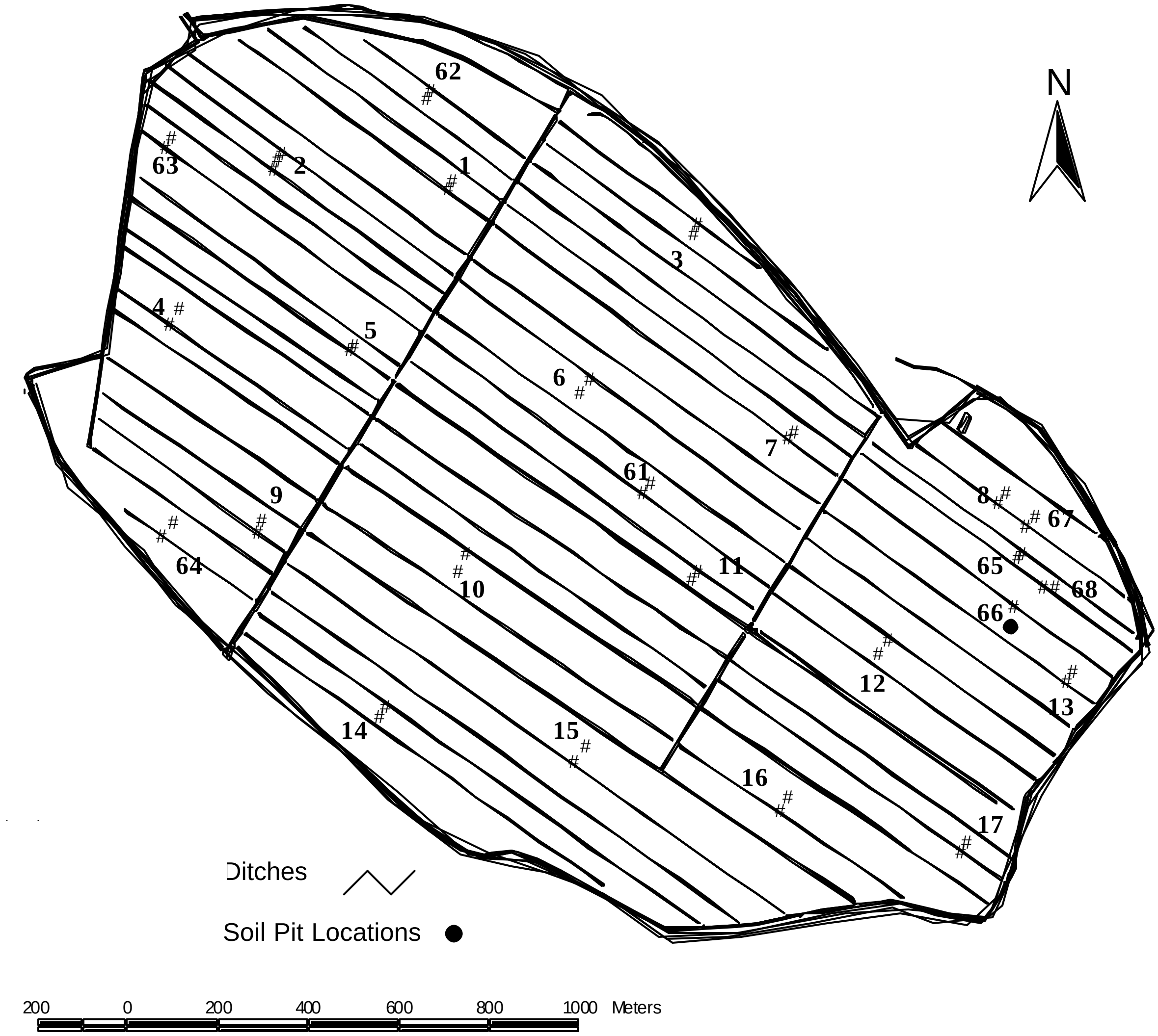
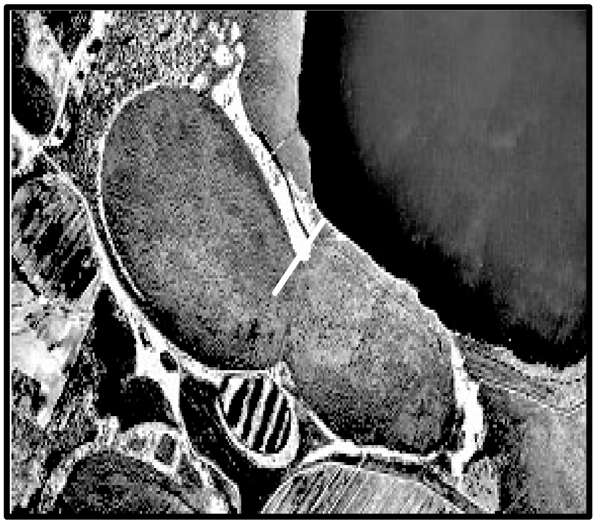
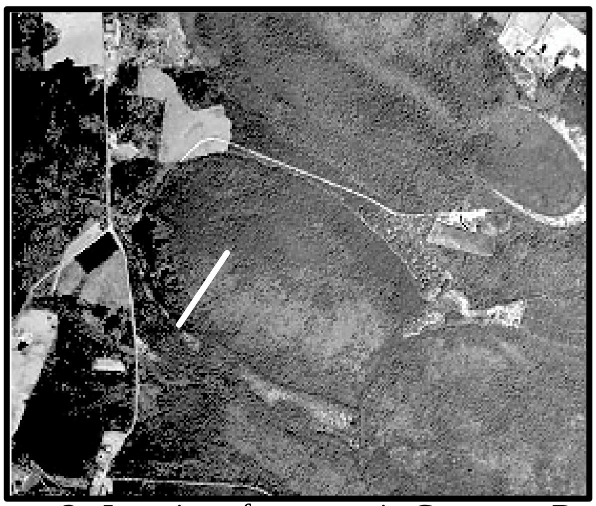


Figure 2. Pit locations at Juniper Bay

a.



b.



c.

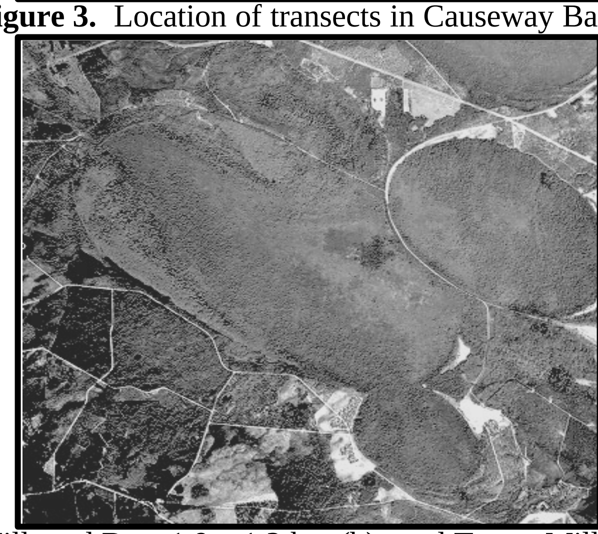
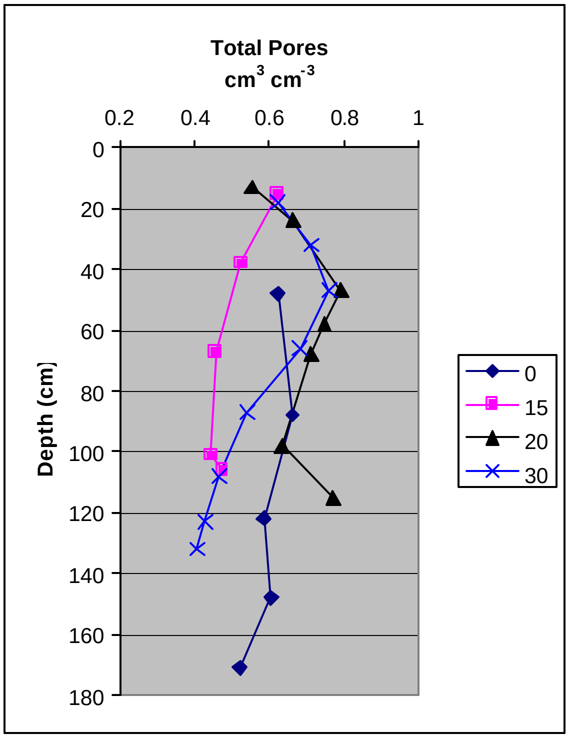
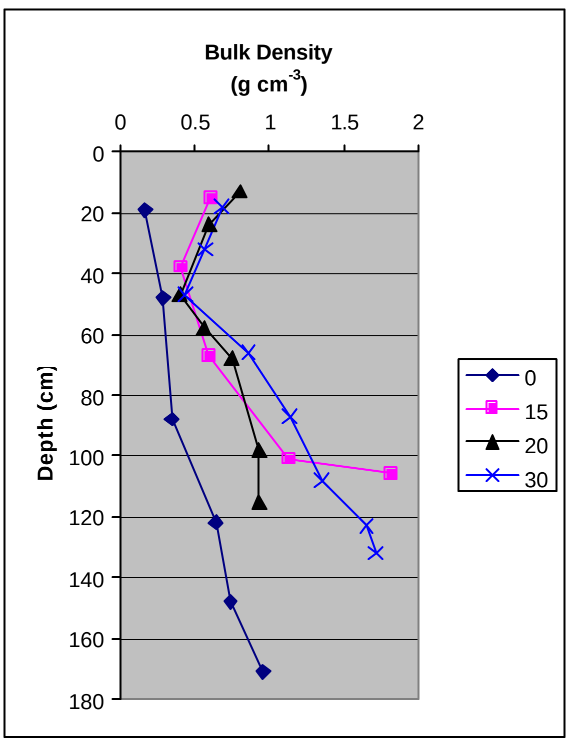


Figure 3. Location of transects in Causeway Bay, 1.8 x 1.15km (a), Charlie Long Millpond Bay, 1.9 x 1.2 km (b), and Tatum Millpond Bay, 4.4 x 2.2 km(c).



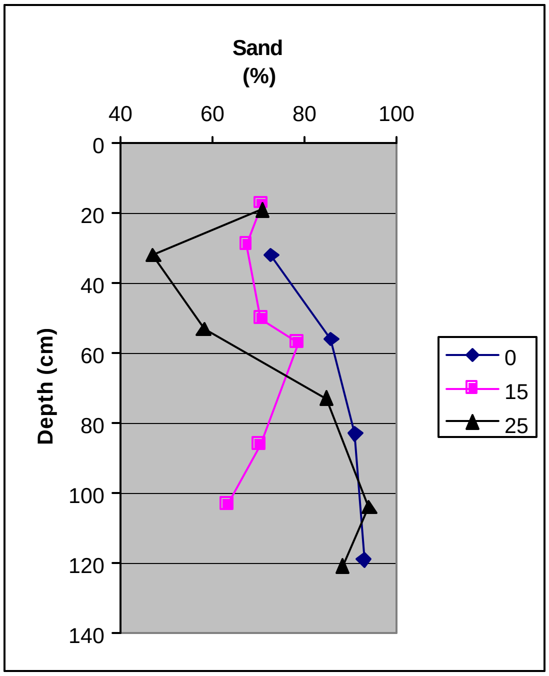
a

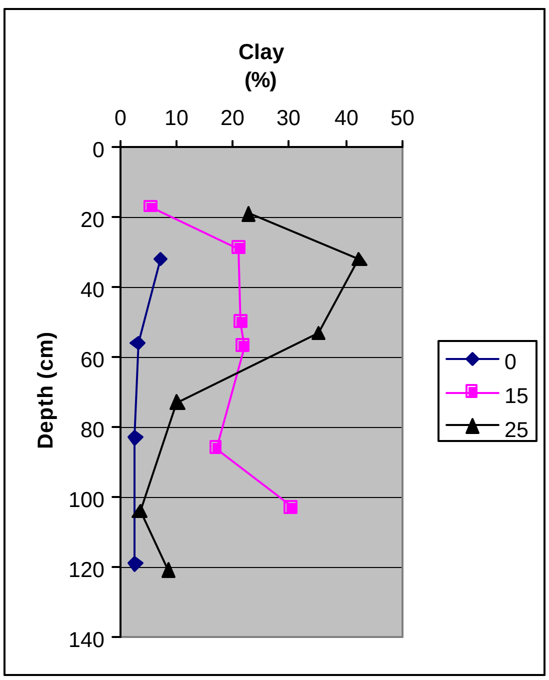


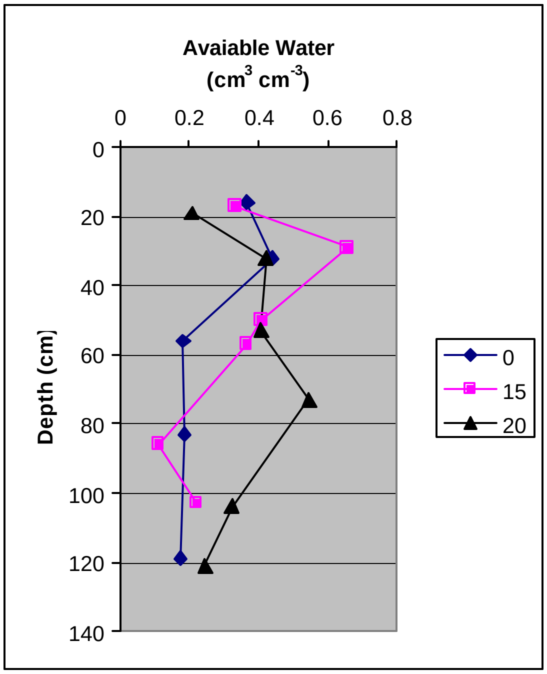
b.

Figure 4. Effects of drainage time on total pores (a) and bulk density (b) of an organic soil. Standard deviation is ± 0.1 g cm^{-3}.

Figure 5. Photo comparison of soils at the crest (left) and ditch (right) at location 16 in in organic soil in Juniper Bay. Scale is in cm.


Sand
(%)
40
60
80
100
0
20
40
60
80
100
120
140
Depth (cm)
0
15
25
a


Clay
(%)
0
10
20
30
40
50
0
20
40
60
80
100
120
140
Depth (cm)
0
15
25
b



c

Figure 6. Effects of drainage time on sand (a), clay (b), and available water (c) in a histic soil.

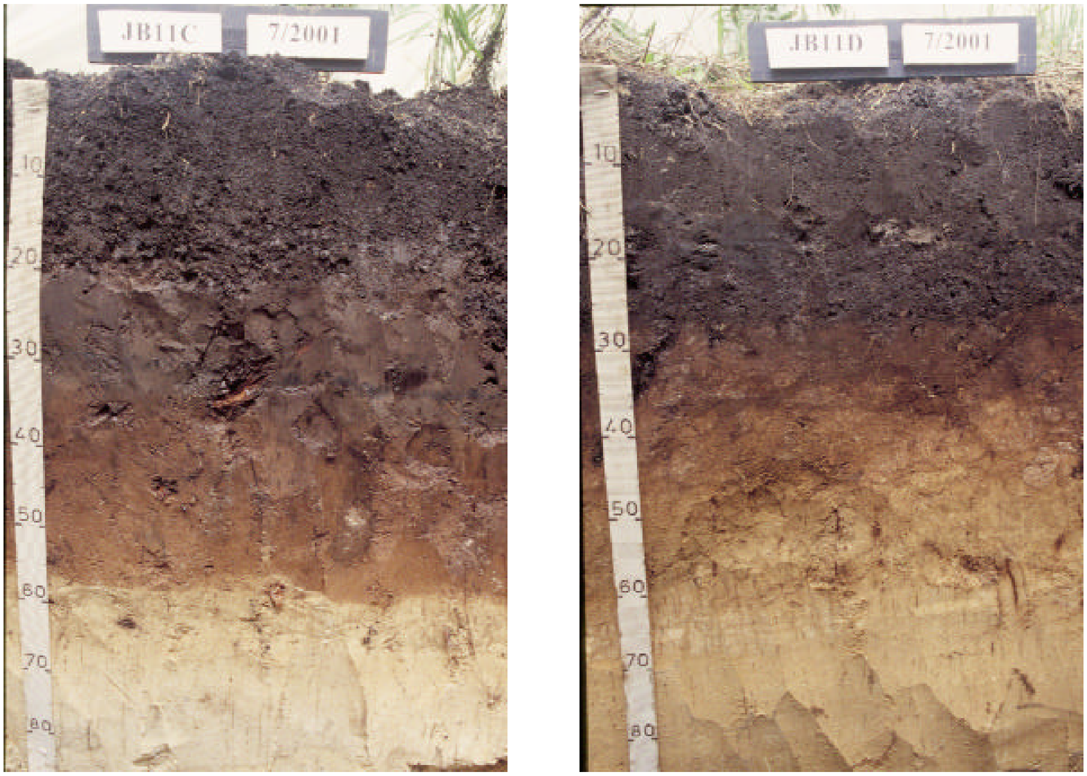
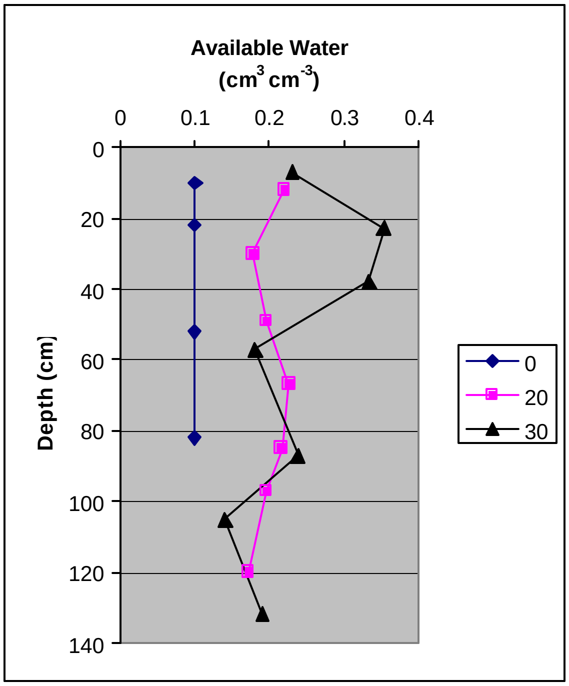
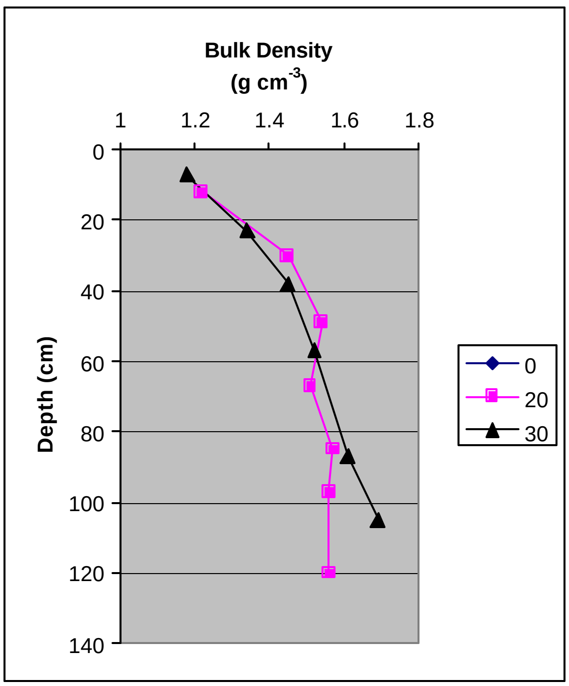


Figure 7. Photo comparison of soils at the crest (right) and ditch (left) at location 11 in a soil with a histic epipedon in Juniper Bay. Scale is in cm.



a



b

Figure 8. Effects of drainage time on available water (a) and bulk density (b) in a mineral soil.

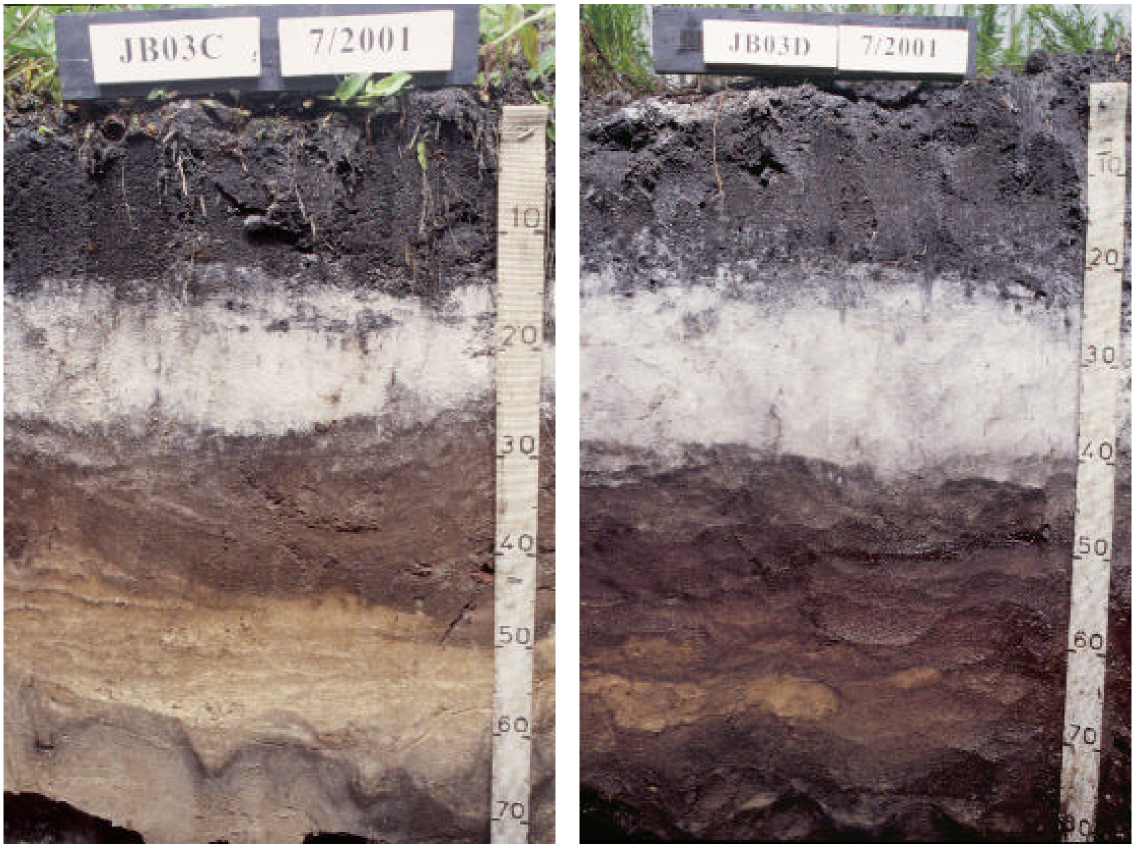


Figure 9. Photo comparison of soils at the crest (left) and ditch (right) at location 3 in a mineral soil in Juniper Bay

Chapter 7

ESTIMATING PRIMARY AND SECONDARY SUBSIDENCE IN AN ORGANIC SOIL 15, 20, and 30 YEARS AFTER DRAINAGE

J.M. Ewing and M.J. Vepraskas

INTRODUCTION

Organic soils form by the accumulation of plant debris under anaerobic conditions (Buol et al. 2003). Most organic soils occur in areas that are saturated for much of the year, because the saturation maintains an anaerobic environment that retards decomposition (Everett, 1983). Glaz (1995) suggested that annual durations of saturation required for organic soil accumulation range from 15 to 94%. Once drained for agriculture, the surface of the organic soils decreases in elevation over time. Processes responsible for the decrease include both primary subsidence and secondary subsidence (Everett, 1983). As shown in Fig. 1, primary subsidence is a relatively rapid process that results from a loss of buoyant force following drainage that causes the soil to sink under its own weight. Secondary subsidence is slower, and caused by decomposition (oxidation) of the organic debris as well as shrinkage following drying. Organic soil material can also be lost by burning which is a rapid form of oxidation and contributes to secondary subsidence.

Rates of primary and secondary subsidence are related to the original thickness of the soil, depth to water table (Stephens, 1954), mineral content (Slusher et al., 1974), temperature, precipitation, and management practices (Shih et al., 1998). Subsidence rates have been determined directly using benchmarks and surveying techniques before and after drainage has occurred (Stephens, 1954; Shih et al., 1998; Millette, 1976). Mathur et al. (1982) estimated subsidence rates of organic deposits from drained and undrained areas using pollen analysis. Unique pollen types or elevated levels of pollen were used as chronological markers to date when an organic layer was exposed at the surface. The differences in the depths of the chronological markers were then used to estimate subsidence. Mathur et al. (1982) found that the rate of subsidence was 6 cm yr^{-1} after 5 years and 3.67 cm yr^{-1} after 15 years.

Dolman and Buol (1967) estimated subsidence in an area in North Carolina that was drained for 50 years, but not farmed, using the "one third thickness loss upon drying rule". Subsidence was estimated by assuming that the thickness of the existing organic soil was one third of its original thickness in drained areas which were not used for agriculture. They extrapolated the estimated original elevation across adjacent agricultural areas and found that the soils used for agriculture had subsidence rates between 1.8 to 3.54 cm yr^{-1}. Rates varied with the thickness of organic layer with the shallower organic layer having the higher subsidence rates.

Several methods been developed to control subsidence through water and land management. Levesque and Mathur (1984) have shown that additions of copper will reduce the rate of subsidence by inhibiting soil enzymes that control the rate of oxidation of organic matter. Covering the surface with mineral material to slow diffusion of oxygen has also been tried with some success (Slusher et al., 1974). Keeping the amount of water in the peat to less than 50% or greater than 80% can slow decomposition (Stephens, 1954). Maintaining a high water table also reduces subsidence (Shih et al., 1998). Brooks and Lowe (1984) predicted that in Florida saturation for 60% of the year would slow subsidence of the soils of the Upper St. Johns River.

Wetland restoration projects frequently plug the ditches of drained agricultural fields and plant trees to recreate original conditions. In areas where organic soils have subsided, it is possible that ditch plugging will raise the level of groundwater above the soil surface. Fennema et al. (1994) predicted that the Everglades Agricultural Area (EAA) would be flooded for up to 360 days a year if man-made structures were removed, because the soils are 1.5 m deeper than the original surface. In extreme cases this may kill the newly planted vegetation before it has become established. We hypothesized that if the amount of subsidence could be predicted before ditches were plugged, then the potential problem of too great a water table rise following plugging might be avoided.

The amounts of subsidence that have occurred at a site will vary because of variations in water table depth, and the effects of past land treatments that were not uniformly applied across the field. Such treatments include drainage, tree removal, crowning of fields, stockpiling and burning of debris, among other things (Lilly, 1981). For these reasons, subsidence predictions should be made at as many locations as possible across a field. Subsidence processes produce two major changes in an organic soil: they increase bulk density through settling and also increase the concentrations of mineral components, such as sand, in horizons. Brewer (1976) showed how measurements of bulk density and mineral concentrations could be used to compute changes in volume of soil horizons following weathering and loss of material. We hypothesized that similar measurements could be made on organic soils to estimate amounts of subsidence using measurements of bulk density and sand percentage. The objective of this work was to estimate the amounts of primary and secondary subsidence that occurred in a drained organic soil using soil property measurements in drained and reference undrained soils.

THEORY AND ASSUMPTIONS

A hypothetical organic soil profile that has undergone both primary and secondary subsidence has two distinctly different organic soil horizons (Fig. 2). The Oap horizon is sapric material or muck that has been plowed for agriculture. It has a strong granular soil structure produced by drying and shrinkage, oxidation, and tillage (Lilly, 1981). This layer turns black in color as the organic materials oxidize. The underlying Oa horizon, also sapric material or muck, is below the tillage zone and remains wetter and less oxidized than the Oap horizon. The Oa horizon has a massive soil structure and shows no evidence of shrinkage and drying. It may have a redder color than that of the Oap horizon when oxidation is limited, and is massive in structure because no shrinkage occurred to create cracks. The Cg horizon is mineral soil material and is not of interest in this study.

We assumed that the Oa horizon with a massive structure experienced primary subsidence but virtually no secondary subsidence. Drying and shrinkage creates soil structure in the form of well-defined aggregates separated by large cracks (Pons and Zonneveld, 1965 and Lee and Manoch, 1974). The Oap horizon was affected by both primary and secondary subsidence because it had well developed structure and also a black color. It was clearly within the depth of plowing and could be easily distinguished from the underlying organic material.

Method for estimating Primary Subsidence

Primary subsidence occurs following drainage when the organic material settles under its own weight and compresses (Fig. 3). Volume is reduced by a reduction of pore space. There is minimal loss of organic material. The thickness of the organic soil layer decreases as it subsides causing bulk density to increase. This change in bulk density before and after drainage can be used to calculate the change in thickness of the organic soil material as a result of primary subsidence.

Loss of volume through primary subsidence was estimated for a volume of organic soil that had a unit cross-sectional area and a height that included the entire thickness of the organic soil material. The volume of the original organic soil (V_o) was computed as:

$$V_o = T_o\ (1cm^2) \tag{1}$$

where T_o is the thickness of the original organic soil material. The volume of the existing soil (V_{sp}) after primary subsidence was computed as:

$$V_{sp} = T_{sp}\ (1cm^2) \tag{2}$$

The mass of the organic soil material before primary subsidence (M_o) is assumed to be equal to the mass of the soil after primary subsidence (M_{sp}). The reduction in volume following primary subsidence occurred only by a decrease in the thickness of the original soil volume (T_o). The cross-sectional area of the soil was assumed to remain unchanged during primary subsidence.

The bulk density of the original soil (D_o) is computed as:

$$D_o = M_o / V_o = M_o / T_o\ (1cm^2) \tag{3}$$

The bulk density for the soil after primary subsidence is computed as:

$$D_{sp} = M_{sp} / V_{sp} = M_{sp} / T_{sp}\ (1cm^2) \tag{4}$$

The ratio of D_{sp} and D_o is related to the ratio of the thickness of the soil layers:

$$D_{sp} / D_o = [M_{sp} / T_{sp}\ (1cm^2)] / [M_o / T_o\ (1cm^2)] = T_o / T_{sp} \tag{5}$$

because we assumed that $M_{sp} = M_o$. The thickness of the original organic soil material (T_o) can be estimated as:

$$T_o = T_{sp}\ [D_{sp} / D_o] \tag{6}$$

The amount of primary subsidence (S_p) that has occurred is the difference between the vertical heights.

$$S_p = T_o - T_{sp} = T_{sp}[D_{sp}/D_o] - T_{sp} = T_{sp}[[D_{sp}/D_o] - 1] \tag{7}$$

In making these calculations we assumed that the drained soil subsides to a uniform bulk density in all organic horizons. Values for D_{sp} and T_{sp} are obtained from the organic soil that had subsided. A value for D_o can be obtained by sampling undrained organic soil. The undrained soil is assumed to have a bulk density that is similar to what the drained soil had prior to subsidence.

Method for estimating Secondary Subsidence

While organic soils form by the accumulation of organic materials, they usually contain small amounts of sand and silt that are deposited by wind and water. The sand and silt consist primarily of quartz, which is a mineral that does not weather or alter over short time periods of < 1000 years or so (Buol et al., 2003). Oxidation of organic material by either decomposition or fire increases the concentration of mineral material in a soil horizon. Therefore, the concentration of mineral material can be used to estimate the amount of secondary subsidence that has occurred. Changes in subsidence of an organic soil following drainage will be discussed using a volume of undrained soil that has a cross section area of 1 cm^2. It is assumed that this area remains constant during subsidence, and the volume decrease occurs only through a decrease in horizontal thickness.

We used a method described by Brewer (1976) to estimate the amount secondary subsidence. Brewer (1976) estimated the soil volume lost when primary minerals weather. While he applied the technique for the weathering of mineral materials, we adapted it for the decomposition of organic material. Two soil volumes must be compared, the parent material or unoxidized organic soil (V_p), and a volume of oxidized soil (V_s). As the parent material weathers (oxidizes) it loses both volume and mass and the minerals that resist weathering actually increase in concentration as compared to the original material (Fig. 4). This relationship was described by Brewer (1976) as:

$$V_s D_s R_s / 100 = V_p D_p R_p /100 \qquad (8)$$

where V_s = volume of present day soil
V_p= volume of parent material from which soil was derived,
D_s = bulk density of present day soil horizon,
R_s= percentage by weight of the stable constituent in present day soil horizon,
D_p = bulk density of parent material, and
R_s= percentage by weight of the stable constituent in the parent material.

Changes in the thickness of a horizon can be calculated by assuming that the change in volume through weathering occurs only in the vertical dimension and the cross-sectional area of the soil remains constant. When a soil mass shrinks it appears that the shrinkage occurs in all dimensions. However, the shrinkage creates voids in the horizontal dimension, and these are part of the soil volume (Fig. 5). As a result, the soil's cross-sectional area is assumed to remains constant throughout the weathering process because solid material is replaced by voids. Secondary subsidence changes volume by decreasing the thickness of the soil horizon (T_s):

$$V_s = T_s\,(1cm^2) \qquad (9)$$

The volume of parent material (V_p) can also be expressed as a function of thickness and unit cross-sectional area. (T_p). Equation 8 can then be arranged to calculate T_p.

$$T_p = T_s * (D_s R_s / D_p R_p) \qquad (10)$$

Secondary subsidence (S_s) would be equal to the difference in the thickness of the parent horizon and the soil horizon.

$$S_s = T_p - T_s \tag{11}$$

We used the underlying sapric material (Oa horizon), which has undergone primary subsidence only, as the parent material for these calculations, and used the percent sand in the organic soil horizons (Oa and Oap) as the stable constituent that increases as a result of oxidation. We assumed that the current Oap horizons formed from material similar to that of the underlying Oa horizons, , and we also assumed that the water table has been maintained at a level to prevent a significant loss of the material due to oxidization from the Oa horizon. We realize that there are many environmental, vegetative, and meteorological situations that factor into the deposition of sand into the organic material. However, we assume that over time, the sand that is deposited on the surface of the accreting organic soil would be uniformly distributed through the soil. North Carolina is in the path of hurricanes that have winds that can carry sand over long distances. Sand deposition that is deposited episodically would be homogenized through the profile over time by tree throw and bioturbation. We feel that such an assumption is valid after examining sand percentages through organic profiles in natural Carolina Bays. Sand percentages varied by less than 5% through the sapric part of the organic profiles (data not shown).

Sample calculations for primary subsidence

Data from one location in the drained Carolina bay (Table 1) will be used to illustrate the calculations. Bulk density (D_o) was measured in organic Oa horizons in the undrained natural bays and was found to be 0.25 g cm^{-3}. Bulk density (D_{sp}) from the subsided soils used for agriculture was determined to be 0.45 g cm^{-3} in the Oa4 horizon. The Oa4 horizon was the deepest organic layer in the soil, and also one with lowest bulk density. Because we assumed that all horizons had a bulk density of 0.45 g cm^{-3} prior to secondary subsidence occurring, then T_{sp} is equal to the sum or all horizon thicknesses from the surface to the bottom of the Oa4 horizon. In this example T_{sp} is equal to 66 cm. Therefore, using equation 4:

$$T_o = 66 \text{ cm } [0.45 \text{ g cm}^{-3} / 0.25 \text{ g cm}^{-3}] = 119 \text{ cm} \tag{12}$$

$$S_p = 119\text{cm} - 66\text{cm} = 53 \text{ cm} \tag{13}$$

This gives us an original thickness of 119 cm and a primary subsidence of 53 cm. The length of time for primary subsidence to occur varies, and because we have no data to suggest how long it took for primary subsidence to occur, we arbitrarily chose 10 years. This would give us a primary subsidence rate of 5.3 cm yr^{-1} if all the estimated primary subsidence occurred during the 10-yr. period.

Sample calculations for secondary subsidence

Using the data in Table 1 for calculating secondary subsidence, the organic horizon that had the lowest sand percentage was determined to be the “parent” horizon from which the horizons above were formed. For this illustration the Oa4 horizon is the parent material, and the overlying horizons are soil material that have experience varying degrees of secondary subsidence. The change in thickness has to be calculated for each horizon above the parent horizon and then summed to determine total secondary subsidence. Using equation 10 for the Oa3 horizon:

$$T_p = T_s * (D_s R_s) / (D_p R_p) \tag{14}$$

$$T_p = 20 \text{ cm} * (0.45 \text{ g cm}^{-3} * 9.96/100) / (0.45 \text{ g cm}^{-3} * 5.84/100) = 34 \text{ cm} \tag{15}$$

$$S_s = 34 \text{ cm} - 20 \text{cm} = 14 \text{ cm} \tag{16}$$

The Oa3 horizon subsided approximately 14 cm through shrinkage and oxidation. Similar calculations were repeated for the Oa2 and Oa1 horizons using the same parent material. The change in depth for Oa1 and Oa2 horizons were 44 cm and 30 cm, and the total amount of secondary subsidence across the three horizons was 88 cm. This sampling area had been drained for 30 years and accordingly secondary subsidence lowered the surface at a rate of 2.9 cm yr^{-1}.

This method did not work for locations in which the lowest amount of sand in the organic soil was in the surface horizon because it produced negative values of subsidence. Such values implied that there was an accumulation of material, probably due to spoil added to the soil surface through ditch cleaning. In cases where the sand content in soil horizons (R_s) were more than three times the sand content in the parent horizons (R_p), it was assumed that the soil horizon was fill material (from ditch excavation) and therefore that soil horizon was not used in the calculations. In addition to using total sand for the secondary subsidence calculations, we tried using the coarse and fine fractions of sand. It was found that using total sand gave an estimate that was a median of the two sand fractions and so total sand was used for all calculations.

MATERIALS AND METHODS

Juniper bay is a 256 ha Carolina bay southeast of Lumberton, North Carolina (34^{o}30’30”N 79^{o}01’30”E) that was drained and placed into agricultural production over a 30-yr period. The Robeson County Soil Survey showed that approximately 60% of the Juniper Bay consisted of organic soils that were classified as members of the Ponzer series (loamy, mixed, dysic, thermic Terric Haplosaprists) (USDA-SCS, 1978). Organic soil layers ranged from 40 to 130 cm. Undrained organic horizons have a massive soil structure, but develop subangluar blocky or granular structure following drainage (official series description). Plant communities believed to have been present in Juniper Bay included a Nonriverine swamp forest, High pocosin, and Peatland Atlantic White Cedar forest communities as described by Schafale and Weakly, 1990.

Aerial photographs and interviews with previous landowners were used to establish the drainage history of Juniper Bay. Approximately one third of the Bay was drained in 1971, another third drained in 1981, and the last third drained in 1986. Drainage ditches were dug to depths of 1 m in most of the Bay, but these fed into larger ditches that extended to depths of approximately 4 m. Field “cuts” were the land areas surrounded by ditches on all sides, which were used for agriculture. At selected field cuts, paired sampling points, with one at the crest and one near a ditch, were placed at locations determined by an equilateral triangle grid randomly placed across the site (Fig. 6). Pits were dug to a depth of approximately 1 m using a backhoe. In each pit, the soil profile was described to determine depth, color, and structure of major soil horizons. Uhland cores (75 cm^3) were taken from each horizon to determine bulk density. Bulk samples were taken from each horizon described in the profile. Total organic carbon was determined through dry combustion with a Perkin-Elmer PE2400 CHN Elemental Analyzer. Particle size was determined with the pipette method on a 10 g sample. Samples were prepared for particle size analysis by first oxidizing the organic matter with concentrated (30%) hydrogen peroxide. The amount of mineral material in the initial 10 g sample was determined with an additional 10 g sample that was placed in a muffle furnace at 400^{o}C for 24 hours to remove organic matter, leaving the mineral material. Percent sand from the total sample was calculated by multiplying the percent sand from the particle size analysis by the mass of the mineral material and then dividing by the mass of the original sample.

Three natural undrained Carolina bays, Tatum Millpond Bay (34^{o}43'00"N 78^{o}33'00"E), Charlie Long Millpond Bay (34^{o}46'00"N 78^{o}33'30"E), and Causeway Bay (34^{o}39'45"N 78^{o}25'45"E), were selected for comparison in Bladen County, North Carolina. These natural bays have organic soils that are classified as a Pamlico series (sandy or sandy-skeletal, siliceous, dysic, thermic Terric Haplosaprists). These soils have organic material 16 to 51 inches thick and are underlain by sand. Plant communities found in these bays were Pond Pine Woodland, Non-riverine Swamp Forest, Bay Forest, and High Pocosin, as described by Schafale and Weakly (1990).

Trails were cut through dense vegetation into the natural bays to reach sampling locations. Soil profiles at four locations in the organic soils of each bay were described using a McCauley peat sampler. Bulk samples were taken from each horizon for carbon and particle size analysis. Bulk density was determined by taking a 10 cm undisturbed sample with the McCauley peat sampler.

The initial study on Juniper Bay was not designed for determining subsidence of organic soils, and because of this we were unable to perform a statistical analysis of the results. Data reported consist of calculated estimates and averages.

RESULTS AND DISCUSSION

The organic soils from Juniper Bay and the natural bays were classified as Terric Haplosaprists. Typical profile descriptions are shown in Table 2, and selected physical and chemical properties are shown in Table 3 for one soil the drained site and another in a reference site. The undrained organic soils had a surface Oi and Oe horizons that combined were 50 cm thick, while these horizons were absent in the drained Carolina Bay. The Oi horizons were composed of fibric material that consisted of dead leaves and dead roots from the surrounding trees. Oe horizons were similar but had undergone more decomposition. Removal of the natural vegetation and use of the field for agriculture prevents Oi and Oe horizons from developing.

The Oa horizons in the undrained bay had massive structure. In contrast the drained Carolina Bay had an Oap horizon at the surface with strong granular structure as a result of tillage and dessication. In some sampling locations, very coarse prismatic to subangular blocky structure had developed in the Oap horizons. The Oa horizons in the drained bay were very dark brown (10YR 2/2) sapric (muck) compared to the black (10YR 2/1) sapric material of the undrained bays. The organic horizons were thicker (up to 170cm thick) in the undrained bay, compared to 52 cm in the drained bay.

Bulk density and sand percentage were two to three times higher in the organic horizons of the drained bay (Table 3). The difference in bulk density and changes in structure between the drained and undrained bays were the result of primary subsidence. The amount of sand in the organic soils of the drained bay was higher in at the surface and decreased with depth, while the amount of sand in the Oa horizons of the undrained bay was relatively constant. This trend in sand percentage change is what we expected to see in areas where secondary subsidence had occurred. Not all organic soil locations that were sampled could be used for analysis. Plots were deleted when the lowest sand percentage was in the surface horizon, or if there was no Oa horizon that could be used as parent material. The locations that were chosen are shown in Table 4.

Estimates for total subsidence varied among locations and with time since drainage (Table 4). Averages of the total subsidence values across the three time periods show that the organic soils subsided approximately 80 cm. Subsidence in the fields drained for 15 years is slightly less, 75 cm, than for fields drained for 20 or 30 years, 77 cm 86 cm respectively. This trend of total subsidence is expected indicating that the longer a site is drained the greater the amount of subsidence occurs. These values for total subsidence pertain to the Oa and Oap horizons which were sampled. We did not measure properties of the Oi and Oe horizons because they had no counterparts in the drained organic soil.

Estimated rates of primary and secondary subsidence varied across locations (Table 4). The average rate of primary subsidence is 4 cm yr_{10}^{-1}. Primary subsidence rates were lowest in the areas drained for 15 years, 3 cm yr_{10}^{-1}, and were highest in the areas drained for 20 years 4 cm yr_{10}^{-1}. This is probably due the water table in the area drained 15 years ago is closer to the surface relative to the other areas, maintaining buoyancy over more of the profile. Shih et al. (1998), showed that the rate of subsidence in the EAA have decreased from 2.5-3.0 cm yr^{-1} during the years 1913 to 1978, to 1.45 cm yr^{-1} during the years 1978 to 1997 as a result of better water management which raised the water table to slow decomposition. The average rate of secondary subsidence was approximately 2 cm yr^{-1} (Table 4). Secondary subsidence rates were highest after 15 years of drainage, 3 cm yr^{-1}, and similar after 20 and 30 years of drainage at approximately 2 cm yr^{-1}.

These estimates of subsidence and subsidence rates are consistent with other reported subsidence rates in previous studies. Stephens (1956) reported a subsidence rate of 4.3 cm yr^{-1} over a 50 year period in Florida, Ireyresr (1963) reported a rate of 1.5 cm yr^{-1} over 100 year period in England, and Jongedyk et al., (1950) reported a rate of 1.5 cm over 6 years in Indiana. Our calculated values are also similar to those found by Tant (1979) in North Carolina. A yearly loss of 1.2 cm was found on a Belhaven muck and 0.38 cm on a Pungo muck. Average annual subsidence in Quebec was 2.1 ± 0.4 cm yr^{-1}

over 38 years (Millette, 1976), and subsidence in New Orleans ranges from 1 to 5 cm yr^{-1} (Slusher et al., 1974).

The proportion that primary subsidence comprised of the total subsidence varied widely (Table 4), but overall the average proportion of primary and secondary were approximately equal. Largest variations occurred in the field drained for 30 years where primary subsidence accounted for between 13 and 85% of total subsidence. This result was unexpected because it was thought that secondary subsidence was a slower process. Previous landowners indicated, however, that fire was used in the clearing process to remove tree debris during the clearing operation, and charcoal was found in soil profiles at Juniper Bay (Table 1). Fires also occurred naturally through lightning strikes. If a site burned shortly after drainage ditches were installed, it is possible that loss through secondary subsidence would exceed that of primary subsidence. Loss of the organic material through burning would concentrate sand, and also lessen the weight of the material compressing the parent material. This would keep the parent material's bulk density low. Several studies have shown that subsidence tends to decrease with increasing distance from a ditch (Burke, 1963; Brandof, 1992), however our estimates neither verified or contradicted their findings when comparisons were made between ditch and crest locations.

Overall, the results did not show greater subsidence near ditches as expected. This could be due to the ditches being shallow in most parts of the site which kept soils wetter and slowed the subsidence processes. The land clearing process is also complex and involves the use of fire, ditch construction and maintenance, and crowning of fields. Considering the variety of operations that are used to prepare and maintain the land in agriculture it is not surprising that we are unable to see a clear effect of the ditches on subsidence rates.

SUMMARY AND IMPLICATIONS

The principal finding from this study is that if the drainage ditches were filled in to restore wetland hydrology in Juniper Bay, we estimate that the water table will rise to approximately 80 cm above the existing organic soil surface. This is determined from the average value of subsidence that was estimated to have occurred across the site (Table 4). There may be some variation in water depth across the site, because soils drained for 15 years have experienced less subsidence. However, as shown in Table 4 the amount of estimated subsidence within the drainage groups was large and so little consistent difference would be expected across the site. In support of our estimate for the amount of subsidence that has occurred we compared the existing elevation of the organic soils in Juniper Bay to the elevation of the mineral surface lying around the Bay's perimeter. The mineral soils around the edge of the Carolina bay are higher in elevation than the organic soils by approximately 60 cm. Previous studies have shown that the surface of organic soils on broad flats can actually be higher than the surfaces of adjacent mineral soils (Daniels et al., 1999). We feel that for restoration planning it is reasonable to assume that 80 cm of subsidence has occurred is justified. This value does not include the thickness of Oi or Oe horizons which may have occurred over the Oa horizons when the natural vegetation covered the site.

We realize that our method for estimating the amount of subsidence that has occurred is based on several assumptions that will not hold true for other sites. Potential sources of error for the results from this study include the following. Some sample locations near ditches had the organic materials contaminated by ditch cleaning operations, leading to increased sand at the surface. This would cause increased estimates of secondary subsidence. The only way to avoid this problem is through careful sampling and eliminating sites with extraordinarily high sand percentages. Our assumptions that original sand percentage and bulk density between the parent material and overlying layers were similar could also be in error. This problem can be minimized when the parent material properties are selected separately for each sampling site. If one sampling location does not have sufficient undisturbed material in a lower horizon, then that site should not be used to estimate subsidence. The impact of fire on increasing the organic soil oxidation rate is unclear, but has been assumed to result in an increase in sand percentage in the burned layers. We feel that these potential sources of error have had only a small impact on our results because the data reported in Table 4 are in line with published findings from elsewhere. The best way to estimate subsidence amounts is with long-term, permanent bench marks whose initial elevation is known. When these are not available, then our method seems to offer a workable solution to approximating subsidence at many sites.

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Table 1. Values for sample calculations. Bulk density from Oa4 is used for estimating primary subsidence because it is the lowest. Horizon Oa4 is used as the parent material in estimating secondary subsidence because of the lowest % sand. All other horizons have a concentration of sand that could be attributed to secondary subsidence.

Horizon	Horizon Thickness	Bulk Density	Sand	Change in horizon thickness
	(cm)	(g cm^{-1})	(%total sample)	(cm)
Oa1	10	0.75	18.7	43.6
Oa2	10	0.75	13.9	12.7
Oa3	20	0.45	10.0	14.1
Oa4	26	0.45	5.8	**0 (parent material)**

Table 2. Typical profile from an organic soil at an undrained natural Carolina bay and from a drained Carolina bay.

Horizon	Depth	Description
	cm	
		Undrained
Oi	0-20	Black (10YR 2/1) fibric to hemic muck. Massive structure. Gradual boundary. Root and debris mat.
Oe	20-50	Very dark brown (7.5 YR 2.5/2) hemic muck. Massive structure. Gradual boundary. Organic bodies 0.5-1 cm. Many roots and debris.
Oa1	50-82	Very dark brown (10YR 2/2) sapric muck. Massive structure. Clear boundary. Common large pieces of wood debris.
Oa2	82-107	Black (10YR 2/1) sapric muck. Massive structure. Gradual boundary. Few large pieces of wood debris.
Oa3	107-145	Black (10YR 2/1) sapric muck. Massive structure. Gradual boundary
OC	145-170	Black (10YR 2/1) sapric muck with <2% sand grains. Massive structure. Abrupt boundary.
C	170-190	Very dark brown (10 YR 2/2) sand. Single grain structure.
		Drained
Oap	0-11	Black (N 2.5/0) sapric muck. Strong medium (2mm) granular structure. Abrupt boundary.
Oa1	11-31	Very dark brown (10YR 2/2) sapric muck with 10% wood fragments and 10% charcoal. Massive structure. Diffuse boundary.
Oa2	31-52	Very dark brown (10YR 2/2) sapric muck with 10% wood fragments and 10% charcoal. Massive structure. Abrupt boundary.
Bw	52-61	Dark reddish brown (5YR 3/3) sandy loam. Moderate coarse (5cm) prismatic structure. Abrupt boundary.
2BC	61-78	Yellowish brown (10YR 5/4) loamy sand with 40% white (2.5Y 8/1) sand in areas 1mm in diameter. There was 10% wood fragments. Massive structure. Clear boundary.

2C1	78-100	Light yellowish brown (10YR 6/4) loamy sand with 5% wood fragments. Massive structure. Clear boundary.
2C2	100+	Dark gray (10YR 4/1) loamy sand. Single grain structure. reaction to alpha, alpha. Dense.

Table 3. Particle size, organic carbon, and bulk density of typical profiles from Juniper bay and undrained natural bays.

Horizon	depth	C	BD	sand	silt	clay
	(cm)	(%)	g cm^{-3}	----------(%)----------		
Drained						
Oap	0-11	26.25	0.76	34.2	14.3	10.3
Oa1	12-31	52.52	0.47	16.7	22.9	7.3
Oa2	32-52	27.91	0.47	41.1	18.1	7.8
Bw	53-61	5.46	0.93	74.0	8.5	9.6
BC	62-78	0.48	1.55	93.1	1.8	4.3
C1	79-100	0.26	1.55	91.3	2.5	5.9
C2	101-110	0.32	---	91.9	1.7	5.9
Undrained						
Oi	0-20	41.25	---	---	---	---
Oe	21-50	37.37	---	---	---	---
Oa1	51-82	42.28	0.18	6.8	11.5	9.0
Oa2	83-107	34.74	0.21	14.0	17.3	10.0
Oa3	108-145	34.56	0.19	14.2	29.9	10.3
OC	146-170	16.35	0.49	46.1	20.4	6.8
C	190	---	0.87	78.7	12.1	1.7

Table 4. Estimated secondary subsidence from selected locations. The C or D in the sample location indicates if the sampling pit was at the crest (C) or near the ditch (D). Rate for secondary subsidence was calculated by dividing the amount of subsidence by

the years of drainage (x). Primary subsidence rate was estimated by dividing the amount of subsidence by 10 years. * Did not include surface horizons that had greater that three times R_p in the calculation of secondary subsidence.

Plot Location	Primary subsidence		Secondary subsidence		**Total subsidence**		
	Amount	Rate	Amount	Rate	**Absolute**	**Primary**	**Secondary**
	(cm)	(cm/yr_{10})	(cm)	(cm/yr_x)	(cm)	------ (%) -----	
				15 Years After Drainage			
66D*	13.9	1.4	42.3	2.82	56.2	25	75
68D	26.8	2.7	55.0	3.67	81.8	33	67
8D	60.2	6.0	26.8	1.79	87.0	69	31
Av.	**33.6**	**3.4**	**41.4**	**2.76**	**75.0**	**42**	**58**
				20 Years After Drainage			
10C*	24.4	2.4	50.0	2.50	74.4	32	68
16C	45.8	4.5	25.3	1.26	71.1	65	35
16D	54.3	5.4	45.2	2.26	99.5	54	46
6C*	72.0	7.2	23.6	1.18	95.6	75	25
11C	20.4	2.0	21.8	1.09	42.2	48	52
Av.	**43.4**	**4.3**	**33.2**	**1.66**	**76.6**	**57**	**43**
				30 Years After Drainage			
2D	33.6	3.3	6.2	0.21	39.8	84	16
4D	61.4	6.1	8.3	0.28	69.7	87	13
5C	52.8	5.2	85.9	2.85	138.7	43	57
5D	14.4	1.4	82.9	2.76	97.3	15	85
Av.	**40.6**	**4.0**	**45.8**	**1.52**	**86.4**	**47**	**53**

Table 5. Mean and range of bulk density and total sand in the surface two horizons of organic soils in Juniper Bay (JB) and the Reference Bays (RB). Notice the inverse relationships in bulk density and total sand of the surface two horizons between Juniper Bay and the Reference Bays. NOTE: The mean and range values include horizons that were excluded in making subsidence calculations.

	Bulk Density ----- (g cm^{-3}) -----		Total sand ----- (%) -----	
	mean	range	mean	range
JB 1	0.77	0.53-1.23	49.0	24.1-88.0
JB 2	0.61	0.32-1.23	41.9	13.2-87.3
RB 1	0.25	0.10-0.74	36.7	11.3-64.0
RB 2	0.52	0.16-0.87	54.8	53.3-83.1

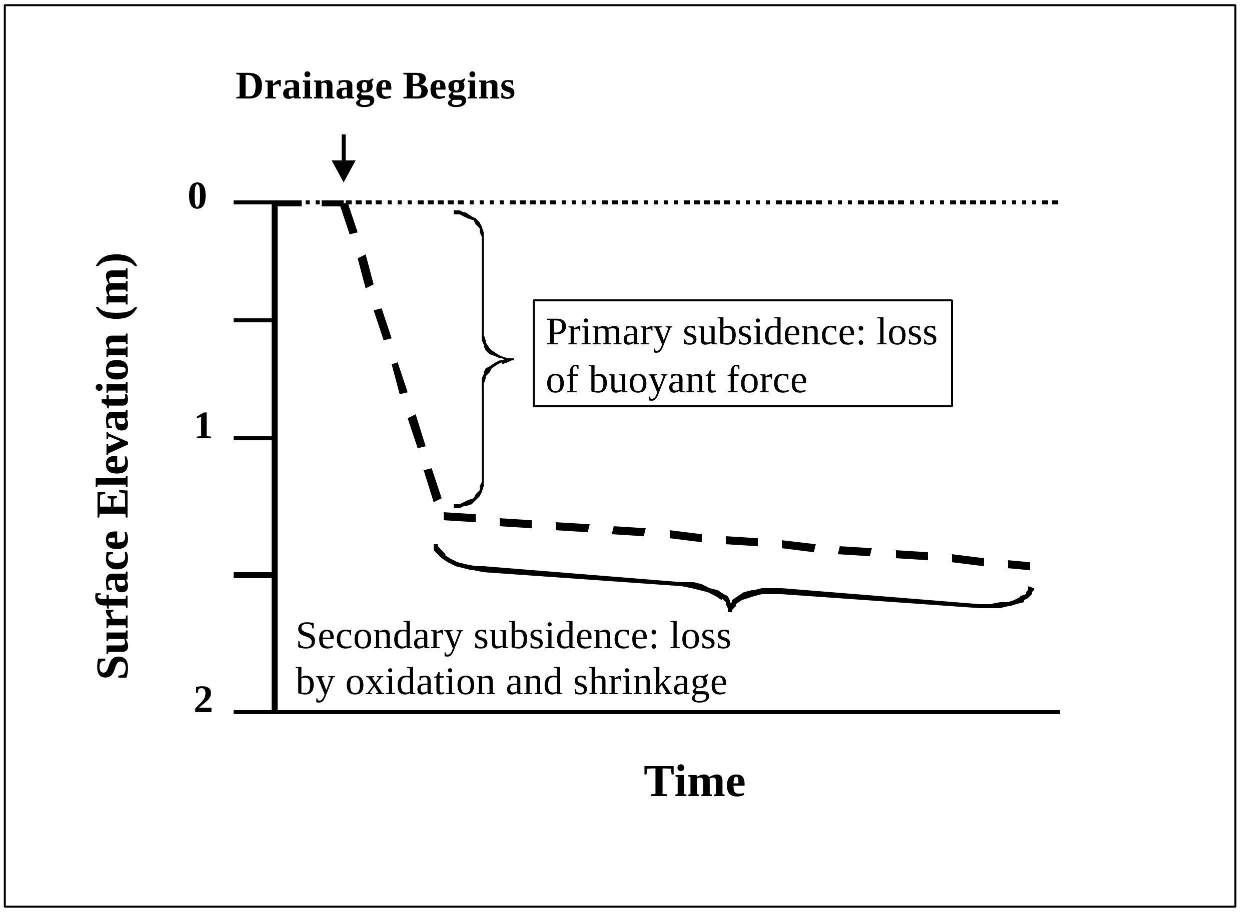


Fig. 1. Hypothetical illustration of the effects of subsidence on the decrease in elevation of an organic soil following drainage. Primary subsidence occurs quickly due to loss of water through drainage. Secondary subsidence is a slower process.

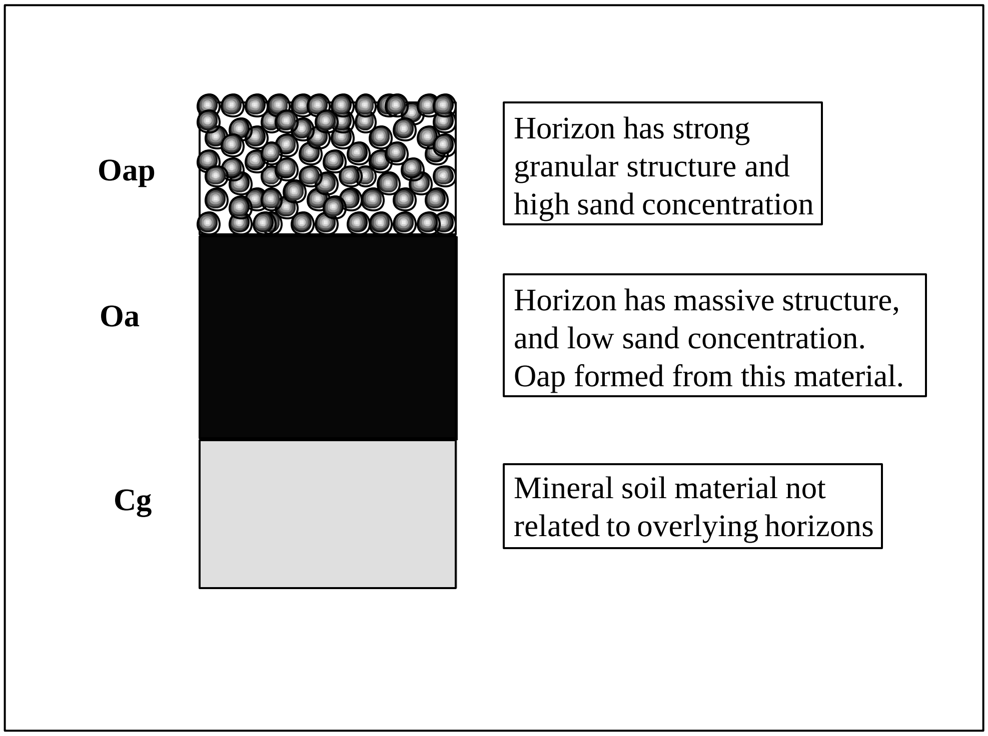


Fig. 2. Example of a soil profile consisting of organic soil material over mineral material. The Oap horizon is tilled and undergoes the most oxidation. The Oa horizon showed little influence of oxidation and was used as the parent material for the Oap horizon. The mineral material was not considered in the calculations.

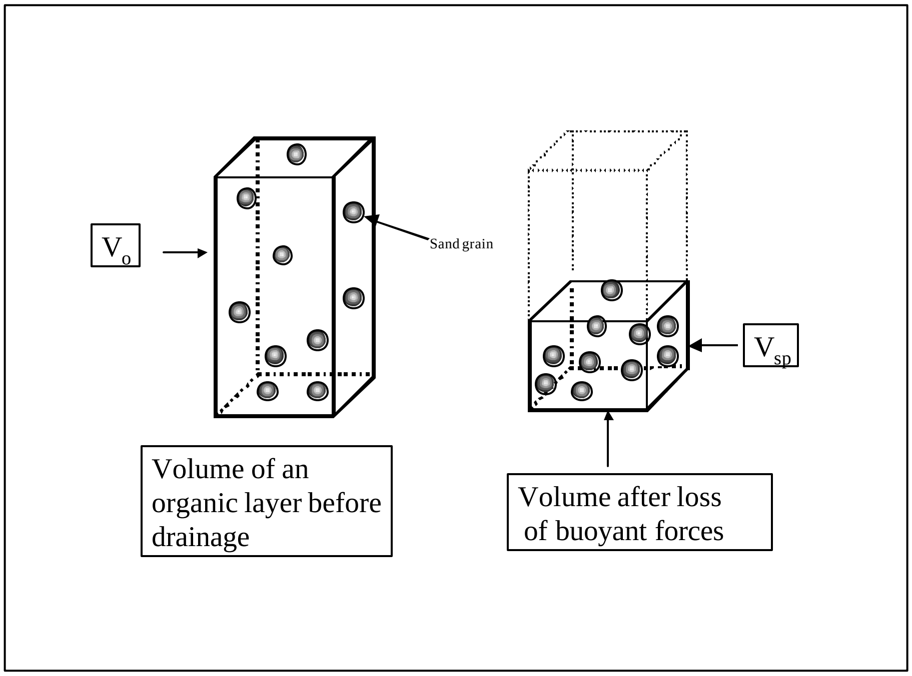


Fig. 3. Illustration of how primary subsidence reduces volume while the mass remains the same in an organic soil horizon following loss of buoyant forces. V_o is the volume of soil having a unit cross-section before primary subsidence occurs. V_{sp} is the volume of soil after primary subsidence, which also has a unit cross-sectional area. It is assumed that subsidence has only altered soil volume in the vertical direction.

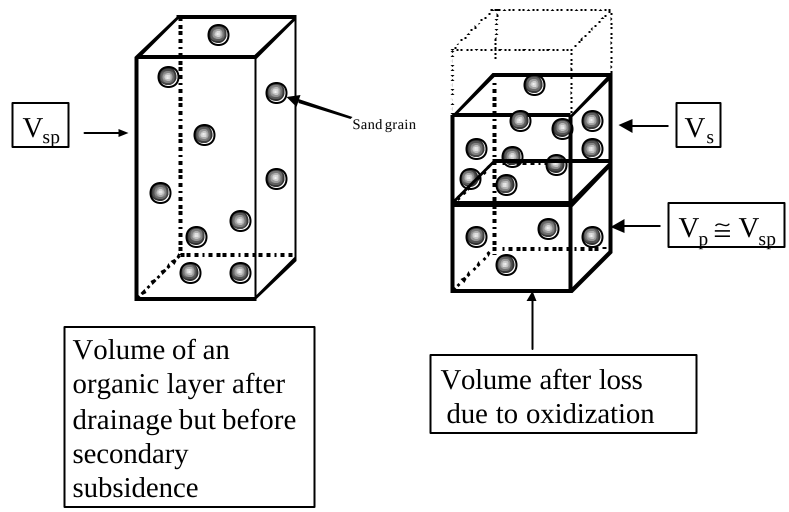


Fig. 4. Illustration of how secondary subsidence due to oxidization reduces volume while also increasing the mass in the surface layers by concentrating the sand. V_{sp} is the volume of soil after primary subsidence but before secondary subsidence. V_p is the volume of parent material that has not undergone secondary subsidence and is approximately equal to V_{sp}. V_s is the volume of soil that has undergone secondary subsidence. It is assumed that all volumes have a unit cross-sectional area and changes in volume occur in the vertical direction.

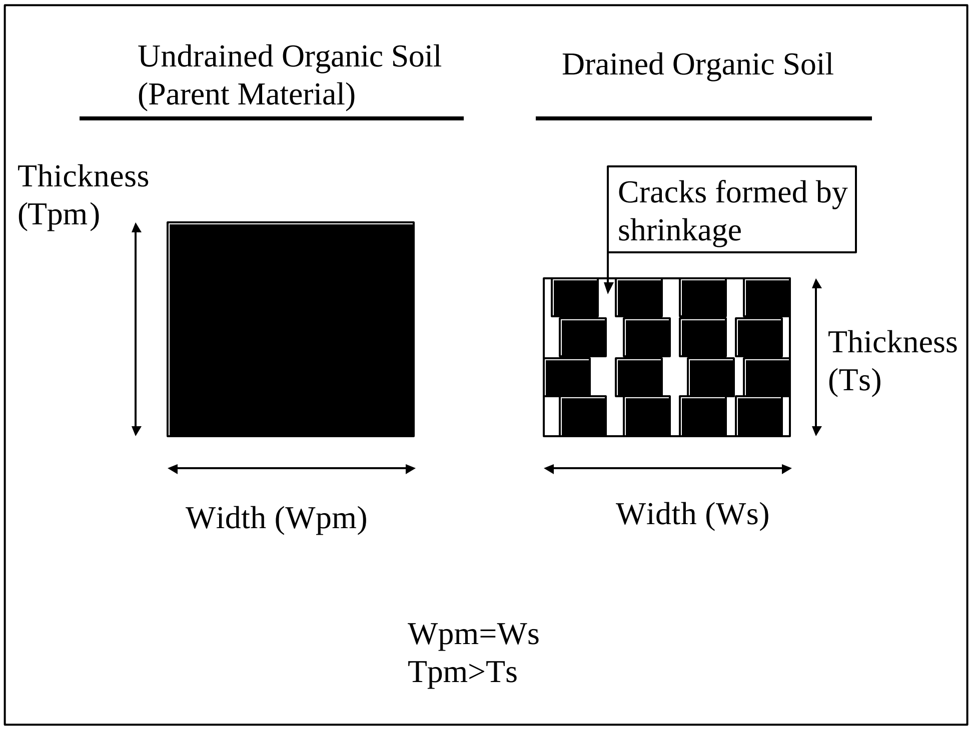
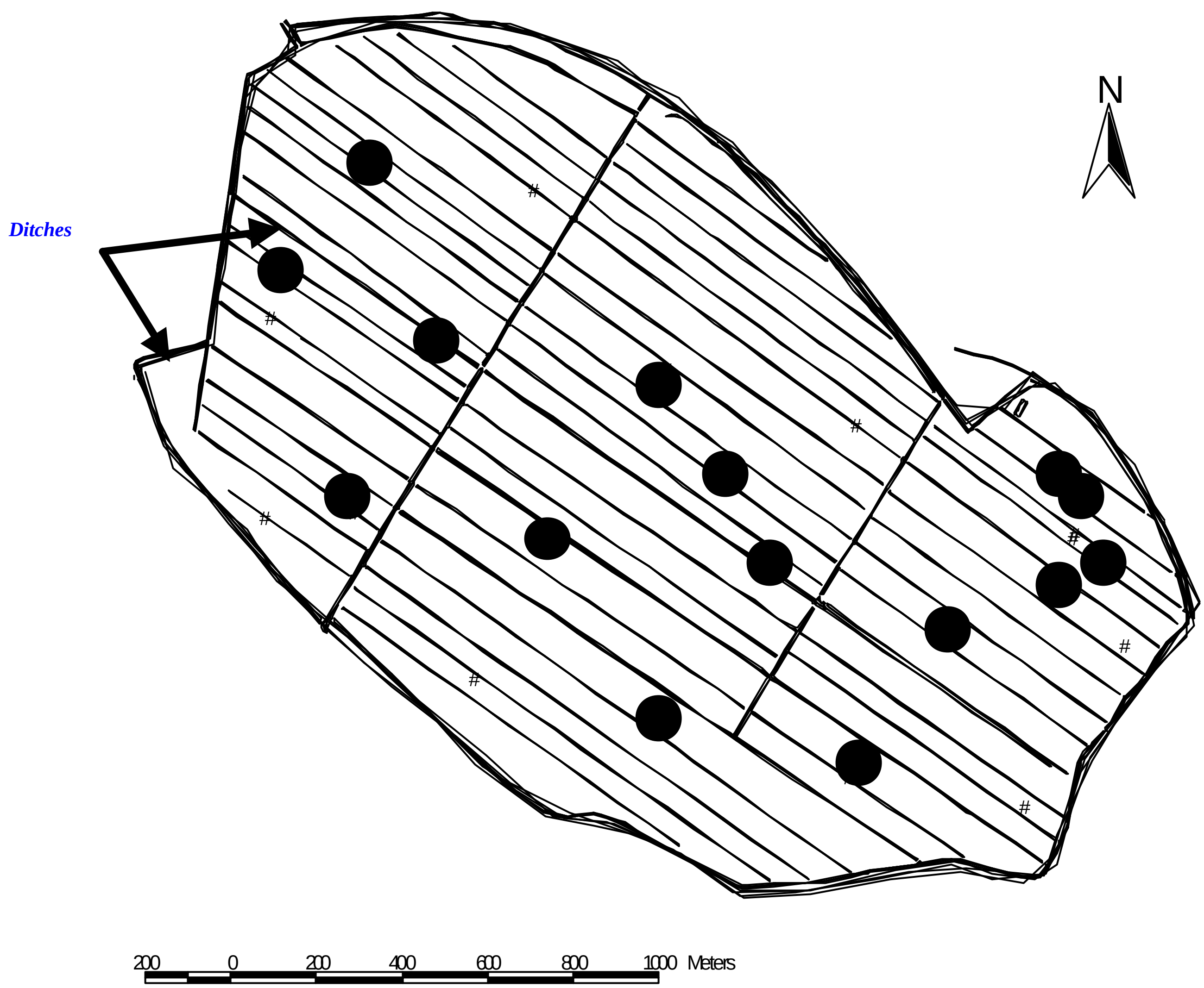


Fig 5. When a soil mass shrinks it appears that the shrinkage occurs in all dimensions. However in the horizontal dimension the shrinkage creates voids, and these are part of the soils volume. As a result, the soil's cross-sectional area is assumed to remain constant throughout the weathering process, with changes occurring in the vertical dimension.

Fig. 6. Schematic diagram showing the drained Carolina Bay (Juniper Bay) with its drainage ditches. Sampling locations within the organic soils are shown by dots. At each dot, one pit was located at the center of the field cut, equidistant between ditches while another pit was placed near (within 2 m) of a ditch.



Chapter 8

NUTRIENT ANALYSIS OF DRAINAGE WATERS FROM JUNIPER BAY

G.S. Kreiser, M.J. Vepraskas, and R.L. Huffman

INTRODUCTION

Many points through the nutrient cycle are strongly influenced by the hydrologic cycle (Bormann and Likens, 1967). Inputs and outputs of nutrients are directly related to the amounts of water that move in and out of an ecosystem. The biological uptake of nutrients by plants and the release of nutrients by decomposition are related to the amount and pattern of water availability. The rate and nature of weathering and soil formation are influenced by the hydrologic regime, since water is essential to major chemical processes (Bormann and Likens, 1967).

Nutrient cycling in wetlands can be defined in the context of water budgets. The source, velocity, quantity, and distribution of water directly control the spatial heterogeneity of the nutrients (Carter, 1986). However, relatively few studies have been performed on nutrient exports and imports based on water budget studies (Carter, 1986).

Water quality in unaltered wetlands reflects the quality of the water into the wetland and the interaction of this water with the soils and vegetation (Carter et. al., 1978). Wetlands affect water quality through element cycling, sediment deposition, and ion and molecule adsorption (Carter, 1986). Wetlands can act as a filter, where the quality of the water leaving the wetland may differ significantly from that of the water entering the wetland.

Carolina Bays are the only abundant lentic systems of natural origins in the coastal plains of North Carolina (Newman and Schalles, 1990). Lentic is defined as being associated with still water systems. These systems occur in basins and lack a defined channel or floodplain (Alberta Natural Heritage Information Centre, 2002). Even though Carolina Bays are very numerous, Schalles and Shure (1989) state, “Carolina Bays are poorly studied with respect to hydrology, community structure and succession, trophic dynamics, and mineral cycling.” Carolina Bays typically have water chemistries that are soft and acidic. Biological production is low to moderate (Sharitz and Gibbons, 1982; Newman and Schalles, 1990).

The United States Environmental Protection Agency (USEPA), in its 1996 National Water Quality Inventory, claimed that 40 percent of streams or rivers surveyed were impaired because of the nutrients N and P (USEPA 1998). Concerns about excess nutrients include adverse effects on humans and domestic animals, aesthetic impairments, negative impacts on aquatic life, and excessive nutrient input into downstream systems (Dodds and Welch, 2000). Eutrophication, which is the addition of excessive nutrients, can cause proliferation of algal masses that can cause degradation of water quality (Dodds and Welch, 2000).

Sources for pollution come from either point or non-point sources. Non-point sources originate from agriculture activities (fertilizer and manure application to land), and residential activities (on-site waste disposal) (Osmond et. al., 1995). Point sources include industries that use nitrates in manufacturing and sewage treatment plants. In the southeastern United States, the main source of nitrogen pollution comes from agricultural fertilizers and animal manure (Osmond et. al., 1995). The limit suggested for nitrate in drinking water is 10 mg/L (Osmond et. al., 1995). Adverse health effects of nitrate above this limit include methemoglobinemia (blue baby syndrome).

Phosphorus in freshwater systems exists either in a particulate or dissolved phase. Particulate matter includes living and dead aquatic organisms, precipitates of phosphorous, and amorphous phosphorus. The dissolved phase includes inorganic phosphorus, which is generally in the soluble orthophosphate form, and organic phosphorus (Osmond et. al., 1995).

The EPA water quality criteria for phosphates states that levels should not exceed 0.05 mg/L if streams discharge into lakes, 0.025 mg/L within in a lake, and 0.1 mg/L in streams or flowing water not discharging into lakes in order to control algal growth (Osmond et. al., 1995). Phosphates do not have notable adverse health effects (USEPA 1986). The primary anthropogenic nonpoint sources of phosphorus include runoff from land areas being mined for phosphate, agricultural areas, and urban/residential areas. Point sources of phosphorus include sewage treatment plants, and industrial waste products (Osmond et. al., 1995).

Many bodies of freshwater are experiencing influxes of both phosphorus and nitrogen from point and nonpoint sources. The increased concentrations of available phosphorus allows for more assimilation of nitrogen before the phosphorus is depleted. Although levels of orthophosphate between 0.08 to 0.10 mg/L may trigger periodic algae blooms, long-term eutrophication will be prevented if total phosphorus and orthophosphate levels are below 0.5 mg/L and 0.05 mg/L, respectively (Osmond et. al., 1995).

The environmental effects on freshwater systems of the addition of N and P are that the growth of macrophytes and phytoplankton is stimulated. Generally, phosphorus (as orthophosphate) is the limiting nutrient in freshwater aquatic systems. If all phosphorus is used, plant growth will cease, no matter how much nitrogen is available (Osmond et. al., 1995). The natural levels of orthophosphate usually range from 0.005 to 0.05 mg/L.

The objectives of this study were to examine a drained Carolina Bay that was in agricultural production in order to determine: 1) the possible inputs and outputs of nutrients into the bay; 2) the overall nutrient status of the bay; and 3) if the nutrients leaving the bay in surface outflow could be a possible source for water quality degradation.

MATERIALS AND METHODS

The North Carolina Department of Transportation (NCDOT) is in the process of restoring a drained Carolina Bay in Robeson County. The project will provide compensatory wetland mitigation in the Lumber River Basin of southeastern North Carolina, which will offset wetland impacts from road construction projects in the river basin (Hauser, 2001). The goal of the restoration project is to restore the functions and values of a Carolina Bay. As part of this restoration project, North Carolina State University is investigating the hydrologic, soil and vegetative changes that occur in Juniper Bay as a result of this restoration project.

The site, known as Juniper Bay, is composed of 300 hectares of an extensively drained Carolina Bay that was limed and fertilized to enhance agricultural production. The nutrient enrichment of Juniper Bay raises the concern that the increased nutrients might lead to high levels of nutrients exiting in the surface outflow from the bay and cause water quality degradation.

Nutrient analysis was performed on bulk precipitation, surface outflow and groundwater. Water samples were sent to the Soil Science Analytical Service Laboratory where they were tested for NH_4^+-N, NO_3^--N, PO_4^{3-}, TOC, Ca^{2+}, K^+, Mg^{2+}, and Na^+. Phosphate, NH_4^+-N, NO_3^--N, and TKN were measured using Lachat Quickechem 8000 slow injection auto analyzer. TOC was measured using a Total Organic Analyzer. Ca, K, Mg, and Na were measured using ICP (Inductively Coupled Plasma - Mass spectrometry).

Bulk Precipitation

Bulk precipitation was collected at three locations, next to the rain gauges in Juniper Bay (Fig. 1). Bulk precipitation was collected weekly and combined monthly for each location. The samples were collected following the system of Likens et al. (1967) where there is a funnel to collect precipitation, tubing and reservoir (Fig. 2). The reservoir container is isolated from the atmosphere by the vapor barrier placed in the tubing. The vapor barriers were used in order to eliminate concentration of solutes by evaporation (Johnson and Swank, 1973). Samples that were contaminated with leaves, bird feces, etc. were discarded. A dilute hydrochloric acid solution was added to the reservoir as a preservative (Radtke, 1999).

Surface Outflow

Surface outflow samples of 100 mL were taken with an ISCO 3700 sampler, which took samples about every 48 minutes. Each bottle could hold ten samples with about 3 bottles a day being collected. Hydrochloric acid was added to the bottles as a preservative. Bottles were collected weekly and stored at 4^{o}C until filtering and testing. Weekly pH readings were made of the surface water using an Accumet AP62 pH/mv/Ion meter.

At the laboratory, the bottles were combined based on outflow data. Bottles that represented low flow events, rising limb, or peak of events were sampled together. Outflow measurements were plotted against time and the bottles' sample time was plotted against time. By using the graph, individual bottles were then placed together for testing (Figure 3). The point of this technique was to sample storm events in order to test whether there is a difference in nutrient levels in the surface outflow during these events. Samples were filtered through a 0.45μm filter to remove particulate material that would interfere with the analysis.

Ground Water

Groundwater samples were taken monthly from piezometers located near cores 1, 3, 17 and 25 (Fig. 4). These locations were selected because it is thought that these locations might be the general area of groundwater inflow or outflow at the bay.

Samples of groundwater were retrieved using a hand bailer. Groundwater pH was taken in the field by using an Accumet AP62 pH/mv/Ion meter. Dilute hydrochloric acid was added as a preservative and samples were stored in cold room until analyzed. Samples were filtered using a 0.45 μm filter, in order to remove any sediment.

RESULTS AND DISCUSSION

Surface Outflow

Over a period of one year the surface outflow nutrient levels did not significantly differ. The only instance of differences in nutrient concentrations in surface outflow occurred during large rain events. In particular, there was a dramatic increase of nutrients when there were more than 5 cm of rainfall in a day. To illustrate this point, nutrient levels from several periods of no rainfall where averaged together. Table 1 lists the average nutrients for these periods. As shown by Table 1 the nutrient levels in the surface outflow are in general quite low.

To compare the effect of rainfall on the nutrient concentrations, several storm events of less than 5 centimeters a day were averaged together. These storm events represent rainfall as little as 0.13 cm to as much as 4.5 cm in a day. Table 2 shows that when there were rain events of less than 5 cm a day, the nutrient concentrations were similar to the periods of no rainfall. This indicates that rain events of less than 5 cm do not have a significant impact on the nutrient concentrations in surface outflow.

There were two rain events that had amounts greater than 5 cm of rainfall in a day. During these periods, the nutrient concentrations increased dramatically in the surface outflow (Table 3). For most nutrients, the concentrations increased by at least two times the non-rainfall values. Some of the biggest increases in nutrient concentrations include TOC and calcium -- an increase of four times the concentrations in base flow conditions.

The pattern of nutrient increase that occurs is that a couple of days after the large rain event the nutrient concentrations peak. The nutrient concentrations in the surface outflow stay elevated for several days after the rain event. Figures 5 and 6 show TOC and calcium levels in the surface water before and after a rain event greater than 5 cm in a day. As seen in the figures it takes about a week for the nutrient concentrations in the water to drop back down to base flow conditions.

A possible explanation of this phenomenon is that during heavy rainfall events, the water entering the soil is greater than the infiltration rate of the soil, and runoff occurs. The extra water carries the higher nutrient levels in the topsoil and enters the ditch network raising the nutrient levels of the surface water. The slow response of the nutrient levels to return to base flow conditions is that Juniper Bay is quite large and it takes a while for the surface runoff to reach the outflow point. Figure 7 shows a possible scenario with the different color areas representing a possible time frame for the drainage of the bay. The area closest to the outflow point would drain the fastest and areas further away (in the red) from the outflow point would take up to a week to drain. This delay in drainage would result in the long time frame where nutrient levels would remain elevated in the surface outflow.

A comparison of nutrient levels by season was also made (Table 4). There was no significant difference in the nutrient amounts based on season. A simple test of ANOVA was performed on all the nutrients by season and the test reveals that there is no difference in the means. More significantly, it indicates that there are no differences in nutrient levels throughout the year, even with the large rainfall events that occurred in the summer and in the fall.

pH

The pH was measured weekly at the surface outflow. Throughout the year the pH of the surface water ranged from 3.7 to 6.4 (Fig. 8). The median value of pH for the year was 5.1. Newman and Schalles (1990) report that for 49 bays that were studied the average pH was 4.6. The liming of the soils for agricultural production probably caused the higher pH for Juniper Bay.

Precipitation

Table 5 compares the three bulk rain gauges and shows little spatial variation in nutrient levels in the rainfall. The nutrient levels in the precipitation are generally lower than the amounts of nutrients in the surface water showing that precipitation is not a major source of nutrients entering the bay. In fact, the nutrient levels are lower than the nutrients in the surface outflow, representing the fact that there is leaching of nutrients from the soil into the surface water. The only nutrients that are higher in the rainfall than the surface outflow are NH_4^+-N, NO_3^--N, PO_4^{3-}, and TKN. This suggests that there might be some sort of deposition of these nutrients from outside sources into the bay. The fact that these higher levels of NH_4^+-N, NO_3^--N, PO_4^{3-}, and TKN do not make it to the surface water could result from the fact that the nutrients are either assimilated by plants or immobilized in the soil.

Ground Water

Groundwater was sampled from possible sites of groundwater input and output from the bay. Table 6 lists the average nutrient levels for each piezometer for the year. Concentrations of NH_4^+-N, NO_3^--N, PO_4^{3-} in the groundwater were low. However, in piezometer 17 there were high levels of calcium. Cores collected at the site showed that a shell layer occurred at this location at a depth of 7 to 8 m. Piezometer 1 had high levels of TOC, which might be caused by buried organic materials, which are also known to occur at the site. According to core descriptions taken at this location at around 10 ft there was evidence of charcoal and wood fragments, which is the depth of the water samples.

The occurrence of high levels of nutrients at locations where it is thought that there is groundwater inflow could indicate that there is groundwater movement into Juniper Bay. For most nutrients, concentrations from all of the piezometers were either two to three times higher than the nutrient levels in the surface outflow. The higher levels at these locations could be diluted by the inflow of water, which would then show up in the surface outflow having lower nutrient levels. Schalles and Shure (1989) indicate that the dilute chemistry of surface waters in Carolina Bays could suggest that subsurface hydrologic exchange must occur.

The pH recorded for all of these locations in general is higher than the pH of the surface outflow (Fig. 9). This is due to the high amount of cations in the groundwater at these locations. Piezometer 17 particularly had the highest levels of calcium and also had the highest pH. Piezometer 3 has the lowest pH and has the lowest amount of calcium in samples.

Implications

On average the nutrient levels of P and N in the surface water were not a concern for water quality degradation and eutrophication. Base flow values for NH_4^+-N were 0.26 mg/L, NO_3^--N were below detection limits, TKN values were 1.21 mg/L, and PO_4^{3-} were 0.02 mg/L. Outflow values for storm events less than 5 cm a day had nutrient levels similar to those of the base flow. Rain events larger than 5 cm a day increased the concentrations of nutrients by two to three times the base flow conditions, and did raise the levels to where there might be short term algae blooms. However, these raised phosphorus levels were low enough not to cause long-term eutrophication. On average the level of P in the surface water was within the natural level limits of 0.05 to 0.05 mg/L. Since the phosphorus concentrations are so low, there should not be any excess algae blooms that would lead to water quality degradation.

Sampling surface outflow by looking at the differences in nutrient levels during storm events showed that only large (> 5 cm a day) storm events needed to be sampled separately. These two large storms that occurred accounted for over two thirds of the total mass of nutrients exported from the bay (Table 7). This indicates that large storm events are a significant source of nutrient export and is important to measure these events. Sampling during periods of baseflow condition could be done less frequent and still get good results.

Juniper Bay on average during base flow conditions has almost three times the amount of calcium in its surface water than those bays that were sampled by Newman and Schalles (1990). This higher level in the surface outflow could be a result of the lime and fertilizer applications that occurred at Juniper Bay during agricultural production. Since the halt of agricultural production, the nutrients are being leached out of the soil and are leaving the bay in surface water.

It seems that there is a steady decrease in nutrient levels and pH in Juniper Bay since the end of agricultural production in 2000. The pH of Juniper Bay is not known during agricultural production, but it is thought that is was higher than the current average pH of 5.1. Since the application of nutrients has stopped, the cations are leaching out of the soil allowing for the pH to return to natural levels.

Schafale and Weakly (1990) report that Carolina Bays are wet and nutrient poor communities. It seems that with the lack of nutrient inputs from precipitation, Juniper Bay will become more nutrient deficient in time and will resort back to natural bay nutrient levels. This loss of nutrients is a good indication that Juniper Bay is in the process of returning to a nutrient poor community. The loss of nutrients will mean that plants that are native and adapted to such sites will have a good chance of being reestablished as part of the mitigation project.

CONCLUSIONS

Nutrient analyses were performed on the water entering and leaving a drained Carolina Bay in order to determine the nutrient input and outputs, and to determine if there was the potential to cause water quality degradation. Our findings indicate that precipitation is not a major source of nutrient input into the bay. The groundwater nutrient analysis revealed higher levels than in the surface water indicating a possible dilution of nutrients by groundwater inflow into ditches.

Surface outflow nutrient levels on average where quite low with little concern that the water leaving Juniper Bay will cause eutrophication at this time. There was little difference between base flow conditions and rain events less than 5 cm a day. However, for rain events greater than 5 cm a day there was a two-fold increase in nutrient concentration in surface outflow. This increase can be attributed to the heavy rain that exceeded the infiltration rate of the soil and caused surface runoff. These nutrient levels stay elevated for about 1 week because of the time it takes for the whole bay to drain. There could possibly be short-term water quality degradation with these storm events but long-term eutrophication should not be a problem.

The sampling scheme at Juniper Bay could be such that surface water samples are taken less frequent, except during large storm events. These large storm events even though they were few and infrequent, still accounted for a significant amount of the total export of nutrients from the bay and are an important component to measure.

With the loss of nutrients from Juniper Bay, the natural nutrient conditions are returning to this site. This return to a nutrient poor community is indicates that plants that are adapted to these conditions will be able to reestablish at the site and allow for Juniper Bay to be restored back to its original community.

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Table 1. Nutrient concentrations in surface outflow for several periods during the year with no rainfall (baseflow) conditions

	PO4	NH4	NO3	TKN	TOC	Ca	K	Mg	Na
Base flow				(mg/L)					
Day 45-50	0.02	0.00	0.00	1.45	44.00				
Day 54-59	0.01	0.00	0.00	0.67	44.30				
Day 142-147	0.02	0.17	0.00	1.07	27.50	4.90	4.05	2.42	
Day 166-170	0.02	0.44	0.00	1.25	19.50	4.55	3.83	2.25	
Day 181-183	0.03	0.25	0.00	0.84	14.00	4.00	3.15	1.90	3.40
Day 240	0.01	0.69	0.00	2.00	21.00	4.40	4.40	2.00	5.30
Mean (6)	0.02	0.26	0.00	1.21	28.38	4.46	3.86	2.14	4.35

Table 2. Nutrient concentrations in surface outflow for several periods during the year that there was rainfall less than 5 cm in a day.

	PO4	NH4	NO3	TKN	TOC	Ca	K	Mg	Na
Stormflow				(mg/L)					
<5 cm									
Day 173-174	0.02	0.38	0.00	1.08	15.00	4.25	3.65	2.05	3.45
Day 165	0.02	0.41	0.00	0.98	12.00	3.20	2.60	1.60	3.20
Day 121-128	0.02	0.26	0.00	1.06	40.00				
Mean (3)	0.02	0.35	0.00	1.04	22.33	3.73	3.13	1.83	3.33

Table 3. Nutrient concentrations in surface outflow for the two rain events that were greater than 5 cm of rain in a day.

	PO4	NH4	NO3	TKN	TOC	Ca	K	Mg	Na
Stormflow > 5 cm	(mg/L)								
Day 241	0.05	0.12	0.13	2.70	85.00	12.40	9.30	5.30	3.00
Day 285	0.13	0.23	0.27	2.2	74	17	8	6.2	3.00
Mean (2)	0.09	0.18	0.20	2.45	79.50	14.70	8.65	5.75	3.00

Table 4. Average nutrient concentrations based on season at Juniper Bay in outflow water.

Season	PO4	NH4	NO3	TKN	TOC	Ca	K	Mg	Na
	(mg/L)								
Winter	0.02	0.01	0.04	1.44	40.23	9.53	7.37	5.97	3.67
Spring	0.02	0.09	0.00	0.91	39.04	5.08	4.93	2.54	3.16
Summer	0.03	0.33	0.00	1.47	30.95	5.86	4.41	2.70	3.54
Fall	0.04	0.40	0.06	1.87	50.24	8.96	6.37	4.47	4.28

Table 5. Average nutrient concentrations for bulk precipitation gauges located in Juniper Bay

	PO_4	NH_4	NO_3	TKN	TOC	Ca	K	Mg	Na
					(mg/L)				
NW	0.23	1.83	0.12	2.90	7.62	0.82	1.12	0.28	1.82
SE	0.30	1.88	0.15	3.87	5.70	0.98	1.45	0.35	2.35
WS	0.16	1.36	0.09	2.68	6.43	0.77	0.87	0.22	1.45

Table 6. Average nutrient concentrations for groundwater for four locations in Juniper Bay.

		PO_4	NH_4	NO_3	TKN	TOC	Ca	K	Mg	Na
	Well no.					(mg/L)				
inflow	1	0.07	0.50	0.00	5.48	155.20	40.78	16.74	2.48	11.08
outflow	3	0.02	0.49	0.02	1.84	35.60	9.63	7.35	1.95	6.93
inflow	17	0.00	0.22	0.06	0.94	35.33	99.70	3.70	2.10	6.18
outflow	25	0.32	0.59	0.04	2.33	63.40	17.53	15.93	5.78	12.18

Table 7. Comparison of storm events and mass export of nutrients out of bay. The two large storm events accounted for a significant amount of nutrient export.

Storm size	PO_4	NH_4	NO_3	TKN	TOC	Ca	K	Mg	Na
cm/day					(kg/yr)				
< 5	4.00	52.00	0.00	242.00	5676.00	892.00	772.00	428.00	870.00
> 5	10.62	21.24	23.60	289.10	9381.00	1734.60	1020.70	678.50	354.00
TOTAL (kg/yr)	14.62	73.24	23.60	531.10	15057.00	2626.60	1792.70	1106.50	1224.00
> 5cm as % of total	73	29	100	54	62	66	57	61	29

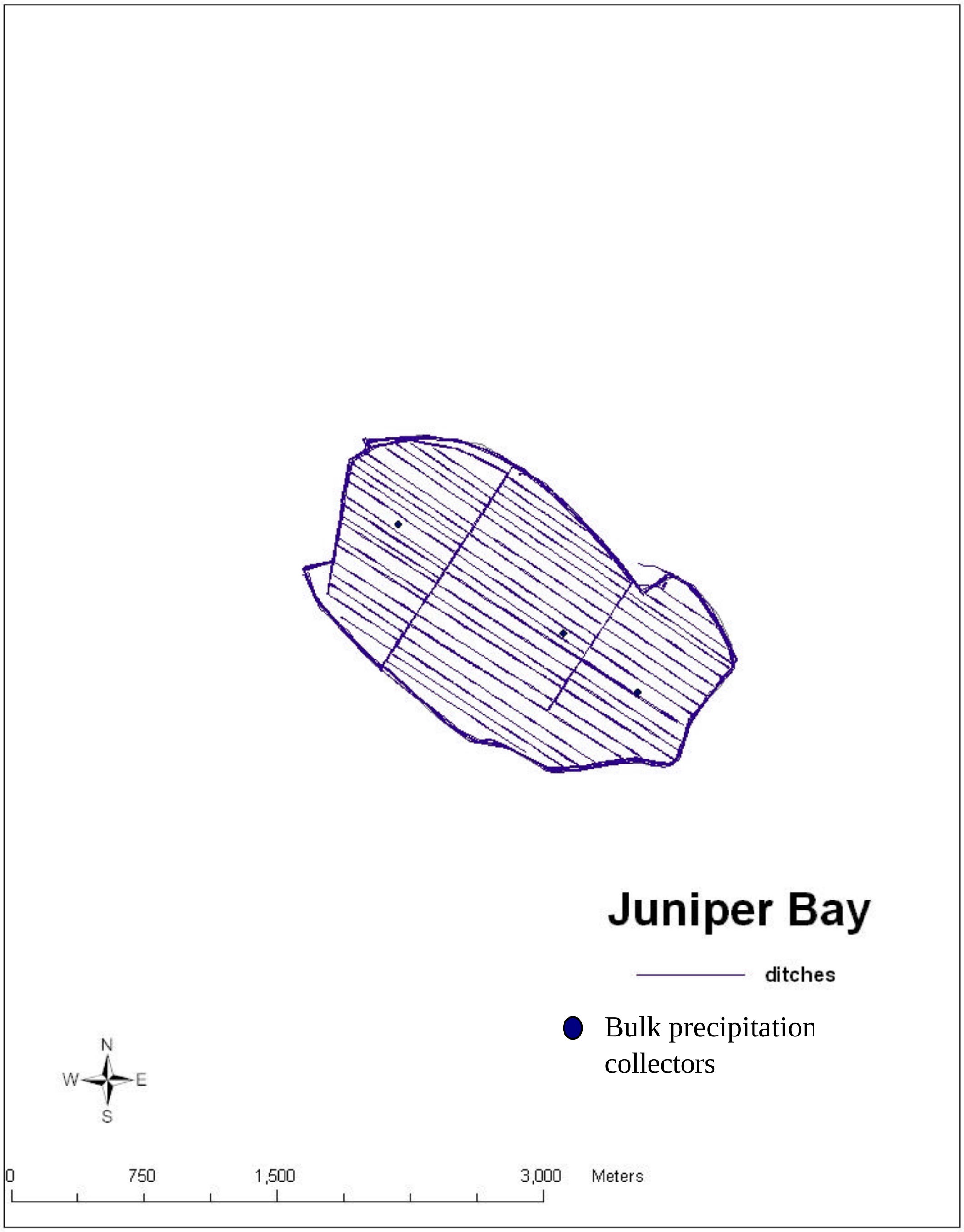

Figure 1. Map of Juniper Bay showing locations of bulk precipitation collectors.

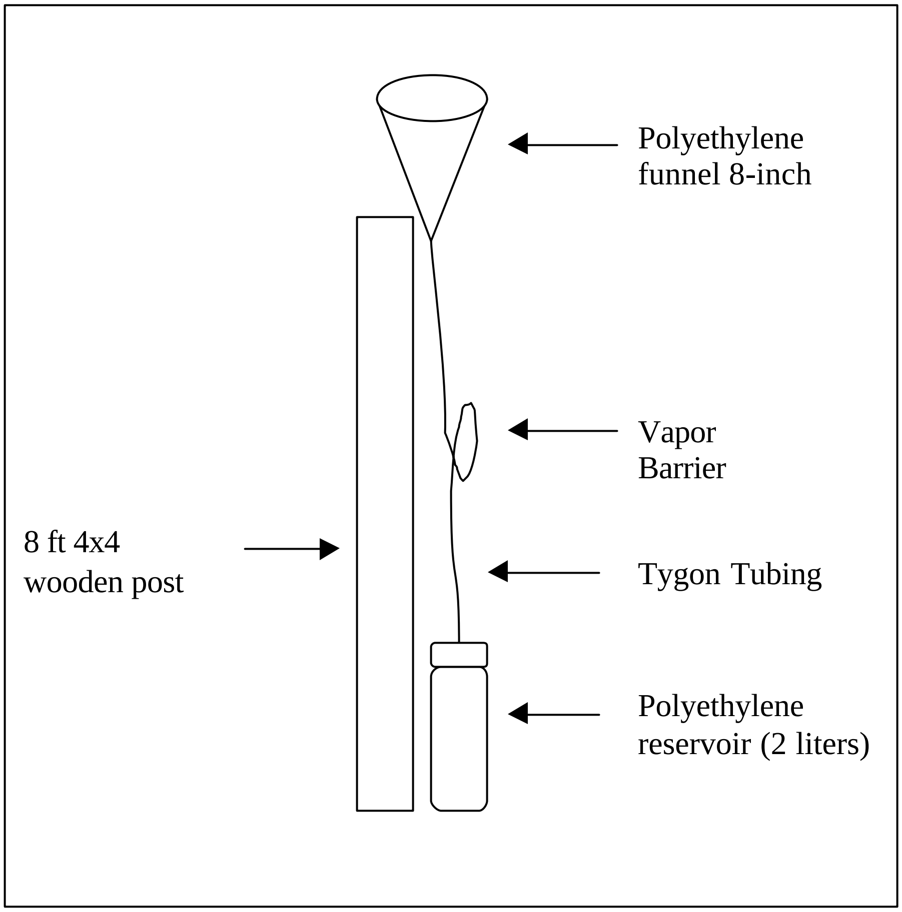

Figure 2: Schematic diagram of Bulk Precipitation Collector (Modeled after Liken et al. 1967).

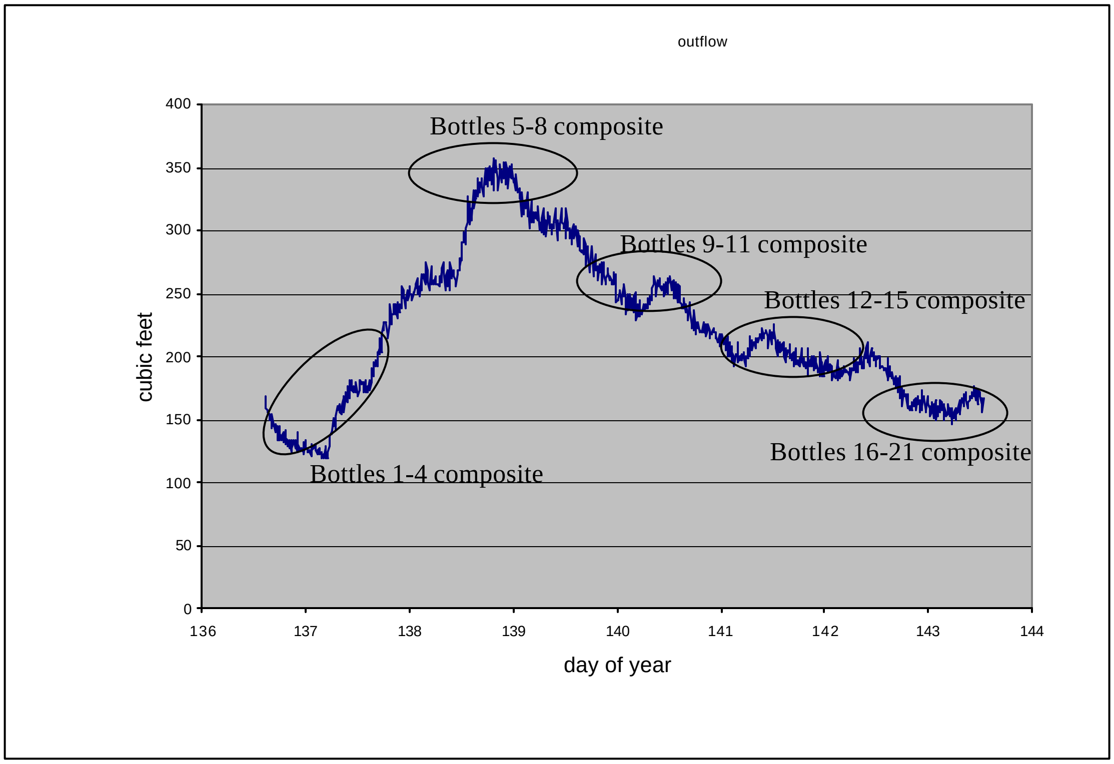

Figure 3. Graph of surface outflow and bottle numbers. This method was used to composite sample bottles together that represented similar periods in the hydrograph.

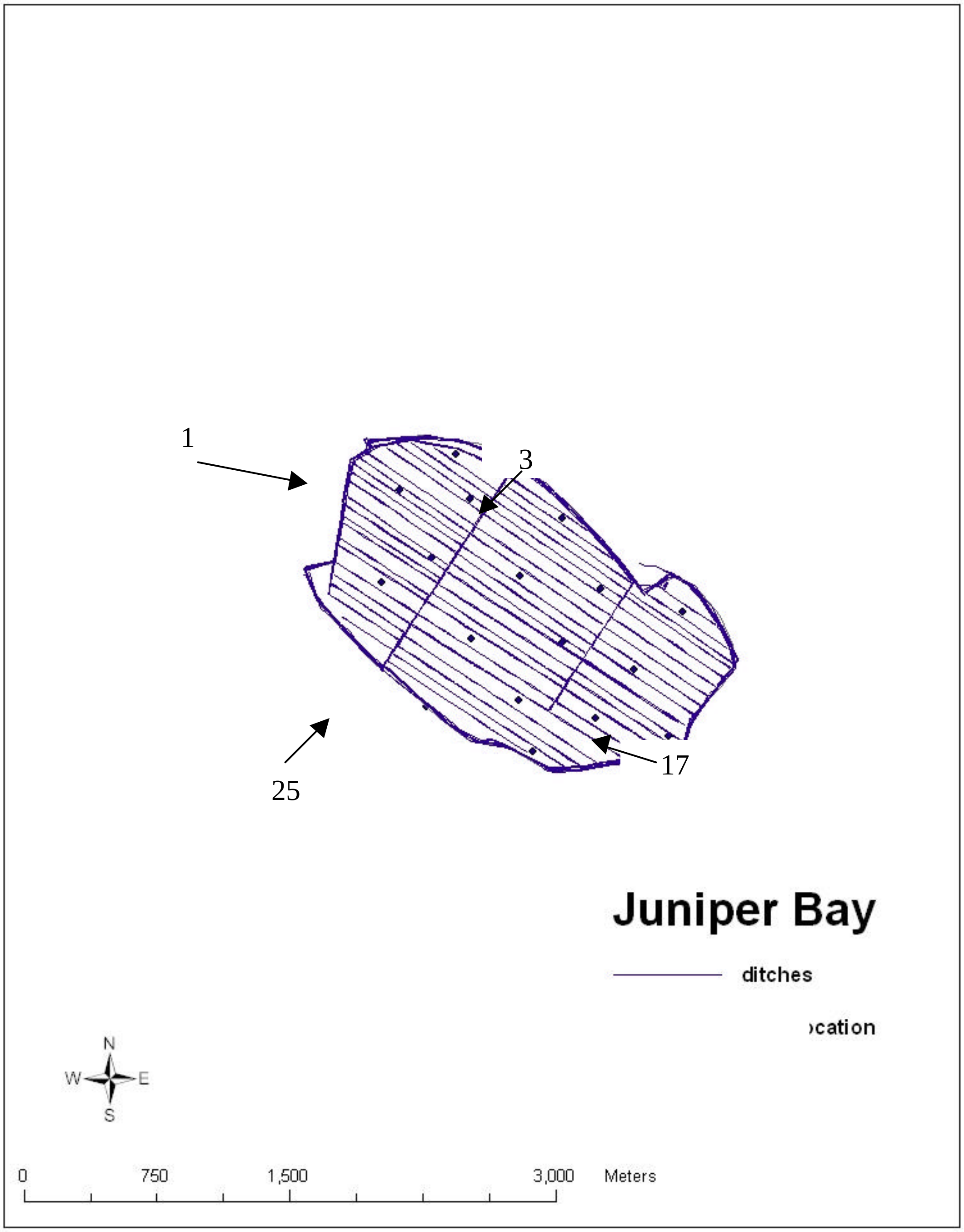

Figure 4. Juniper Bay showing location of where groundwater was sampled. Numbers represent piezometers that where used for collection of groundwater.

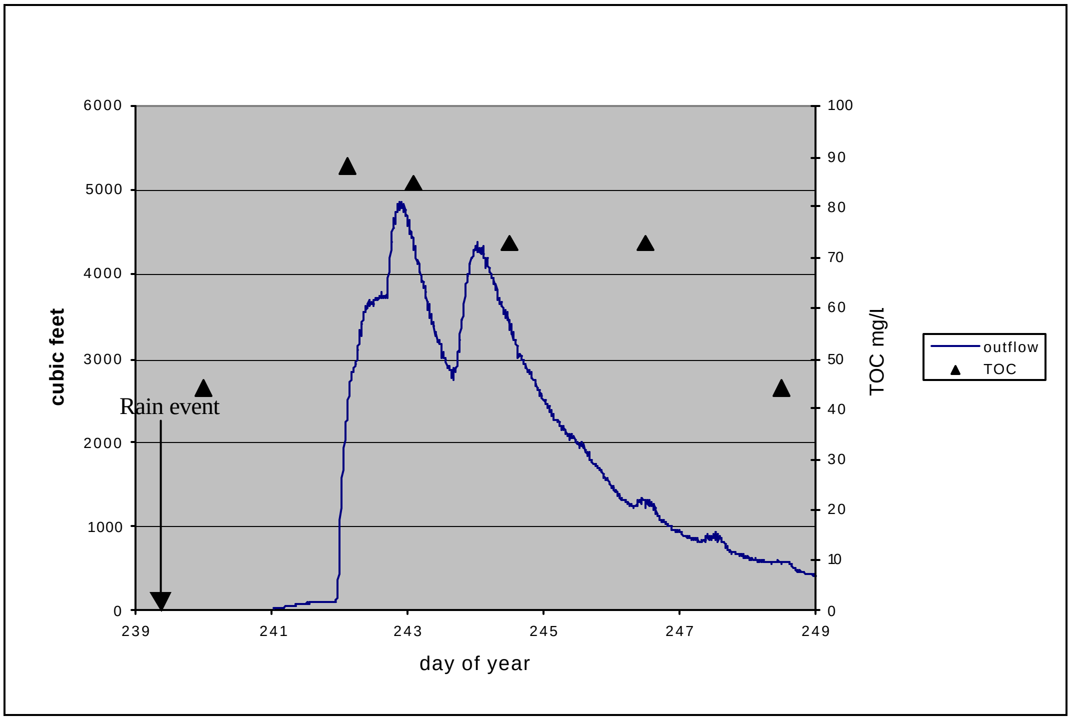

Figure 5. Total organic C concentrations during a rain event greater than 5 cm in a day. Increase of nutrient occurred a couple of days later and nutrient levels remained high for a week.

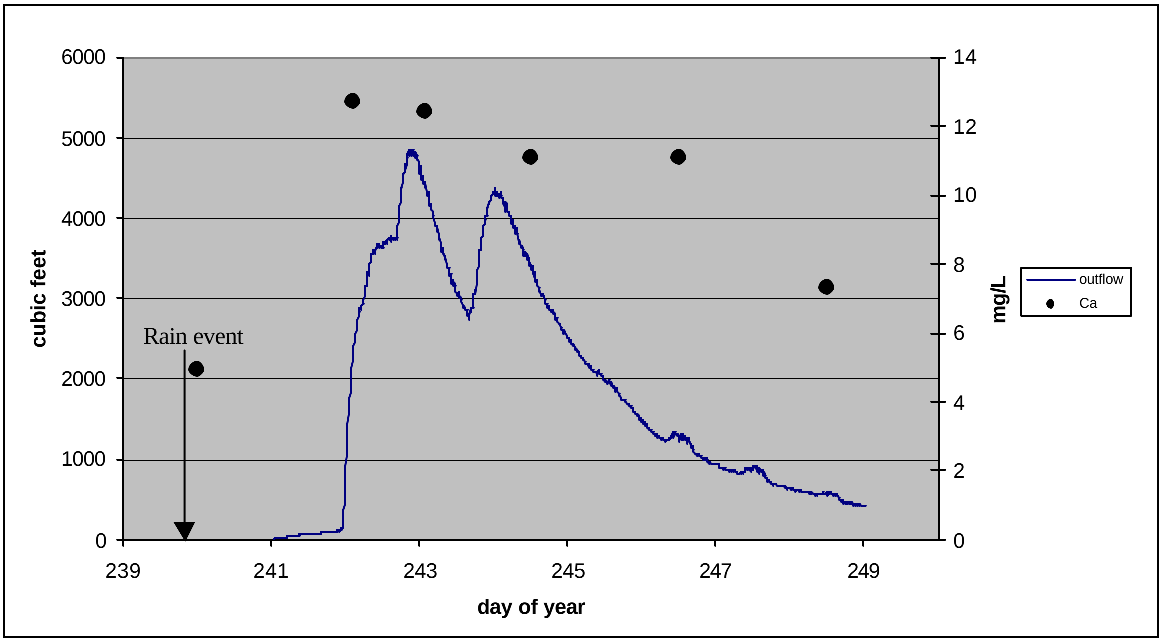

Figure 6. Calcium concentrations during rain event greater than 5 cm in a day. Calcium peaks a couple of days after rain event and takes a week for level to almost return to base flow conditions.

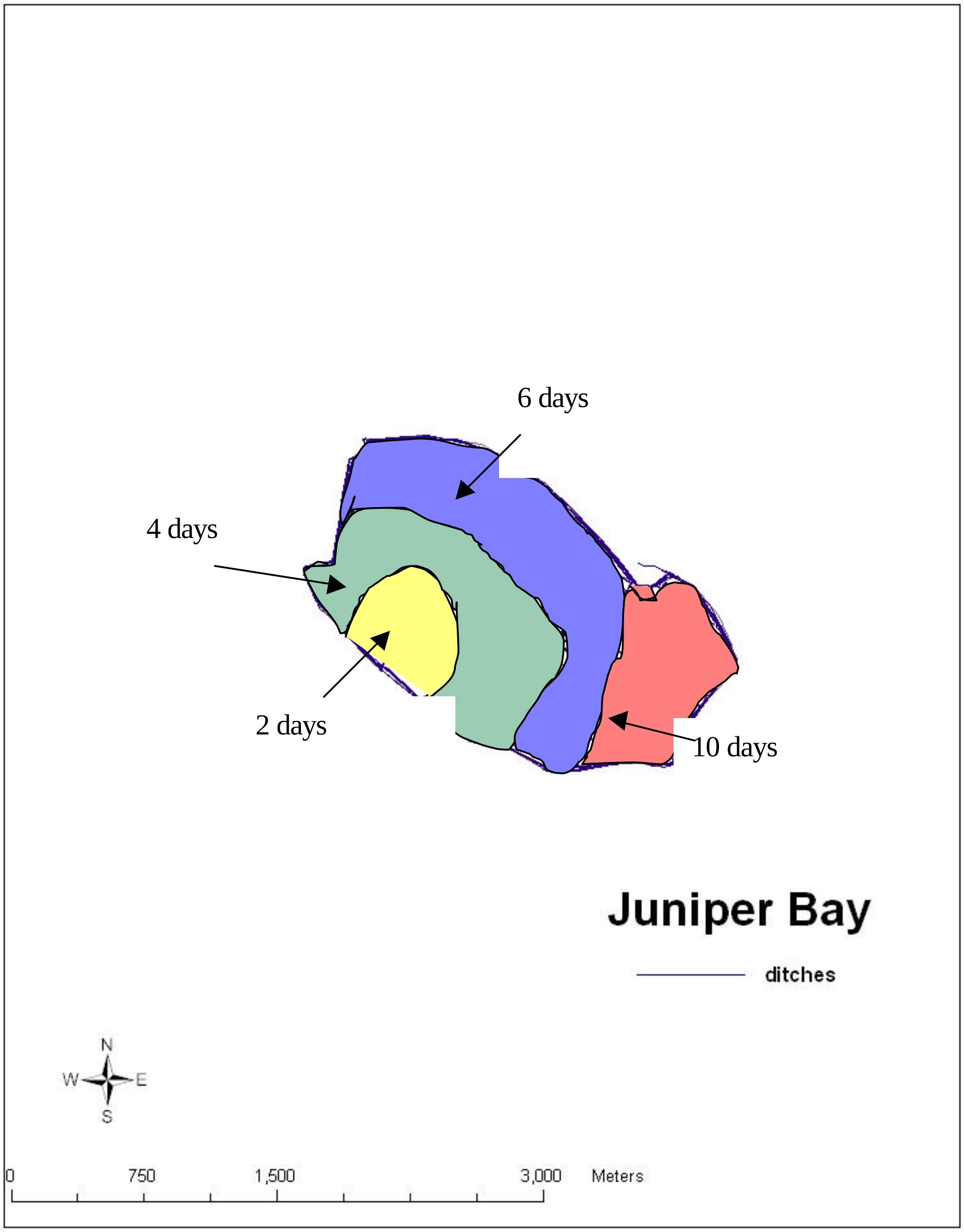

Figure 7. Juniper Bay showing possible drainage regions, which could be a possible explanation as to why it takes so long for nutrient levels to decrease after large rain event. The areas closest to the main outflow point would drain the fastest. The area shaded in red is farther away and would take about a week to drain.

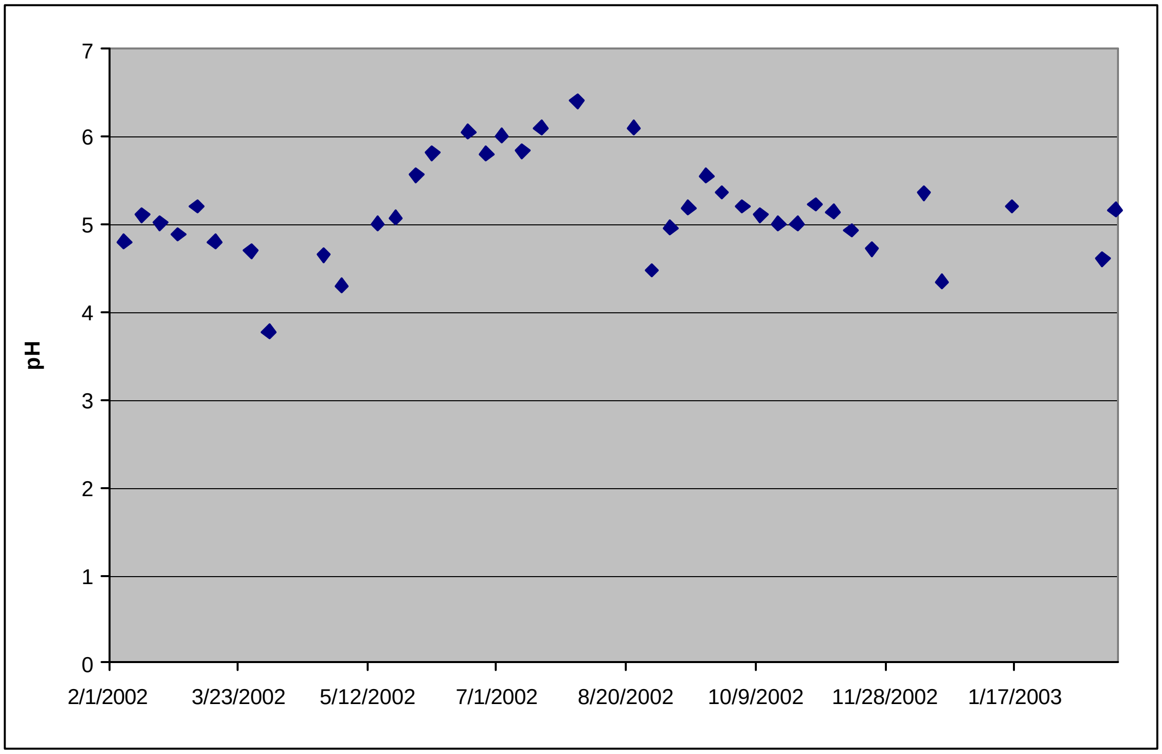

Figure 8. Weekly pH readings for surface water at main outflow. The average pH for the year is 5.1

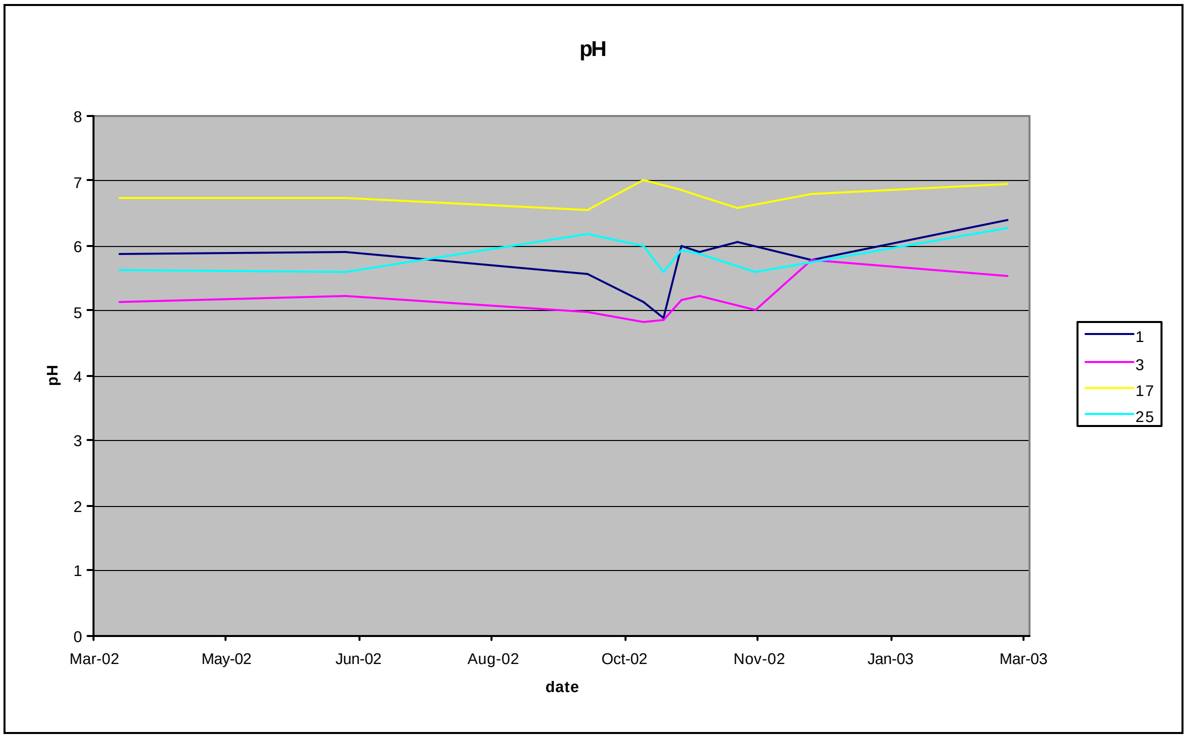

Figure 9. pH measurements for groundwater at different locations in Juniper Bay. 17 had the highest pH and had the highest amounts of Calcium. 3 had the lowest pH and had the lowest amounts of Calcium.

Chapter 9

GROUND PENETRATING RADAR EVALUATION OF JUNIPER BAY'S SUBSURFACE STRATIGRAPHY

R.P. Szuch, J.G. White, and M.J. Vepraskas

INTRODUCTION

Clayey soil horizons within Juniper Bay should act as aquitards and may aid the hydrologic restoration of the site. Where such aquitards are near enough to the surface, they may foster inundation or saturation such that wetland hydrology requirements will be met. The presence of such aquitards also might aid the establishment of hydrophytic vegetation. Where aquitards are not present, precipitation should infiltrate to the water table and have no appreciable impact on surface or near-surface hydrology. The depth, extent, and continuity of clayey soil horizons are being investigated via ground-penetrating radar (GPR).

MATERIALS AND METHODS

The GPR technique allowed spatially continuous transects of the site to be surveyed for the presence of clayey soil horizons. To date, GPR surveys have been conducted in 15 "fieldlets" at Juniper Bay (Fig. 1), totaling 23.2 km of GPR images. Three GPR transects were performed in each fieldlet: (1-center) longitudinally down the center, (2-edge) longitudinally along a ditch edge, (3-cross) laterally across the fieldlet.

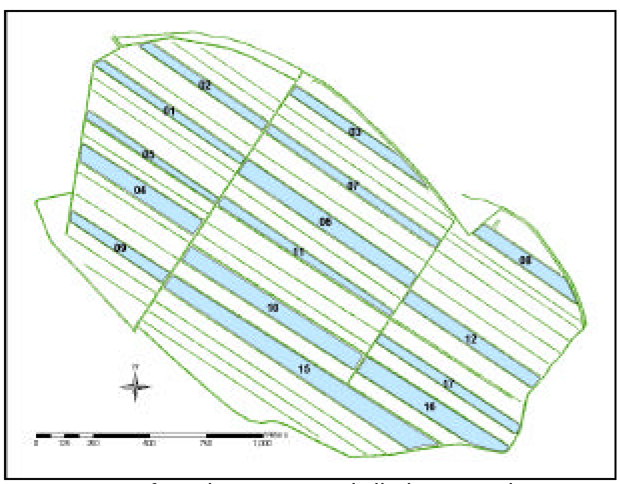

Figure 1. Map of Juniper Bay and ditch network. "Fieldlets" (areas enclosed by ditches) where GPR surveys have been performed are highlighted.

All GPR fieldwork and data post-processing were supervised by Jim Doolittle of the NRCS. The GPR unit is dragged along the soil surface as it emits high-frequency electro-magnetic waves. These waves penetrate the soil, and some of the energy is reflected when a stratigraphic interface (such as sandy to clayey soil) is encountered. The GPR unit measures the travel time for the waves to reach the stratigraphic interface and return to the surface. Associated hardware and software produce an image of the GPR return. The images have an x-dimension of distance along the ground surface and a y-dimension of two-way travel time (time for GPR waves to travel down and reflect back). Clayey soil horizons manifest themselves as bright reflections along the GPR images (Figure 2).

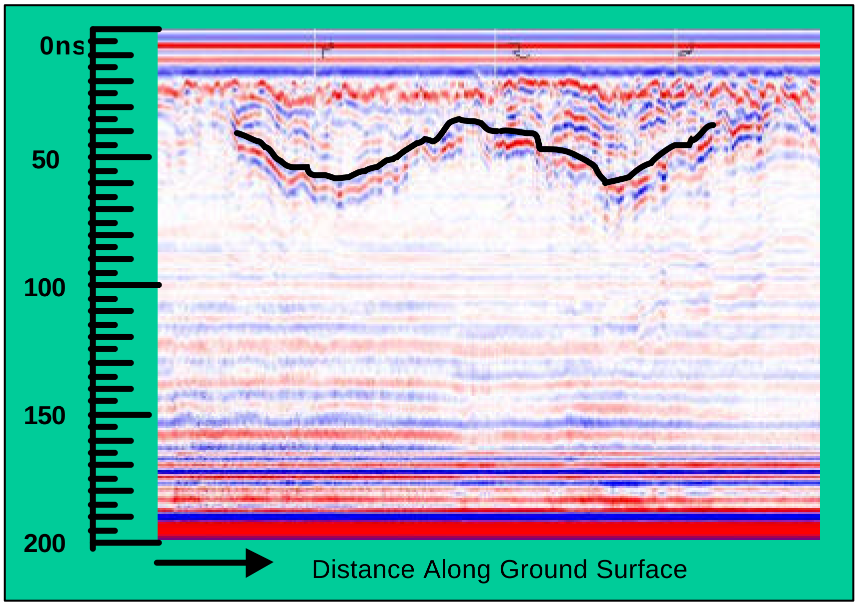

Figure 2. Typical GPR image, showing a bright reflection delineated with a thick black line. The x-dimension is distance along the ground surface, and the y-dimension is two-way travel time in nanoseconds.

Using a scalebar (as in Fig. 2), the location of bright reflections were interpreted from the GPR images. However, the interpretations had to be calibrated so that the y-dimension of two-travel time was converted to a useable depth value. This involved two steps. First, we determined the location of the soil surface on GPR images. Second, we developed a calibration equation to convert the y-dimension from time to depth.

The top of GPR profiles contains several straight, parallel lines. These lines do not represent the soil surface or any subsurface interface. In the literature, the line that represents the soil surface is not always clearly delineated. A simple method to determine the location of the soil surface was to begin a GPR scan with the antenna stationary on the ground, lift it to shoulder-height (Fig. 3a), and return it to the soil surface. Relative to the antenna, the soil surface was deeper when the antenna was raised; this resulted in a dip on the GPR profile. The uppermost dipping line was identified as the soil surface (Figure 3b).

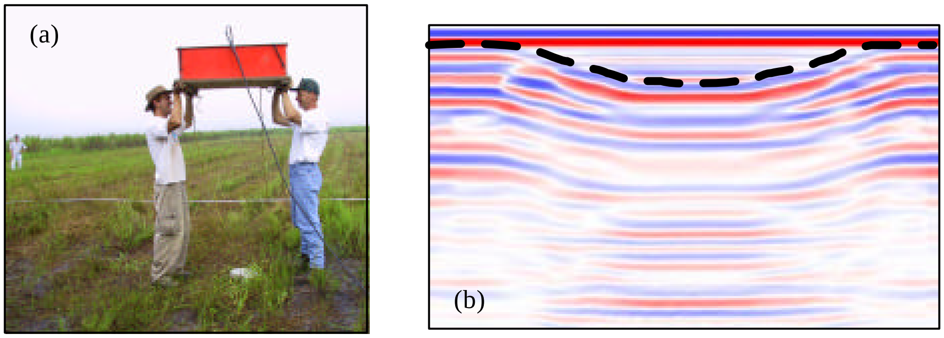

Figure 3. **(a)** Demonstration of "lift method" at JB. **(b)** Resulting GPR trace, soil surface shown with dotted black line.

The calibration equation was determined using reflector-interface matching. The depth of a clayey-sandy interface was determined from soil coring, and the interface was matched to a bright reflector on a GPR trace at the coring site. This calibration method yields a time-depth data pair: time - drawn from the GPR's time scale, and depth - drawn from the core's depth scale. This method is relatively accurate, especially when the coring is done immediately after the GPR survey. A reflector-interface pair was obtained at 16 locations throughout Juniper Bay. This calibration data was plotted on a scatter diagram and a linear trendline and equation were obtained (Fig. 4). Velocity of GPR waves at JB was highly dependent on saturation due to the water table (see Table 1). When the interface was beneath the water, the velocity was nearly constant and was considerably slower than when the interface was above the water table. On days of GPR surveys, the water table was above most clayey-sandy interfaces that were of interest to this study. The "below water table" calibration points were used to obtain a linear equation between two-way travel time to a reflector and depth to a stratigraphic interface (see Figure 4: $y = 0.0274x + 0.1631$, $R^2 = 0.8691$). This equation was used to convert the interpretations from GPR surveys, which are obtained in time (ns), to depths (m).

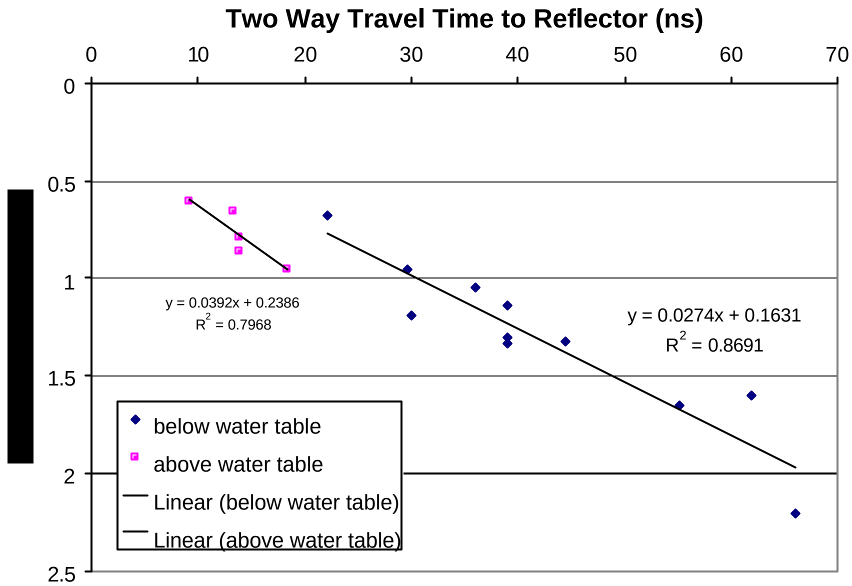

Figure 4. Relationship between depth to clayey-sandy interface and two-way travel time to reflector (n=16), with equations of trendlines and R^2. The data is split based on the interfaces' relation to the water table. The equation to the right would be used during interpretation of GPR surveys.

Table 1. Average, maximum, and minimum GPR wave velocities based on calibration points above and below the water table.

Dataset	Avg. Velocity (m/ns)	Max. Vel.	Min. Vel.
Above Water Table	0.115	0.133	0.099
Below Water Table	0.063	0.079	0.052

Coring was performed during the summers of 2002 and 2003 to ground-truth the GPR interpretations. Most coring was performed by hand-augering to a depth of 1-3 m. The actual depth of clayey layers found via coring was compared with the depths as predicted via GPR.

RESULTS AND DISCUSSION

Actual and predicted depth to clayey layers were compared by plotting both on Excel diagrams (Fig 5). This has been performed for all "cross" and "center" GPR surveys within each fieldlet. To date, accuracy has ranged from 1 to 95 cm and averages 25 cm. This average accuracy is considered good for this type of geophysical survey.

The spatial variation in accuracy can be viewed in Figure 6. Further investigation is being performed to see if interpretations can be improved in regions of the bay with poor accuracy. Ground-truthing along the "edge" GPR surveys will be concluded in the late summer of 2003.

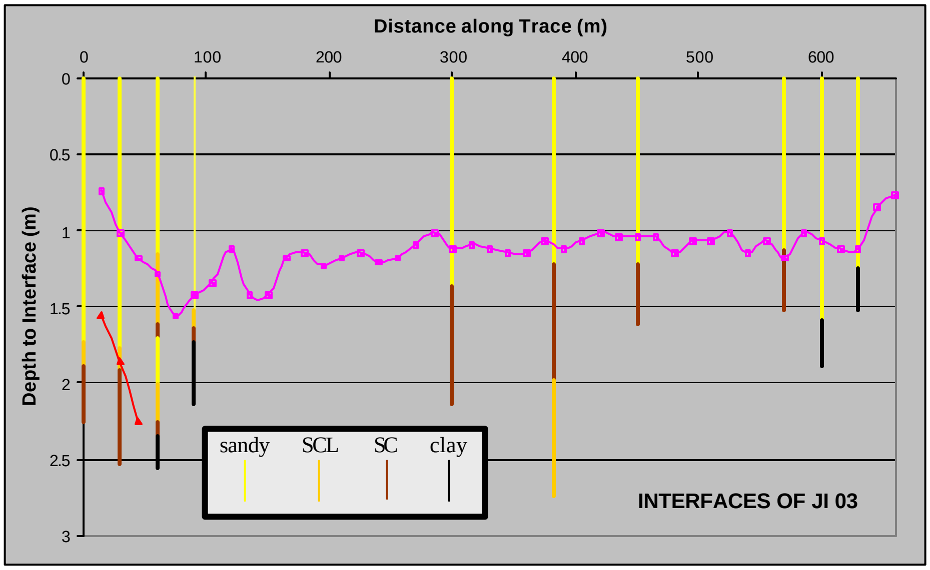

Figure 5. Graph showing depth of clayey horizons as determined via coring and via GPR interpretations. Vertical lines indicate locations where coring was performed. Colors indicate the soil texture found. Colored horizontal lines indicate the location of clayey horizons according to GPR interpretations. Accuracy is measured as difference between the horizontal lines and the point where sandy soil changes to SCL, SC, or clay(C).

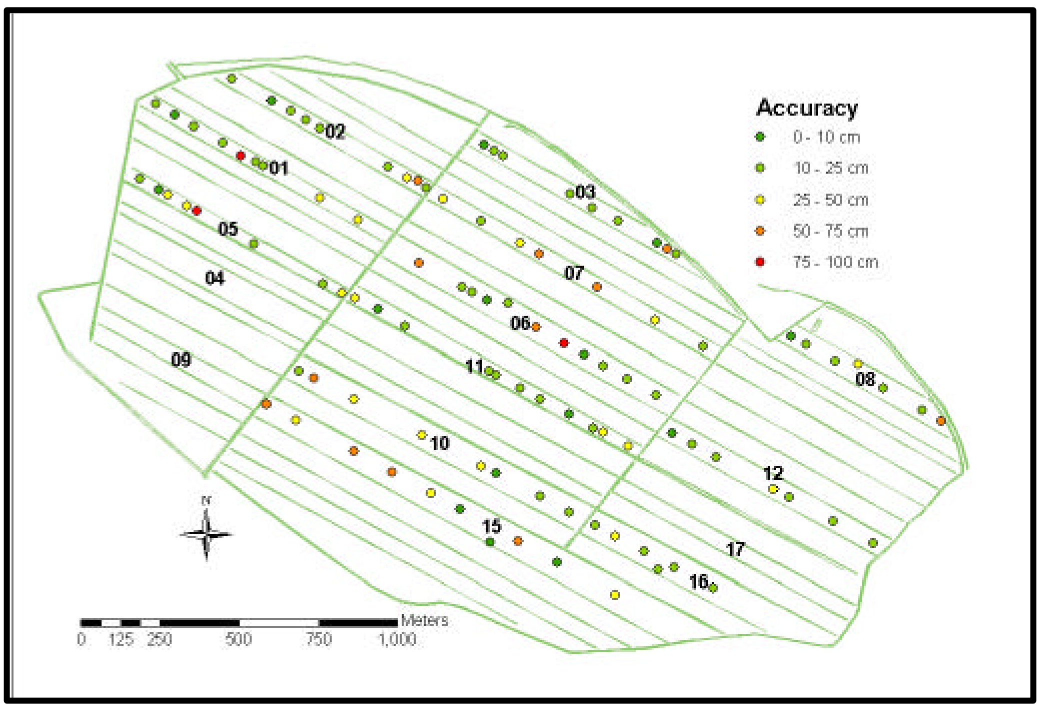

Figure 6. Map of Juniper Bay showing spatial variation in accuracy. Accuracy being the absolute value of the difference between clayey horizon depth as determined by coring versus GPR interpretation.

Once the calibration and accuracy of the GPR survey was established, we began to address our general aim - to investigate the depth, extent, and continuity of clayey soil horizons via GPR. We determined that this aim could be expressed as three distinct objectives:

1- Find areas where aquitards are not present or very deep
2- Find ditch-induced aquitard discontinuities
3- Find natural aquitard discontinuities

GPR interpretations show that aquitard depth ranges from 0.5 to 3.0 m with an average of 1.5 m. One, two, or more aquitards are present throughout Juniper Bay, with aquitards frequently overlying each other. However, the GPR shows an anomaly in the southeast corner of Juniper Bay that may indicate a region with no aquitard present. Coring in this region has confirmed that no clayey soil horizons exist near the surface. The predicted extent of this anomaly, based on GPR surveys, is shown in Figure 7. The size of the anomaly is estimated to be 3 ha, or approximately 1% the area of Juniper Bay. No aquitard exists in this anomaly, or the aquitard is at a depth below current coring depth (deepest have been nearly 5 m). In either case, surface and near-surface hydrology should not be impacted by any clayey soil horizons in this region.

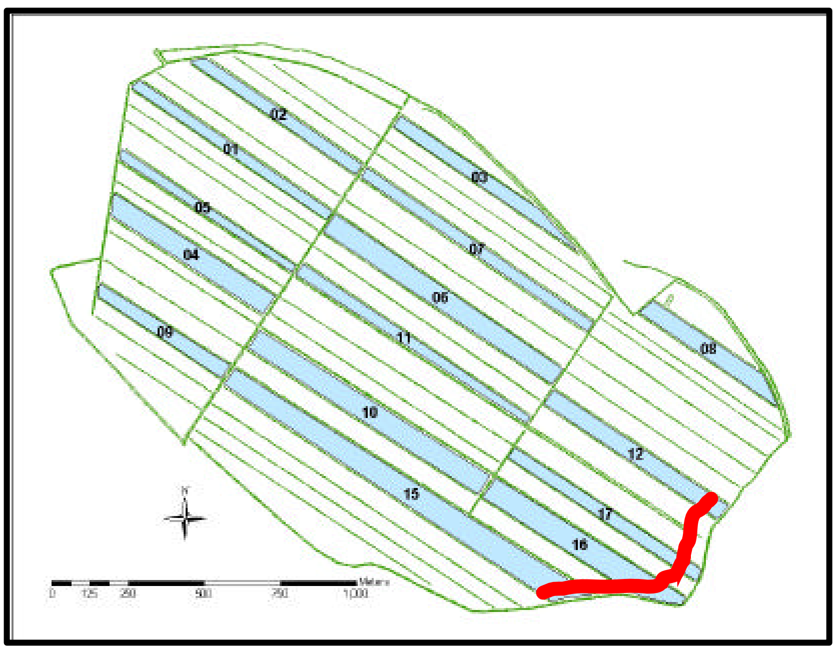

Figure 7. Map of Juniper Bay showing the location of an anomaly (red band) in the GPR survey that seems to have no clayey aquitard near the surface.

Ditch induced aquitard discontinuities would result where the depth of a drainage ditch is greater than the depth of a clayey soil horizon. A GIS coverage of Juniper Bay's topography, provided by NCDOT, was used to determine the depth of ditches throughout the bay. This data was compared with the depth of clayey aquitards as determined by the GPR interpretations. According to this comparison, ditches have pierced aquitards in at least 18 locations throughout the bay, predominantly along main N-S ditch. Coring had been done near some of these locations, and coring data confirmed that ditches should have pierced the aquitards in 10 of the 18 locations. Thus far, this analysis has only been performed with the "center" and "cross" GPR surveys. Comparing the ditch depths to the "edge" survey should yield more valuable results.

Natural aquitard discontinuities might be found in the interior of fieldlets, perhaps where two adjacent clayey horizons do not overlap and water could infiltrate below these potential aquitards. There is some evidence of natural discontinuities in several regions of the bay, but these occurrences require further investigation and documentation before we are prepared to report on them.

CONCLUSIONS AND RECOMMENDATIONS

GPR surveys have been conducted successfully in the interior of a drained Carolina Bay. To our knowledge, this had not been previously accomplished. The “lift method” for defining the soil surface on GPR traces should increase accuracy of interpretations. Calibration via reflector-interface matching has proven an effective method at JB. A calibration equation based on multiple calibration points, from various locations and depths, was created (Fig. 4). This approach appears to be advantageous for a site of such great size and complexity. Interpretation of GPR surveys from JB is complete, and its application toward the stated objectives is continuing. At the current time, two important findings are brought to the attention of NCDOT. First, an anomaly of approximately 3 ha exists in the southeast corner of Juniper Bay. Unlike the rest of Juniper Bay, this anomaly appears to have no clayey aquitards. NCDOT may want to consider the ramifications of this finding in their restoration plans. Second, it seems likely that at least the main N-S ditch has pierced underlying aquitards. Any water that might have been retained near the surface by these aquitards will be drained off site. NCDOT may want to consider a clay or synthetic lining in the base of the main ditch or other ditches to prevent such water loss. More detailed and complete information regarding ditch-induced aquitard discontinuities should be available in fall of 2003. Information on natural aquitard discontinuities should be available in fall of 2003 as well; however, due to the location of such discontinuities in the interior of fieldlets, it does not seem likely that NCDOT would take any action to account for their presence.

Chapter 10

GROUNDWATER HYDROLOGY OF JUNIPER BAY PRIOR TO RESTORATION, AND GROUNDWATER HYDROLOGY OF REFERENCE BAYS

S. Luginbuhl, J.D. Gregory, and M.J. Vepraskas

INTRODUCTION

This portion of the overall project evaluated the pre-restoration ground water hydrology at Juniper Bay. Major objectives were to determine the current ground water flow paths and the water table regime both inside and outside the bay. In addition, the water table fluctuations in the three reference bays were monitored to determine whether parts or all of the reference bays met wetland hydrology requirements. These data would be useful in planning the restoration strategy.

MATERIALS AND METHODS

A network of shallow water table monitoring wells, 28 total, was installed inside and outside the bay to determine that the water table regime at various locations in the bay and to determine lateral hydraulic gradients in the near surface ground water (Figure 1). A network of piezometers, nested with the water table monitoring wells was installed inside and outside the bay to determine vertical and lateral hydraulic gradients below the near surface clay layers in a plan to collect pre-restoration data for two years and post-restoration data for three to five years. There are a total of 11 nests of piezometers and wells (Figure 1). Figures 4 through 7 include water table hydrographs for all Juniper Bay and reference bay wells. Appendix A includes all graphs from the nests of piezometers. Another goal was to determine how the water table regime is affected by rainfall, soil characteristics, topographic variation, and near-surface hydraulic gradients. Figure 2 shows core locations.

In each reference bay, four monitoring wells were installed in one transect from the rim to the center of the bay. The first well was installed in mineral soil, the second well in mineral soil with a histic epipedon, the third well in shallow organic soil, and the fourth well in deep organic soil. The goal was to determine how the water table regime was affected by rainfall, soil characteristics, and vegetation type. Three bays were selected as the reference bays to provide data on the variability among natural Carolina Bays.

RESULTS AND DISCUSSION

Juniper Bay

Some of the main factors that affect the hydroperiod of Juniper Bay and the reference bays are rainfall, soil type, elevation, and vegetation. Carolina Bays typically have hydrologic inputs consisting mainly of precipitation and, as some suggest, ground water discharge (Lide et al, 1995; Schalles and Shure, 1989). Some bays experience surface run on as another input, but Juniper Bay does not have surface run on due to the perimeter ditch. The hydrologic outputs in Juniper Bay consist mainly of evapotranspiration, surface outflow, and possible ground water recharge. Soil type influences how much rainfall infiltrates and percolates down through the soil profile. Elevation influences direction of surface and ground water flow, and the vegetation present on the site influences how much soil water in lost through evapotranspiration (ET) and how much water reaches the soil surface. A dense canopy cover will reduce the amount of water that enters the soil, as in the reference bays.

Rainfall

The monthly, seasonal, and annual averages from 1971 through 2000 for rainfall at the weather station in Lumberton, North Carolina and Elizabethtown, North Carolina (N.O.A.A., 2001), and from the weather station at Juniper Bay are shown in Table 1. Juniper Bay is about 12 kilometers south of Lumberton, Tatum Millpond Bay is about 12 km north of Elizabethtown, Charlie Long Millpond Bay is about 17 km north, and Causeway Bay is about 18 km east northeast of Elizabethtown.

As Table 1 shows, the yearly averages for Juniper Bay in 2001 and 2002 are below the long term averages. Certain months and seasons, however, were above normal. The summer of 2001 was wetter than average, as was the fall of 2002. The fall of 2001, though, was far drier than normal. Fall is typically the time before the wet season, and normally has the least amount of rain. Summer usually has the most rainfall, followed by winter, than spring. The water table data (Figs. 4 to7) shows that many wells showed a drop, some sharp, in the water level during the fall of 2001. Most also show a significant drop in the summer of 2002. This second drop was likely due to increased ET due to the heat of the summer and the denser, taller vegetation that was present on the site compared with last summer. The summer of 2002 was also hotter than the summer of 2001 and had slightly below average rainfall.

Juniper Bay Water Table Regime

A wetland is defined by its hydrology, soils, and vegetation. The hydrology component varies slightly between agencies, but generally it is that the water table must stay within 30 cm of the soil surface for a certain amount of time during the growing season in most years. The amount of time is important because water must be consistently present at the 30 cm or shallower depth for a certain amount of time for the soils to become hydric and for hydrophytic plants to dominate. The hydrology component is often said to be the most important component because if it is not present, hydric soils and hydrophytic plants will not exist for long.

Monitoring the hydrology of Juniper Bay before restoration is important in order to determine which areas of the bay may pose more problems when trying to restore wetland hydrology. There were 28 water table monitoring wells in and around the bay (Fig. 1). Parts of the bay already met some of the hydrology requirements (mainly the southeast section). The percentage of Juniper Bay that meets wetland hydrology requirements depends on which requirements are used. According to Corps of Engineers criteria, 22% of the bay meets wetland hydrology requirements, which are that the water table be within 30 cm of the soil surface for at least 5% of the growing season in most years (Table 4). The Corps uses 5% as the criteria for wetland delineation purposes and 12.5% as the criteria for wetland restoration purposes. Only 12% of the bay meets the criteria for wetland restoration.

Response of Water Table to Precipitation Events

Well 2A is located in mineral soil near the rim, in the northwest section of Juniper Bay. Its elevation is the second highest of the wells in that section, at 36.47 m, and that section is the highest in elevation in the bay. In the last days of May, 2001, it rained about 0.4 cm. The water table in well 2A did not begin to rise until the third day of rain. On the 151st and 152nd day of 2001 (the beginning of June), there was an additional 0.43 cm of rainfall, for a total of 0.83 cm of rain over 7 days. The water table rose approximately 61 cm in those 7 days. For two days in the middle there was no rain, and the water table had a brief period (day 152) in which it barely rose (Fig. 4). The water table rose from day 149 to day 153 even though the rain events took place on day 147 through 149 and days 151 and 152. Another rain event took place on days 230 through 233. The rainfall totals were approximately 1.23 cm. The water table rose almost 59 cm from day 232 to 233. The above rainfall totals and subsequent water table rise indicate that in the last spring of 2001 a rain event that produced approximately 0.83 cm of rain resulted in a water table rise of about 61 cm, while a larger rain event of 1.23 cm in late August of 2001 resulted in a slightly smaller but basically equal water table rise of 59 cm. The additional rain that fell in August was likely eliminated by the increased rate of ET in the late summer, resulting in a relatively equal rise in the water table. The other wells behaved in a similar manner. A day or two after a rain event the water table would start to rise and would stop rising a day or two after the rain event ceased (Figs. 4to7).

Water table well 2A showed seasonal variation. During the summer of 2001, the water table was 80 cm below the surface for the entire season. Summer 2001 did have greater rainfall than the long term averages, which likely accounted for the higher water table. In the fall of 2001, a very dry fall (Table 1), the water table dropped steadily about 40 cm. During the winter of 2001/2002, the water table recovered, with the help of a decent amount of rain (still below the long term average), and lower temperatures. The spring of 2002 saw the water table spike up and down, and then steadily drop down (with a few spikes due to rain events) towards the summer of 2002. The summer of 2002 had below average rainfall and the water table dropped to a low of -142 cm below the soil surface in mid-August. By the fall of 2002 the rainfall became closer to the average and the water table rose again. This seasonal pattern was evident in all water table wells in Juniper Bay. All wells saw water table declines during the fall of 2001 and the summer 2002 due to lack of rainfall.

Water table wells 8, 12, and 16 (Fig. 1) showed the water table staying above or just under the soil surface for much of the winter and spring of 2002 (see Fig. 6). Well 8 is located in organic soil but wells 12 and 16 are not. The soil profile at well 8 consists of a muck layer over a thin sand layer, which is over a very thick clay layer. Water at this location cannot percolate easily down through the soil, and therefore stays closer to the surface during the wetter months. During the dry summer of 2002, however, the water table dropped very deep. The affects of lack of rain, thick clay and hot temperatures made water at this location scarcer than at other locations in the bay. Wells 12 and 16 have similar soil profiles that consist of a thin muck layer at or near the surface and over mainly sand, with thin clay lenses also present.

Water table levels in Juniper Bay rise with rainfall totals as small as 0.762 mm and then fall once the rain slows to 0.254 mm or less. The fall of the water table is most likely due to the ditches plus some ET and evaporation of water from the top layer of the soil.

The soil stratigraphy can greatly affect water table movement. Some of the areas in the bay have thick clay layers near the surface, which may perch water on top of them causing that area to be wet (such as the area around well 8). Other areas have thick sand layers which allow surface water to drain away. There is a wide variety of soil profiles at Juniper Bay, which adds to the complexity of its hydrology. The wells that meet wetland hydrology requirements, 12.5% of the growing season, have varying soil profiles. The location of well 8 has a muck layer about 45 cm thick and is an organic soil. Under the muck is clay. Wells 12 and 16 are in mineral soils with muck layers near the surface. They are all located in a section of the bay where elevations are lower compared with the other sections of the bay. Other areas of the bay with similar profiles do not meet wetland hydrology requirements, so it has something to do with this area of the bay, possibly the elevation, or a lack of crowning of the fields in this area.

The surrounding land use may play a part in whether the bay will exhibit “typical” bay hydrology once restoration is complete. Since most of the land adjacent to Juniper Bay is in agriculture, the regional water table may be lower than it was years ago. It may be unrealistic to try to get the water table in Juniper Bay to behave as it did prior to drainage. The regional water table around Juniper Bay may be lower than the regional water table around the reference bays due to this agricultural land use. The land around at least two of the reference bays is not in heavy agriculture. This may allow the reference bays to be wetter than Juniper Bay could ever be.

Reference Bays

Rainfall patterns in the reference bays are similar to those in Juniper Bay (Table 1). The water table data from the wells in the reference bays indicate that there is more water present in these systems. The water table is consistently higher in the mineral soils in the reference bays than in the mineral soils in Juniper Bay, and this same pattern exists in the shallow organic soils and in the transition soils (mineral soils with histic epipedons). Vegetation in the reference bays is much denser than in Juniper Bay, consisting of trees and shrubs whereas the vegetation in Juniper Bay consists of mainly weeds. This would mean that ET is higher in the reference bays and that less rainfall is reaching the surface due to interception by the leaves. Yet the water table is closer to the surface, with most wells exceeding all wetland hydrology requirements. The wells in the organic soils had water tables closer to the surface, followed by wells in the mineral soil with a histic epipedon, and the wells in the mineral soil had water tables that were the deepest. Even though the water tables in the mineral soils in the reference bays were generally shallower than those in Juniper Bay, the water table in Juniper Bay spiked above the water table in the reference bays. This did not happen very often in the other soil types; the water table in the reference bays generally remained shallower than the water table in Juniper Bay. The only wells in Juniper Bay that spiked above the water tables in the reference bays were the wells that had water tables shallow enough to meet wetland hydrology requirements.

U.S. Army Corps of Engineers requirement for wetland hydrology is inundation or saturation to the surface continuously for 5% of the growing season in most years (50% probability of reoccurrence) (U.S. Army Corps of Engineers, 1987). Requirement for this restoration project by the North Carolina Department of Transportation is 12.5% of growing season in order to be closer to the hydroperiod of the reference bays. We will also use 8.75% of the growing season to assess wetland hydrology.

As shown in Table 5, 22% of Juniper Bay has a water table shallow enough to meet the minimum wetland hydrology requirement of 5% of the growing season, as set by the Army Corps of Engineers. As the time requirement for number of consecutive days the water table has to be within 30 cm of the soil surface increases, the percentage of wells in Juniper Bay that meet the requirement decreases. When the requirement is 12.5% of the growing season, only 12% of the bay is wet enough.

Figure 7 shows the data from the wells in the three reference bays. U.S. Army Corps of Engineers requirement is inundation or saturation to the surface continuously for 5% of the growing season in most years (50% probability of reoccurrence) (U.S. Army Corps of Engineers, 1987). Requirement for this restoration project by the North Carolina Department of Transportation is 12.5% of growing season in order to be closer to the hydroperiod of the reference bays. I will also use 8.75% of the growing season to assess wetland hydrology.

Ground Water Movement

The soils in Juniper Bay are a mixture of mineral and organic, and are all hydric soils. Where the soil transitions from mineral to organic it is a mineral soil with a histic epipedon (a thin layer of organic soil at the surface too thin to be let the soil be classified as organic). The organic soils occur mostly in the center of the bay, the mineral soils with histic epipedons encircle the organic soils, and the mineral soils occur closest to the rim of the bay. Beneath the surface at different depths, there is a clay layer, in varying thickness throughout the bay and probably continuous, that acts as a restrictive layer to water movement. However, the large collector ditches may cut through this clay layer. This clay layer occurs between 0.3 to 4.27 m below the soil surface. The sandy or organic material above this clay layer and below the soil surface we have called aquifer "zone 1" (Fig. 3). Below this restrictive layer of clayey material more sandy material occurs, in most areas, and this area of sandy material is called aquifer "zone 2". Below zone 2 is the top of the Black Creek Formation, a clay layer that acts as another restrictive layer and the bottom of the bay. Beneath the top of the Black Creek Formation is alternating sand and clay material and is called "zone 3". Within zone 2 there are thin clay layers in some locations.

The North Carolina Coastal Plain is an eastward-dipping and thickening sequence of sand, silt, clay, and limestone. Beds primarily consisting of sand or limestone compose aquifers, and beds largely consisting of clay and silt are confining units (Giese, Eimers, and Coble, 1992). Ground water follows the eastward-dipping geologic material towards the Atlantic Ocean. Ground water generally enters the confined aquifers in interstream areas (Giese et al, 1992). Juniper Bay is located between the Lumber River and the Pee Dee River, but it is closer to the Lumber River. This means that water is entering the confined aquifer, zone 2 and zone 3, to the south of Juniper Bay, closer to the interstream divide between the Lumber and Pee Dee Rivers. Ground water enters the confined aquifers in the interstream divides because this is where there is the least pull from the large river systems. The geologic makeup of Juniper Bay consists of the surficial aquifer, the Black Creek confining unit, and then the Black Creek Aquifer underneath. Regional water table contours for the surficial aquifer (A10) show that the water table flows towards the Atlantic Ocean in general, unless a large river is nearby, in which case the water table flows towards the river (Giese et al, 1992). The same is true for ground water above the Black Creek confining unit and in the Black Creek Aquifer (possible zone 2 and zone 3 ground water in Juniper Bay, respectively).

Hydraulic Gradients

Hydraulic gradient is defined as the change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head; in other words, ground water moves from regions of higher head to regions of lower head (Fetter, 2001). The localized ground water flow patterns within Juniper Bay are complicated. In the zone 2 region, ground water seems to flow towards the center of the bay from the northwest and southeast ends of the bay, and then out of the bay through the north and south sides. This follows the localized topography, with the west and southeast ends being higher in elevation and the north and south sides being lower in elevation. Piezometer 25 deep is on the south rim (Fig. 1) of the bay and has a lower water pressure than all piezometers north of it *inside* the bay. Piezometer 22 is on the north rim and has the lowest pressure of *any* other piezometer. Both of these piezometers are likely in zone 2. Piezometers 20 shallow and deep are located outside the bay to the north of the rim (north of Piezometer 22), in what looks like another Carolina Bay, and have very low pressures starting in the late spring and lasting through the fall of 2002. Piezometer 11, in the middle of the bay, also has a low pressure but this is probably due to the two main collector ditches located close by.

The top of the Black Creek Formation, a clay layer, is closest to the soil surface at core 10, and then dips down towards the north and south sides of the bay. This is the same way that the ground water in zone 2 is flowing. Data from piezometers in zone 3 (Appendix A) suggest that ground water in this zone is moving in a southeast direction, towards the Atlantic Ocean. Piezometer 17B has a lower pressure than piezometer 1D, suggesting the above is true. Piezometer 17 may be in zone 2 or 3, it is unclear.

East of Juniper Bay is Shelley Bay. This may be drawing ground water in the zone 3 region towards it. Piezometer 1D, equipped with a pressure transducer, has a lower pressure than piezometer 17. Piezometer 1B, west of piezometer 1D, has a lower pressure than piezometer 1D. West of Juniper Bay is Hog Swamp, 30.48 meters above sea level, and it may be drawing zone 3 ground water towards it. Juniper Bay is in the middle of Hog Swamp and Shelley Bay, approximately 33.5 meters above sea level, and the zone 3 ground water may be recharging them. Just west of Juniper Bay the elevation is about 38 meters above sea level, and core 19, located to the west of Juniper Bay (figure 5), shows a sand layer approximately 4 meters thick from 28 to 32 meters above sea level. This sand zone may be intercepted by Hog Swamp, approximately 30.5 meters above sea level. The same situation occurs to the east of Juniper Bay with Shelley Bay. Cores 17, 26, and 28 all show mainly sand for meters down. Shelley Bay may be drawing zone 2 and 3 ground water from this side of the bay. However, since there are only three or four piezometers in zone 3, the exact direction of ground water flowing in this zone cannot be precisely determined.

In Carolina Bays, reversal of the direction of ground water flow appears common, with net ground water outflow from the bay being the dominant direction (Lide et al, 1995). Where piezometer data show upward movement of water, ground water discharge is likely happening. Upward movement occurs in the northwest section of the bay, from piezometer 1S, located in zone 2, to well 1 (in zone 1) from mid winter through the summer of 2002 (Appendix A). This time period saw below average rainfall amounts (Table 1). Piezometer and well data show that the pressure is the highest in the shallow piezometer (4.5 m deep), a depth between those of the well (2.44 m) and the deep piezometer (10.4 m). Ground water is likely entering the bay from the west side in zone 2 and can move upward and downward. Water moving downward runs into a thick clay layer that separates zone 2 from zone 3. A perched water table above this clay layer may exist.

Upward movement of ground water also occurs at the locations of piezometers 2S and 2D, both of which are in zone 2, and well 2 (Appendix A). This nest is also in the northwest section of the bay, where ground water may be entering through zone 2. Upward movement was constant from the deep piezometer (4.4 m deep) to the shallow piezometer (2.44 m deep) during 2002, indicating probable ground water inflow in this section. Water pressure, and hence, direction between the well and the shallow piezometer fluctuates from winter through mid-spring, 2002. From then on, their pressures were approximately equal.

If the ground water and surface water have roughly the same pressure, then the there is no real vertical movement between these two zones. Zone 1 is influenced hydrologically by rainfall while zone 2 may be influenced by direct rainfall and from rain falling a certain distance from the bay and making its way to the zone 2 area and entering the bay laterally from outside. To the west of Juniper Bay is a water table divide. Rainfall falling to the east of the divide may make its way into Juniper Bay. Rainfall falling on the west side of the divide will make its way towards Hog Swamp. Core 21, west of the bay and east of the water table divide, shows mainly sand from the surface to 5.5 meters deep. Rainfall occurring in this area can move down through the sand into zone 2 and then flow into the bay.

During the winter and early spring of 2002, data from the piezometers indicated that the water pressure outside the bay to the north was equal to or above water pressure inside Juniper Bay (Appendix A). Manual measurements, however, showed that the pressure was always lower to the north of the bay. This discrepancy may be due to human error when pulling up the pressure transducers to download the data. The data from the manual measurements of piezometers 20S and 20D indicated that during the fall of 2001, the water level was the lowest of all measurements taken. This was during a time of below average rainfall (Table 1). During the winter months of 2002 the water level increased, probably due to increased rainfall and a lack of ET. Piezometer 22, on the north rim of the bay, had the lowest water pressure of all piezometers. The piezometer is about 7 meters deep. It is probably located in zone 2, but may intercept zone 3, leaking ground water from zone 2 into zone 3.

In Juniper Bay, from mid-spring through mid-fall of 2002, the water pressure dropped substantially more outside the bay to the north (where another Carolina Bay may exist) than it did anywhere else inside or outside the bay. This may have been due to that area being heavily wooded and the rate of ET having been higher in the late spring and summer, and rainfall having been less. Inside Juniper Bay there were no trees, except in the south-eastern part where there is a stand of longleaf pine trees about 8 years old. The water table in that section, as shown in well 16A (Fig. 6), was much lower due to the drawdown of the water table by those trees.

Juniper Bay may be a recharge area since it is not the lowest point on the local landscape. Hog Swamp and Shelley Bay are both lower in elevation, as the Carolina Bay to the north, and ground water in Juniper Bay may be recharging them.

Ground water response to precipitation

Ground water levels in Juniper Bay began to respond immediately after a large rain event, but the rate of rise of the water levels is different between piezometers. Some piezometers located in sandy material had water levels that rose quickly while some did not, and some piezometers located in soil with more clay had water levels that rose quickly, while some did not.

One thing that may be influencing the ground water in the vicinity of piezometer 2S is the main collector ditch. It may cut through the clay layer above this piezometer and into zone 2. If so, ground water in this region may flow towards it since it will be the area lowest in pressure. An open ditch, if deep enough, attracts near-surface ground water. This increase in ground water flow to the ditch increases the infiltration amount and rate of surface water (Dunn et al, 1996).

Hydraulic Conductivity

Data from the network of piezometers (Appendix A) in and around Juniper Bay suggest that ground water enters the bay primarily from the northwest side and the southeast side of the bay, both higher in elevation than the rest of the bay. Water flows towards the lowest pressure head. The areas to the north and south of the bay are lower in elevation. During the summer months of 2002, data suggest that ground water flowed out of the bay towards the north and possibly the south. Manual measurements of the water level in the piezometers on the north-south transect show that the water level is consistently lower outside the bay than inside the bay. Within the bay, ground water flows towards the middle of the bay where piezometer 11 is located (Fig. 1). This may be due to two larger ditches meeting near piezometer 11 and influencing the flow of ground water. Piezometer 11 is also in the lowest elevation in the bay.

Slug tests were performed in most piezometers to determine saturated hydraulic conductivity in order to calculate specific discharge, which is a velocity. Knowing the specific discharge at specific locations will allow the approximate determination of vertical and horizontal ground water flow patterns. Table 12 shows the saturated hydraulic conductivity measurements obtained from analysis of the slug test data.

The slug tests show that the soil near piezometer 6 has the fastest hydraulic conductivity, meaning ground water flows faster at this location. The soil at this location is sandy and water can move faster through the larger pores of the sand than through soils with more clay and silt present in the texture.

Estimated Direction and Rates of Ground Water Flow

Table 13 shows the specific discharge between certain piezometers in zone 2. The first table shows the specific discharge in centimeters per hour. With these data the approximate amount of ground water flowing into and out of the bay can be determined.

Table 13 shows that ground water flowed fastest from piezometer 3 to piezometer 22. It is unclear, however, if the zones that the two piezometers are in are connected. The manual measurements also show a larger water level difference between piezometer 3 and 22 than between 3 and 6. If the zones are connected then water is likely flowing from piezometer 3 to 22, meaning water is moving out of the bay at this location. The data also show that there may be some ground water movement from piezometer 3 to 6, since the water level, or pressure, is lower at 6 than at 3 (Appendix A). Flow became faster as the seasons changed from winter to spring to summer from piezometer 3 to 6, 6 to 11, and 20 to 22. In many cases, however, flow decreased as the weather became warmer. This is probably due to the increase in ET and soil evaporation.

Ground water levels are higher inside the bay than outside the bay along the north-south transect (Appendix A). This feature of having higher ground water levels inside the bay was also found in other Carolina Bay studies. This is due to the thick clay layer that exists below the surface of these bays. The clay layer below Juniper Bay shows up in the soil profiles between 6 and 10 meters deep. The outside areas to the north and south also represent where ground water may be moving out of the bay.

There are not as many piezometers along the east-west transect outside the bay as there are along the north-south transect (Fig. 1). There is one to the west and one to the east of the bay. There are also no soil cores from these two locations. This makes the determination of which zone they are in more difficult. The same pattern of lower water levels outside the bay in these two piezometers exists. If these two piezometers are in zone 3, then ground water in zone 2 can still be entering the bay from the west and east and exiting to the north and south.

Hydrologic Restoration

The goal of the Juniper Bay mitigation project is to re-establish a stable wetland system that will restore natural processes, structure, and species composition to mitigate for wetland functions and values that will be impacted by highway construction activities in the Lumber River Basin (N.C.D.O.T., 2001).

Reference bay data are useful in the restoration process because they provide target data on the hydrology of a natural Carolina Bay. As shown in Figure 7, the reference bays have the water table closer to the surface and for longer periods of time than most wells in Juniper Bay, and the length of time that wetland hydrology occurs is longer than the 12.5% of the growing season criteria set by the Corps for wetland restoration. This means that the target water table depth and duration for Juniper Bay may be longer than the restoration plan calls for.

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Table 1: Rainfall averages for Lumberton, N.C., Juniper Bay, and the Elizabethtown, N.C.

Time Period	Lumberton averages, 1971-2000 (cm)	Juniper Bay averages, 2001 (cm)	Juniper Bay averages, 2002 (cm)	Elizabethtown, averages, 1971-2000 (cm)
January	10.9	-	9.1	11.1
February	8.6	-	5.3	8.4
March	10.9	9.4	7.7	11.5
April	7.2	0.6	6.25	7.8
May	10.1	6.2	3.8	9
June	11.58	14.1	7.3	10.4
July	14.24	17.8	9.7	14.7
August	13.1	19.2	22	15.6
September	11.7	6.2	3.4	13.6
October	8.5	5.4	10.5	8
November	6.8	4.6	8.4	6.8
December	8.2	1.8	8.3	8.7
Spring	28.9	20.9	17.35	27.2
Summer	39.04	43.2	36.5	43.9
Fall	23.5	11.8	27.3	23.5
Winter	30.4	-	22.1	31
Annual	121.9	85.4*	103.4	125.6

* only includes data from March through December, 2001.

Table 2: Wells in Juniper Bay that meet the minimum wetland hydrology requirements set by the Army Corps of Engineers.

Juniper Bay			
Wells that meet minimum wetland hydrology requirements	**Consecutive days requirements were met, 2001 growing season***	**Consecutive days requirements were met, 2002 growing season***	**Soil series; mineral, mineral with histic epipedon, organic**
Well 3	-	24	Leon, mineral
Well 8	35	30	Leon, mineral with histic epipedon
Well 12	28	28	Leon, mineral
Well 15	-	14	Ponzer Muck, organic
Well 16	28	28	Ponzer Muck, organic

* Growing season for project site is March 26 through October 30.

Table 3: Percentage of the soil at Juniper Bay that is mineral, mineral with a histic epipedon, and organic.

Juniper Bay		
Percentage of Bay	**Soil Series**	**Soil Type**
25%	Leon	Mineral
15%	Leon	Mineral with histic epipedon
10%	Pantego	Mineral
20%	Rutlege	Mineral
70%		Total Mineral soil
30%	Ponzer Muck	Organic

Table 4: Percentage of Juniper Bay that meets the U.S. Army Corps of Engineers requirements for wetland hydrology.

Juniper Bay			
Percentage of:	**Saturated to within 30 cm from soil surface for:**		
	5% of growing season (11 days)	**8.75% of growing season (19 days)**	**12.5% of growing season (27 days)**
Juniper Bay	22%	15%	12%
Mineral soil total	43%	43%	29%
Mineral soil: Leon	43%	43%	29%
Mineral soil: Pantego	0%	0%	0%
Mineral soil: Rutlege	0%	0%	0%
Mineral soil with histic epipedon: Leon	33%	33%	33%
Organic soil: Ponzer Muck	29%	14%	14%

Table 5: Number of consecutive days the water table was within 30 cm from the soil surface in the reference bay wells.

Wells that meet minimum wetland hydrology requirements	**Consecutive days during 2002 growing season (March 25 – November 4) that the water table is within 30 cm of soil surface***	**Soil type (mineral, histic mineral, shallow organic, deep organic)**
*Causeway Bay well 1***	*4*	*mineral*
Causeway Bay well 2	1, **45*****, 1, 4, 5, **13**, 7, 1	histic mineral
Causeway Bay well 3	3, **45**, 8, 4, 4, 5, 4, 4	shallow organic
Charlie Long Bay well 1	*3, 1*	*mineral*
Charlie Long Bay well 2	3, **45**, 1, 8, 1, 21	histic mineral
Charlie Long Bay well 3	3, **16**, 5, 3, 2, 2, 2	shallow organic
Charlie Long Bay well 4	*3, 7*	*deep organic*
Tatum Millpond Bay well 1	3, **21**, **21**, **25**, 8, **21**	mineral
Tatum Millpond Bay well 1A	3, 1, 4, 1, 2, 2, 1, 4, 1, **30**, **21**	mineral
Tatum Millpond Bay well 2	3, **21**, **21**, **18**, **12**, 1, 5, **21**	histic mineral
Tatum Millpond Bay well 3	3, **21**, **21**, **18**, **13**, 5, 9, **21**	shallow organic
Tatum Millpond Bay well 4	**33**, **21**, 2, **19**, 8, 3, 8, **21**	deep organic

*** breaks in the wells meeting wetland hydrology requirements due to water table dropping below 30 cm or lack of data for that period of time, as shown in graphs.**
**** wells in italics indicate there was no period that wetland hydrology requirements were met.**
*** bold numbers indicate an amount that meets the minimum wetland hydrology requirement of 5% set by the U.S. Army Corps of Engineers.

Table 6: Percentage of Charlie Long Millpond Bay in the three soil types.

Charlie Long Millpond Bay		
Percentage of Bay	**Soil Series**	**Soil Type**
30%	Lynn Haven/Leon	Mineral
20%	Lynn Haven/Leon	Mineral with histic epipedon
50%		Total Mineral soil
50%	Pamlico Muck	Organic

Table 7: Percentage of Causeway Bay in the three soil types.

Causeway Bay		
Percentage of Bay	**Soil Series**	**Soil Type**
7%	Lynn Haven/Leon/Kureb	Mineral
3%	Lynn Haven/Leon/Kureb	Mineral with histic epipedon
10%		Total Mineral soil
90%	Pamlico Muck	Organic

Table 8: Percentage of Tatum Millpond Bay in the three soil types.

Tatum Millpond Bay		
Percentage of Bay	**Soil Series**	**Soil Type**
20%	Lynn Haven/ Torhunta	Mineral
10%	Lynn Haven/ Torhunta	Mineral with histic epipedon
30%		Total Mineral soil
70%	Pamlico Muck/Croatan Muck	Organic

Table 9: Percentage of the soil types in Causeway Bay that meet the wetland hydrology requirements in objective one.

Causeway Bay			
Percentage	Saturated to within 30 cm from the soil surface for:		
	5% of growing season (11 days)	8.75% of growing season (19 days)	12.5% of growing season (27 days)
Whole Bay	93%	93%	90%
Mineral soil	0%	0%	0%
Mineral soil with histic epipedon	100%	100%	0%
Organic soil	100%	100%	100%

Table 10: Percentage of the soil types in Charlie Long Millpond Bay that meet the wetland hydrology requirements in objective one.

Charlie Long Millpond Bay			
Percentage	Saturated to within 30 cm from the soil surface for:		
	5% of growing season (11 days)	8.75% of growing season (19 days)	12.5% of growing season (27 days)
Whole Bay	70%?	20%?	20%?
Mineral soil	0%?	0%?	0%?
Mineral soil with histic epipedon	100%	100%	0%
Organic soil	100%	0%	0%

Table 11: Percentage of the soil types in Tatum Millpond Bay that meet the wetland hydrology requirements in objective one.

Tatum Millpond Bay			
Percentage	Saturated to within 30 cm from the soil surface for:		
	5% of growing season (11 days)	8.75% of growing season (19 days)	12.5% of growing season (27 days)
Whole Bay	100%	100%	100%
Mineral soil	100%	100%	100%
Mineral soil with histic epipedon	100%	100%	100%
Organic soil	100%	100%	100%

Table 12: Saturated hydraulic conductivity values obtained through slug tests.

Piezometer	**Saturated hydraulic conductivity**
1-S	0.1901
2-S	0.0367
2-D	0.1997
3	0.0582
6	0.3884
10-S	0.0185
10-D	0.2013
11	0.0265
12	0.0512
17	0.0758
20-S	0.0871
20-D	0.2642
22	0.0374
25-S	0.1515
25-D	0.0435

Table 13: Specific discharge calculated from saturated hydraulic conductivity values.

	Specific discharge, v, cm/hr			
from:	Fall 2001	Winter 2002	Spring 2002	Summer 2002
P2 to P1		0.000057	0.000053	0.000057
P3 to P6	0.000108	0.000124	0.000162	0.000143
P10 to P6	0.000146	0.000137	0.000148	0.000077
P6 to P11		0.000091	0.000117	0.000155
P10 to P11		0.000094	0.000117	0.000081
P12 to P11		0.000042	0.000042	0.000031
P20 to P22		0.000508	0.000512	0.000560
P10 to P25		0.000273	0.000266	0.000263
P2 to P6		0.000236	0.000207	0.000120
P3 to P22		0.000766	0.000794	0.000891

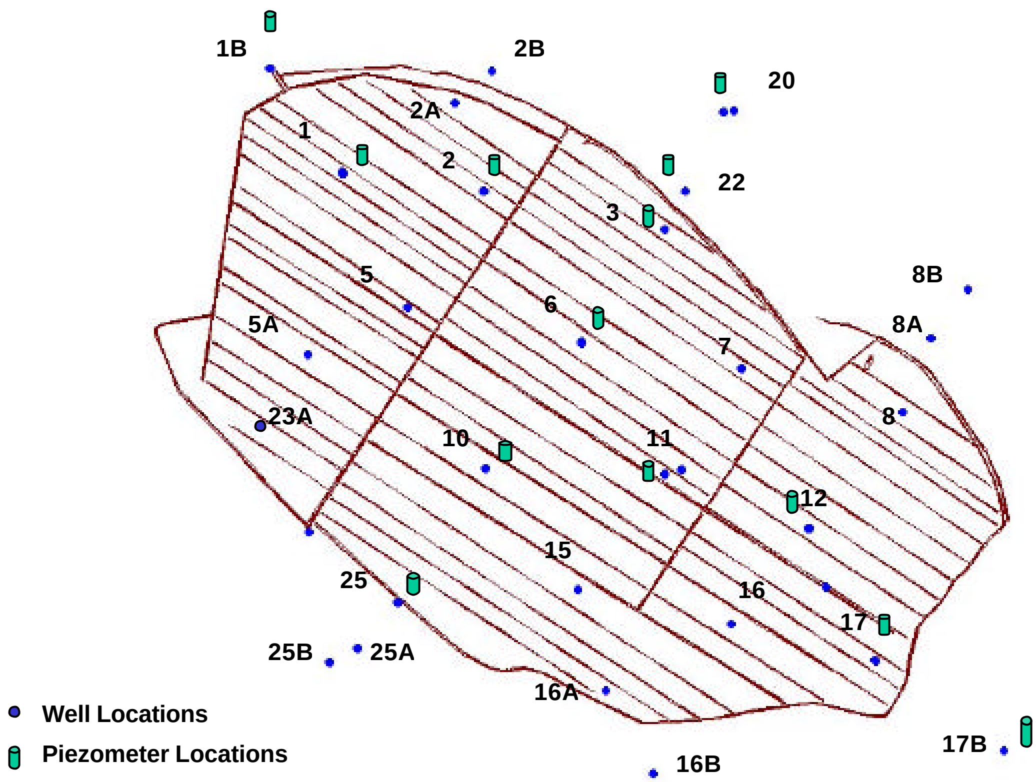


Figure 1. Map of piezometer and well locations.

Figure 2. Soil core locations.

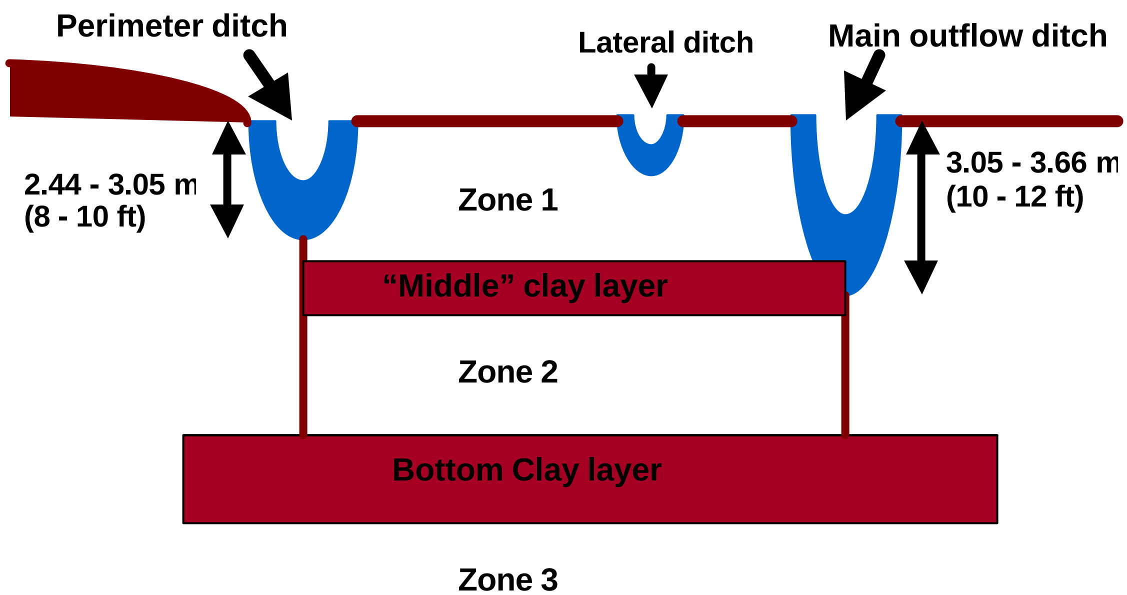


Figure 3. Internal system boundaries. Clay layers break sediments into three distinct zones or aquifers. Each zone consists largely of sandy deposits and is responsible for most ground water movement. Ditches currently penetrate into zone 1. A few deep ditches may penetrate into zone 2. Most lateral moving ground water is believed to move through zone 2 at this time. Zone 3 is believed to be uninvolved in the current hydrology of Juniper Bay.

Figure 4: Wells located in the northwest section of Juniper Bay

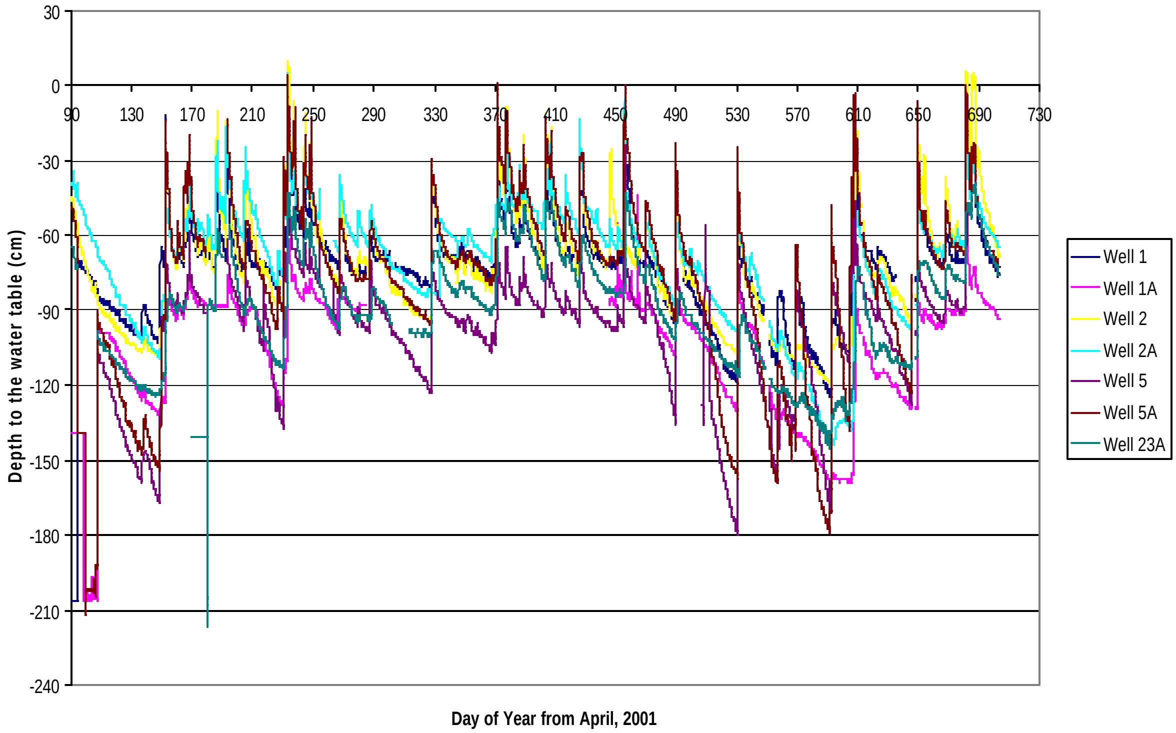


Figure 5: Wells located in the middle of Juniper Bay

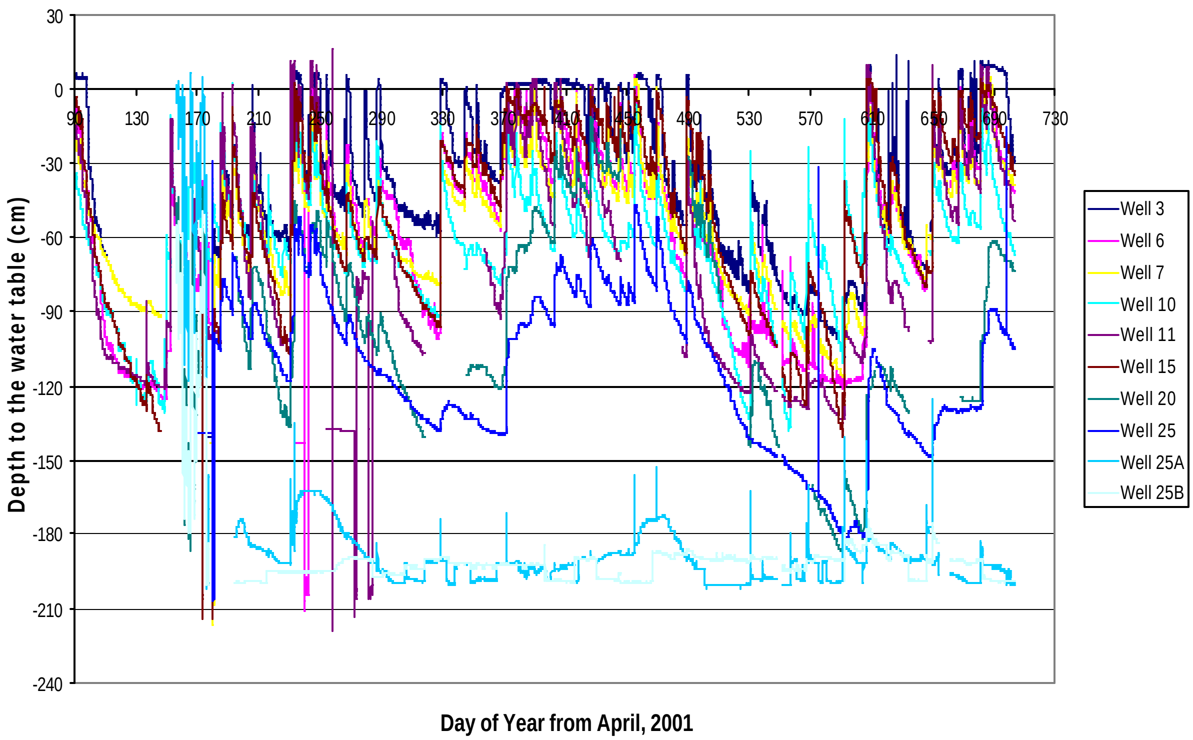
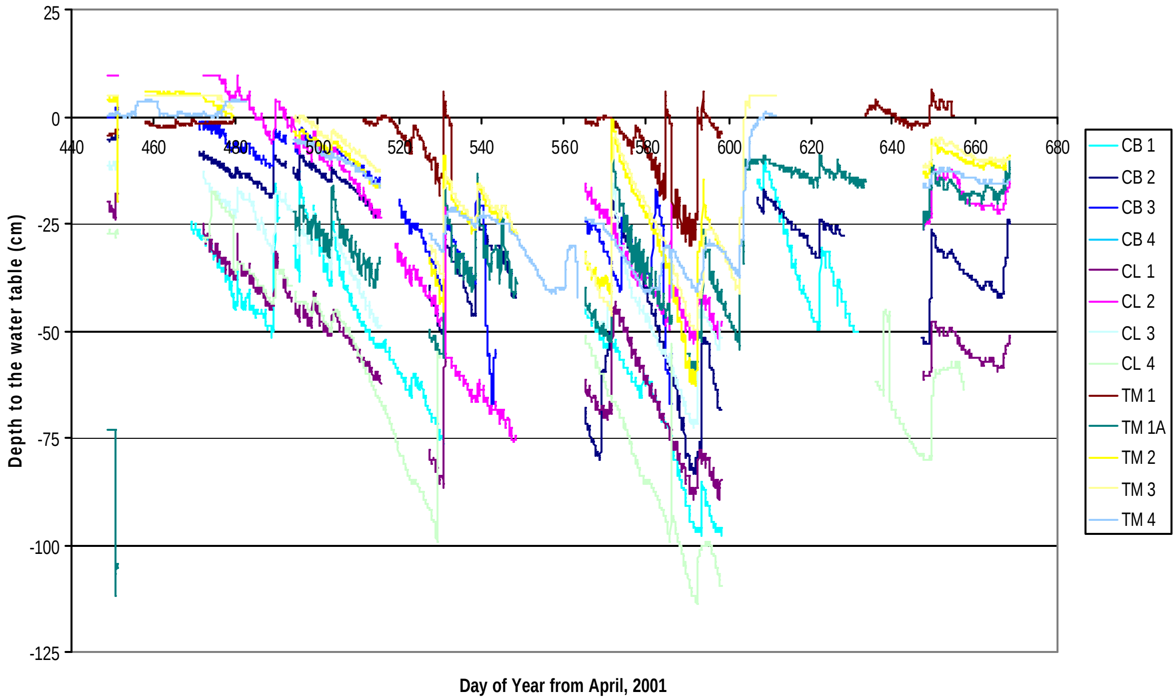


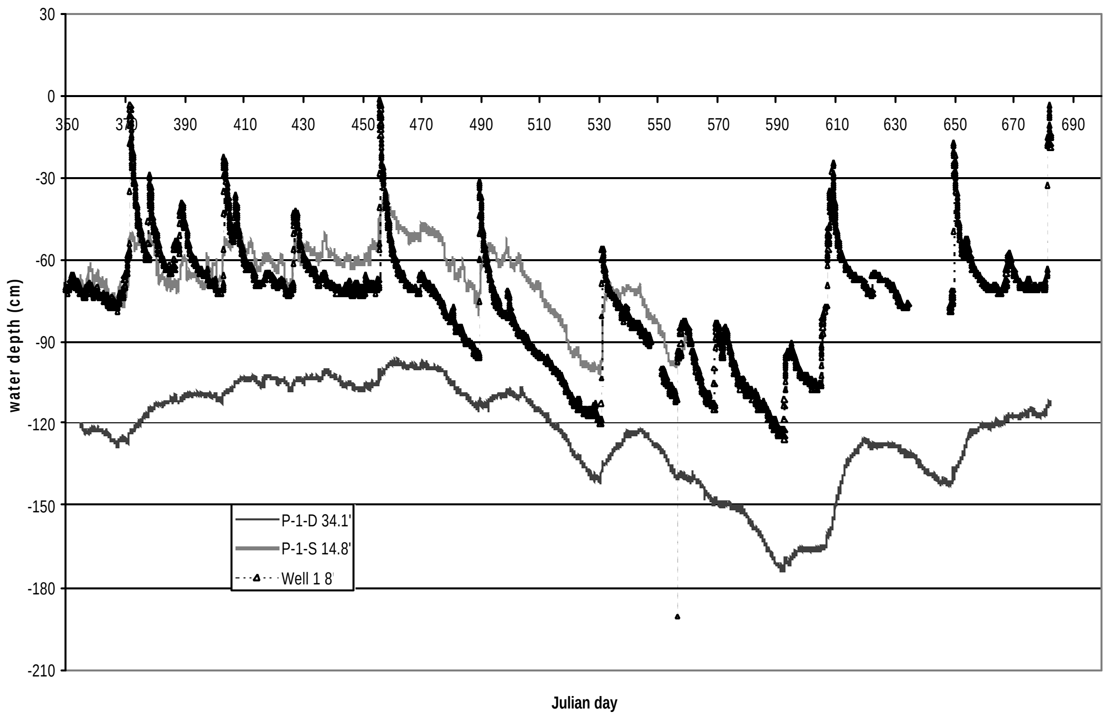
Figure 6: Wells in the Southeast section of Juniper Bay

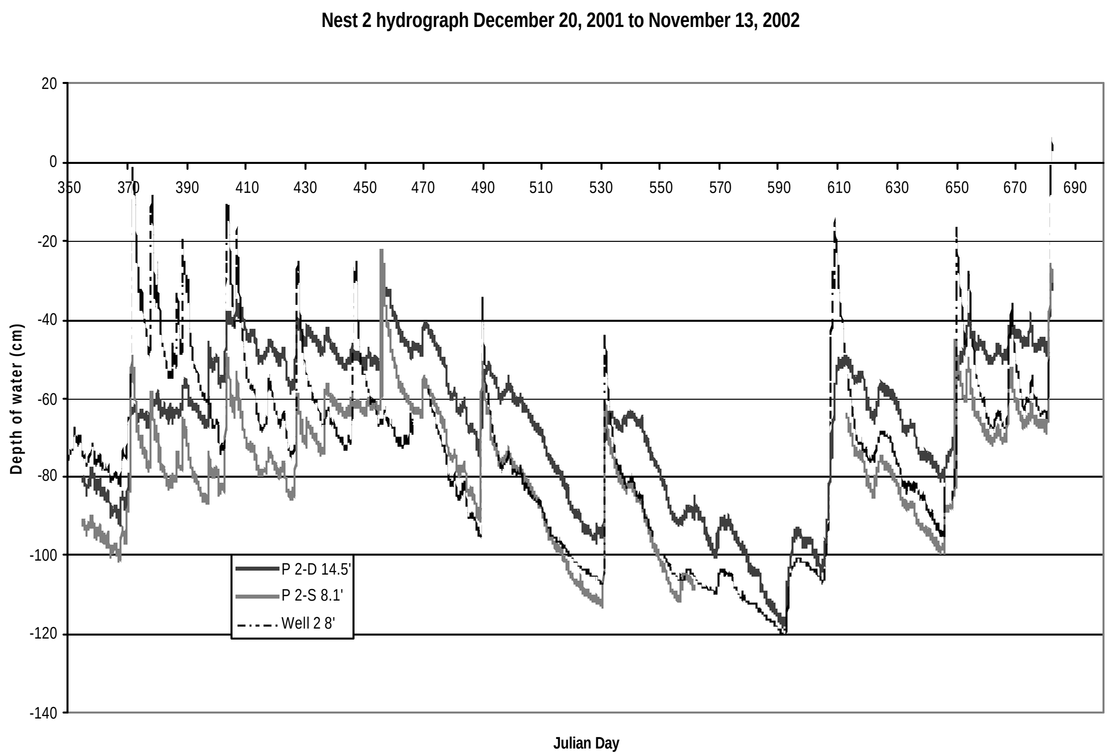
Figure 7: Wells in the reference bays (CB=Causeway Bay, CL=Charlie Long Millpond Bay, TM=Tatum Millpond Bay)

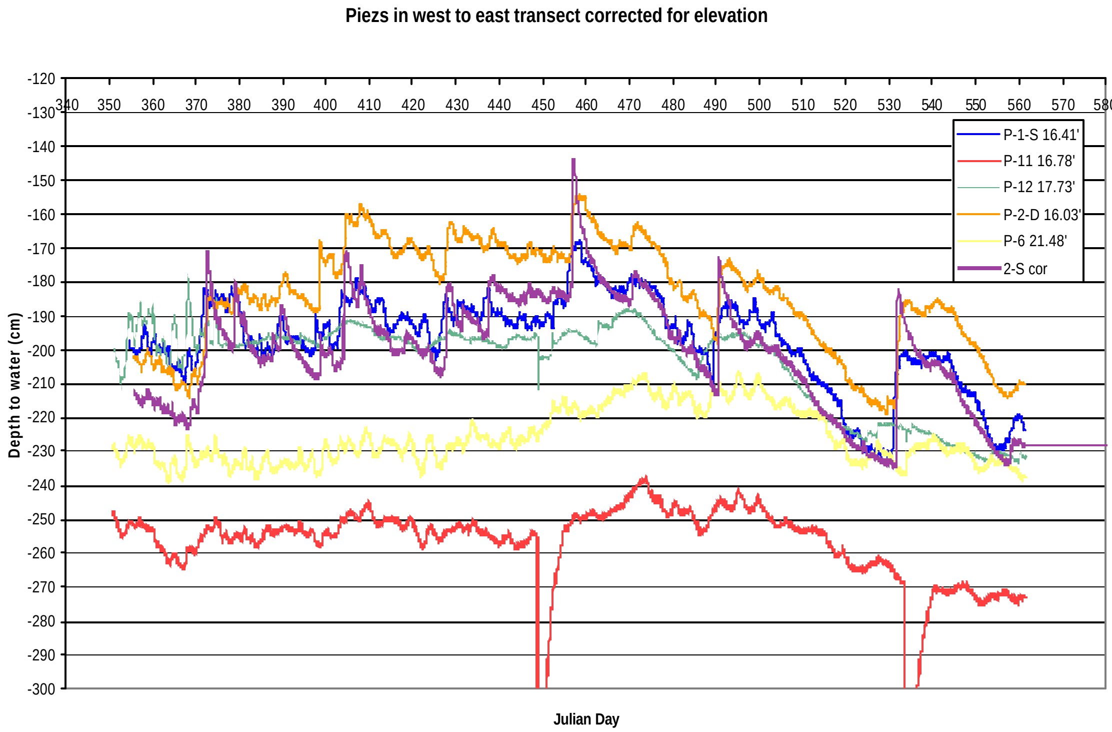


Appendix A: Piezometer data.

Nest 1 hydrograph December 20, 2001 to November 13, 2002

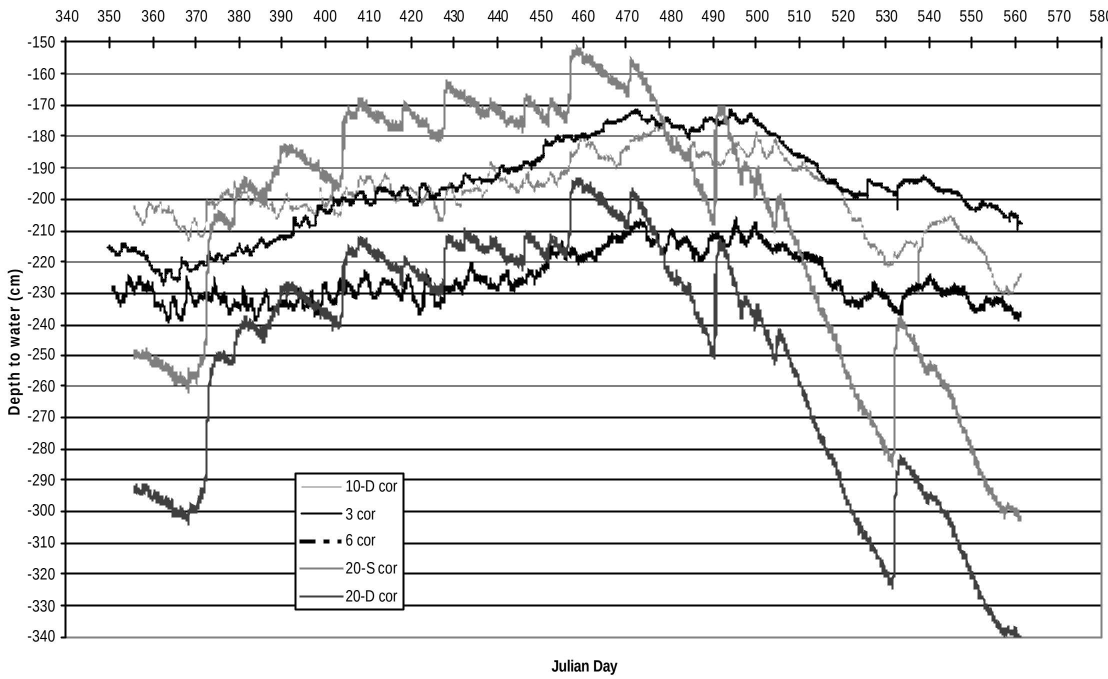


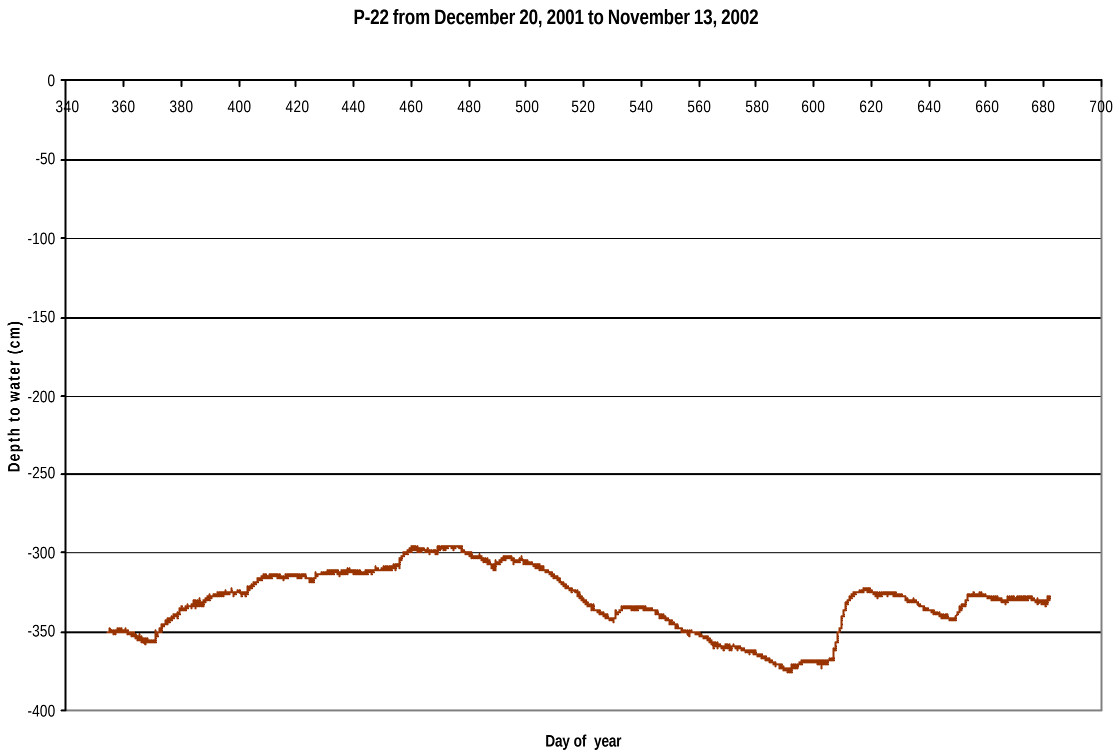

Nest 2 hydrograph December 20, 2001 to November 13, 2002
20
0
-20
-40
-60
-80
-100
-120
-140
350
370
390
410
430
450
470
490
510
530
550
570
590
610
630
650
670
690
Depth of water (cm)
Julian Day
P 2-D 14.5'
P 2-S 8.1'
Well 2 8'



Piezs in west to east transect corrected for elevation
Depth to water (cm)
Julian Day
P-1-S 16.41'
P-11 16.78'
P-12 17.73'
P-2-D 16.03'
P-6 21.48'
2-S cor
-120
-130
-140
-150
-160
-170
-180
-190
-200
-210
-220
-230
-240
-250
-260
-270
-280
-290
-300
340
350
360
370
380
390
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540
550
560
570
580

Piezometers in north to south transect in Aquifer 2 region





P-22 from December 20, 2001 to November 13, 2002
0
-50
-100
-150
-200
-250
-300
-350
-400
340
360
380
400
420
440
460
480
500
520
540
560
580
600
620
640
660
680
700
Depth to water (cm)
Day of year

Chapter 11

WATER BUDGET FOR JUNIPER BAY

G.S. Kreiser, R.L. Huffman, and M.J. Vepraskas

INTRODUCTION

Hydrology is the most important variable in the creation and maintenance of different types of wetlands and wetland processes (Mitsch and Gosselink 1993). For the classification, assessment, and restoration of wetlands, there is a need to know the amounts and timing as well as the sources of water (Owen 1995). Even though hydrology is known to be important, it is often overlooked and the least understood aspect of wetlands. This may be due to the fact that assessing hydrology is a complex and time-consuming process.

Early wetland studies concerning hydrology dealt with the relationship between wetland productivity and species composition (Mitsch and Gosselink 1993). In the last twenty years, numerous papers have dealt with the various broad aspects of hydrology in wetlands (Carter et. al 1978; Carter 1986; Carter and Novitzki 1988). However, there have been few studies that have described the detailed hydrologic characteristics within specific types of wetlands. Exceptions to this include studies of northern peatlands, salt marshes, cypress swamps, and large-scale wetland complexes (Mitsch and Gosselink 1993).

Hydrologic studies must be well planned in order to quantify the temporal and spatial distribution of water, and must consider all possible inputs and outputs of a wetland. This process for accounting all of the water sources and sinks within a defined site is commonly called a water budget (Roig 2000). Figure 1 illustrates the components of a wetland. Water budget equations are often used in detailed hydrologic assessment of wetlands (Rykiel 1984; Hyatt and Brooks1984). Water budgets are also useful for the calculation of nutrient budgets. In addition, they can be used to estimate unknown hydrologic components such as groundwater flow and for the prediction of the effects of natural and anthropogenic changes on water inputs and outputs (Carter 1986; Roig 2000).

The general components of a water budget equation showing the water storage, inflows, and outflows of a wetland may be expressed as (Mitsch and Gosselink1993):

$$?V/?t=P_n+S_i+G_i-ET-S_o-G_o\pm T \qquad [1]$$

where:

$?V/?t$	=	change in volume of water storage in wetland per unit time, t
P_n	=	net precipitation
S_i	=	surface inflows, including flooding streams
G_i	=	groundwater inflows
ET	=	evapotranspiration

S_o	=	surface outflows
G_o	=	groundwater outflows
T	=	tidal inflow or outflow

It is important to note that not all variables occur in all wetlands. There are many different forms of this equation, all of which are essentially the same (Carter et. al. 1978; Roig 2000).

The water budget (Eq. 1) at first glance seems deceptively simple, where water inputs equals water outputs, plus or minus the change in storage, but care must be taken when using it to establish the hydrology of a wetland (Winter 1981). The central problem in determining water budgets for a wetland is how well the individual inputs, outputs, and change of storage can be measured or estimated and the magnitude of the associated errors (Dooge 1972; Winter 1981; Carter 1986). For most hydrologic studies, it is desirable to measure or estimate all of the components in order to calculate a water budget (Dooge 1972; Hyatt and Brook 1984; Carter 1986). However, this is not always possible due to the difficulties in making hydrologic measurements, and one component is calculated as the residual of the water budget equation (Eq. 1).

The inherent problem with the residual component is that it contains the sum of all errors from the other terms in the budget. Errors can be classified into two categories of either measurement or interpretation (Winter 1981). Measurement errors occur from trying to take measurements using imperfect instruments, inadequate sampling design, and data collection procedures. Interpretation errors occur as a result from using point data in order to estimate quantities for a longer period of time (Winter 1981). These errors can have a significant effect on the calculations of a water budget. However, error analysis is not commonly used and the residual term is given a great deal of interpretation and importance, even though the residual term has little meaning. Winter (1981) recommends that any hydrologic budget, however derived, include error analysis in order to allow for realistic use of water budgets. By including error analysis Equation 1 becomes:

$$?V/?t=Inputs-Outputs \pm error \qquad [2]$$

The inputs and outputs are the same as in Equation 1. Error is calculated from the standard deviations of measurement and the known instrument error and then is summed up in the final water budget equation (Owen 1995).

Water budgets are useful because they provide “a first approximation of inputs and outputs as a basis for nutrient balance and energy studies, hydrologic models, and predictions of impact” (Carter 1986). Carter (1986) notes that water budgets are commonly used in wetland analysis. While there are known errors associated with calculating a water budget, water budgets provide an initial base for further detailed analyses of wetland hydrology.

In order to determine the sources of water occurring at Juniper Bay, the hydrology is being studied. To determine the hydrologic inputs and outputs into the bay, a water budget is being used. The objectives of this research are to establish a water budget, compute the magnitude of water inflow and outflow into the bay, and predict possible impacts of the restoration.

MATERIALS AND METHODS

The North Carolina Department of Transportation (NCDOT) is in the process of restoring a drained Carolina Bay in Robeson County. The project will provide compensatory wetland mitigation in the Lumber River Basin of southeastern North Carolina, which will offset wetland impacts from road construction projects in the river basin (Hauser 2001). The site, known as Juniper Bay (Figure 2), is composed of 300 hectares of an extensively drained Carolina Bay that was used for agricultural production. The goal of the restoration project is to restore the site back to a wetland, thus recreating the functions and values of a Carolina Bay. As part of this restoration project, North Carolina State University is investigating the hydrologic, soil and vegetative changes that occur in Juniper Bay as a result of this restoration project.

Juniper Bay is located approximately 16 kilometers southeast of Lumberton, NC (Figure 3). The bay contains an extensive network of ditches that were installed in order to drain the bay for agricultural production (Figure 4). All of the surface water exits the bay through a perimeter ditch and a large main ditch. The soils of the bay were classified during the summer of 2001 with Juniper Bay having both organic and mineral soils.

Precipitation

Precipitation was measured using three tipping bucket gauges that were located within the bay (Fig. 4). Gauges located in the NW and SE measured rainfall to the nearest .01- inch, while the gauge at the weather station measured rainfall amounts to the nearest 0.1-millimeter. The rain gauges at NW and SE were Davis Instruments, Rain Collector II. The event recorder used a HOBO Event Logger, by ONSET Computer Corporation. The rain gauge at the weather station was Texas Electronics, Inc. TE525MM. Monthly totals for all rain gauges were computed and then compared. Gauges that obviously had inaccurate totals for a month were discarded. The remaining gauges were then used to determine the average monthly total of precipitation for the entire bay.

Evapotranspiration

Data that were used to estimate PET were collected at the weather station located near the center of bay (Figure 4). Measurements included hourly readings of direct radiation, net radiation, wind speed, and wind direction. Wind speed and wind direction were measured with Climatronics Wind Speed and Direction Sensors (Model CS 800-L). Net radiation was measured with a REBS Net Radiometer (Model Q7_1). Direct radiation was measured with a LI-COR LI200SZ Silicon Pyranometer. Air temperature and relative humidity were measured using Valsala-Temperature and RH probe Model HMP45C. All measurements recorded were stored in a Campbell Scientific CR-10X data logger.

Reference ET was calculated using software from University of Idaho at Kimberly (University of Idaho at Kimberly 2002). The reference crop was assumed to be a short cool-season grass, which gave a reference ET (ET_o). Potential evapotranspiration was calculated by using the Penman-Monteith equation where:

$$ET = \frac{?(R_n - G) + ?_a c_p (e^o_z - e_z)/r_a}{? + ?(1 + r_s/r_a)} \qquad [3]$$

where:

R_n	=	net radiation
G	=	soil heat flux
?	=	slope of satruation vapor pressure
?	=	psychrometric constant
e^o_z	=	mean saturation vapor pressure
r_s	=	bulk surface resistance
r_a	=	aerodynamic resistance
e_z	=	actual vapor pressure of air
$?_a$	=	air density
c_p	=	specific heat of dry air

The hourly weather data was used to calculate hourly ET_o values, which were then summed to get a monthly total. A crop cover coefficient was applied in order to get estimated ET_c (using equation $ET_c = ET_o K_c$). A crop (cover) coefficient was constructed using the procedure outlined in ASCE Hydrology Handbook (1996). The K_c curve was constructed by dividing the growing season into four parts that describe the growth stages: the initial period, development period, midseason period, and late season period.

One of the dominant plant species at Juniper Bay during the study was Dog Fennel (*Eupatorium capillifolium L.*). Dog Fennel is an aggressive weed species that is native to the southeastern United States, which commonly occurs on sites such as old fields, ditches, and disturbed pastures (Van Deelen 1991). Dog Fennel is often described as an annual that can grow to heights of 4 to 5 feet (1.2-1.5 m). Using information from the ASCE Hydrology Handbook (1996), a crop similar to dog Fennel was picked in order to get the crop coefficient. Millet (*Panicum miliaceum L.*) was listed as a crop with a maximum height of 1.5 m, which is similar to dog fennel. Using the numbers for millet, a K_c curve (Figure 5) was developed for Juniper Bay. Using the K_c graph, crop coefficients were picked for each month, which are listed in Table 1. Using the reference equation of ET_o multiplied by K_c will provide a monthly estimated ET_c for Juniper Bay.

Surface Outflow

Surface outflow was measured at the main outlet using dual compound weirs (Figure 4). Dual compound weirs were selected because they measure both low and high flow events, and also because a cement structure was already in place to support two weirs. Compound weirs consist of a rectangular notch with a V-notch cut into the center of the crest. Determining discharge from compound weirs requires the use of two different equations. Which equation is used depends on whether the discharge is contained in the V-notch or rectangular portion of the weir. If there are high flow events that are contained in the rectangular portion of the weir then the following equation is used (USBR 2003):

$$Q=3.9h_1^{1.72}-1.5+3.3Lh_2^{1.5} \quad [4]$$

Where:
Q= discharge in ft^3/s
h_1= head above the point of the V-notch in ft
L = combined length of the horizontal portions of the weir in ft
h_2= head above the horizontal crest in ft

However, if the flow is confined to only in the V-notch portion of the weir then the standard V-notch equation is used (USBR 2003)

$$Q = 2.49 \times h_1^{2.48} \quad [5]$$

In order to determine the stage of the water, pressure transducers were located above and below the weir. Knowing the elevation of the weir invert and the height of the water above the weir gives the height of water that is passing over the weir. This height of water determines what part of the weir the water is in and this then determines which equation is used. A Campbell Scientific CR-10X is used to run the calculations and to store the data. Surface outflow volumes were converted to equivalent depths of water by dividing by the surface area of the bay. The outflow measurements were then summed in order to get monthly totals.

During failure of the primary outflow measurement system, surface outflow was estimated by comparing the water elevations during the failure with water elevations during non-failure periods. This assumes that similar water elevations would have similar outflow amounts. Using this assumption, surface outflow was estimated when there was system failure.

Water Table Depth

Sixteen automatic monitoring wells (Remote Data Systems, Inc., Wilmington, NC) were installed inside the bay (Figure 6). Wells were installed by boring a hole 4 inches in diameter to a depth of 80 inches. The area around the well screen was back filled with sand in order to prevent clogging of the screen. A layer of bentonite was placed on top of the sand layer in order to seal the well from surface water. A conical mound of soil was then placed on top of the bentonite as a preventive measure to keep surface water away from the well. Water table depths each well were recorded hourly. In order to get average water table depth for the whole bay, all the well depths were averaged together. The average water table depth was then used in calculating the change in storage of the bay for each month.

Change in Storage

Change of storage was determined from the differences in water table depth at the beginning and end of each month. Change in storage was determined by multiplying the change in the average water table depth by the average drainable porosity of the soils. Drainable porosity is the amount of water drained for a given drop in the water table (University of Minnesota 2003). Drainable porosity is affected by the soil texture and structure, with sands having larger drainable porosities and clays having smaller drainable porosities (University of Minnesota 2003). Most of the soils in Juniper Bay have been classified as either sandy clay or sandy loam (Ewing and Vepraskas unpublished). According to the *FAO Irrigation and Drainage Paper 38* (1980) the drainable porosity for these types of soils is between 0.03 and 0.12 cm^3/cm^3. A drainable porosity of 0.1 was used as an average drainable porosity of the whole bay. Multiplying the average drainable porosity by the change in water table depth for each month gave the monthly change in storage for Juniper Bay.

Groundwater

Groundwater inflow and outflow were estimated as the residual of the water budget equation (Eq 1). Using a modified version of Equation 1 groundwater was calculated where:

Inputs-Outputs=?Storage
?Storage=(Precip + Gi) –(ET+Go+So)
Precip + Gi = ET + Go +So + ?Storage
Gi-Go = ET +So + ?Storage – Precip

The groundwater component of the water budget is the net groundwater movement in the bay and it was estimated for each month. The term Gi-Go was computed as a length measurement, but can be converted to a volume by multiplying by the area of the bay.

Statistics

Statistical software (SAS) was used to perform summary statistics and multivariate correlation on all components of the water budget.

Results and Discussion

Precipitation

Average monthly precipitation amounts are shown in Figure 7. These are the average values determined from the rain gauges at Juniper Bay. Long-term normal rainfall levels are also shown in Figure 7. Seven months had lower than normal rainfall, particularly from April through July. Rainfall after August was generally normal or wetter than normal.

Evapotranspiration

There was a seasonal trend in the amount of PET (Figure 8). The total amount of ET was estimated at 845 mm for the year. This seems to be a reasonable estimate since others have estimated ET in the coastal area of North Carolina to be approximately 900 mm (van Bavel and Verlinden 1956). Evapotranspiration has a negative correlation with surface outflow (R^2= -0.5805). In months when there was high ET there was a low amount of surface outflow. In the summer months of June, July and August the highest rates of ET were calculated for Juniper Bay. During these months there were corresponding low amounts of surface outflow. ET is the biggest sink and accounts for 54 percent of all water leaving the bay.

Change in Storage

Throughout the year the monthly change in storage was quite variable as expected (Table 2). A negative number represents a drop in the average water table at Juniper Bay during that month and a positive number indicates a rise in the water table (Figure 9). The two main driving forces for the fluctuation of the change in storage appear to be precipitation and ET. Table 2 shows that when ET was greater than precipitation during the month, in most instances, there was a negative change in storage. Likewise, when there was more precipitation than ET during the month, the change in storage was positive, representing a rise in the water table. However, statistical analysis did not show this relationship to be significant. There was no significant correlation between change in storage and ET (R^2= -0.0127). There was however, a significant correlation between the change in storage and the amount of rainfall during a particular month (R^2=0.9364). This seems reasonable, as precipitation is the main hydrologic input into Juniper Bay. Since precipitation is the main input into the system it is logical that the system would respond the most to precipitation. A possible explanation as to why ET was not statistically significant may be that precipitation is the main driving force for change of storage and only when there is little rainfall will ET cause a drop in the water table. The small amount for change in storage is consistent with the fact the over a long time period the change in storage equals about zero; that is, there is almost no net change in the water tables.

Surface Outflow

Monthly surface outflow was also quite variable and followed a trend opposite to that of ET (Figure 10). There was failure of the primary system during a two-week period in April of 2002 that required the estimation of outflow during that period. Outflow was estimated and added to the monthly total for April. The summer months had the lowest outflow and amounts increased in the fall and winter. During the summer months there was little surface outflow when there was little precipitation and high amounts of ET. There were higher outflow amounts during the fall and winter when there was adequate rainfall and lower ET rates.

Net Groundwater Input

The groundwater input and output were estimated as the residual of the rest of the water budget equation as mentioned in the method section. For this reason, groundwater is calculated as the net groundwater input, which could be either positive or negative.

The net groundwater input was calculated as 563 mm for this year. This means that more groundwater was entering the bay than leaving and the excess groundwater was leaving as surface outflow. When the groundwater component was negative, more groundwater was leaving the bay than entering, and Juniper Bay was acting as a recharge wetland. Figure 11 shows that for most of the year Juniper Bay had a positive net groundwater movement and was acting as a discharge wetland. The net groundwater component accounts for 35 percent of the total water inputs into Juniper Bay. The groundwater component is large suggesting that Juniper Bay has a significant groundwater input.

Error Analysis

All components in the water budget that were measured contain errors that are propagated through the water budget equation and are contained within the residual term; in this case groundwater. Significant errors in interpretation can occur if the residual term is used without respect to errors that are inherent to it. Table 3 lists all the associated errors for each component and the range. Errors were taken from the literature (Winter 1981; Owen 1995). All the errors combined equal to 171 mm. If all the errors are either added or subtracted, the range for groundwater is 392 mm to 734 mm. Even with all the errors associated with using the residual, the groundwater component is still positive indicating net groundwater movement into Juniper Bay.

The ET calculation has by far has the largest potential for error, and could have the biggest effect on the estimate of groundwater input. Taking that into consideration, ET was calculated with different percent error and graphed with the assumption that all other components remained the same. Figure 12 shows that if ET calculations were off by fifty percent there would still be a net positive groundwater component of 141 mm for the year.

Groundwater Flow into Juniper Bay

After taking into consideration all of the errors associated with the water budget, even in the worst-case situation of being off by fifty percent in the ET calculation there still is a positive net groundwater component. This raises the question as to where the groundwater comes from. In order to determine the possible sources of groundwater it is important to look at the topography of Juniper Bay and the surrounding area.

Juniper Bay lies at an intermediate landscape position, at 112 feet above sea level (Figure 13). Uplands occur to the east and west of Juniper Bay with elevations of about 124 to 131feet. Lowlands occur to the south and north of Juniper Bay with elevations around 112 feet. These differences in elevation create a hydraulic gradient that might account for groundwater inputs into the bay. The higher elevations or uplands would be possible sources for groundwater inputs and the lower elevations would be possible locations for groundwater output.

Two possible sources for groundwater into Juniper Bay are local and regional groundwater. The difference between precipitation (1014 mm) and ET (845 mm) provides an estimate for the amount of water recharging the groundwater. In this case, 169 mm of water has the potential to become groundwater for this year. The volume of water entering Juniper Bay was figured as the amount of groundwater multiplied by the bay's area. The recharge area needed to supply this amount of water was calculated as the volume of the bay divided by the potential amount of groundwater.

The adjacent uplands are the areas to the east and west of Juniper Bay and only account for about 16 percent of the area needed to meet the water requirements for groundwater. The only other possible source for groundwater is from more distant or regional sources. If that is the case then the regional sources account for over 80 percent of the groundwater entering Juniper Bay.

If actual ET were 50 percent of ET then the net groundwater input would be less. If the PET calculations were equal to ET then there would be a groundwater inflow of 563 mm a year, which accounts for 35 percent of the total inputs into the bay (Figure 12). However, if the ET calculations were off by 50 percent then there would be groundwater inflow of 141 mm a year, which accounts for about 11 percent of the total inputs into Juniper Bay. Even if there is a 50 percent error in the ET calculations there still is a groundwater inflow that could be significant in the restoration project.

Monitoring wells located in the east and west of Juniper Bay suggest that there is groundwater inflow into the bay. Wells 1 and 17 are in locations where it is thought that there is groundwater inflow. During a two-week period of no rainfall in August of 2002 the wells show evidence of groundwater inflow (Figure 14 and 15). These two figures show that during the day there is a draw down in the water table that is caused by ET. At night, when there is no ET, the water level rises due to groundwater input from outside the bay. For a well that is located further inside Juniper Bay there is not that cyclic pattern of water table falling and rising in twenty-four hours. Figure 16 shows well 10 that is located near the center of the bay, and unlike the other two wells there is not a replenishing of the groundwater. For well 10 during the same time period there is a steady drop in the water table caused by ET.

Other evidence of groundwater inflow into Juniper Bay is that there are organic soils located in the center of the bay (Figure 17). Organic soils form when soils are saturated long enough at the surface for significant organic matter to accumulate. This suggests that where there are organic soils in Juniper Bay, breaks in the clay layer allow for the upwelling of groundwater. Early findings of ground penetrating radar have shown that these areas of organic soils in Juniper Bay do have an indication of breaks in the clay layer (Szuch, personal communication 2003).

Implications

The water budget analysis suggests that Juniper Bay is currently acting as a discharge wetland, where groundwater is entering the bay and leaving as surface outflow.

Topographically Juniper Bay lies at an intermediate elevation and in a natural setting it could be acting as a flowthrough wetland. Figure 18 represents the topographic relationship of Juniper Bay to the surrounding areas.

There are two possible scenarios after restoration for what effect groundwater will have on restoration. If the perimeter ditch is left open, then wetland hydrology can be restored, and the excess water will be taken away as surface outflow. The bay will continue to function as a discharge wetland. Figure 19 shows that with the main ditch closed and the perimeter ditched left open, the perimeter ditch can still remove the excess groundwater.

However, if the perimeter ditch is closed (Figure 20), then there will be no outlet for the groundwater, and the water levels might rise above the present soil surface. Water levels may rise because it has been estimated that the subsidence of organic soils could be as great as 80 cm (Ewing and Vepraskas 2003). Which means that previously the soil surface at Juniper Bay was higher. Restoration of Juniper Bay with the perimeter ditch closed could possibly raise the water table above the surface and also might cause groundwater outflow, which might raise the water table in the surrounding area. Such instances of hydrological trespass could be a potential problem for the restoration project.

CONCLUSIONS

This study utilized a water budget in order to determine the potential of a drained Carolina Bay to be restored into a wetland. Measured components of the water budget included: precipitation, ET, surface outflow, and change in storage. Groundwater was estimated as the residual from the water budget equation.

A water budget for Juniper Bay was estimated for 2002 to 2003. There was a significant relationship between rainfall and change in storage as well as a negative correlation between surface outflow and ET. In addition, there was a positive relationship between surface outflow and groundwater. These findings indicate that Juniper Bay has a significant groundwater component and that this groundwater inflow could possibly influence the restoration project.

Two possible scenarios upon restoration of Juniper Bay must be evaluated in light of this information. In scenario one, the main ditch is plugged while the perimeter ditch would remain open. Under this scenario, wetland restoration would occur, and the perimeter ditch would intercept the excess groundwater.

Under scenario two, the perimeter ditch would be closed resulting in groundwater entering the bay and possibly raising the water table above the soil surface. This excess water might cause groundwater outflow into the lower surrounding areas. The movement of groundwater into neighboring areas could possibly cause hydrologic trespass.

Upon restoration, it appears that Juniper Bay will function as a flowthrough wetland with the groundwater entering and leaving the bay. These findings indicate the restoration project must take into account the groundwater component of the site. If the mitigation project does not address the ground water component, it may have adverse effects to the surrounding areas even if it provides mitigation credits for NCDOT.

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Table 1. Crop Coefficient for each month taken from the K_c curve in Figure 6.The crop coefficient term is used in the reference ET equation of $ET_c=K_cET_o$

Month	K_c
February	0.3
March	0.3
April	0.4
May	0.6
June	1
July	1
August	1
September	0.8
October	0.4
November	0.3
December	0.3
January	0.3
February	0.3

Table 2. Monthly totals for February 2002 to February 2003 for all water budget components.

	Change in Storage	Potential Evapotranspiration	Surface Outflow	Precipitation	Net Groundwater
	mm	mm	mm	mm	mm
February	-9.52	23.10	32.00	52.96	-7.38
March	12.89	32.70	60.00	106.17	-0.58
April	-60.38	58.80	64.50	39.54	23.38
May	-12.25	93.00	22.20	43.05	59.90
June	-9.42	164.00	3.40	70.10	87.88
July	-12.17	169.00	0.06	59.94	96.95
August	87.26	133.00	4.90	171.07	54.09
September	-55.19	66.64	19.30	33.91	-3.16
October	43.60	29.86	97.38	147.20	23.64
November	3.55	18.91	239.74	79.12	183.08
December	16.89	17.14	59.71	83.30	10.43
January	-35.70	19.93	43.10	25.02	2.31
February	36.50	18.43	80.33	103.13	32.13
Total	6.06	844.50	726.60	1014.51	562.65

Table 3. Sensitivity analysis for all water budget components. Percent error for each component taken from literature.

Component	Estimate	% Error	Error	Range
	mm		mm	mm
Precipitation	1014	5	±50.7	963-1065
Change in Storage	6.1	5	±0.305	5.8-6.4
Surface Outflow	727	5	±35.4	692-762
Evapotranspiration	845	10	±84.5	761-930
Total error		25	±171	

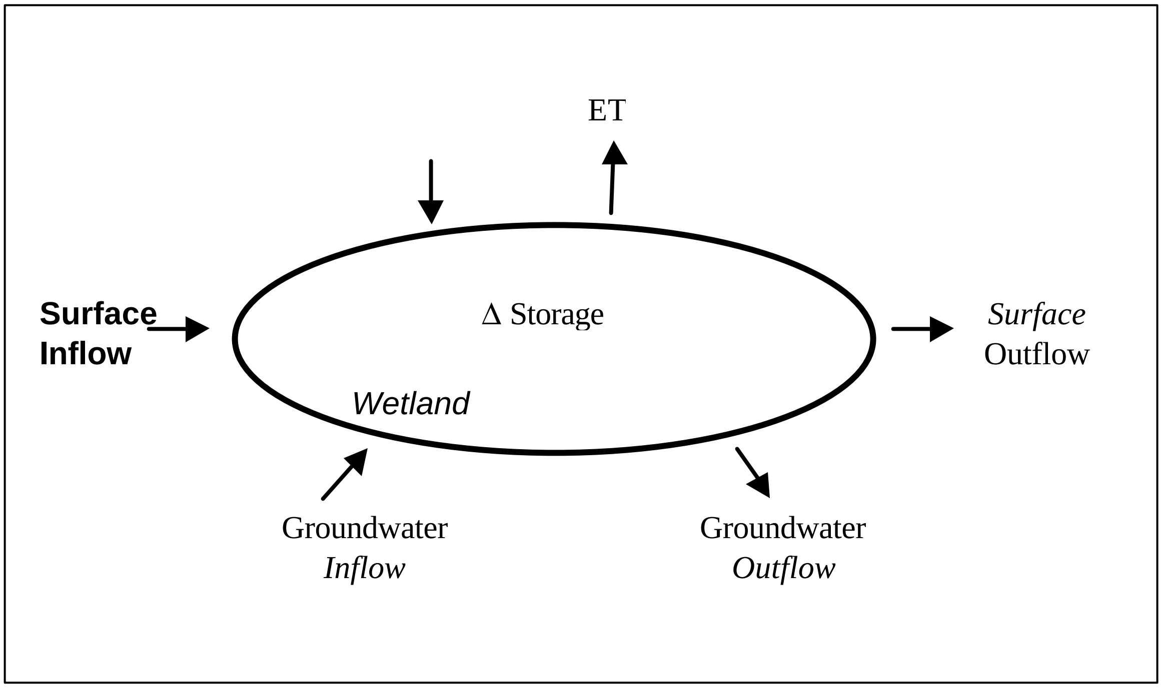

Figure 1. Schematic diagram representing some of the possible inputs and outputs into a wetland. Oval represents wetland, with arrows indicating direction of water movement.

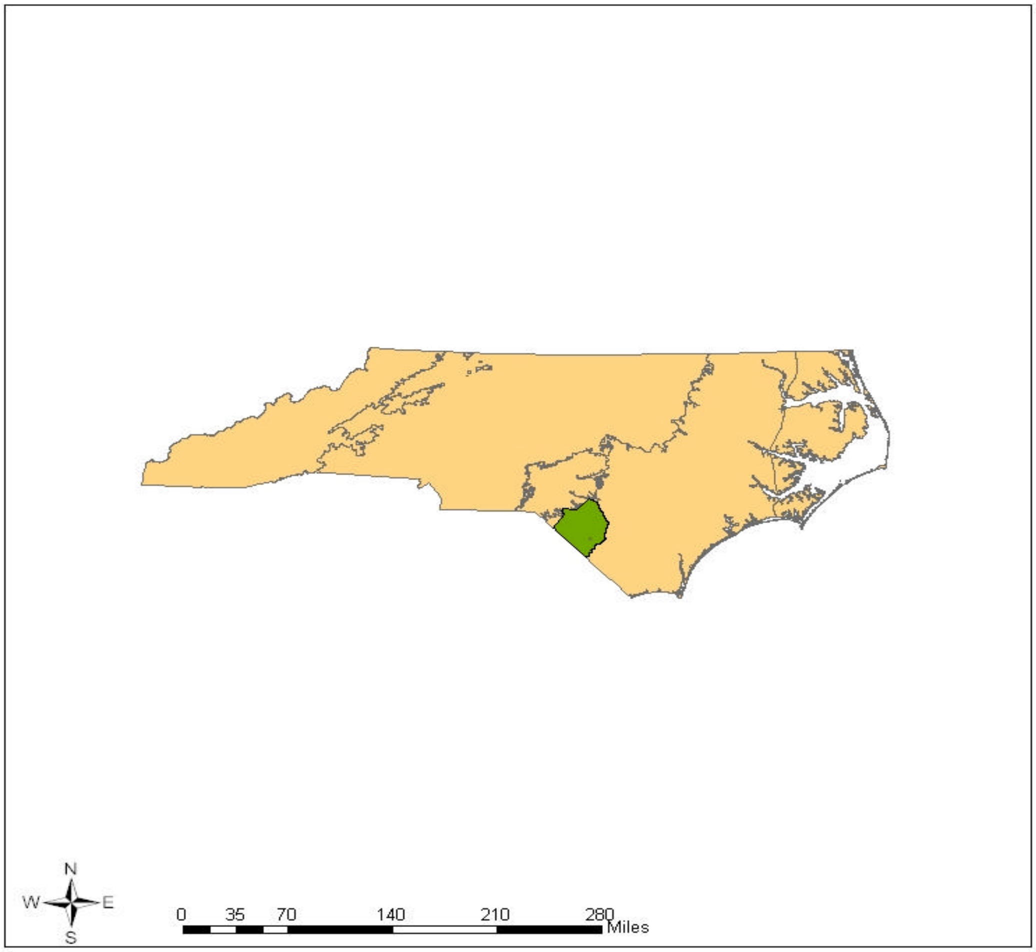

Figure 2. Map of North Carolina showing location Robeson County.

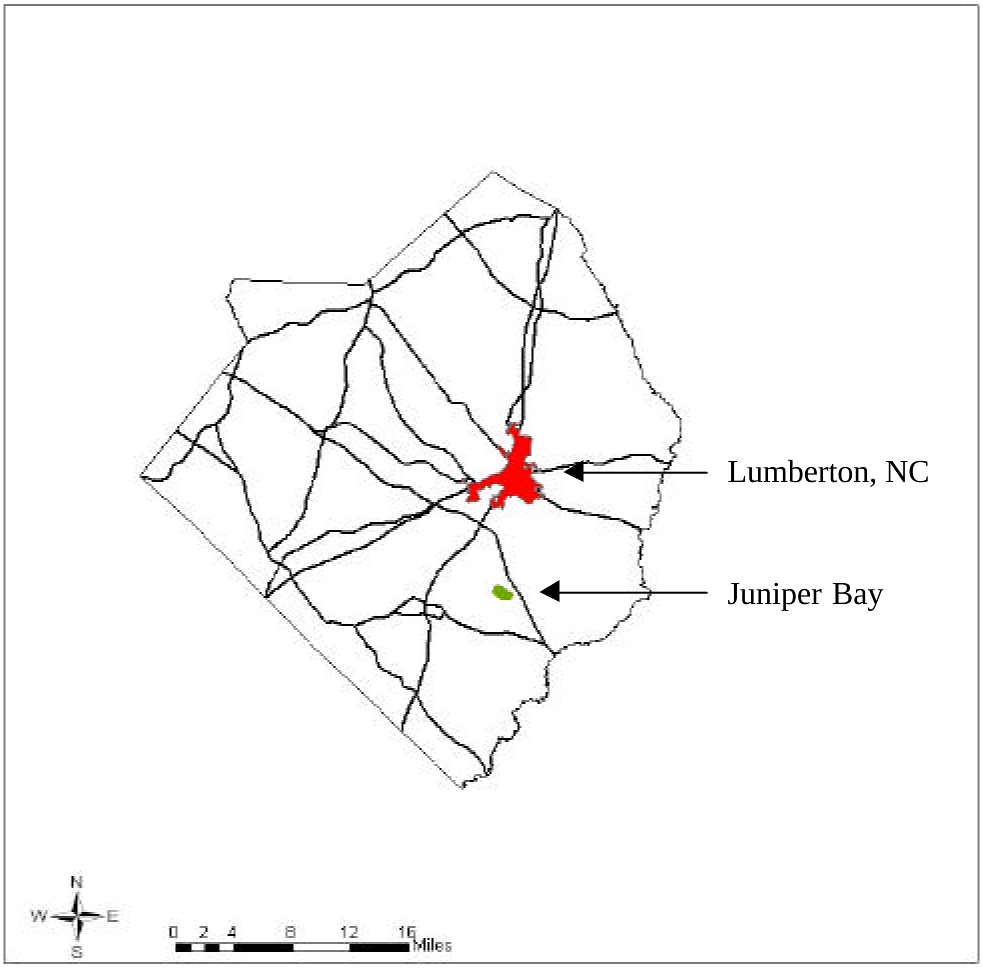

Figure 3. Map of Robeson County showing Juniper Bay location in relationship to Lumberton, NC.

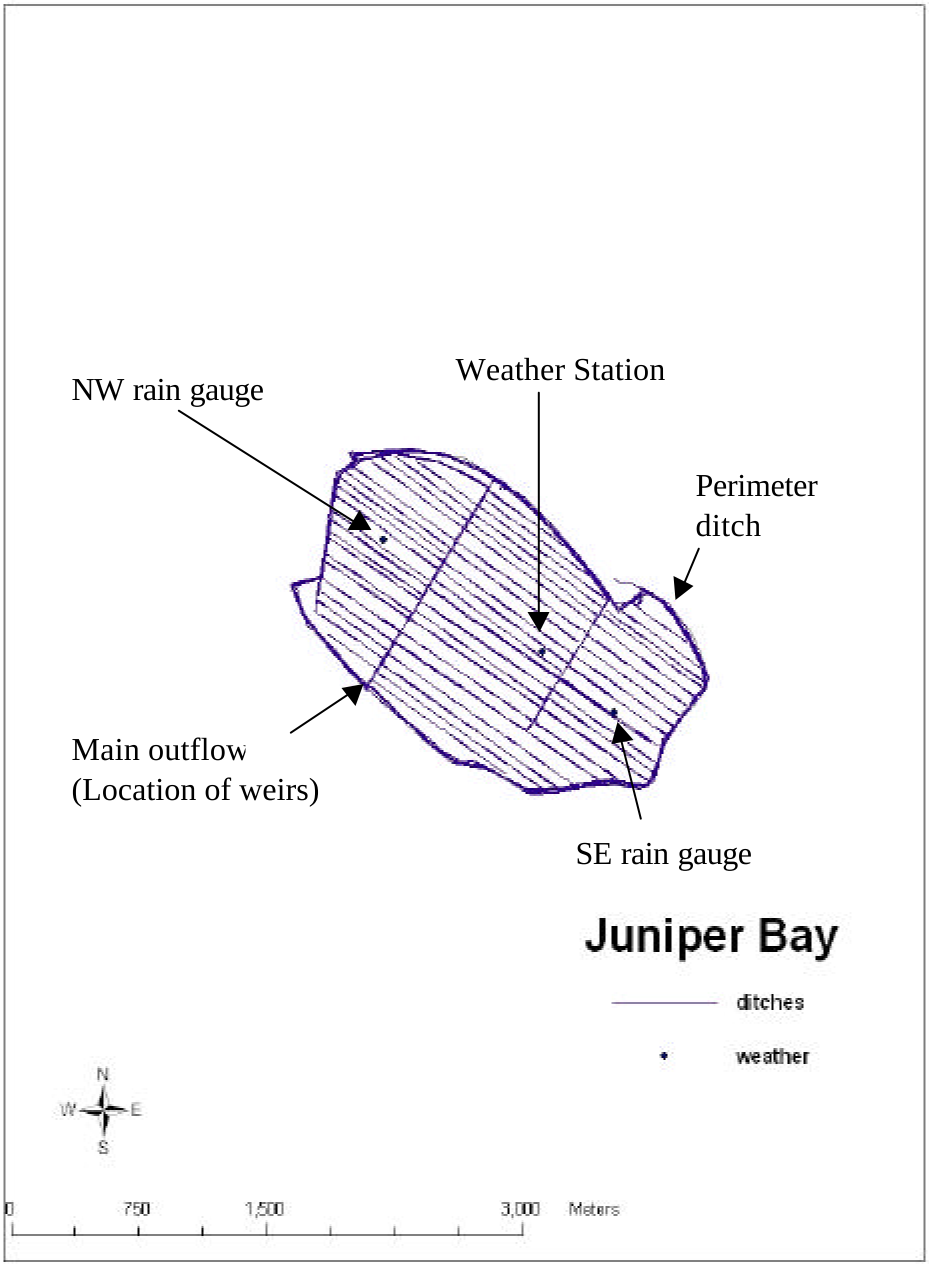

Figure 4: Map of Juniper Bay showing location of instrumentation. There is perimeter ditch and one main outflow ditch. The main outflow point is the location of the weirs. Circles represent location of rain gauges along with the weather station near the center of the bay.

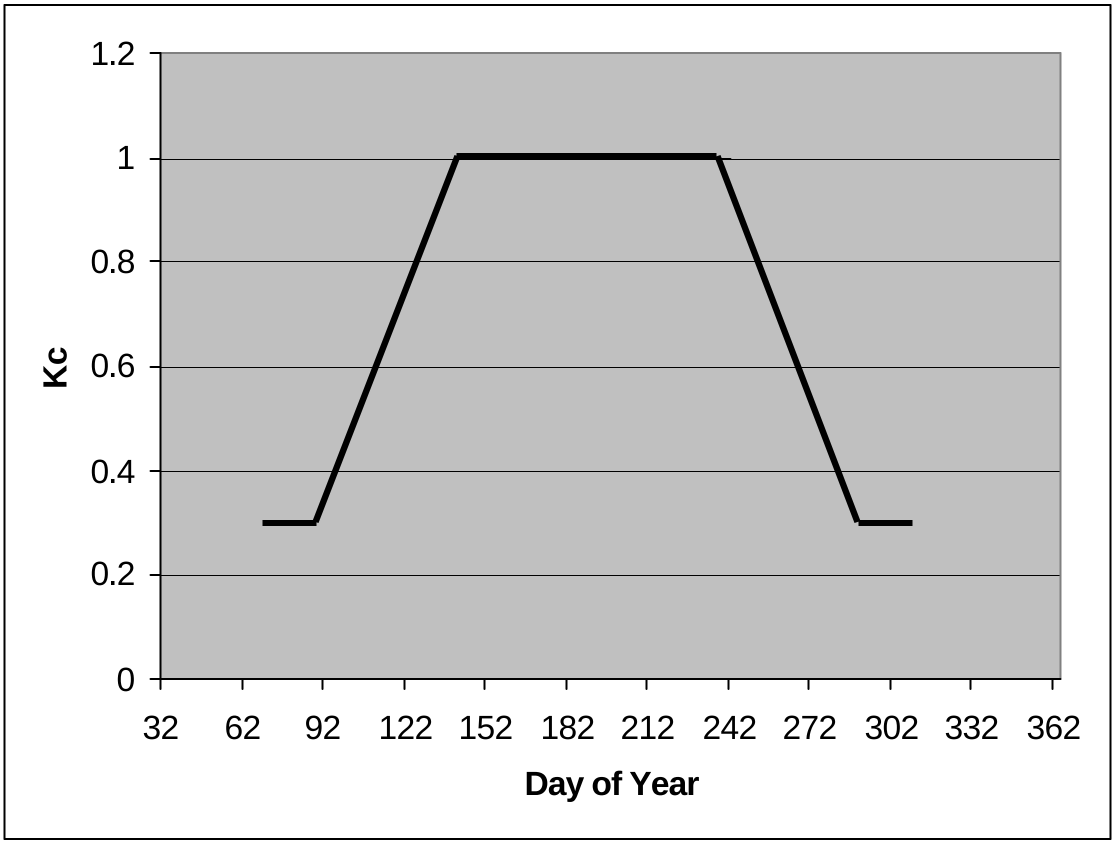

Figure 5. Crop coefficient Curve for Juniper Bay. Constructed using the ASCE Hydrology Handbook procedure. Crop coefficient is used in the $ET_c = ET_o K_c$ equation.

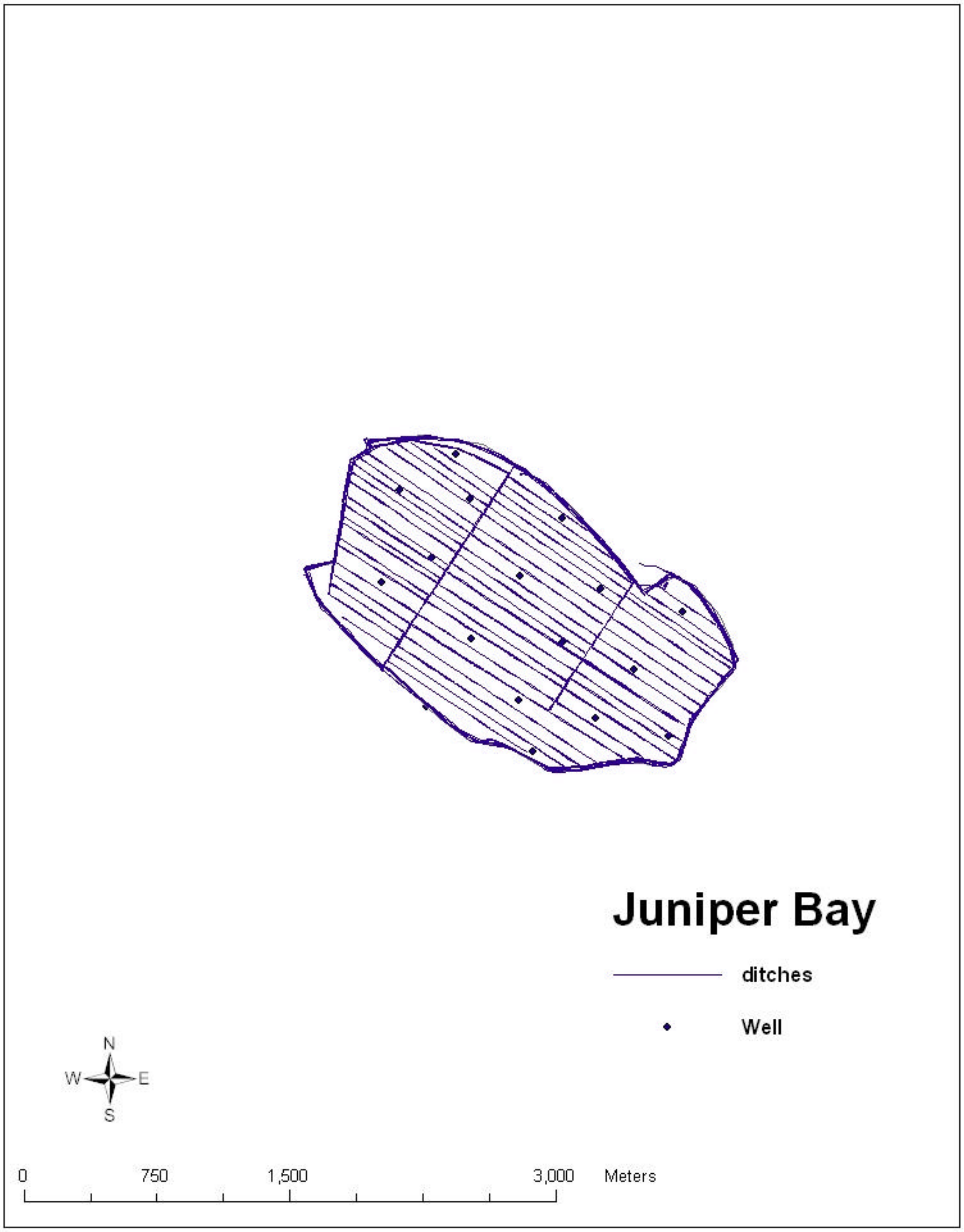

Figure 6. Map of Juniper Bay showing locations of monitoring wells.

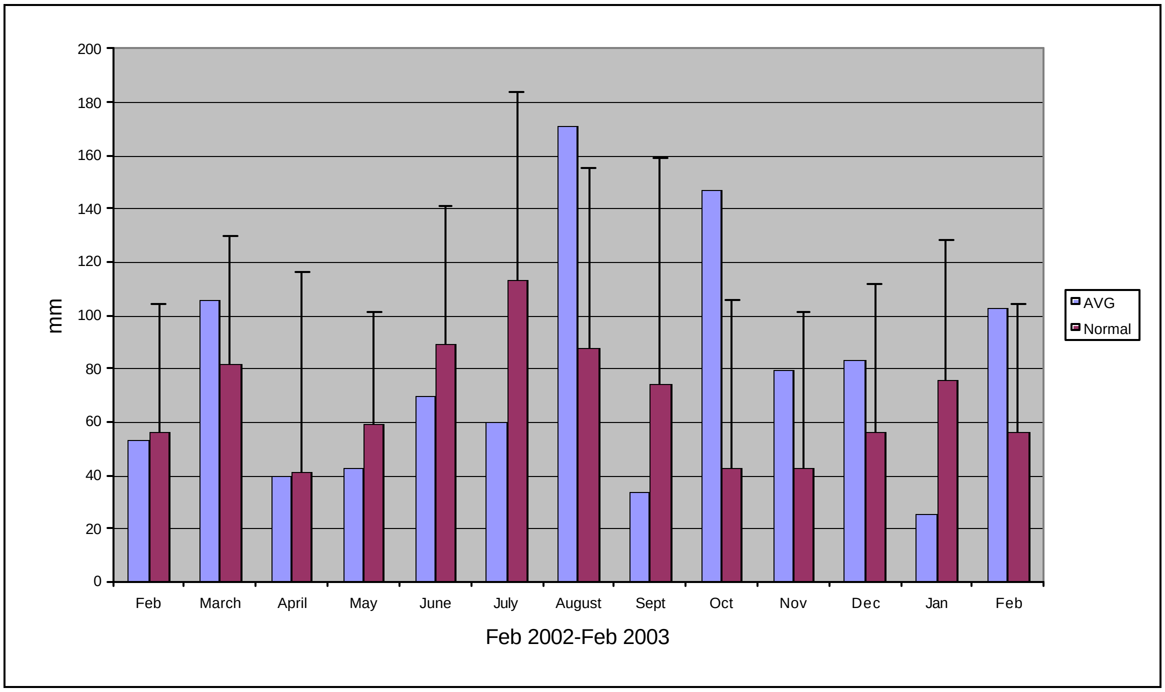

Figure 7. Precipitation totals for each month during February 2002 to February 2003 compared to normal year precipitation totals. Totals are the average of rain gauges at Juniper Bay. Bar in normal year precipitation totals is the maximum values for month during normal year.

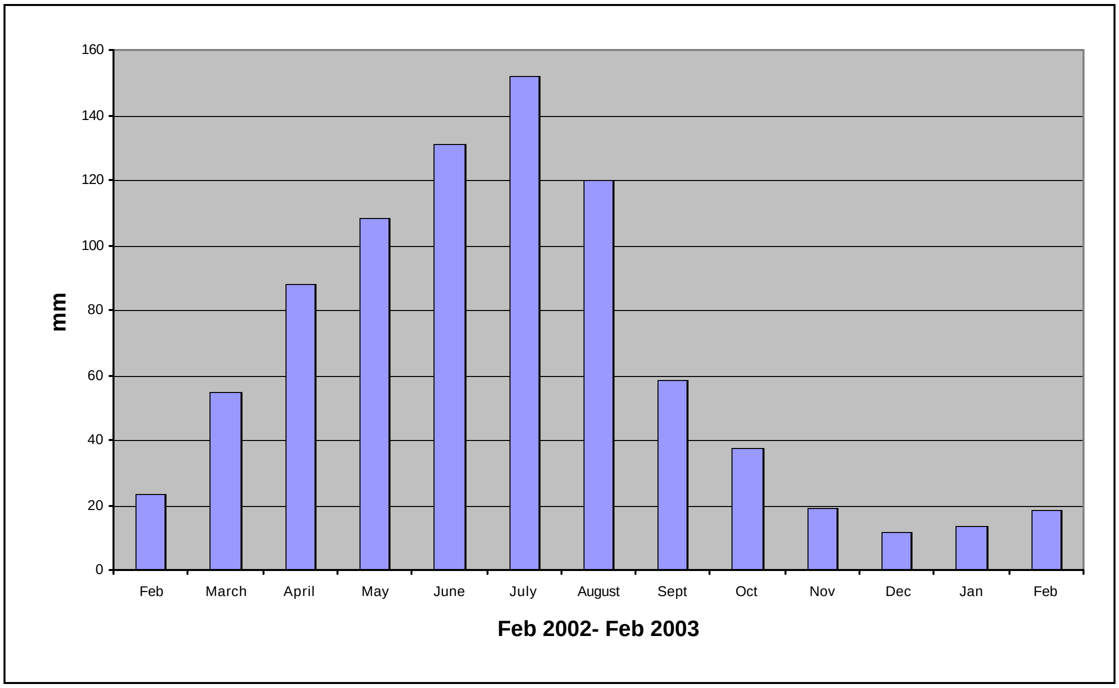

Figure 8. ET totals for each month during February 2002 to February 2003

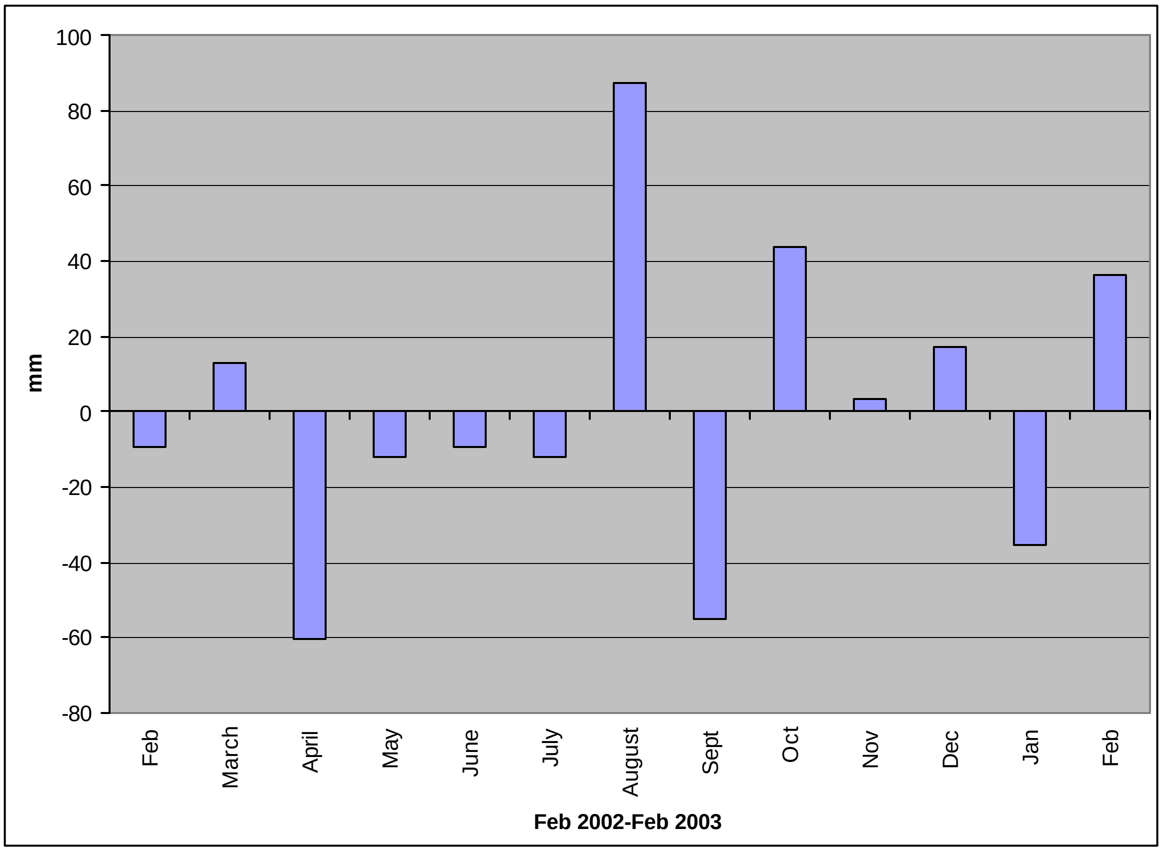

Figure 9. Monthly totals for change in storage at Juniper Bay. Positive numbers indicate a rise in the water table. Negative numbers indicate a fall in the water table.

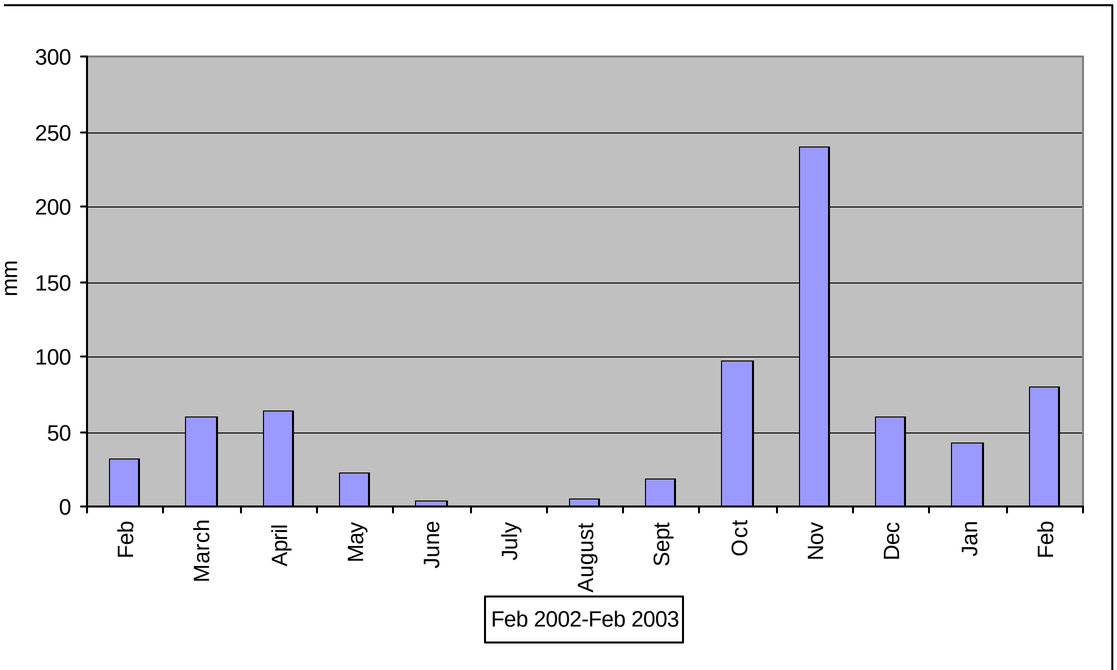

Figure 10. Monthly totals for surface outflow at Juniper Bay.

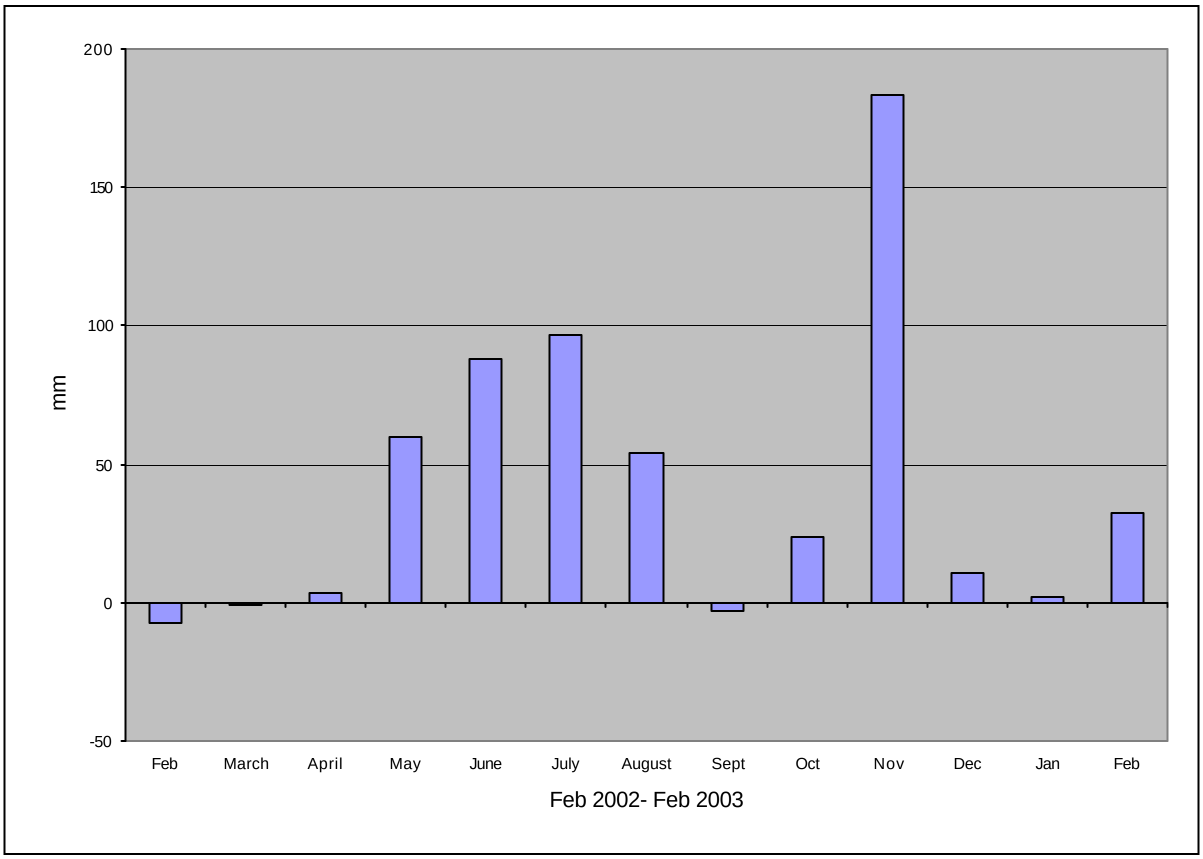

Figure 11. Monthly totals for Net Groundwater at Juniper Bay. Positive numbers indicate Juniper Bay acting as a discharge wetland. Negative numbers indicating Juniper Bay acting as a recharge wetland.

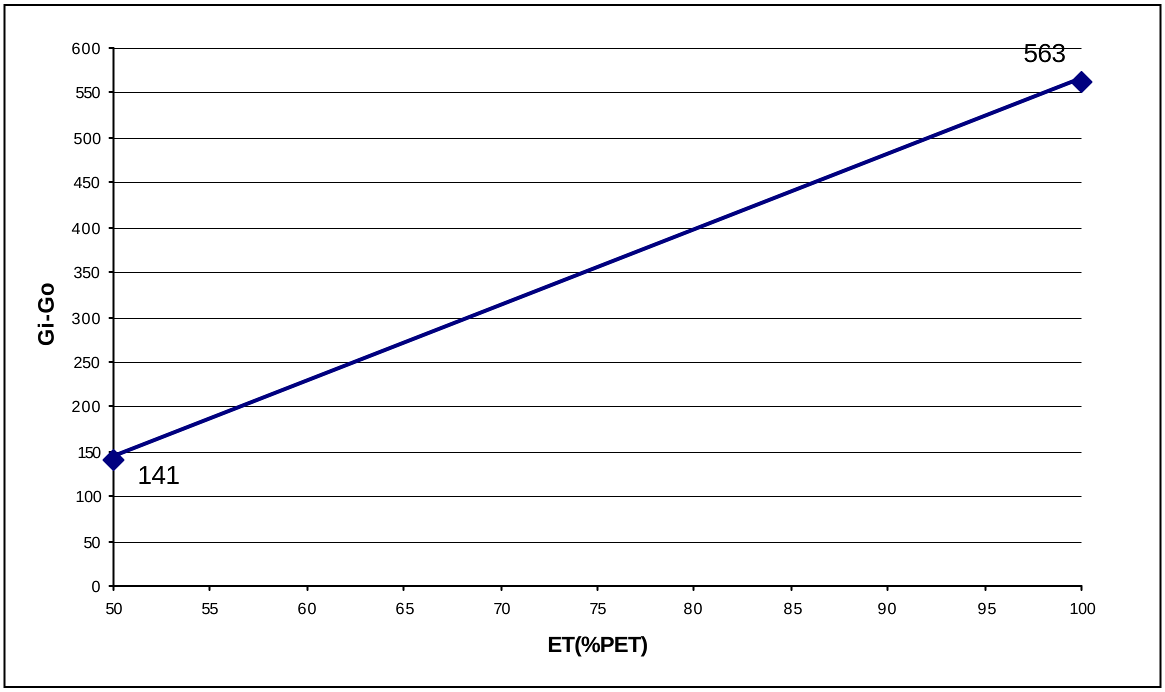

Figure 12. Estimated Net Groundwater versus Evapotranspiration (ET) as a percent of potential evapotranspiration (PET). If PET was off by as much as 50 percent there is still a positive net groundwater. Estimates of ET are needed to compute the water budget, but PET was estimated from meteorological data. Gi-Go is the residual of the water budget equation and is considered the groundwater component.

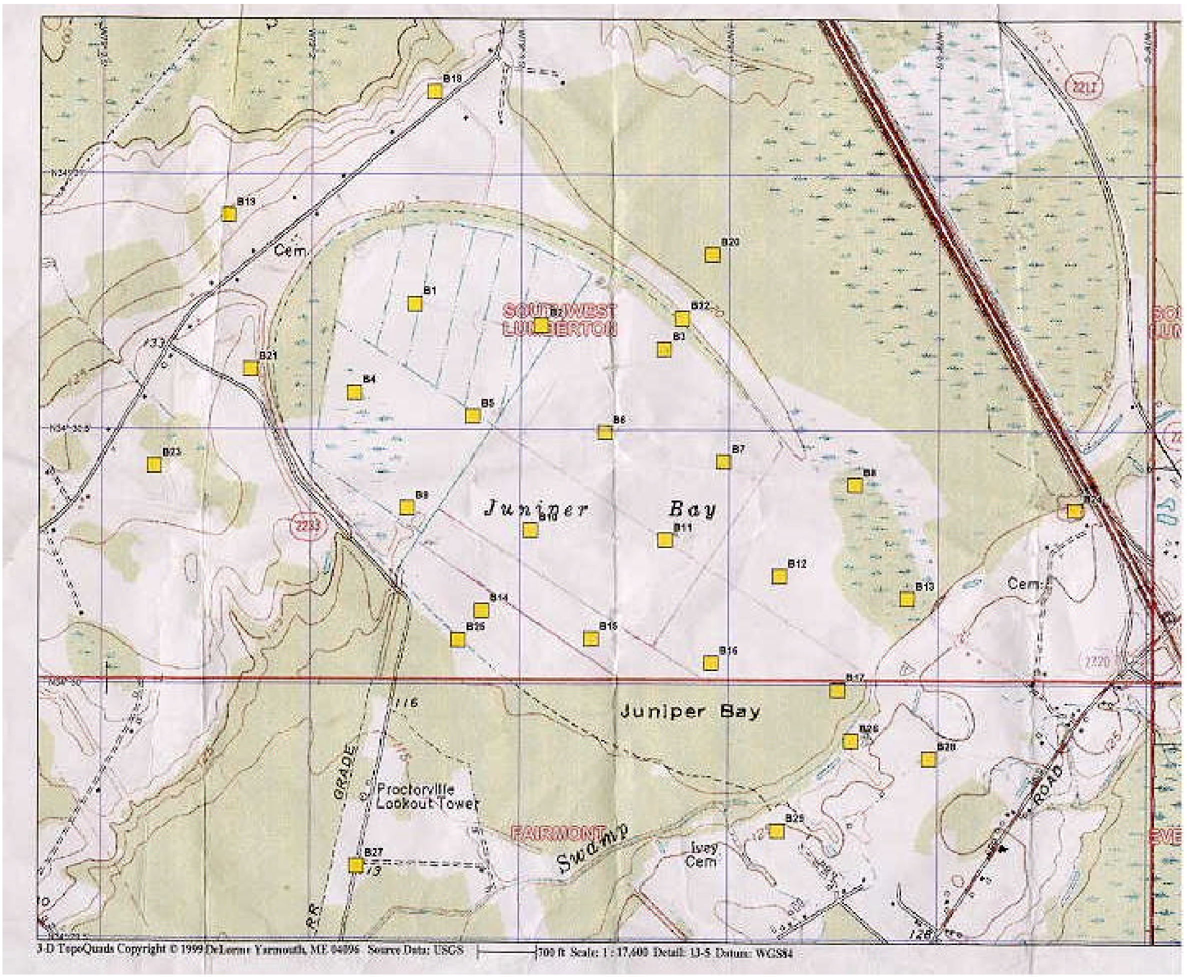

Figure 13. USGS topographical map of Juniper Bay and surrounding area-showing elevation (in feet above sea level). Higher elevations are to east and west and lower elevations are to north and south.

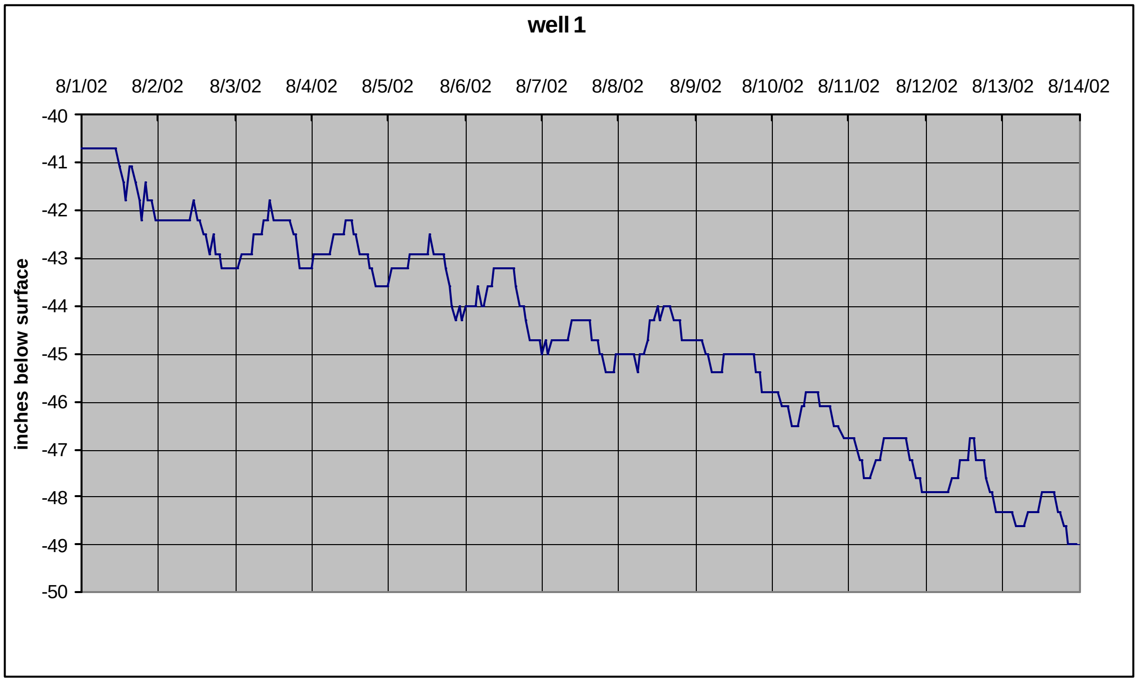

Figure 14. During two-week period of no rainfall, water table indicates ET draw down during the day and replenishing of water by groundwater at night. Well 1 is located in the west, where it is thought that there is possible groundwater inflow.

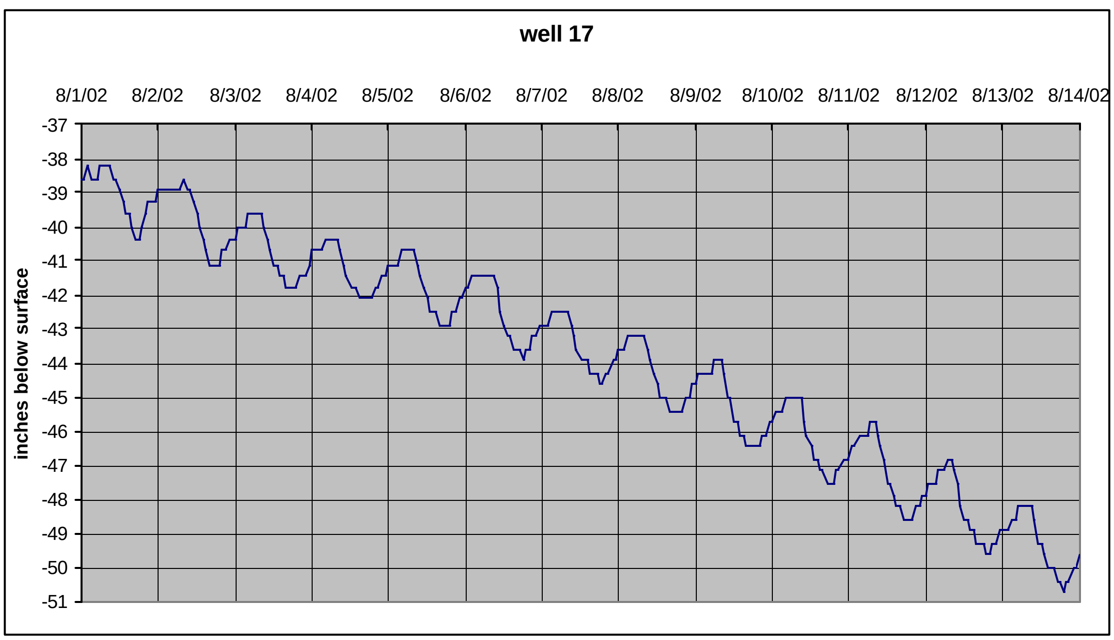

Figure 15. Well 17 located in the eastern part of bay. Also has the cyclic pattern of ET draw down and groundwater inflow.

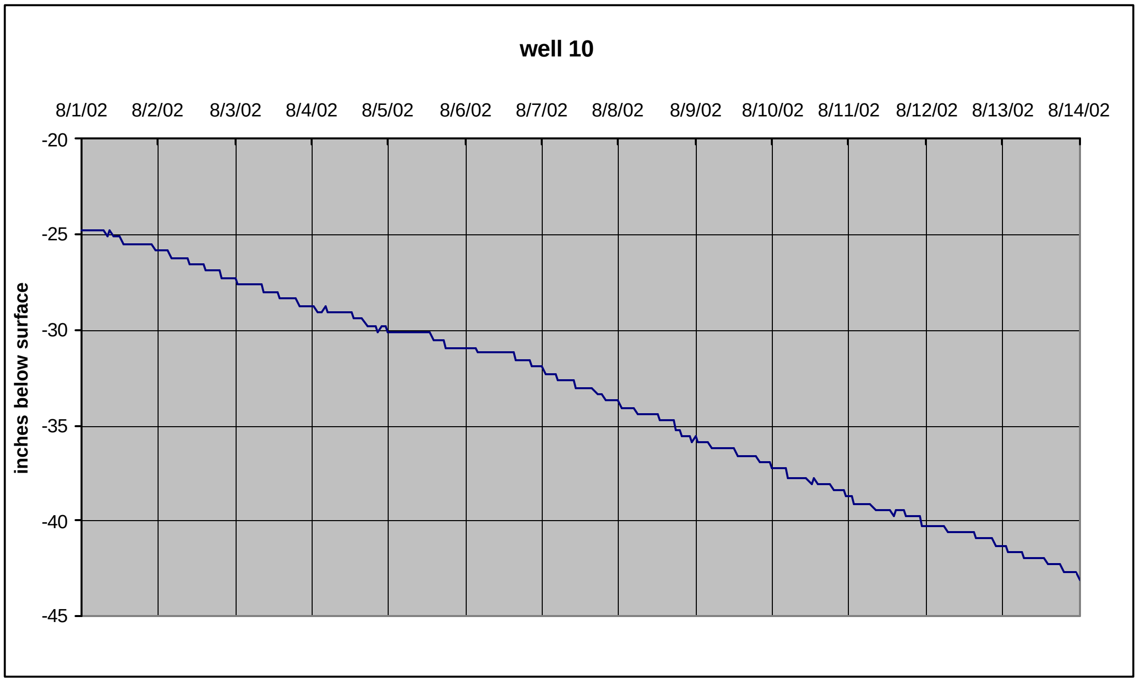

Figure 16. Well 10 located in center of bay. It does not have the cyclic pattern of ET and groundwater inflow indicating that there is no groundwater inflow in center of bay.

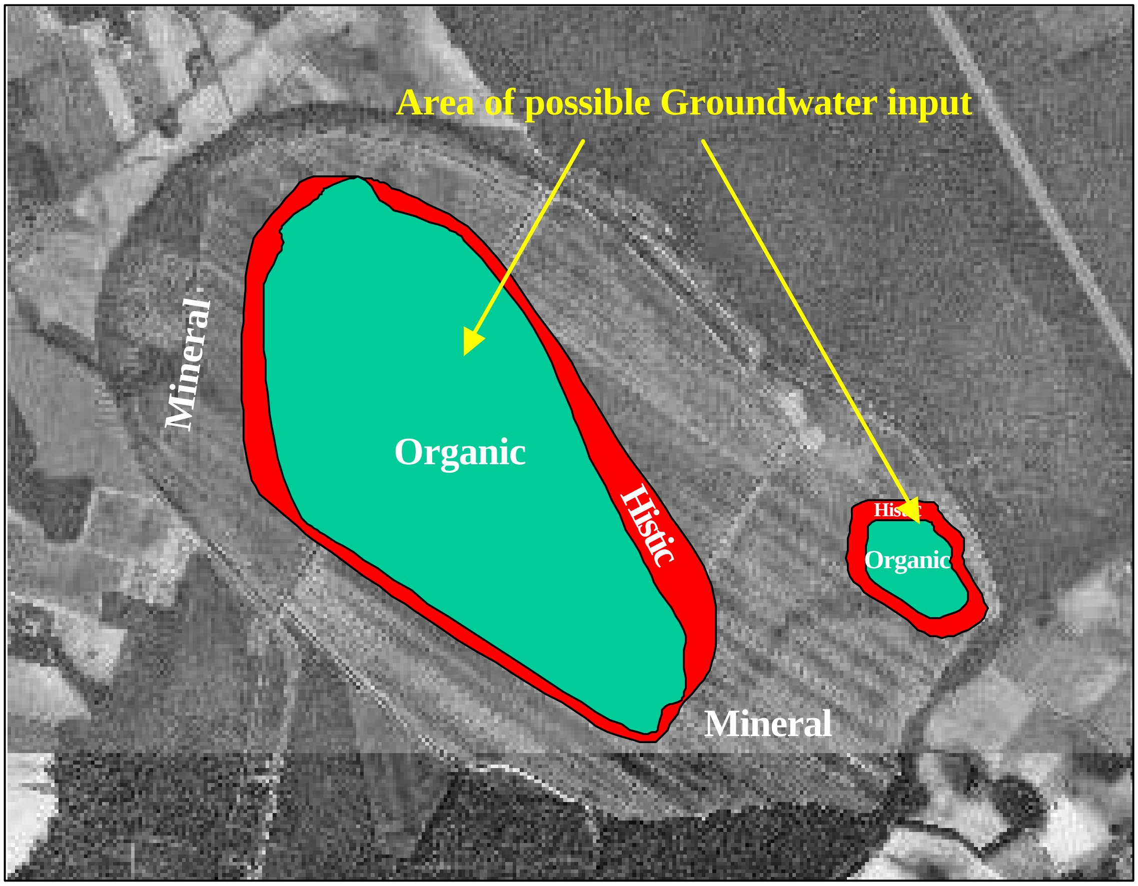

Figure 17. Soil types of Juniper Bay. Areas with organic soils are possible areas with breaks in clay layer allowing for groundwater inflow.

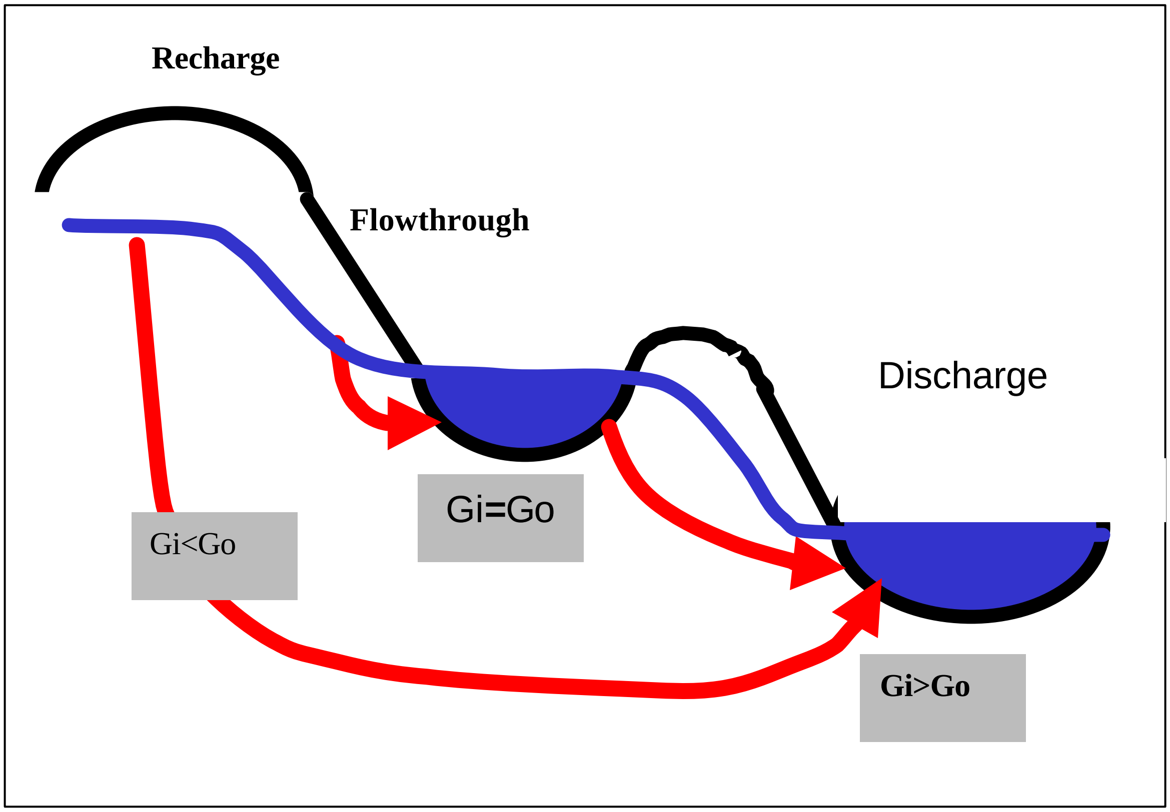

Figure 18. Topographical relationship of Juniper Bay with surrounding area. When Groundwater inflow is less than outflow, there is recharge of the groundwater. When groundwater inflow is greater than outflow, there is a discharge of surface water. Flowthrough situations occur when groundwater inflow and outflow are equal. Juniper Bay is in the intermediate elevation and should be a flowthrough wetland. However, due to the ditch network Juniper Bay is acting as a discharge wetland.

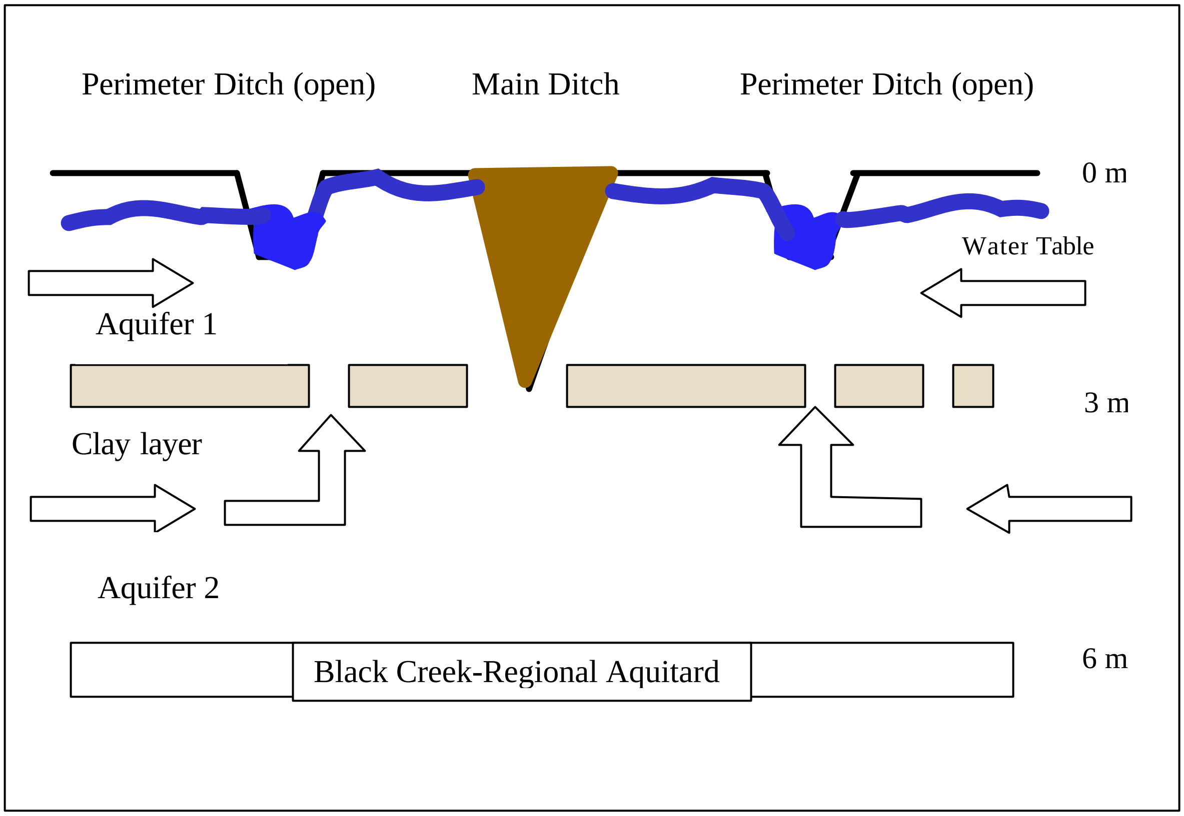

Figure 19. Schematic diagram of Juniper Bay after restoration if the perimeter ditch is left open. Groundwater from Aquifer 1 (Zone 1) will be intercepted by perimeter ditch and leave as surface outflow. Groundwater from Aquifer 2 (Zone 2) will seep into Juniper Bay and restore wetland hydrology.

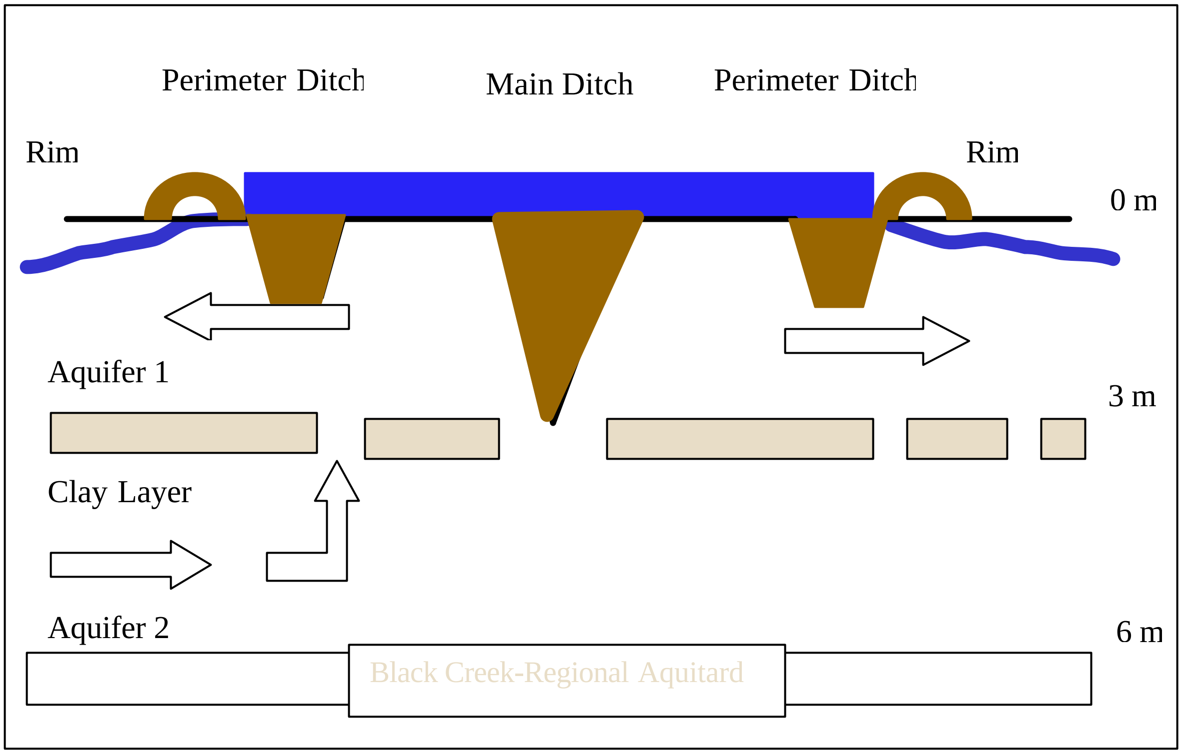

Figure 20. Schematic diagram of Juniper Bay after restoration if perimeter ditch is closed. The water table might rise above the surface of the soil. Since there is no outlet for the groundwater inflow, there could be groundwater outflow that might have offsite impacts.

Chapter 12

HYDROLOGIC EVALUATION OF RESTORATION OPTIONS FOR JUNIPER BAY

G.P. Fernandez, R.W. Skaggs, and M.J. Vepraskas

INTRODUCTION

Carolina Bays are found on the Atlantic Coastal Plain between northern Florida and New Jersey (Lide et al., 1995). They are mostly heavily concentrated in eastern North and South Carolina (Sharitz and Gibbons 1982). Most Carolina Bays are shallow, closed depressions of uncertain origin and usually contain significant areas of wetlands. Normally they function similar to an intermittent pond with water table that fluctuates in response to seasonal or long-term climatic conditions. Hydroperiods can range from permanently flooded to seasonally saturated condition. The topographic gradient in the bays may induce a drainage gradient where higher elevations are excessively drained and lower elevations are poorly or very poorly drained.

The bays are generally elliptical in shape or ovate and may range from less than 50 meters in length to over eight kilometers (Richardson and Gibbons 1993). Despite their abundance (Richardson and Gibbons (1993) estimates their numbers to vary from 10,000 to 20,000), few studies have described their hydrologic regime. Recently, detailed hydrology studies have been conducted to characterize the complex hydrology of Carolina Bays (e.g. Lide et al., 1995; O'ney et al., 1999).

This study examines the hydrology of Juniper Bay, a 705 ac Carolina Bay located in Robeson County in southeastern North Carolina. The main objective of the study is to describe the hydrology of the bay. As part of an ongoing wetland mitigation project of the North Carolina Department of Transportation (NCDOT), this study will document the water table fluctuations in the bay, assess the current hydrologic regime to determine if there are areas within the bay that are jurisdictional wetlands (satisfies the wetland hydrologic criterion under its current condition of land use) and evaluate the various methodologies proposed by NCDOT to restore wetland hydrologic functions in the bay.

BACKGROUND

The North Carolina Department of Transportation (NCDOT) in compliance with Section 404 of the Clean Water Act is mandated to restore wetlands to replace those lands that were altered or destroyed in the course of road construction and maintenance. This study is part of an ongoing wetland restoration project of NCDOT on Juniper Bay, a prior converted Carolina Bay depressional wetland in Robeson County, North Carolina. In cooperation with North Carolina State University, a research study is being conducted to evaluate the various strategies and performance of the restoration of wetland functions within the bay.

Wetland Determination. Land-use regulations require that frequency and duration of saturated conditions be determined to assess if the site satisfies jurisdictional wetland criterion. Several criteria have been proposed for defining the hydrology of wetlands as regulated by Section 204 of the Clean Water Act. Among the criteria given is the 1987 US Army Corp of Engineer Wetlands Delineation Manual (Environmental Laboratory, 1987) which states that wetland hydrology requires an area to be saturated to the surface during the growing season, for a duration between 5% and 12.5% of the growing season with a frequency of at least 5 in 10 years. Saturation to the surface is assumed if the water table is within 30 cm of the surface. Since 1992, the COE wetlands delineation manual has been applied in making Section 404 jurisdictional wetland determinations.

Water table monitoring is commonly used to determine whether or not a site satisfies the wetland hydrologic criterion (Hunt et al., 2001). However, long-term monitoring is usually needed in order make reliable assessment of the hydrology of the site. The variability in climate requires that a longer monitoring period be used in order for results to be representative of normal conditions. Short-duration monitoring is inexpensive and easy to do but it is not guaranteed that the monitoring period represents the normal climatic condition of the site. Hunt et al., (2001) have shown that decisions based on short-term monitoring data may be significantly in error even when weather data appears to be normal for the site.

An alternative approach is to use simulation models to predict water table fluctuations over a long-term period. DRAINMOD is an example of a simulation model that have been applied in wetland hydrologic determinations (Skaggs and Evans, 1990; Hunt et al, 2001). When properly calibrated with site-specific data, the model accurately predicts the water table fluctuations in a given site as demonstrated in various field testing and application (e.g. Skaggs et al., 1981; Skaggs, 1982; Chang et al., 1983; Gayle et al., 1985; Rogers, 1985; Fouss et al., 1987; Susanto et al.,1987; McMahon et al., 1988; Broadhead and Skaggs, 1989; Wright et al., 1992; Cox et al., 1994).

DRAINMOD. The field scale hydrology model, DRAINMOD, simulates water table levels and drainage outflow on a day-to day and hour-by-hour basis (Skaggs, 1978). The model requires precipitation, ET, drainage design parameters, soils and crop data as inputs. The model is generally used to simulate the performance of drainage and related water table management systems over a long period of climatological data. DRAINMOD has been well tested in numerous field experiments on a wide range of soils, crops and climatological conditions (e.g. Skaggs et al., 1981; Skaggs 1982; Fouss et al., 1987). It has been accepted by the USDA Natural Resource Conservation Service (USDA NRCS) as a model for design and evaluation of drainage and sub-irrigation systems in humid regions.

MATERIALS AND METHODS

Site Description

Juniper Bay is located in Robeson County, North Carolina. The bay is approximately elliptical in shape with length of 2.4 km, width of 1.6 and an area of approximately 300 ha (major axis oriented NW to SE). Maximum relief is about 2 m, with the perimeter of the bay at 37 m and the lowest point within the bay at 35 m above mean sea level. The bay was developed for agriculture several decades ago. It was an intensively managed and drained agricultural land up to year 2000 when the restoration project of NCDOT began. It is not currently a jurisdictional wetland due to its status as a prior converted agricultural land.

The organic soil in the bay is predominantly Ponzer Muck. The mineral soils found are Pantego fine sandy loam and Leon sand. NCDOT classified the soils in the bay into three soil mapping units which generally corresponds to the major soil series. According to the NCDOT classification, the mapping units are a) soil unit 1 (SU-1, mostly Ponzer Muck which comprises 36% of the site, b) soil unit 2 (SU-2, mostly Leon sand which is about 50% of the site) and c) soil unit 3 (SU-3, mostly Pantego loam about 13% of the site). About 1% of the area are upland soils. The bay is drained by an extensive network of drainage ditches. These ditches are from 0.6 to 1.8 m deep and spaced from about 60 m to 90 m apart. A perimeter ditch, about 4 m deep and 5 m wide, encircles the bay.

Monitoring of the existing hydrology consists of a network of water table wells installed at regular intervals within and outside the bay (Fig. 1). Two well networks were installed, 18 wells monitored by NCDOT (data collection starting January 2000) and another network installed by NCSU (17 wells inside and 15 wells outside the bay). Data collection for the wells monitored by NCSU started in March 2001. Water tables are monitored hourly to depths of 2 m using RDS automatic monitoring wells (Remote Data Systems, Inc., Wilmington, NC). Rainfall is also measured at the bay using automatic recording gauges. A weather station is located near the center of the bay where hourly climatic data (rainfall, air temperature, humidity, solar radiation and other weather parameters) are measured and recorded.

DRAINMOD **Modeling**

DRAINMOD was calibrated using three years of observed data and water table measurements collected at six well locations within the bay. Six sites (well locations) were selected to be representative of the major soils within the bay. The model was calibrated separately for each site using site-specific drainage parameters (e.g. drain spacing and depth) and soil parameters. Drain spacing and drain depths for each site were obtained from air photos and NCDOT survey. Soil water characteristics, saturated hydraulic conductivity and other soil properties were also determined from soil cores obtained near the location of the wells. A composite rainfall data file was generated and used in the model. The composite file consisted of observed data from two recording gauges in the bay and from the weather station at Lumberton, NC. There were gaps in the rainfall data collected on the site. Missing data from the recording gauges in the bay were filled in with the data from the Lumberton weather station. The calibration procedure involves the minimization of the mean absolute water table difference between the observed and model predictions.

Long-term simulations (1950-2001) were conducted using the calibrated model parameters and weather data from Lumberton, NC to characterize the hydroperiods of the sites. The hydroperiod, as defined here, is the saturation period when water table was within 30 cm of the surface continuously for a number of days, either at 5% or 12.5% of the growing season. The growing season in Robeson County is from March 14 to November 14 (246 days). The number of wet years (hydroperiods equal to or greater than one) was of interest in characterizing the hydrologic status of the bay based on historic weather data. Following the hydrologic wetland criterion, a site would be considered to have ‘wetland hydrology’ if more than half of the years qualify as ‘wet years’. That is, a site is considered to have wetland hydrology if the hydrologic criterion is satisfied in more than 50% of the years. Evaluation of the hydrologic status prior to implementing wetland restoration methodologies is important as baseline conditions to evaluate the effectiveness of wetland restoration.

Hydrologic restoration methods proposed for Juniper Bay includes filling the lateral ditches or placing plugs at specific intervals in the drainage ditches. Several surface management treatments are proposed in the NCDOT project. They include retaining the crowned surfaces and roughing the surface to form natural depressions. The key question that needs to be addressed is how will the proposed treatments affect the water table hydroperiods. In addition, effects of the treatments on soil properties, the establishment of wetland vegetation and the desired community structure need to be addressed.

Long-term DRAINMOD simulations (52 years) were conducted to evaluate the effectiveness of the proposed wetland restoration methodologies. Results of the simulations were summarized in terms of the number of wet years. The methods evaluated are described below along with a brief description of how the treatment is simulated with DRAINMOD:

a) Ditch filling, no crown – simulated with a shallow drain depth (e.g. 5 cm)
b) Ditch filling, with crown – simulated with a 30 cm drain depth
c) Ditch filling, no crown, increased surface storage – simulated similar to method a but with increase surface storage (e.g. 2.5 cm).
d) Ditch filling, with crown, increased surface storage – simulated similar to method b but with increase surface storage (e.g. 2.5 cm).

Filling the ditches without removing the field crown effectively decreases the subsurface drainage from the site resulting in frequent shallow water tables in response to rainfall events. Increasing surface storage generally decreases surface runoff and may cause water to pond on the surface. This then increases the available water for infiltration that will result in a consequent rise in water table by an amount dependent on the drainable porosity of the soil. The effect of ditch filling or plugging ditches and surface treatments is not straightforward. The combined effect depends on soil properties and drainage system design among others.

RESULTS AND DISCUSSION

Water Table Fluctuations

Figure 2 shows the water table fluctuations of the six wells used in this study for the period from January 2000 to November 2002. The water table fluctuations are generally dependent on the location of the wells, the drainage system in place and the soils of the site. Wells located on higher elevations have water table drawdowns (e.g. wells 2 and 3) as deep as 80 to 95 cm. Even during wet periods, the water table does not stay on the surface for a long time. In contrast, wells in lower elevations have longer periods of saturation, with water tables near or at the surface for long periods, and maximum water table drawdown 70 to 80 cm (e.g. wells 10 and 16). Water table fluctuations of the well in soil unit 2 are similar to the responses of the wells in soil unit 1. However, water tables in soil unit 1 frequently rose to the surface and stayed much longer. In contrast, the frequency of water tables rising to the surface in wells 2 and 3 (soil unit 3) was much less than for the wells in soil units 1 and 2. Well 16 was an exception because it is located in a relatively low elevation compared to wells 2 and 3. The fluctuation in water tables is of course dependent not only on the soil properties of the site but also on the drainage system, as well as, surface cover and rooting depths. As shown by the three years of data, the temporal fluctuations of the water tables within the bay are also spatially variable. The spatial distribution has to be accounted for when implementing wetland restoration methodologies.

DRAINMOD Simulations

DRAINMOD was calibrated with water table data for 2000 and validated with the 2001-2002 data. Figures 3 to 8 show the predicted and observed water tables for six wells (wells 10 & 11 in soil unit 1, Figs. 3 & 4; well 6 in soil unit 2, Fig. 5; and wells 2, 3 & 16 in soil unit 3, Figs. 6 to 8). The plots show that the model predictions are comparable to observed water tables for all the wells. The water tables in soil unit 1 (wells 10 & 11, Figures 3 and 4) were adequately predicted. However, there are errors in predictions during the later part of 2001 and early 2002 where the model under predicted the observed water tables. The rainfall events during the early part of 2002 brought the observed water tables to the surface. During this period, the water table was within 30 cm of the surface. Although the predicted response of water table to the rainfall events was similar to the observed, predicted drawdown during this period was greater. This can be explained by the installation of a control structure in late 2001 in the lateral ditch located near the ditches where the wells are located. The control structure resulted in higher water levels in the ditches that reduced the subsurface drainage outflow from the fields near the structure. More work on the model inputs is needed to consider this effect.

The predictions of the water tables in the wells of soil unit 2 (well 6, Fig. 5) and soil unit 3 (wells 2, 3 and 16, Figs. 6 to 8) were much better than the predictions in soil unit 1. Except for well 16 where the control structure has a pronounced effect, predictions for the other wells especially during the later part of 2001 and early 2002 were much better. Wells 2 and 3 are located on a higher elevation than the other wells. Water tables for these wells, especially during 2001 and 2002, were much deeper than for the other wells. The water table rarely rose to the surface in response to rainfall events.

Table 1 shows the statistics for goodness-of-fit of the predictions. In all cases, predictions of water table for all wells and for all years are within 9 cm of the measured water tables. Absolute error of prediction ranges from 8 cm to 13 cm. There is variability in prediction errors from year to year. The variability may be due to errors in rainfall measurements, estimation of potential ET, and spatial variability of rainfall.

Wetland Determination

Using the calibrated DRAINMOD parameters, long-term simulations (1950-2001) were conducted for each site using the weather data from Lumberton weather station. DRAINMOD simulations were conducted for each well location to characterize the hydroperiods of each site. The number of 'wet years' was determined. The analysis was conducted to assess whether the sites meet the wetland hydrologic criterion under current condition of land use. Simulations were conducted for both the 5% and 12.5% criterion. For a growing season of 246 days (day 73 to day 318), the 5% criterion requires that the water table be within 30 cm of the surface continuously for 13 days in 26 or more years of the 52 years simulation period. Similarly, the 12.5% criterion requires 31 days of continuous saturation.

Table 2 summarizes results of the long-term simulations. The table shows the number of years that the well location satisfies the 5% or 12.5% criterion. For example, at the 12.5% criterion, the water table at well 6 is within 30 cm of the surface continuously for 31 or more days in 6 out of 52 years. Based on the 5% criterion, only well 10 and 11 satisfies the hydrologic wetland criterion. Wells 10 and 11 are located in a relatively low elevation compared to the other wells. However, if the 12.5% criterion is used, simulation results indicate that all the well locations do not satisfy the hydrologic wetland criterion under current condition. It is important to determine the hydrologic status of the bay prior to wetland restoration. If analysis indicates that majority of the areas within the bay satisfy the wetland hydrologic criteria, NCDOT will not get full credit for their wetland restoration efforts.

Evaluation of Wetland Restoration Methods

DRAINMOD simulations were conducted to evaluate various methods proposed for restoring the hydrology of Juniper Bay site to a condition that would satisfy wetland hydrology. Results of the simulations are summarized in Table 3. All the sites within the bay that were evaluated will satisfy the hydrologic wetland criterion (at 12.5%) if field ditches are plugged or filled, field crowns are removed and surface storage is increased (Table 3). Filling or plugging the ditches without removing the crown will not be sufficient to restore wetland hydrology for any of the sites studied. On average, the frequency of saturation would only be around 35% for sites in the lower elevation (wells

10 & 11). For sites in the higher elevation such as wells 2 and 3, the frequency of saturation would be much lower at 4%. A dramatic increase in frequency of saturation is obtained if surface storage in the sites is increased and field crowns are not removed. Although sites in the higher elevation (wells 2 and 3) would still not satisfy the hydrologic wetland criterion at 12.5%, the frequency of saturation of the sites in the lower elevation (wells 10 and 11) increases to 78%.

If the criterion was based on water table within 30 cm of the surface for 5% of the growing season, ditch filling with field crowns would be sufficient to restore the hydrology of the bay to wetland conditions (Table 3, last line). The predicted frequency of saturation ranged from 73% to 96%. These results demonstrate the importance of the criterion on the methods that must be used to implement wetland restoration.

SUMMARY AND CONCLUSIONS

This study documents the water table fluctuations in several sites within Juniper Bay, a prior converted agricultural land. Monitoring data for three years (2000-2002) indicated considerable spatial variation in the temporal patterns of the water table fluctuations. Sites at lower elevations have water tables frequently rising to the surface or within the top 30 cm of the surface in response to rainfall events. Moreover, the duration of saturation is much longer. This is in contrast to sites at higher elevations. In addition to topographic differences, water tables were affected by soil properties and drainage system characteristics.

DRAINMOD was calibrated with observed water table data for three years and site-specific parameters. Using the calibrated parameters, long-term simulations were conducted to characterize the long-term variations in water table levels under current condition of land use and drainage characteristics. The long-term simulations indicated that, under current conditions, the six sites considered do not satisfy the hydrologic criterion for wetlands if the duration is based on 12.5% of the growing season. On the other hand, if the criterion were based on 5% of the growing season (13 days), sites at the lower elevations (represented by wells 10 and 11 in the organic soils) would satisfy jurisdictional wetland status under current conditions.

Evaluation of the various restoration methodologies showed that, in order to satisfy the 12.5% criterion for all sites, the drainage ditches would have to be filled or plugged, field crowns would have to be removed and the surface roughness increased such that surface storage exceeds 2.5 cm. If the hydrologic criterion was based on 5% of the growing season, filling or plugging the ditches even with field crown, would be sufficient to restore all the sites to wetland hydrology. In all these analyses, it was assumed that deep or lateral seepage has insignificant impact on the water table fluctuations.

Continued research is needed in the treatment phase of the project to determine if the model accurately predicted the effects of filling the ditches on water table depths and wetland hydrology. Future work will consider all of sites in the bay for both pre-treatment and post-treatment conditions.

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Table 1. Statistics for goodness-of-fit of the predicted water tables for 2000-2002.

	Well 2	**Well 3**	**Well 6**	**Well 10**	**Well 11**	**Well 16**
	Error, cm					
2000	1.8	5.0	-1.4	-9.4	-1.6	-4.2
2001	-11.6	-2.4	1.2	-7.7	-7.7	-11.9
2002	2.1	1.2	-1.7	-5.2	-7.6	-8.2
2000-02	-3.0	1.1	-0.6	-7.4	-5.6	-8.3
	Absolute Error, cm					
2000	6.6	8.6	6.6	12.2	7.2	8.5
2001	15.8	9.2	8.5	10.1	10.1	17.0
2002	7.3	6.6	9.5	12.2	14.0	15.2
2000-02	10.2	8.2	8.2	11.5	10.5	13.8

Table 2. Number and percentage of wet years in 52 years of simulation.

	Soil Unit 3			***Soil 2***	***Soil Unit 1***	
	Well 2	**Well 3**	**Well 16**	**Well 6**	**Well 10**	**Well 11**
5 % (13 days)	5 (10%)	6 (12%)	20 (38%)	21 (40%)	***37 (71%)***	***37 (71%)***
12.5% (31 days)	0	0	0	0	6 (12%)	4 (8%)

Table 3. Number and percentage of wet years in 52 years of simulation (12.5% or 31 days saturation).

	Soil Unit 3			***Soil 2***	***Soil Unit 1***	
Treatment	**Well 2**	**Well 3**	**Well 16**	**Well 6**	**Well 10**	**Well 11**
Ditch Fill, with crown	2 (4%)	2 (4%)	2 (4%)	6 (12%)	19 (33%)	17 (37%)
Ditch Fill, no crown	10 (19%)	10 (19%)	3 (6%)	10 (19%)	22 (42%)	23 (44%)
Ditch Fill, with crown, surface storage = 2.5 cm	17 (33%)	17 (33%)	23 (42%)	20 (38%)	***40 (77%)***	***41 (78%)***
Ditch Fill, no crown, surface storage = 2.5 cm	***31 (60%)***	***31 (60%)***	***32 (62%)***	***33 (63%)***	***43 (83%)***	***45 (87%)***
Ditch Fill, with crown, at 5% (13 days)	***42 (81%)***	***38 (73%)***	***38 (73%)***	***43 (83%)***	***50 (96%)***	***50 (96%)***

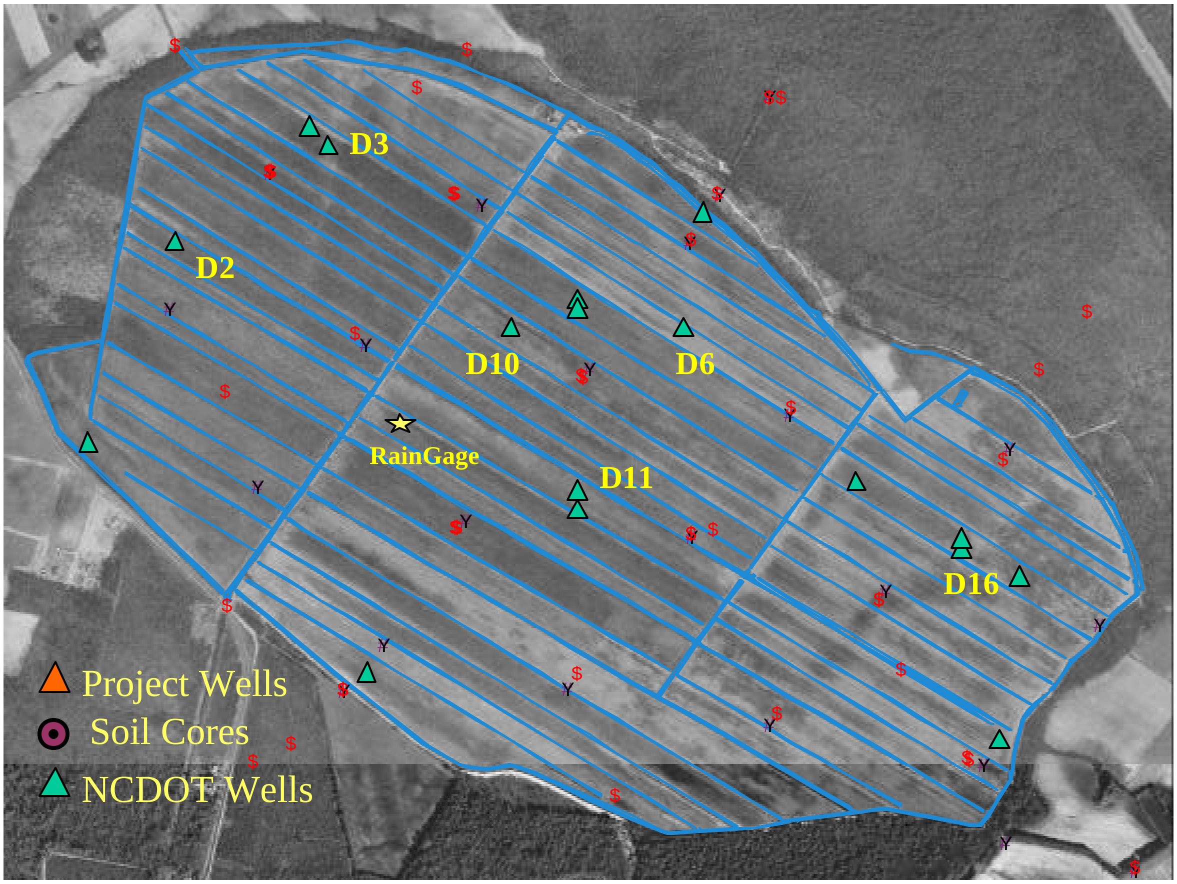


Figure 1. Juniper Bay with the network of monitoring wells and soil core locations. The D labeled wells were used in the study.

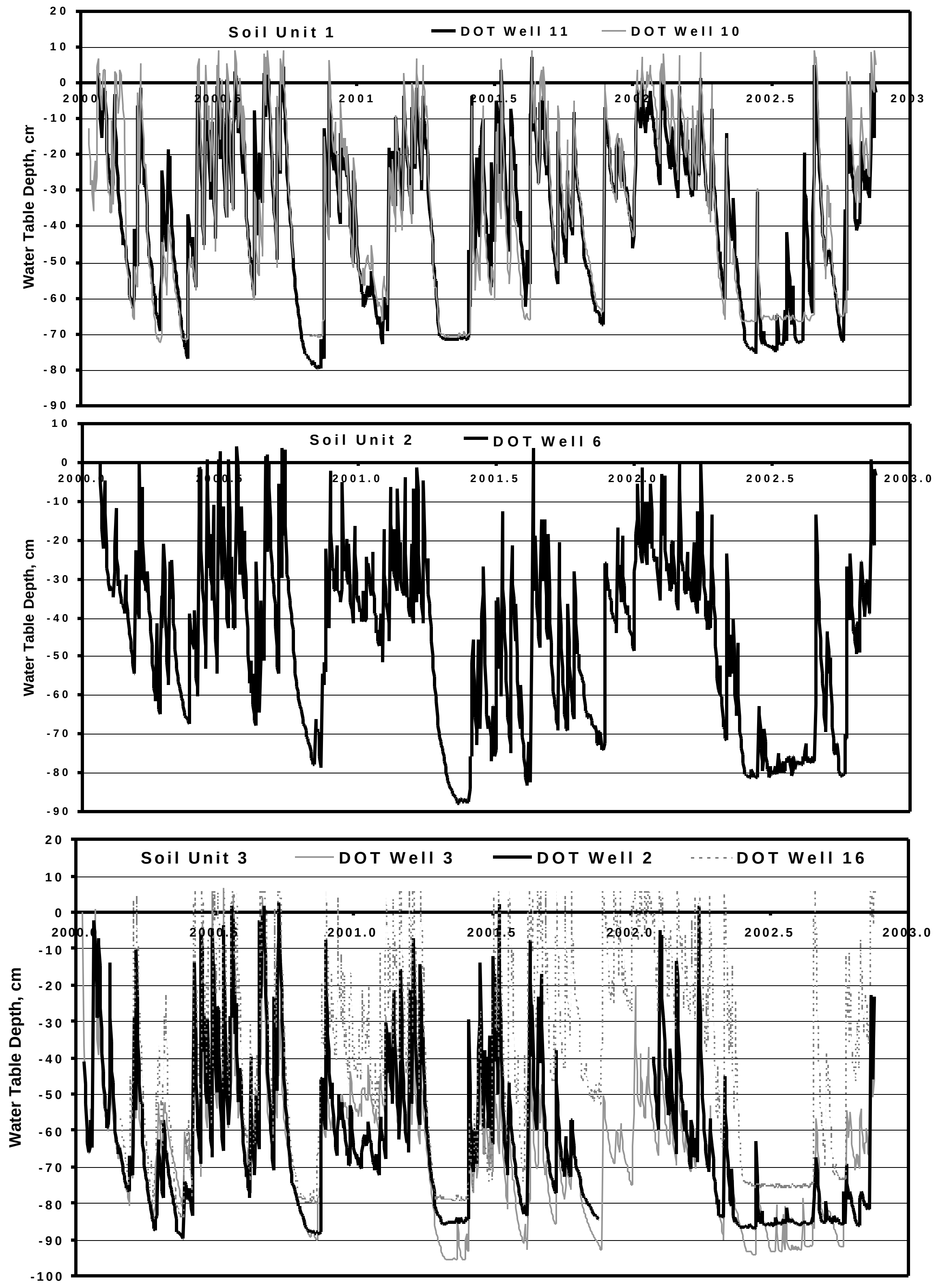


Figure 2. Water table fluctuations from January 2000 to November 2002 at six wells in Juniper Bay.

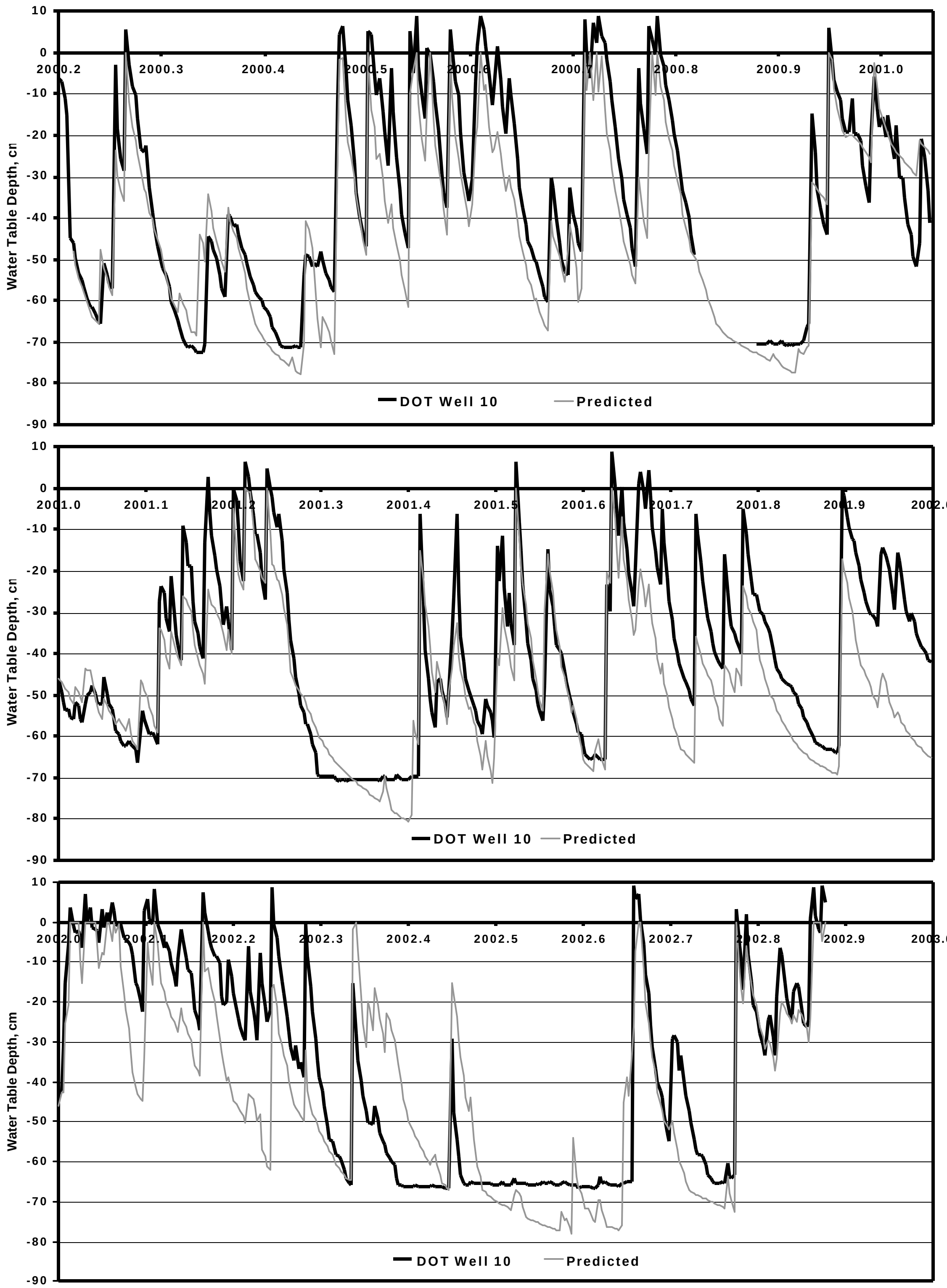


Figure 3. Observed and predicted water table depth at well 10 in Soil Unit 1.

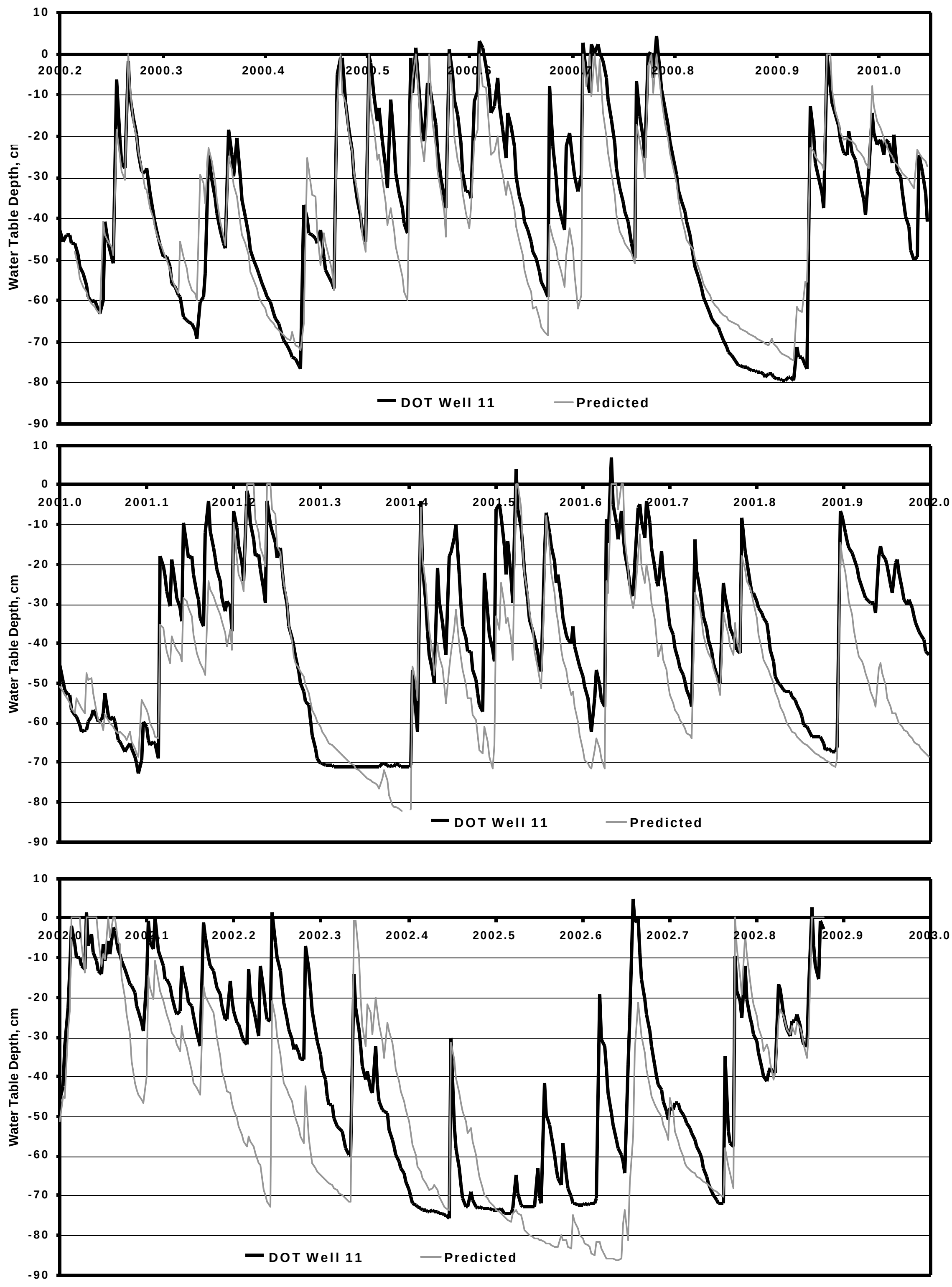


Figure 4. Observed and predicted water table depth at well 11 in Soil Unit 1.

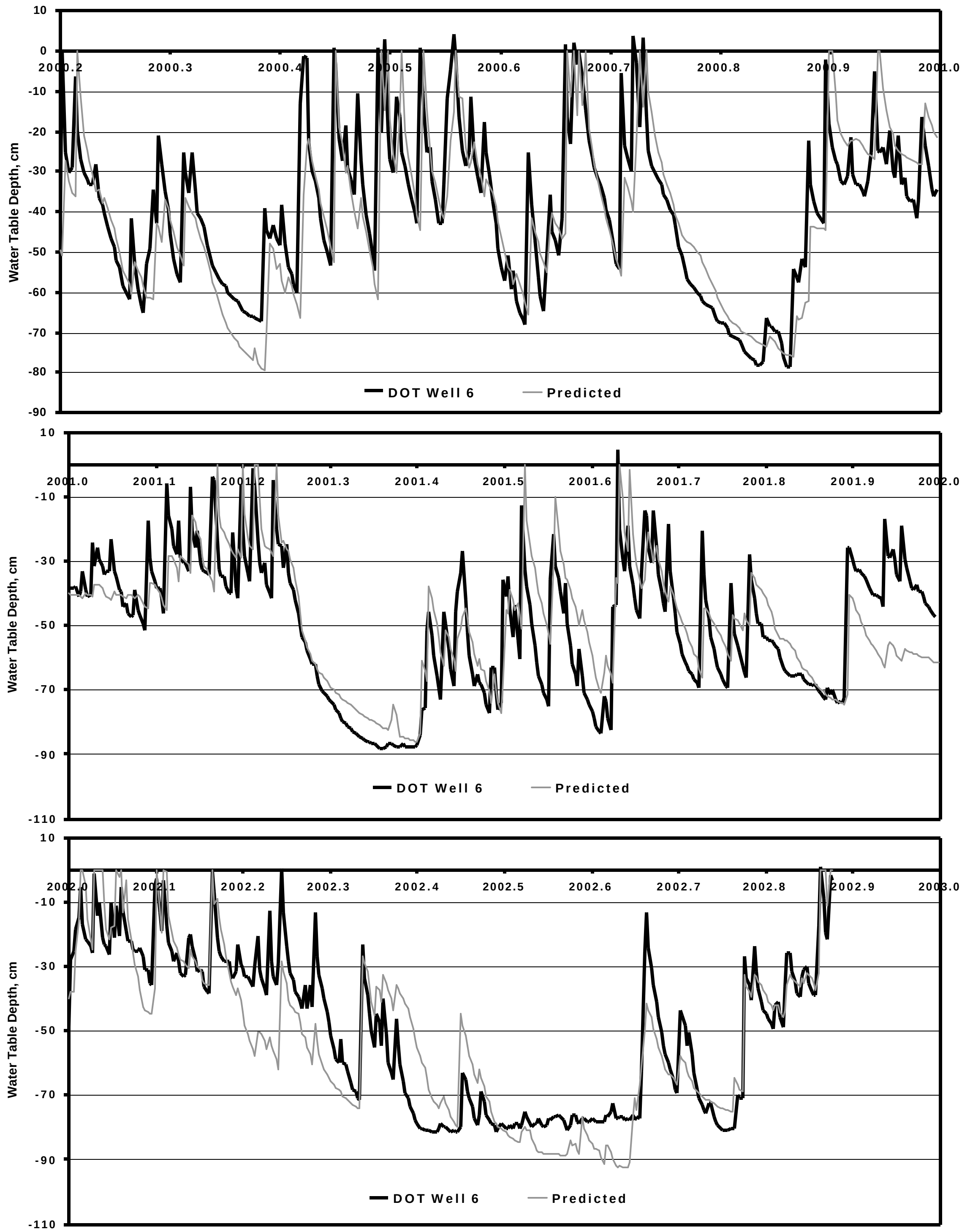


Figure 5. Observed and predicted water table depth at well 6 in Soil Unit 2.

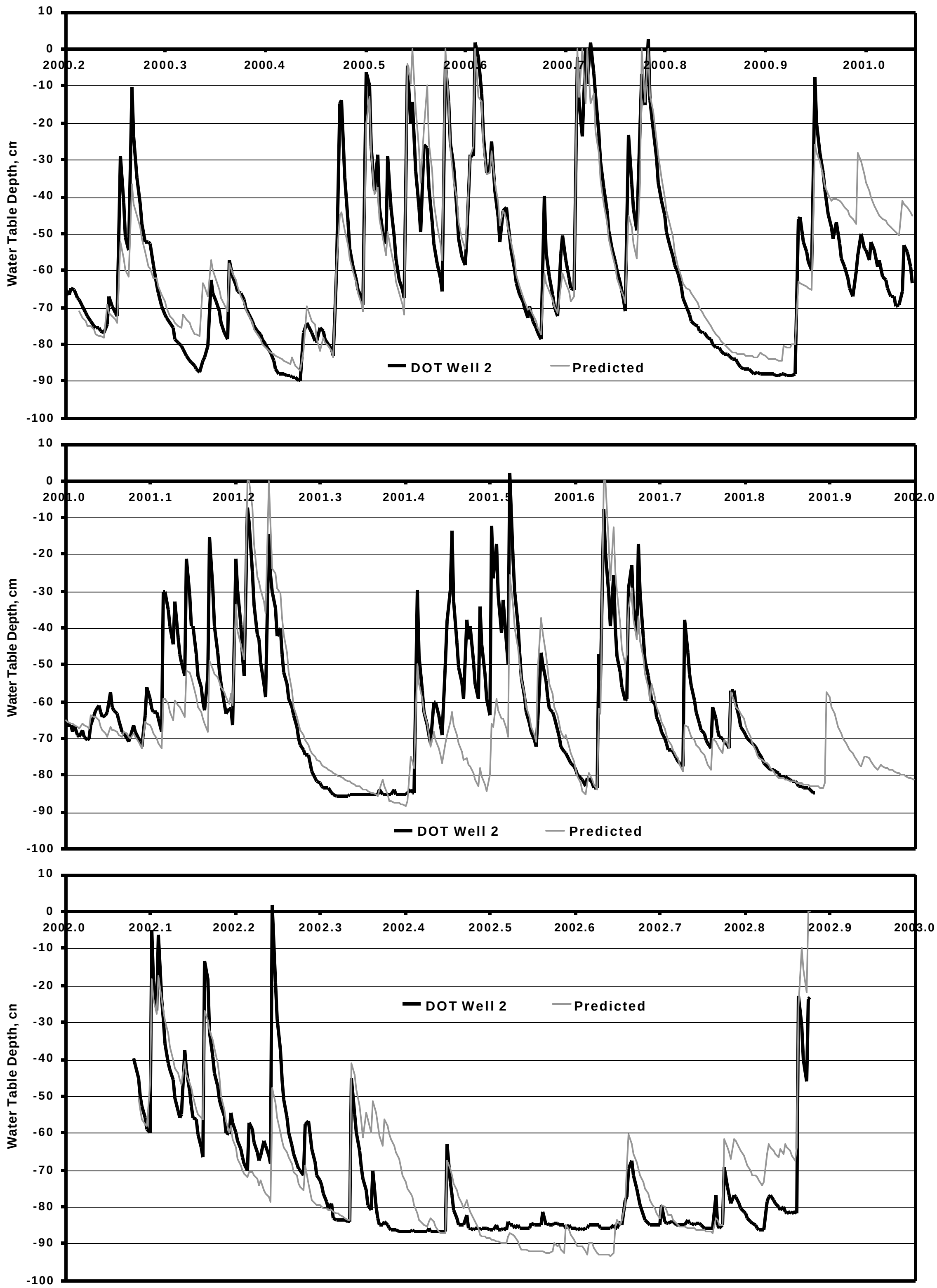


Figure 6. Observed and predicted water table depth at well 2 in Soil Unit 3.

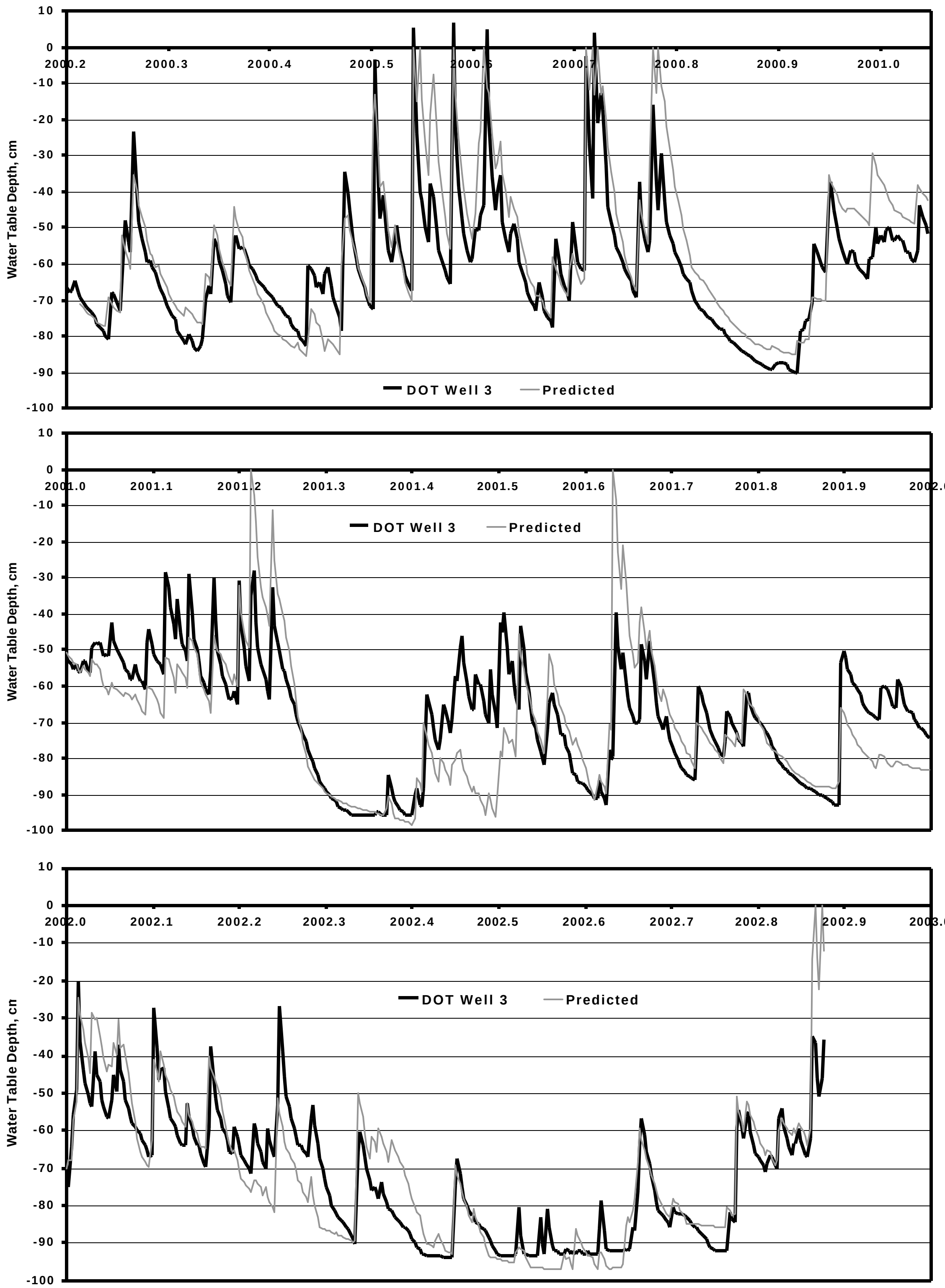


Figure 7. Observed and predicted water table depth at well 3 in Soil Unit 3.

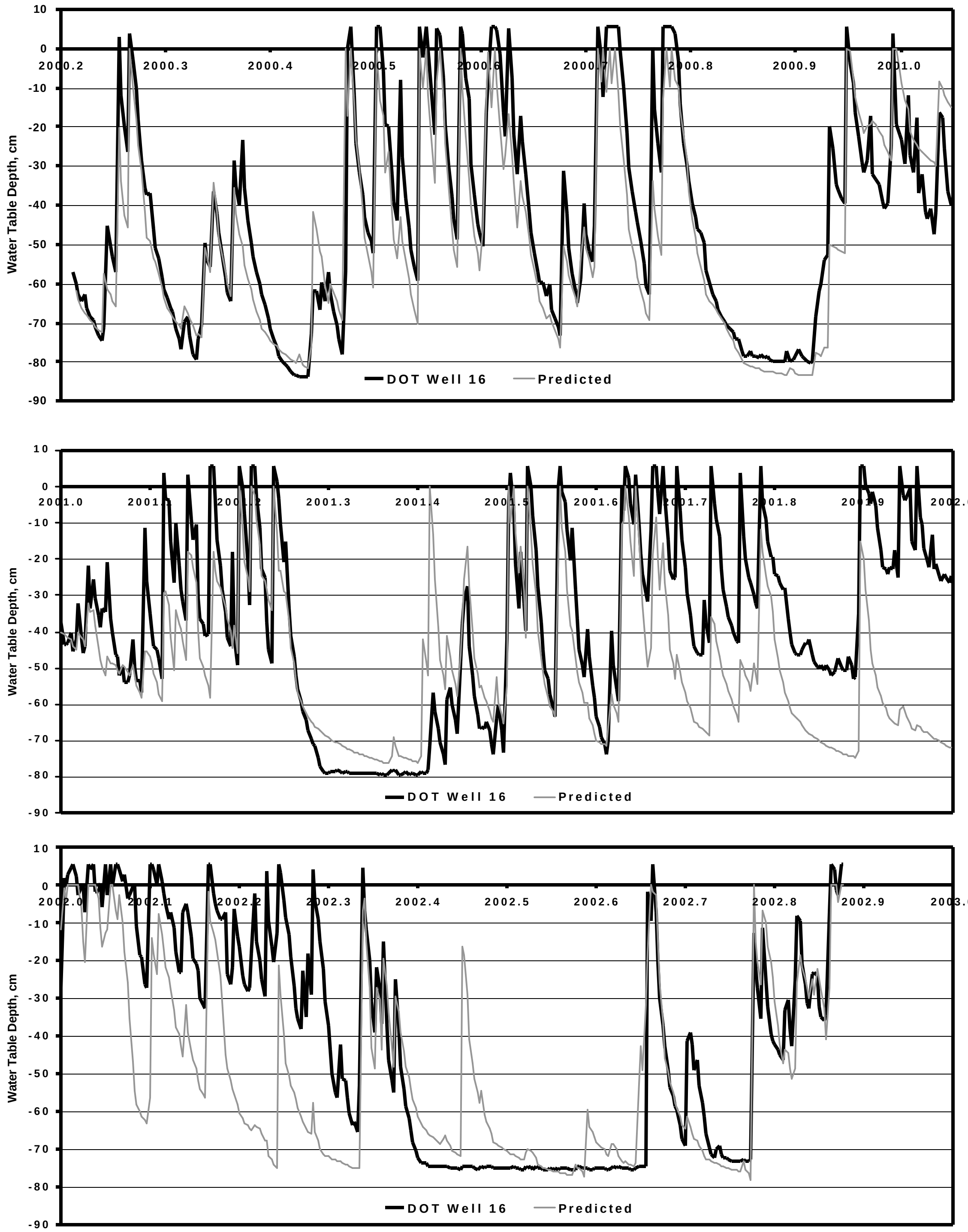


Figure 8. Observed and predicted water table depth at well 16 in Soil Unit 3.

Chapter 13

PRINCIPAL FINDINGS AND CONCLUSIONS

M.J. Vepraskas

1. Juniper Bay was formed in sediments that comprise the Middle Atlantic Coastal Plain. Borings ranging to depths of 20 to 50 ft showed the sediments below the bay consist of alternating layers of clay and sand of varying thicknesses. Lateral variability in the concentrations of clay is considerable above a depth of approximately 20 ft. Below 20 ft., a continuous clay layer may extend beneath the bay and the surrounding area. This sediment had a characteristic sequence of layers which were found both within and outside the bay. Clay layers within 20 ft. of the surface may not be continuous beneath the bay, in part because the sediments appear to have been cut by river or stream channels that have filled in.

2. A compilation of the history of land use at Juniper Bay showed that the upper 3 ft of soil has been extensively modified by activities extending back to 1909. Major land modifications have occurred since the land was prepared for agriculture, beginning in 1979. The northwest section of the Bay has had two different ditch networks placed within it, the first one having been filled in 1981 when the current ditch network was constructed. While clearing the land for agriculture, debris was burned on site. The organic soil did catch fire and 2 to 3 ft of the soil was burned off, possibly over a 2-year period. A small lake formed in the depression until filled in. Agricultural chemicals have been applied to the soil annually since 1979.

3. Vegetation surveys were conducted in three references bays found in Bladen County. Four plant communities were identified: pond pine woodland, non-riverine swamp forest, bay forest, and high pocosin. Of these types, only the pond pine woodland seems appropriate for Juniper Bay. Non-riverine swamp forest was found in only one bay and its hydrologic requirements are unknown at this time. Bay forests and high pocosins were found on deep organic soils, which do not occur at this time in Juniper Bay.

4. Annual chemical additions over the last 30 years have raised the levels of Ca, Mg, P, and K in the soils of Juniper Bay to a depth of 30 in. Soils in reference bays had miniscule quantities of plant nutrients, particularly below the upper 12 in., as compared to Juniper Bay. The effect of the increased nutrient levels on native plant establishment is unknown at this time.

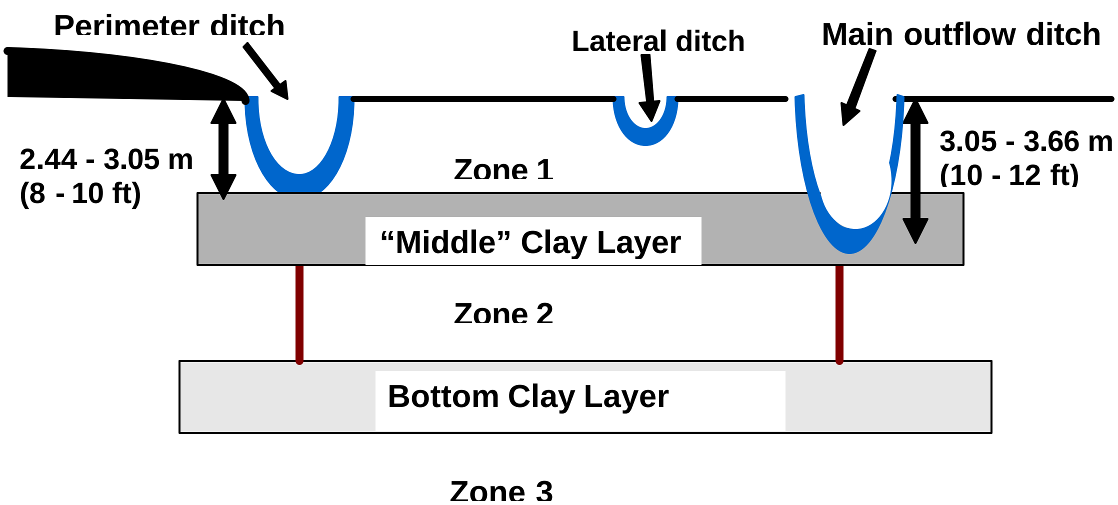
5. Soil physical properties have changed the most in Juniper Bay's organic soils following being placed into agricultural production. The organic soils have become aggregated in the upper 12 in. as compared to similar soils in the reference bays. The effect of this on plant establishment of native species will probably be minor.

6. A procedure was developed to estimate the amounts of subsidence the organic soils have undergone in Juniper Bay over the last 30 years. The results showed that the organic

surface is approximately 24 in. lower today than before the Bay was cleared. Considering that the restored water table is generally at or near the top of the organic surface during the course of a year, this finding suggests that if the ditches are completely plugged at Juniper Bay the water will rise to a level 24 in. above the present surface.

7. Surface outflow nutrient levels in Juniper Bay were generally low, and probably too low to cause eutrophication in downstream waters at this time. There was little difference between nutrient concentrations in surface water outflow between storms, and that leaving the Bay in storms whose intensity was less than 2 in./day. However, for rain events greater than 2 in./day there was a two-fold increase in nutrient concentrations in surface outflow. This increase can be attributed to the heavy rain that exceeded the infiltration rate of the soil and caused surface runoff. These nutrient levels stay elevated for about 1 week because of the time it took for ditches in the entire Bay to drain. There could be short-term water quality degradation with these storm events but long-term eutrophication should not be a problem. It should be emphasized that these measurements pertain to pre-restoration conditions.

8. Ground penetrating radar (GPR) surveys showed that the shallow aquitard (clay layer) depth ranged from 20 in. to 10 ft. with an average depth of 60 in. across the site. One or more aquitards are present below Juniper Bay, with aquitards frequently overlying each other. However, the GPR survey detected an anomaly in the southeast corner of Juniper Bay that where no aquitard could be detected. Coring in this region confirmed that no clayey soil horizons existed within 15 ft of the surface. The size of the anomaly is estimated to be 8 acres, or approximately 1% the area of Juniper Bay. In addition, it is likely that at least the main N-S ditch has pierced underlying aquitards. Any water that might have been retained near the surface by these aquitards could be drained off site. NCDOT may want to consider a clay or synthetic lining in the base of the main ditch or other ditches to prevent such water loss.
9. Measurements of hydraulic gradients indicated that groundwater is moving below Juniper Bay in three zones or aquifers, as shown below, which are separated by one or more clay layers.



Zone 2 may consist of alternating clay and sand layers. Hydraulic gradient measurements showed that groundwater was entering Juniper Bay through zone 2 in the western and eastern sides of the bay. Groundwater was discharging to the north and south. Groundwater moving through zone 2 appeared to be moving into zone 1 in the northwestern portion of the bay. Groundwater flowing through zone 3 moved to the southeast and did not appear to move into the overlying zones. Groundwater moving in zone 1 flowed to the ditches and was removed as surface water.

10. The water budget showed that net groundwater input into Juniper Bay may comprise between 10 and 35% of the total water input into the Bay. The wide variation in the estimate is due to uncertainty in the actual value of evapotranspiration. Fluctuation in well levels and hydraulic gradients support a conclusion that some groundwater is entering the Bay from the east and west. A portion of the groundwater is probably leaving the site as surface water.

11. Modeling of the current hydrology using DRAINMOD showed that under current conditions, the six sites considered do not satisfy the hydrologic criterion for wetlands if the duration is based on 12.5% of the growing season. On the other hand, if the criterion were based on 5% of the growing season (13 days), sites at the lower elevations (represented by wells 10 and 11 in the organic soils) would satisfy jurisdictional wetland status under current conditions.

    Evaluation of the various restoration methodologies showed that, in order to satisfy the 12.5% criterion for all sites, the drainage ditches would have to be filled or plugged, field crowns would have to be removed and the surface roughness increased such that surface storage exceeds 2.5 cm. If the hydrologic criterion was based on 5% of the growing season, filling or plugging the ditches even with field crown, would be sufficient to restore all the sites to wetland hydrology. In all these analyses, it was assumed that deep or lateral seepage has insignificant impact on the water table fluctuations.

Chapter 14

RECOMMENDATIONS AND TECHNOLOGY TRANSFER PLAN

RECOMMENDATIONS

1. Further research is needed to determine the amount of ground water entering Juniper Bay. Until we fully understand the impact of the groundwater on the Bay's hydrology, the perimeter ditch should be left open and it should be maintained to keep water flowing. Beaver dams need to be removed periodically, the beaver population controlled.

2. Soils have unnaturally high fertility levels near the surface. Removal of more than 24 in. of soil material will expose less fertile subsoil material. This will have an as yet unknown impact on planted vegetation. Modifications to the soil surface should be kept to the minimum necessary to reestablish the natural hydrology. All surfaces should be covered in topsoil after modification.

3. Once hydrology is restored and the soils become anaerobic, the concentration of P in the ground water and surface outflow through the perimeter ditch will increase and may exceed acceptable levels. NCDOT needs to evaluate the potential regulatory problems this could pose.

TECHNOLOGY TRANSFER

The data collected to date comprise one of the largest sets of information on Carolina Bays in the country. This information will be disseminated through research articles, talks at professional meetings, and field trips. Chapters 2 through 12 of this report each represent a scientific article that is being prepared for publication. Information in each of the chapters has or will be presented at a scientific meeting.

Beginning in 2004, we plan to conduct field tours at Juniper Bay to illustrate the soil properties, and hydrology of Carolina Bays. Field tours will be conducted annually for the foreseeable future.