ABSTRACT

Caldwell, Peter V. Characterization of the hydrologic regime of four Carolina Bay plant communities. (Under the direction of Dr. J. D. Gregory and Dr. M. J. Vepraskas.)

Successful restoration of a wetland requires that wetland vegetation be established at the site. Unfortunately, the hydrologic regime of restored wetlands is frequently incompatible with these communities and the vegetation cannot survive. This is sometimes a result of improper hydrologic design, but in many cases it is due to a lack of understanding of the hydrology required by these plant communities. The objective of this study was to provide quantitative data describing the long-term (40 yr) hydrology associated with the Pond Pine Woodland (PPW), Nonriverine Swamp Forest (NRSF), High Pocosin (HP), and Bay Forest (BF) plant communities found in three undisturbed Carolina Bays on the North Carolina Coastal Plain. This objective was achieved by simulating water table depths in the various plant communities in the bays over a 40 yr period with calibrated DRAINMOD hydrologic models. The hydrology of the PPW community differed significantly from that of the NRSF, HP, and BF communities in that water tables were deeper in the soil profile, water was ponded on the surface less often and for shorter durations, and the water table dropped to mineral soil horizons more frequently for extended periods of time. Further, the PPW received an average of 15% of its water input from groundwater inflow, whereas the other communities did not exhibit groundwater inflow. The source of the groundwater inflow is not known but it is believed to be a local phenomenon. The water could enter the bays either laterally from adjacent uplands or vertically from confined aquifers below. A confined artesian aquifer below one of the bays was likely the source of inflow for that bay. The hydrology of the NRSF, HP, and BF communities were very similar. The water table in the NRSF and HP occasionally dropped to mineral soil horizons, which may provide them with

the opportunity to extract additional nutrients relative to BF. The results of this study will enable wetland restoration engineers to better approximate the natural hydrology of these plant communities at a restoration site, thereby improving vegetation establishment success.

CHARACTERIZATION OF THE HYDROLOGIC REGIME OF FOUR CAROLINA BAY PLANT COMMUNITIES.

by

PETER VERNON CALDWELL

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APPROVED BY:

Dr. James D. Gregory Chair of Advisory Committee	Dr. Michael J. Vepraskas Co-Chair of Advisory Committee
Dr. Rodney L. Huffman Advisory Committee Member	Dr. R.Wayne Skaggs Advisory Committee Member

DEDICATION

I dedicate this work to my wife, Sarah. She provided me with selfless, unwavering support throughout my career transition from mechanical engineering to forest hydrology and throughout my graduate school career. While many would question the wisdom of leaving a well paying, promising career in pursuit of one's passion, Sarah never did. I could not have done this without her, and I am forever in her debt.

BIOGRAPHY

Peter Vernon Caldwell was born in Norfolk, Virginia in 1972. He spent his adolescent years growing up in Ocala, Tampa, and Boca Raton Florida. As a child, his family did quite a bit of camping, including an epic 10,000 mile, five-week journey from Tampa to Seattle, Washington and back. It was trips like this that instilled in him a deep appreciation for the natural world. He enrolled at North Carolina State University in 1990 and received his bachelor's degree in Mechanical Engineering in 1996. He began work as a design engineer at Caterpillar, Inc. in Clayton North Carolina, where he performed system level design and analysis of backhoe loader performance. It was at Caterpillar that he met his future wife, Sarah, also a mechanical engineer. They were married on August 21, 1999. Peter found the work he performed at Caterpillar interesting, but he had a strong desire to apply his analytical skills to the understanding and conservation of the environment. In the fall of 2001, Peter left Caterpillar to pursue a graduate degree in forest hydrology, again at North Carolina State University.

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CHAPTER 1

A LITERATURE REVIEW OF CAROLINA BAY PLANT COMMUNITIES

Geologic history and development of coastal plain wetlands

Christensen (2000) described the processes that created the modern day Coastal Plain. It began during the Triassic period, approximately 200 million yr BP, when the African continent separated from what is now the east coast of the United States. At this time, the southern Appalachians were huge mountains rivaling the modern day Rockies. Over time these mountains eroded, and the sediment resulting from this erosion spilled across the continental shelf forming the Coastal Plain. About 40,000 yr BP, during the Wisconsinan Ice Age, the Coastal Plain was dominated by boreal forest tree species such as jack pine (*Pinus banksiana* L.) and black spruce (*Picea mariana* L.). At this time the sea level was approximately 150 m lower than today. The resulting higher level of potential energy created fast flowing drainage ways that incised the Coastal Plain sediments (Sharitz and Gibbons, 1982) forming rivers.

The glaciers retreated about 12,000 to 14,000 yr BP, followed by a warming trend. This led to the widespread extinction of the boreal forest along the southern east coast. Sea levels rose to present day levels about 4,000 yr BP, altering the hydrology of the Coastal Plain. There was a general cooling trend about this time that likely reduced evapotranspiration rates from the vegetation. The combination of the reduced drainage and evapotranspiration slowed river flows and raised the water table across the area. The slow flows, obstructed stream drainages, and the emergence of aquatic vegetation caused a build up of sediments in drainageways and the accumulation of organic material in the form of peat (Sharitz and Gibbons, 1982). As the peat accumulated, water perched above old drainage ways due to low lateral hydraulic gradients, facilitating the formation of organic soil materials across the interstream divides.

There is no unified theory on the origin of Carolina Bays on the Coastal Plain. Many theories including meteor showers (Melton and Schriever, 1933), whale wallows (Grant, 1945), dissolution of subsurface minerals (Smith, 1931), and artesian springs (Prouty, 1952) have been postulated but never proven. The most widely accepted explanation is that the combined effect of wind and wave action created the shape and orientation of existing depressions (Kaczorowski, 1977). There exists, however, no proven explanation for the cause of the original depressions.

The Establishment of Plant Communities on the Landscape

As the drainage-ways filled with sediment and peat, swamp forest plant communities consisting of Black Gum (*Nyssa biflora* L.) and Pond Cypress (*Taxodium ascendens* L.) among others, replaced the open water communities originally present (Ash et al., 1983). Since these areas are situated at a lower elevation on the landscape, they received groundwater and nutrients from adjacent areas of higher elevation. Today, swamp forests occur along the southern edges of lakes and the outflows of drainage ways in soils with 50 to more than 150 cm of organic soil material (Richardson, 2003). Shrub bog vegetation became established on the broad interstream divides (Sharitz and Gibbons, 1982). Native Americans called these areas pocosins, meaning “swamp-on-a-hill” (Tooker, 1899) because they are slightly higher in elevation than the surrounding landscape. These plant communities exhibited extremely dense shrubby evergreen vegetation with scattered pond pine trees (*Pinus serotina* L.) interspersed (McDonald et al., 1983). The nutrient poor organic soil in combination with the higher elevation which precludes any inflow of nutrients via groundwater serves to prevent pocosin vegetation from achieving appreciable stature (Ash et al., 1983). Pocosin vegetation communities are typically classified as “tall” or “short” based

on their height and the amount of above ground biomass (Richardson, 2003). The canopy of short pocosin vegetation is around 3 m high, while that of tall pocosin vegetation is about 8 m (Otte, 1982). Short pocosin communities tend to occur over deep organic deposits (greater than 1 m thick) while tall pocosin communities occur over shallower peat (50 to 100 cm).

The generally accepted theory on plant community succession across the Coastal Plain in the Carolinas was proposed by Otte (1981). This theory postulates that nutrient availability controls the establishment of plant communities. According to this theory, the sequence of succession is marsh – swamp forest – bay forest – tall pocosin – short pocosin (Richardson, 2003). The nutrient that is most limiting to plant growth appears to be phosphorus (Walbridge, 1991). Other theories include fire as an agent of plant community change (Wells, 1928). Unfortunately, the relative contributions of nutrient status, fire, and hydrology to plant community succession and establishment are difficult to distinguish and quantify (Richardson, 2003).

Environmental Factors Affecting Plant Community Establishment

Fire

Fire can be a major influence on plant community structure and composition. Pocosin soils tend to become driest during spring and summer, and are susceptible to fires during these times. Fires historically have occurred on a 10 to 30 yr interval (McDonald, et al., 1983). As a result, only vegetation types with special adaptations to live in a recurring fire regime can survive in these environments. Ash et al. (1983) noted that the above ground biomass in pocosins depends on the amount of time passed since the area was burned. After a fire has occurred, the vegetation sprouts vigorously due to the spike in nutrients released by the fire.

Otte (1982) described four types of fires and their effect on plant communities. The first type is a shallow peat burn. With this fire type, the surface vegetation and near surface peat is burned, but the plant roots and rhizome mat remain intact. Water tables near the ground surface protect the plant roots, so it could be inferred that this fire type may occur during wet periods or seasons. In this case, the plant community will recover to its original plant community type. The second fire type is a severe burn in deeper peat that destroys the plant roots and rhizome mat, but does not create a large hole in the peat that can fill with water or bring the underlying mineral soil within reach of the plant roots. In this case, the plant community will "regress" to one of lower stature (e.g. from high pocosin to low pocosin). The third fire type is like the second, only in this case the peat is burned to a depth that brings the mineral soil within reach of the plant roots. The same vegetation will recolonize, but will be taller and more dense (e.g. from low pocosin community to high pocosin or from high pocosin to pond pine woodland). The fourth fire type is a severe burn over shallower peat that destroys all peat material. If this fire were to occur when the water table is deep, it could leave a large area that becomes a lake during wet periods. In this case, a non-pocosin plant community could become established, such as swamp forest.

Wells and Whitford (1976), as reported by Sharitz and Gibbons (1982) claimed that swamp forest converted to pocosin after fires first set by Native Americans and later by European settlers. According to Wells and Whitford, fire frequency plays a role in its effect on plant community composition. If the frequency is roughly every 10 yr, the swamp forest tree species will give way to pond pine. If fire is more frequent, the swamp forest was converted to fire resistant shrubs and shrubby tree species such as bays. If the fire frequency

was every year, the shrubs gave way to grasses, sedges, and herbs. They also claimed that if fires were eliminated altogether, the swamp forest plant community will return.

Human Disturbance

Humans have affected wetland plant community composition in the Coastal Plain in three ways. First, the widespread suppression of natural wildfires over the last century has likely altered the dynamics of the communities. This has allowed the dominance of a particular community over the others rather than a shifting, patchy mosaic of various plant communities across the landscape determined by fire history (Schafale and Weakley, 1990). In addition, the absence of periodic fires has led to a gradual decline in the plant species diversity that these fire regimes maintain (Ash et al., 1983).

The second way that human activities have altered plant community composition is through drainage. Drainage in the Coastal Plain likely began in the Great Dismal Swamp in the mid eighteenth century (Sharitz and Gibbons, 1982). Approximately 69% of natural pocosins were developed in one way or another between 1962 and 1980, and of those, 52% were cleared and drained for agricultural or silvicultural purposes (McDonald et al., 1983). With the exception of wetland restoration sites, these drained peatlands are not generally allowed to return to a natural plant community. The effects of drainage on adjacent plant communities are apparent on the boundaries of ditches and canals. Before widespread drainage began, pocosins were expanding across the landscape and peat was getting thicker (Otte, 1982). Drainage has stopped the spread of pocosins, and has potential of stopping growth of peat thickness in undisturbed areas by lowering the water table in areas near artificial drainage ways. Otte (1982) further notes that drainage decreases the length of time that water is ponded on the surface, and increases the length of time the upper part of the soil

profile is aerated. This increases the rate of oxidation of organic soil materials, possibly increasing the rate of nutrient release. As a result, vegetation patterns along drainage canals change. Pond pines and bays grow from shrub size to tree size. High pocosin and pond pine woodland have been observed near canals in peat thicknesses that would normally only support low pocosin.

The third way in which Coastal Plain plant communities have been affected by anthropogenic changes is through logging. In the late nineteenth and early twentieth centuries, widespread logging of Atlantic white cedar trees (*Chamaecyparis thyoides* L.) and cypress tree species such as bald cypress (*Taxodium distichum* L.) and pond cypress (*Taxodium ascendens* L.) occurred across the area. Sites that are now considered non-riverine swamp forest may have been Atlantic white cedar forests before the bald cypress and cedar were selectively removed (Schafale and Weakley, 1990). Most pond pine woodlands are thought to be the result of natural succession, but some areas are believed to have developed after logging of non-riverine swamp forest. Kologiski (1977), as reported by Ash et al. (1983) noted that the Green Swamp in Brunswick and Columbus counties was once dominated by cypress and gum tree species. After logging and burning of slash and brush during wildfires, fire tolerant pocosin species became established. Logging, therefore, may have increased extent of pocosin communities and decreased swamp forest (Ash et al., 1983).

Soils

Pocosin plant communities can be found on soils ranging from mineral to organic mucks and peats (Richardson, 2003). These soils are highly acid, with the pH of organic horizons between 3.5 and 4.1. The pH of surface mineral horizons is 0.3 to 0.4 pH units higher than organic horizons, and the pH of subsurface mineral horizons is between 4.1 and

4.7 (Sharitz and Gibbons, 1982). Despite having a large percentage of organic materials, pocosin soils are extremely deficient in natural fertility. Very few plant species can adapt to these nutrient deficient and acid organic soils (Ash et al., 1983). Richardson (2003) notes that the depth of organic soil materials for short pocosin, tall pocosin, and Gum swamps/Bay forests are greater than 1 m, 0.5 to 1 m, and 0.5 to more than 1.5 m, respectively.

Otte (1982) found that the majority of pocosin plant communities occur over deep peat (greater than 1 m), but peat thickness is not a critical factor in the vegetational transition from swamp forest to pocosin. He also discovered that peat found in swamp forests has more mineral matter than in pocosins, and the mineral portion is mostly clay in texture. This trend was further validated when Bridgham and Richardson (1993) found that the bulk density of peats found in swamp forests was greater than that of pocosin peats, and was lower in organic carbon percentage. Both of these observations could result from a higher mineral concentration in the organic soil horizons. Otte (1982) theorized that the clay mineral soil particles were carried into the swamp forest from uplands in runoff water.

Otte (1982) claimed that soils can affect plant community establishment when, in areas of shallow peat, the plant roots are able to reach the mineral soil horizons below when water tables drop into these horizons. If mineral soil is nutrient poor, as in the case of quartz sand, there is still relatively low fertility and a pocosin plant community will still develop. Perhaps if the mineral soil has more slightly more fertility, it could be the difference in high and low pocosin, or possibly high pocosin and pond pine woodland. Schafale and Weakley (1990) note that in pond pine woodlands, the water table lowers to the mineral soil, encouraging plants to seek water in these soil materials, thus tapping into the slightly more fertile soils there.

Nutrient Availability

Pocosin plant communities, by nature, are oligotrophic systems in that rainfall is the only source of nutrients for the vegetation (Richardson, 2003). The peat is typically too thick to allow plants to root in the potentially more fertile mineral soils below, and water tends to drain out of, rather than into, these slightly raised locations. Barnes (1981), as reported by Sharitz and Gibbons (1982) found that total nitrogen levels in pocosin organic soils are high, but more than 70% of the total nitrogen is unavailable to plants. Phosphorus, though present in the soil, was also largely unavailable.

Bridgham and Richardson (1993) found that swamp forest soils have a lower N:P ratio, greater total soil nutrients, and greater extractable PO_4^{-3} and NO_3^- than pocosin soils to the 30 cm depth. Higher nutrient availability in swamp forest versus high pocosin was also observed by Bruland et al. (2003). It has been postulated that the higher fertility in the swamp forest soils could be due to groundwater entering these communities. Daniel (1981) noted that there can be a transition from swamp forest near the source of the groundwater to pocosin further away from the source.

Bridgham and Richardson (1993) found no discernable difference in extractable nutrients between high and low pocosin plant community soils to the 30 cm depth. However, Walbridge (1991) studied the gradient from low pocosin, to high pocosin, to bay forest plant communities, and discovered that it corresponded to a gradient in available phosphorus in the soil, studied to a depth of 15 cm. In addition, as more phosphorus was available to bay forests, the N:P ratios were lower. Otte (1982) attributes the higher above ground biomass of high pocosin compared to that of low pocosin to soil fertility by way of the ability of vegetation to get roots into the mineral soil horizons underlying the peat. Further, the

establishment of the pond pine woodland community may be a result of access to mineral soil horizons as well as an influx of dissolved minerals in groundwater from adjacent uplands. The work of Bridgham and Richardson as well as Walbridge consider only the nutrient availability of the surface organic horizons, but do not take into account the fertility of the underlying mineral horizons that may be accessible to the vegetation.

Hydrology

The hydrology of pocosin wetlands has been described as a balance between rainfall and evapotranspiration (Bruland et al., 2003). When rainfall exceeds evapotranspiration, water tables rise in the soil. When the opposite is true, the water table lowers. More than 90% of the water output from pocosins is lost through evapotranspiration if the rainfall occurs during summer and fall, but the output shifts more toward runoff in winter and early spring (Richardson, 2003). Runoff from pocosins occurs as sheet flow over broad stretches rather than channelized flow in streams or ditches (Ash et al., 1983). Sheet flow occurs just below the litter layer, following small but relatively discrete channels. The surface layer of organic soils, commonly called “root mat”, is a zone of dense plant roots and partially decomposed organic material that has a very high hydraulic conductivity.

Otte (1982) claims that the primary difference in processes affecting plant community establishment with respect to swamp forest versus pocosin plant communities is the direction of subsurface water flow. In swamp forests, water flows into and through the system whereas in pocosins, water flows out of the system due to elevated domes of peat. In pocosins, during winter, spring, and early summer months, the water table ranges from just below the surface to above the surface, and living roots are limited to the upper 30 cm of saturated soil. During dry periods, the upper meter or so of the soil is aerated and plant roots

extend downward in search of water, which may or may not bring them in contact with mineral soil. Bridgham and Richardson (1993) discovered that swamp forests had greater seasonal changes in water table depth than high and low pocosin communities. They attributed this to a reduction in lateral seepage during periods with deeper water tables, and larger above ground biomass which could yield higher rates of evapotranspiration. Low pocosin exhibited the least seasonal change in water table depth, likely due to its lower plant biomass.

Fire, soils, nutrient availability, and hydrology are so intermingled that it is difficult to separate their effects on plant community establishment. However, hydrology may control the relative contribution of the other factors. Steven and Toner (2004) found that the hydrologic regime was the strongest correlate of vegetation type in depressional wetlands on the Coastal Plain. Sites with water tables near the ground surface will have less frequent and less intense fires. Kirkham et al. (2000) claimed that as many wetlands are no longer susceptible to natural fires, plant community development is primarily controlled by hydrology. Sites with water tables near the ground surface will tend to accumulate more organic matter, making deeper peat and dictating the soil type. As this organic matter accumulates, the ground surface rises to a higher elevation in these areas with shallow water tables than adjacent areas with deeper water tables. Due to very low hydraulic gradients and low hydraulic conductivities, the water table in these areas of higher elevation "mounds" above the surrounding areas. As a result, these sites of higher elevation become nutrient poor because groundwater flows out of, rather than in to these sites, making rainfall the only source of nutrients for plants. Areas lower in elevation will have a higher nutrient status than

adjacent areas that are higher in elevation because they receive nutrients from groundwater inflow from these uplands in addition to rainfall.

Descriptions of the plant communities found at the reference bays

Pond Pine Woodland

The Pond Pine Woodland plant community (PPW) was described by Schafale and Weakley (1990). This community occurs near the edges of domed peatlands on poorly drained interstream flats and peat-filled Carolina bays. Pond Pine Woodlands have an open to nearly closed canopy composed mostly of pond pine (*Pinus serotina* L.) with some loblolly bay (*Gordonia lasianthus* L.) and lesser amounts of red maple (*Acer rubrum* L.), loblolly pine (*Pinus taeda* L.), swamp red bay (*Persea palustris* L.), and Atlantic white cedar (*Chamaecyparis thyoides* L.). The pond pine trees reach heights up to 18 m, with diameter at breast height (DBH) up to 61 cm (Otte, 1982). The shrub layer is very dense and can exceed 5 m in height, taller than the shrub layer of the typical high pocosin community. Shrub species include ti-ti (*Cyrilla racemiflora* L.), fetterbush (*Lyonia lucida* L.), maleberry (*Lyonia ligustrina* L.), gallberry (*Ilex coriacea* L.), inkberry (*Ilex glabra* L.), blue huckleberry (*Gaylussacia frondosa* L.), coastal sweet-pepperbush (*Clethra alnifolia* L.), and swamp red bay (*Persea palustris* L.). PPW plant communities have shallow water tables and are low in fertility, though less so than high or low pocosin communities. PPW communities occur on sites with 30 to 60 cm of organic soil materials (Otte, 1982). During dry periods, this community is susceptible to wildfires, which can affect vegetation stature and species distribution. Otte (1982) described the hydrology associated with the PPW community. During the wet season, soils are temporarily flooded to saturated, and standing water is uncommon. During the dry season, the water table drops down to the underlying mineral

soil, enabling plant roots to reach these horizons of relatively higher nutrient status. There may be groundwater inflow to these areas from nearby uplands that can provide additional nutrients. PPW communities are believed to be a natural phenomenon, but in some locations it is believed that they have become established after logging of Non-riverine Swamp Forests (Schafale and Weakley, 1990).

High Pocosin

The High Pocosin plant community (HP) was described by Schafale and Weakley (1990). They occur on intermediate to central portions of domed peatlands on poorly drained interstream flats and peat-filled Carolina bays. The canopy consists of scattered pond pine, swamp red bay, loblolly bay, and sweet bay (*Magnolia virginiana* L.). The pond pines are widely scattered, exhibiting upper trunks that are twisted and gnarled. They reach a height of about 7.6 m, with DBH up to 15 cm (Otte, 1982). HP communities have a dense shrub layer between 1.5 to 3 m tall which is dominated by fetterbush, ti-ti, inkberry, and blaspheme vine (*Smilax laurifolia* L.). The shrub layer is tallest on pond pine hummocks and lowest over recent burns (Otte, 1982). HP communities have shallower water tables than PPW communities, and generally have groundwater flowing out of them rather than in, making them extremely nutrient poor. HP communities occur at sites with organic soil materials that are 60 to 120 cm deep (Otte, 1982). They are susceptible to intense fires during dry periods, but recover quickly. PPW communities can resemble a HP after an intense fire that destroys the canopy, but can be distinguished from HP by the charred remains of burned pond pines. Otte (1982) described the hydrology of HP communities. During the wet season, soils are saturated and flooded with surface water. Standing water is common in pools burned in the

peat. During the dry season, the water table drops 30 to 60 cm below the surface, rarely reaching the mineral horizons.

Bay Forest

The Bay Forest plant community (BF) was described by Schafale and Weakley (1990). This plant community occurs on the outer parts of domed peatlands on poorly drained interstream flats, and peat-filled Carolina bays. The canopy consists predominantly of loblolly bay, sweet bay, and swamp red bay, with pond pine, swamp tupelo (*Nyssa biflora* L.), red maple, loblolly pine, and Atlantic white cedar as co-dominants. The shrub layer is dense, but can be relatively open, comprised of fetterbush, ti-ti, maleberry, gallberry, and dahoon (*Ilex cassine* L.). The BF canopy is 3 to 10 m high, and the shrub layer tends to blend with the canopy (Kologiski, 1977). Similar to HP, BF communities have very shallow water tables and are low in fertility, but probably less so. Soils under BF communities typically have organic layers greater than 40 cm thick (Sharitz and Gibbons, 1982). Walbridge (1991) studied a BF plant community that resided over peat 67 to 150 cm thick, deeper than that of an adjacent HP but with a higher mineral content. BF communities are believed to be a late successional plant community that replaces Peatland Atlantic White Cedar Forests and PPW communities after an extended absence of fire. Fires in BF communties can be intense, but the vegetation quickly regenerates. Not much is known about the hydrology of this community. Shafale and Weakley (1990) question whether the hydrology differs from that of PPW and Peatland Atlantic White Cedar Forest. Kologiski (1977) observed an intermediate to long hydroperiod. Overall, the BF plant community is poorly understood.

Non-riverine Swamp Forest

The Non-riverine Swamp Forest plant community (NRSF) was described by Schafale and Weakley (1990). This plant community occurs over very poorly drained upland flats and peat deposits with shallow water tables. The canopy consists of bald cypress (*Taxodium distichum* L.), pond cypress (*Taxodium ascendens* L.), swamp tupelo, loblolly pine, Atlantic white cedar, pond pine, tuliptree (*Liriodendron Tulipifera* L.), and red maple. The shrub layer ranges from open to dense, consisting of sweet bay, swamp red bay, ti-ti, fetterbush, coastal sweet-pepperbush, blueberry (*Vaccinium* spp. L.) and blaspheme vine. This plant community generally occurs over deep organic deposits, 100 to 150 cm thick (Richardson, 2003). It is believed that NRSF communities receive groundwater from nearby uplands that increases nutrient concentrations in the soil solution such that larger trees can become established (Otte, 1982). Fires are probably rare in NRSF communities due to shallower water tables, but they could occur during dry periods. Not much data on the hydrology of Swamp Forest exists in the literature. Schafale and Weakley (1990) describe the hydrology as seasonally or frequently saturated or shallowly flooded by high water table. Like the BF plant community, the NRSF is poorly understood.

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CHAPTER 2

SAMPLING DEVICE TO EXTRACT INTACT CORES IN SATURATED ORGANIC SOILS[a]

[a] As formatted for the *Soil Science Society of America Journal.*

ABSTRACT

Physical property data on organic soils are lacking due to difficulty in collecting undisturbed samples from these frequently saturated and weakly consolidated soils. A sampling device was constructed to extract undisturbed cores from saturated organic soils in a forested setting. The sampler consists of a 100-cm-long, 3-in.-diam. schedule 40 PVC pipe that was fitted with female threaded adapters on either end. A cutting head was constructed to cut through the fibric root mat and other woody debris in the profile by gluing a 3-in.-diam. hole-saw to a male threaded adapter that was attached to the PVC pipe. The sampler was rotated by hand into the organic soil with gentle downward pressure. When the desired depth was reached, the remaining air space in the PVC pipe was filled with water and a threaded cap was used to seal the top of the sampler. A 0.5-in.-diam. galvanized pipe was inserted next to the sampler to add water to the bottom of the core, relieving the suction created as the core was pulled from the soil. The sampler and vent pipe were pulled from the soil either by hand or with a tripod/winch arrangement. Before the cutting head was raised above the water table, it was removed and replaced with another threaded PVC cap. The 100-cm-long pipe containing the soil core was then cut into 7.6-cm-long sections using a wheel-type PVC pipe cutter. Saturated hydraulic conductivity and soil water characteristics were then measured in the laboratory using the resulting 7.6-cm-long samples encased in the PVC cylinders.

INTRODUCTION

Hydrologic computer models are powerful tools for predicting water table levels in soils. Most models require soil property data such as saturated hydraulic conductivity and soil water characteristic curves to simulate the movement and storage of water in the soil profile (Skaggs, 1978; McDonald and Harbaugh, 1988). These properties are frequently measured on undisturbed soil cores in the laboratory. Various mechanical devices have been developed for the collection of undisturbed soil cores. Many samplers are attached to tractors and use hydraulic pressure to either pound or push the sampler into the soil (Abu-Hamdeh and Al-Jalil, 1999; Janssen et al., 1998; Vepraskas et al., 1990). Others have used more portable, manual means to push or pound the sampler into the soil profile (Chong et al., 1982; Jackson, 1987; Seaby, 2000; Swanson, 1950; Stolt et al., 1991). Most of these methods work well only in soil of sufficient strength to withstand compaction or disturbance during sample collection.

Little data are available for the saturated hydraulic conductivity or soil water characteristic of saturated organic soils under forest vegetation, because it is difficult to collect undisturbed samples from these soils. Organic soils in forested settings have a dense, interconnected mat of roots at the surface that must be severed when collecting core samples. These organic soil materials are usually saturated and have very low soil strength. Collecting undisturbed cores using traditional methods virtually destroys the sample during the collection process. Additional problems are encountered when collecting samples in flooded conditions. When a sampler is successfully inserted into a saturated organic soil, the action of lifting it out of the ground induces suction at the bottom of the sampler that causes the soil core to be pulled from the sampler.

The objective of this study was to develop a sampler that could be used in saturated organic soils to collect undisturbed soil cores suitable for laboratory measurements of saturated hydraulic conductivity and the soil water characteristic curves.

SAMPLER DESIGN AND CONSTRUCTION

The sampling device was made from a section of 3-in.-diam. schedule 40 PVC pipe that was 100-cm-long (Fig. 2.1). Diameters of all parts of the apparatus are 3 in. (7.6 cm) unless otherwise noted. Two female-threaded adapters were glued to the ends of the PVC pipe using PVC cement. A cutting head was fashioned from a threaded male PVC adapter with a short piece of PVC pipe glued into the slip-fit end (Fig. 2.2). The edge of the male adapter and PVC pipe were tapered to a 45° angle using a belt sander to facilitate easier penetration into the soil. The arbor end of a hole-saw was removed using a pneumatic cut-off wheel, resulting in a 3-in.-diam. diameter saw-toothed ring that was 3.8 cm long. This ring was glued into the PVC pipe in the male adapter using epoxy cement such that the saw teeth extended approximately 1.3 cm from the end of the PVC pipe. Additional supplies included a 120-cm length of 0.5-in.-diam. galvanized-steel tubing, a plastic funnel that fit into the galvanized tube, and two PVC male threaded caps.

SAMPLER OPERATION

To collect samples, the sampler cutting head was threaded onto one end of the PVC pipe. The cutting head was then placed on the soil surface and slowly rotated by hand using gentle downward pressure. The saw cut through fibric organic soil material as well as the numerous roots encountered in the profile. Once the sampler reached the desired depth, the remaining air space in the top of the sampler was filled with water. The pipe was then capped on the top with one of the threaded PVC caps using sealant on the threads. Capping

the top of the sampler helped maintain suction inside the sampler to prevent loss of the core when it was raised from the ground, similar to holding one's finger over the end of a drinking straw and lifting it out of the glass. Next, the galvanized tubing was pounded into the ground immediately adjacent to the sampler such that the end of the tube was at the same depth as the cutting head of the sampler. The tube was cleared of debris with a length of steel rod, and was then attached to the sampler using duct tape. A small hole was then dug into the soil next to the sampler with a spade to allow removal of the saw adapter just before the bottom of the sampler was raised above the water table.

Before the sampler was raised from the soil, water was poured through the funnel into the galvanized tube until the tube was full. At this point, the sampler and galvanized tube were lifted from the soil either manually or with a tripod/winch arrangement. As the sampler was lifted, the void created beneath it was filled with water from the galvanized tube to relieve the suction that would otherwise draw the sample out of the pipe. Cuttle and Malcolm (1979) suggested inserting a tube adjacent to the sampler to allow air into the area below the sampler to relieve the suction. However, we found that due to the weight of the saturated organic soil sample and the low friction between the sample and the sampler tube, it was necessary to fill the void below with water to prevent loss of the core. Depending on the depth of sampling, it may be necessary to add water to the funnel as the sampler is being raised. When the sampler was lifted to within a few centimeters of the top of the water table, the cutting head was removed and a threaded cap installed in its place using sealant on the threads. By keeping the bottom of the sampler below the water table, pressure was maintained on the bottom of the core to minimize the possibility of losing the sample. With both ends capped, the sampler was completely raised from the soil surface and stored. The

sampler could then be transported to the laboratory in a vertical orientation to prevent damage to the saturated soil material inside. The soil core can be removed from the sampler by either cutting the PVC pipe lengthwise to expose the sample, or by pushing it out of the PVC pipe using a plunger-type device. Short core samples (e.g. 7.6 cm long) can also be prepared by cutting the PVC pipe cross-wise and leaving the soil surrounded by a PVC ring.

EXAMPLE OF USE

Samples were collected from organic soils using this device in three Carolina Bays in NC located approximately at 34°40'59" N and 78°34'54" W. The organic soils were members of the Croatan series (loamy, siliceous, dysic, thermic Terric Haplosaprists) and Pamlico series (sandy or sandy-skeletal, siliceous, dysic, thermic Terric Haplosaprists). The dominant vegetation at these sites consist of pocosin plant species, with trees such as pond pine (*Pinus serotina* L.), swamp red bay (*Persea palustris* L.), loblolly bay (*Gordonia lasianthus* L.), and sweetbay (*Magnolia virginiana* L.), and shrub species including fetterbush (*Lyonia lucida* L.), ti-ti (*Cyrilla racemiflora* L.), inkberry (*Ilex glabra* L.), and blaspheme vine (*Smilax laurifolia* L.). Hydrologic models of the three bays were to be developed, requiring soil data such as saturated hydraulic conductivity and soil water characteristic curves to be measured from intact soil cores. Three cores were taken in each of the three bays.

The apparatus that was used to measure hydraulic conductivity and soil water characteristic required samples of approximately 7.6-cm-diam. and 7.6-cm in height. The 100-cm-long soil core was cut into 7.6-cm-long sections by first setting the PVC pipe into a bucket while maintaining its vertical orientation. The top threaded cap was removed, and the water above the core surface was siphoned out. The location of the upper core surface was

marked on the outside of the sampler, and marks were made at 7.6-cm intervals to the bottom of the pipe. A wheel-type PVC pipe cutter was used to gently cut through the pipe at the marked locations while leaving the soil sample intact.

When the PVC pipe was cut completely through, a 4-in. wide, sharpened spatula was inserted into the cut and gently worked across the sample. Any roots in the sample were cut using razor blades or thin saws to minimize damage to the sample. The PVC section containing the sample was then removed while being supported on the bottom by a spatula. The sample was then inverted onto another spatula, and a piece of cheesecloth was secured to the bottom of the sample using a rubber band. The sample was then flipped back over and placed in a pan of water to maintain saturation.

The saturated hydraulic conductivity was measured using the constant head method (Klute and Dirksen, 1986). The soil water characteristic curve was also determined using a pressure cell apparatus (Klute, 1986). At the completion of these tests, the samples were placed in cans, weighed, oven-dried at 105^{o} C for 24 hours, and reweighed to determine water content. Bulk density was computed using the oven-dry weight and inner volume of the PVC ring.

The saturated hydraulic conductivity and bulk density for the Oi, Oe, and Oa horizons in the organic soils sampled are shown in Table 2.1. The organic soil horizons had very low bulk densities (< 0.2 g cm^{-3}) due to the lack of mineral soil material in the matrix. The surface (Oi) horizons, composed mostly of undecomposed leaves and fibrous roots, generally had saturated hydraulic conductivities too high to be measured with the laboratory apparatus (Table 2.1). The soil water characteristic data (Fig. 2.3) showed that the organic soils had a porosity of approximately 0.9 cm^3 cm^{-3}. Most of the water drained from the cores at soil

water pressures >-50 cm. These pores had equivalent cylindrical diameters >0.1 mm as estimated from the capillary rise equation (Hillel, 2004).

DISCUSSION

The sampler successfully removed intact cores from the sites in most cases. The surface Oi horizon, which consisted of loose leaves and some fibrous roots, was occasionally compressed during the coring process. Extreme care should be taken not to exert excessive downward force when taking the sample, which can destroy the fragile structure of the organic surface horizons. Samples collected from Oe and Oa horizons showed no apparent compaction in that the surface of the samples remained at a constant elevation as the sampler was pushed into the ground. Despite the slightly smaller (2 mm) inner diameter of the hole saw, no gaps between the sample and core wall were visible to the naked eye.

This sampling device was also applied to saturated sandy mineral soils at some sites. For these soils, 3-in.-diam. thin-walled steel tubing replaced the PVC piping. No cutting head was necessary in these soils, but the leading edge of the steel tubing was sharpened using a grinder to facilitate cutting through roots during the sampling process. The steel tubing was pounded into the soil using a fence-post driver until it reached the desired depth. In this case, rubber end caps with gear clamps were used on either end of the sampler to secure the core inside. No apparent compaction of samples was observed in these soils. Extraction of the cores from the soil and sample preparation was performed as described previously for the organic soils.

The sampler has proven reliable in collecting virtually undisturbed samples from saturated Oe and Oa horizons in over 30 plots. The undisturbed samples can be used to determine soil bulk density, saturated and unsaturated hydraulic conductivity, soil water

characteristic curves, among others. The samples can also be used to evaluate root growth and soil micromorphology. The same cutting head apparatus was used for all organic soil cores without the need to replace or re-glue the hole-saw. Soil data collected by this method have successfully been used in hydrologic models predicting water table levels with a high degree of accuracy, with typical average absolute deviations between simulated and measured water table depths of less than 5 cm. Distinct advantages of this sampler are its low cost, ease of construction, light weight, and the ability to section the core into samples that can be tested in the laboratory.

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Table 2.1. Laboratory bulk density and hydraulic conductivity measurements conducted on organic soils across all three Carolina Bays.

Horizon	Organic soil material	Bulk density			Saturated hydraulic conductivity		
		Number of samples	Mean	Standard error	Number of samples	Mean	Standard error
			----g cm^{-3}----			----cm h^{-1}----	
Oi	Fibric (Peat)	4	0.10	0.01	1	18	ND[†]
Oe	Hemic (Mucky Peat)	10	0.11	0.01	6	15	6.7
Oa	Sapric (Muck)	14	0.13	0.01	14	2	0.7

[†]ND Saturated hydraulic conductivity of Oi horizon generally exceeded capability of laboratory apparatus to measure.

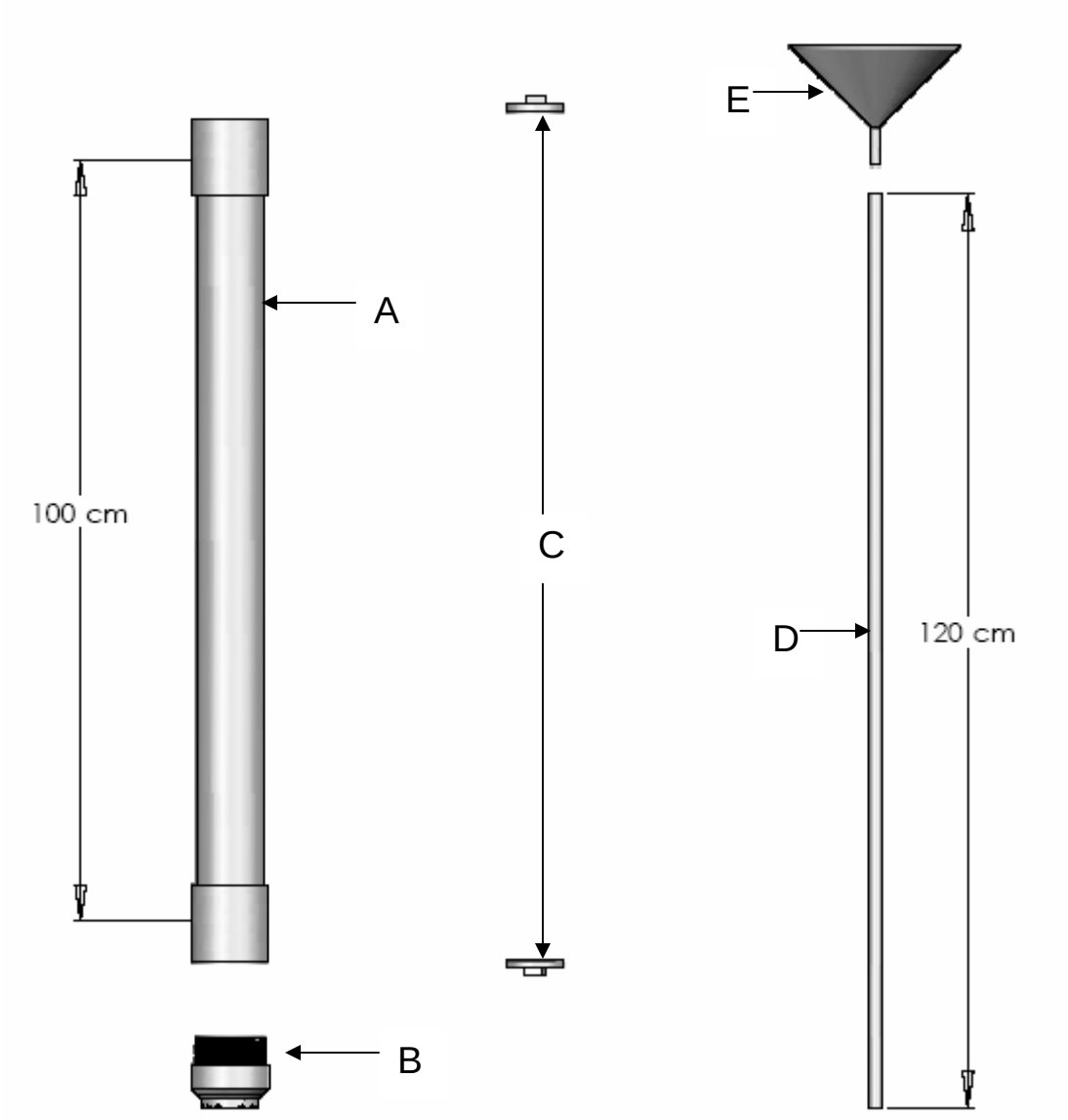

Figure 2.1. Schematic diagram of the core sampler. Components are: A) a 100-cm-long 3-in-diam. schedule 40 PVC pipe with female threaded adapters on each end, B) a sampler cutting head, C) two 3-in.-diam. male threaded PVC caps, D) a 120-cm-long, 0.5-in-diam. galvanized pipe, and E) a plastic funnel.

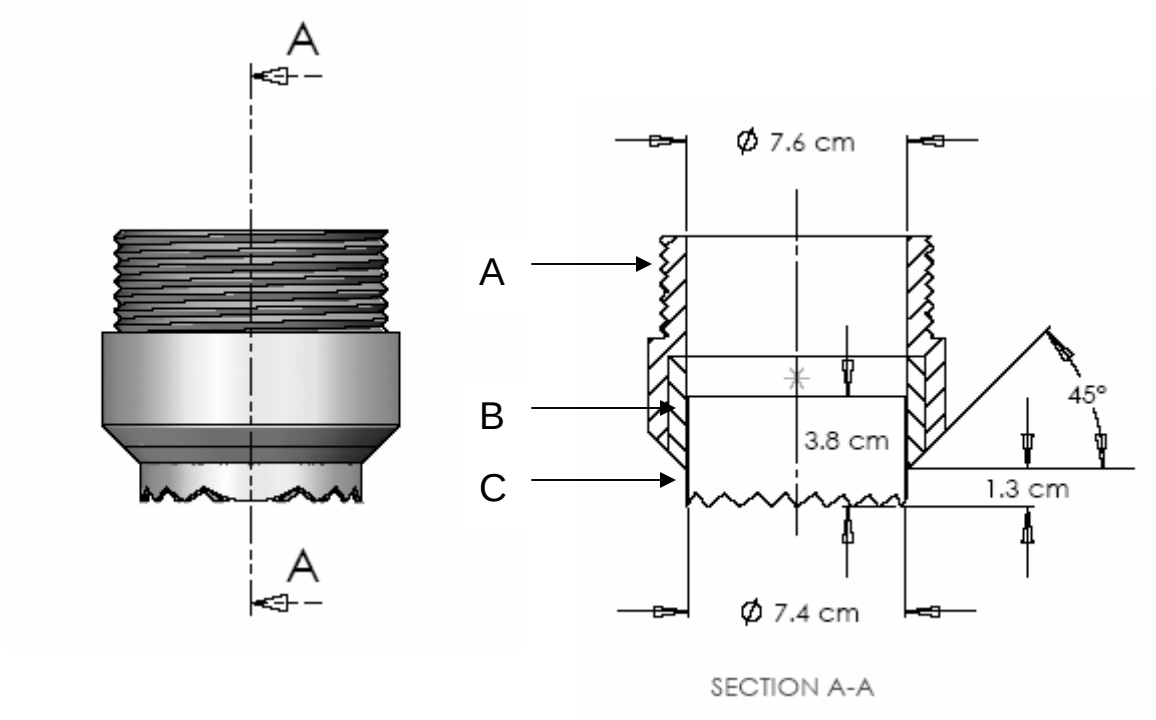

Figure 2.2. Drawing and relevant dimensions of the sampler cutting head. Components are: A) a 3-in.-diam. male threaded adapter, B) a 3-in-diam. section of PVC pipe glued into (A), C) a 3-in.-diam. hole-saw with arbor end removed.

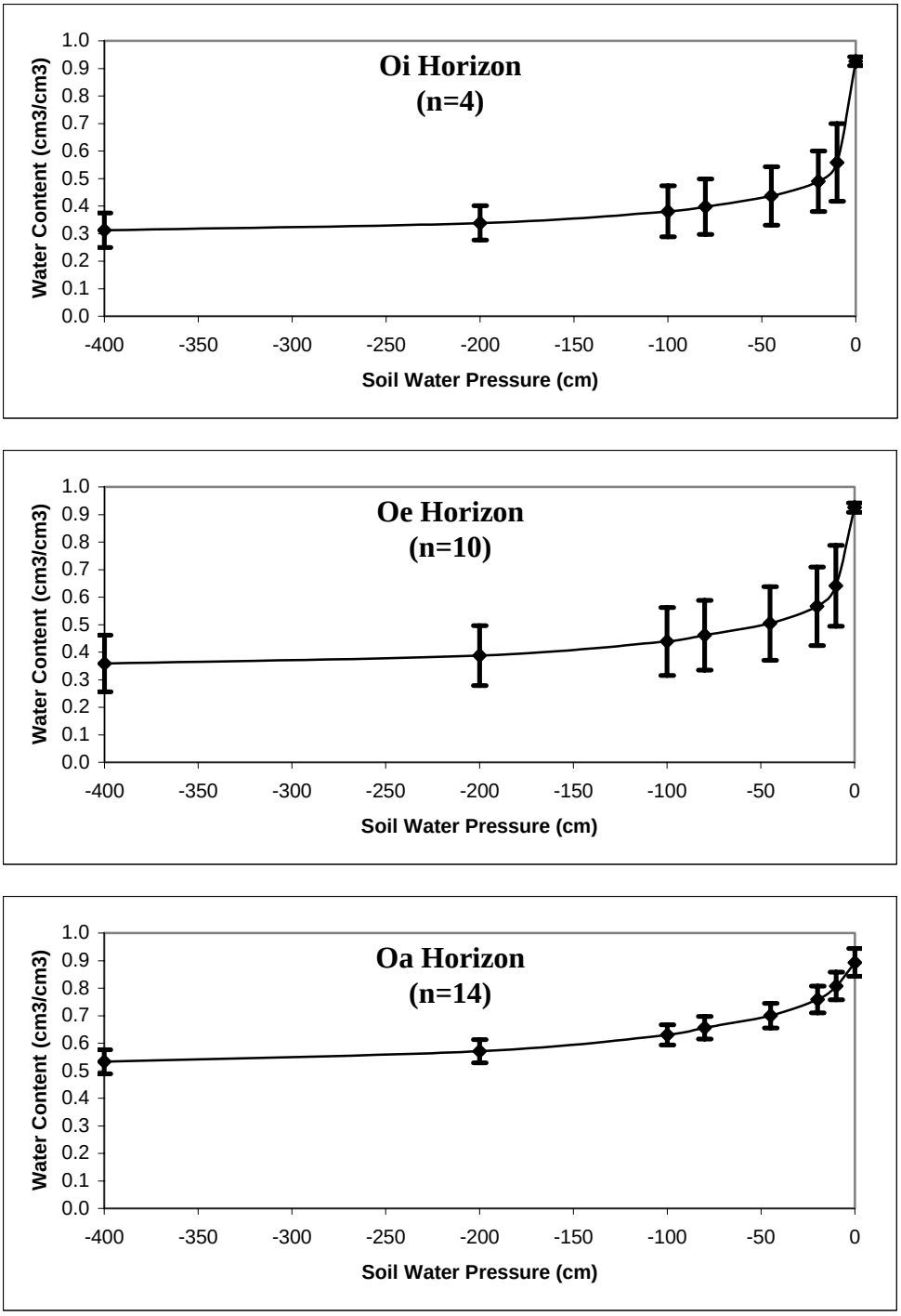

Figure 2.3. Mean soil water characteristic curves for the Oi, Oe, and Oa horizons of organic soils. Error bars show one standard deviation around the mean.

CHAPTER 3

PHYSICAL PROPERTIES OF NATURALLY VEGETATED CAROLINA BAY SOILS

ABSTRACT

Hydrologic models can be extremely effective tools in designing wetland restoration projects. However, little soil property data are available for natural organic soils, preventing effective use of the models for these sites. The objective of this study was to estimate the hydrologic properties of organic and mineral soils in natural, unmanaged Carolina Bay wetlands for calibration of hydrologic models. Three Carolina Bays in Bladen County, NC were selected as reference sites for a wetland restoration project in neighboring Robeson County. Access trails (straight line transects) were cut through existing vegetation in each bay, and soils were classified as mineral, histic, shallow organic, and deep organic, based on the depth of organic soil horizons in the profile. Undisturbed soil cores were taken along each transect for laboratory measurement of bulk density, total porosity, saturated hydraulic conductivity, and soil water characteristic curves. In addition, field measurements of saturated hydraulic conductivity were made. Organic soil horizons tended to have low bulk densities, high total porosities, and high saturated hydraulic conductivities when compared to other organic soils in the literature. Soil water characteristic data collected in this study revealed an abundance of large pores in many of the soil horizons, which is likely the reason for these observations. In general, bulk density tended to increase with depth in the soil profile, while total porosity, saturated hydraulic conductivity, and pore size all decreased with depth. Physical properties of the soils studied are similar across the three bays for similar soil types. As a result, we believe that these data could be used for other natural Carolina Bay sites with similar soils, hydrology, and vegetation.

INTRODUCTION

Wetlands can provide habitat for wildlife, improve water quality, store floodwaters, and provide recreation for outdoor enthusiasts. Wetlands in the United States are protected under section 404 of the Clean Water Act. The wetland mitigation banking system was developed in response to the Act, such that if a developer destroys a wetland, they must agree to restore, enhance, or create an equivalent number of wetland acres as compensation.

Carolina Bays are popular candidates for wetland restoration in the southeastern United States. Carolina Bays are elliptical depressions oriented on the landscape such that the major axis of the bay is in the northwest-southeast direction (Prouty, 1952). They are formed in poorly drained Coastal Plain sediments all along the Atlantic seaboard from northern Florida to New Jersey, but are concentrated in the Carolinas. Their estimated numbers range from 100,000 to 500,000 (Nifong 1998; Prouty 1952), and they can be as small as 90 m along the major axis or as large as 11 km (Prouty, 1952). They tend to have a rim of well drained sandy textured soils that is more pronounced in elevation on the southeastern edge (Sharitz and Gibbons, 1982; Prouty, 1952). Within the sandy rim, the bays have poorly drained and darker colored soils that may be of both mineral and organic composition (Daniels et al., 1999). In some cases, organic soil layers within the bays can reach 4.5 m thick (Ingram and Otte, 1981). There is much debate as to the age of the bays, but the accepted age range is between 10,000-250,000 years old (Sharitz and Gibbons, 1982).

Hydrologic models are powerful tools used to predict the present and future hydrology of wetland restoration sites. Models such as DRAINMOD (Skaggs, 1978) and MODFLOW (McDonald and Harbaugh, 1988) require soil property data such as saturated hydraulic conductivity and soil water characteristic curves to simulate the movement and

storage of water in the soil profile. These properties can have a great impact on the hydrology of a wetland restoration site. For instance, soils with high saturated hydraulic conductivities drain more freely, and thus will generally have lower water table levels than lower conductivity soils under the same hydraulic gradients. Furthermore, the amount of change in the elevation of the water table due to evapotranspiration and rainfall events will depend on the water retention characteristics of the soil (Boelter, 1964).

There have been many studies performed in North Carolina to estimate the hydrologic properties of soils at wetland sites as well as to model their hydrology (He, et al., 2002; Amatya and Skaggs, 2001; Amatya, 1993; McCarthy et al., 1992). However, the properties of these soils have been affected by drainage and management and are different from natural undrained and undeveloped wetlands, particularly in the case of organic soils. When organic soils are developed for agricultural purposes, the undecomposed fibric organic (Oi) surface horizons and the slightly decomposed hemic organic (Oe) horizons are removed, and any accessible buried wood is dug out. These horizons tend to have higher porosities and hydraulic conductivities than the highly decomposed sapric organic horizons that are left after development (Boelter, 1969). Once the organic soils are drained, further irreversible changes to the porosity and hydraulic conductivity occur to the remaining sapric soil horizons (Ilnicki and Zeitz, 2003).

Unfortunately, published soil property data for natural Carolina Bay soils are lacking, especially the organic soils. This is largely due to the difficulty in obtaining the undisturbed soil samples required to estimate these properties. Dense vegetation, fragile surface horizons, woody debris in the soil profile, and flooded conditions all serve to complicate the sample collection process. Numerous studies have been performed in the midwestern U.S.

and in northern Europe to estimate organic soil hydrologic properties (Boelter, 1964, 1965, 1969; Rycroft et al., 1974). However, differences in vegetation type, degree of decomposition, and hydrology all affect soil properties, so these soil data may not be applicable to natural Carolina Bay soils. The objective of this study was to estimate the hydrologic properties of organic and mineral soils in natural, unmanaged Carolina Bay wetlands so that models of the hydrology in these bays could be developed.

MATERIALS AND METHODS

Juniper Bay, a drained Carolina Bay located in Robeson County, NC, was selected as a wetland restoration site by the North Carolina Department of Transportation (NCDOT). The bay was in agricultural production for as many as 30 yr before being purchased by the NCDOT. As part of the project, three undrained and naturally vegetated Carolina Bays were selected as reference sites for the restoration. A DRAINMOD (Skaggs, 1978) hydrologic model of the reference bays was developed, requiring estimates of the soil hydrologic properties at these sites.

The reference bays, Charlie Long Millpond Bay (CL), Tatum Millpond Bay (TM), and Causeway Bay (CW), are located in Bladen County NC, adjacent to Robeson County. They are all in or near Bladen Lakes State Forest, at approximately 34^{o}40’59” N and 78^{o}34’54” W (Fig. 3.1) in the Cape Fear River flood plain soil system (Daniels et al., 1999). The area has a high density of Carolina Bays positioned on abandoned flood plains of the Cape Fear River.

Tatum Millpond Bay and Charlie Long Millpond Bay have both been managed by the N.C. Division of Forest Resources since 1938, and have not been extensively burned in the last 65 to 70 yr (Ewing, 2003). Causeway Bay, which is located on privately owned land,

also has not been burned in the last 65 to 70 yr. In the past, Tatum Millpond Bay was selectively logged for Atlantic White Cedar (*Chamaecyparis thyoides* L.) between 1938 and 1954 (Lees, 2004). Charlie Long Millpond Bay reportedly has never been logged, though it was used to practice fireline construction in the 1970s (Ewing, 2003). Past management practices in Causeway Bay are unclear, but it is known that the last timber harvest occurred on the northeast end in the 1960s (Ewing, 2003). None of these bays have had their hydrology altered by extensive drainage.

Soils types in the reference bays typically transition from mineral nearest the bay perimeter to organic in the center. Torhunta (Coarse-loamy, siliceous, active, acid, thermic, Typic Humaquepts), Lynn Haven (Sandy, siliceous, thermic, Typic Alaquods), and Leon (Sandy, siliceous, thermic, Aeric, Alaquods) soil series are found along the perimeter (Leab, 1990). Meanwhile, Pamlico (Sandy or Sandy-skeletal, siliceous, dysic, thermic, Terric Haplosaprists) and Croatan (Loamy, siliceous, dysic, thermic, Terric Haplosaprists) soil series can be found near the centers of the bays (Leab, 1990). The soils were described by Ewing (2003), and divided into four classes by the depth of organic material as indicated by the percentage of organic carbon. Mineral soils had an organic layer less than 20 cm thick, histic soils 20 to 40 cm thick, shallow organic soils 40-60 cm thick, and deep organic soils had organic layers greater than 60 cm thick. For all soils at the reference bays, a 10 to 20 cm thick fibric organic horizon (Oi) composed of root mat and undecomposed leaf litter was present on the surface. In the case of the mineral soils, this layer was underlain by sandy textured mineral horizons. The histic soils had an approximately 20 cm thick layer of highly decomposed sapric organic matter (Oa) between the surface organic layer and the mineral subsurface. The shallow and deep organic soils had a 15 to 30 cm thick moderately

decomposed hemic organic layer (Oe) below the surface layer, followed by a 20 to more than 60 cm thick sapric organic layer, below which was sandy textured mineral soil. Soil textures of the mineral horizons include sandy loam, loamy sand, and sand.

Lees (2004) studied the plant communities that were established in the reference bays. Charlie Long Millpond Bay and Causeway Bay generally exhibited Pond Pine Woodland plant communities nearest the perimeter and High Pocosin plant communities nearest the center of the bays, as defined by the classification system developed by Schafale and Weakley (1990). Tatum Millpond Bay transitioned from Pond Pine Woodland, to Nonriverine Swamp Forest, to High Pocosin, and finally to Bay Forest from the periphery to the center of the bay. These plant communities differ in vegetation species composition, relative abundance of the various species, and the size and stature of the vegetation. Typical tree species include Pond Pine (*Pinus serotina* L.), Swamp Tupelo (*Nyssa Biflora* L.), Loblolly Bay (*Gordonia lasianthus* L.), Sweetbay (*Magnolia virginiana* L.), and Swamp Red Bay (*Persea palustris* L.) The understory consisted of Gallberry (*Ilex coriacea* L.), Giant Cane (*Arundinaria gigantean* L.), Fetterbush (*Lyonia lucida* L.), Coastal Sweet-pepperbush (*Clethera alnifolia* L.), Highbush Blueberry (*Vaccinium corymbosum* L.), and Green Briar (*Smilax Laurifolia* L.) (Lees, 2004).

Water table depths in the reference bays were recorded in 2003 to 2005. Rainfall during this time was above normal for 2003, but at the lower limit of normal for 2004. Water was ponded on the surface most of the time in the histic, shallow organic, and deep organic soils in Tatum Millpond Bay and Causeway Bay, going no deeper than 30 cm below the surface. The mineral soils in these bays, presumably at a higher elevation, had average water levels approximately 15 cm below the surface, with a maximum depth of about 50 cm.

Charlie Long Millpond Bay, which tended to be the driest of the three reference bays, had average water table depths of 5 cm and 15 cm in the deep and shallow organic soils, respectively, with maximum water table depths of 42 cm and 63 cm. The mineral soils at this bay had average water table depths of 11 cm, extending to a maximum of 58 cm.

Access trails (straight line transects) were cut through the natural vegetation roughly along the minor axes of the bays from the perimeter to the center (Fig. 3.2). Along each transect, water level recording wells were installed. Four wells were installed in Causeway Bay and Charlie Long Millpond Bay, while seven were installed at Tatum Millpond Bay. The water table data recorded by the wells were used to calibrate and test the DRAINMOD hydrologic models. Soil cores were taken in close proximity to each well that were later analyzed to provide soil inputs for the models.

Saturated soil conditions, dense forest vegetation, and woody debris in the soil profile all served to make the collection of intact soil samples difficult at the reference bays. As a result, the development of a new sampling device was required (Caldwell et al., 2005). For organic soils, the sampler consists of a 100-cm-long, 3-in.-diam. schedule 40 PVC pipe that was fitted with female threaded adapters on either end. A cutting head was constructed to cut through the fibric root mat and other woody debris in the profile by gluing a 3-in.-diam. hole-saw to a male threaded adapter that was attached to the PVC pipe. The sampler was rotated by hand into the organic soil with gentle downward pressure. When the desired depth was reached, the remaining air space in the PVC pipe was filled with water and a threaded cap was used to seal the top of the sampler. A 0.5-in.-diam. galvanized pipe was inserted next to the sampler to add water to the bottom of the core, relieving the suction created as the core was pulled from the soil. The sampler and vent pipe were pulled from the soil either by

hand or with a tripod/winch arrangement. Before the cutting head was raised above the water table, it was removed and replaced with another threaded PVC cap.

For mineral soils, the sampler consisted of a 100-cm-long, 3-in.-diam. thin-walled steel tubing that replaced the PVC piping. No cutting head was necessary in these soils, but the leading edge of the steel tubing was sharpened using a grinder to facilitate cutting through roots during the sampling process. The steel tubing was pounded into the soil using a fence-post driver until it reached the desired depth. In this case, rubber end caps with gear clamps were used on either end of the sampler to secure the core inside.

Once the soil cores were brought to the laboratory, they were cut into 7.6-cm-long sections by first setting the pipe into a bucket while maintaining its vertical orientation. The top threaded cap was removed, and the water above the core surface was siphoned out. The location of the upper core surface was marked on the outside of the sampler, and marks were made at 7.6-cm intervals to the bottom of the pipe. A wheel-type pipe cutter was used to gently cut through the pipe at the marked locations while leaving the soil sample intact.

When the pipe was cut completely through, a 4-in. wide, sharpened spatula was inserted into the cut and gently worked across the sample. Any roots in the sample were cut using razor blades or thin saws to minimize damage to the sample. The pipe section containing the sample was then removed while being supported on the bottom by a spatula. The sample was then inverted onto another spatula, and a piece of cheesecloth was secured to the bottom of the sample using a rubber band. The sample was then flipped back over and placed in a pan of water to maintain saturation.

Once the samples were prepared, the saturated hydraulic conductivity was measured using the constant head method (Klute and Dirksen, 1986). The horizontal saturated

hydraulic conductivity was also measured in situ for soil horizons below the water table using the piezometer method (Luthin and Kirkham, 1949). This procedure consisted of placing a 4-in.-diam. PVC pipe with 10 to 15 cm of screen on one end on the soil surface. A 4-in.-diam. bucket auger was used to bore down into the soil profile inside the PVC pipe until the screened section was positioned in the soil horizon of interest. Three replications of conductivity measurements were made before boring down to the next soil horizon. This method was chosen over the auger hole method (Boast and Kirkham, 1971) primarily because it was expected that the conductivity of the undecomposed surface horizon would greatly exceed that of the more decomposed subsurface horizons, making it difficult to distinguish the relative contribution of each horizon (Rycroft et al., 1975). In addition, the fluid nature of some of the organic and sandy layers required the use of a tube to prevent a total loss of soil structure when boring into the soil profile. The slug test method (Bouwer and Rice, 1976) was not used because it required piezometer tubes with a closed bottom, which would prevent the ability to auger down into the soil profile inside the tube.

After the saturated hydraulic conductivity measurements were made on the laboratory samples, the soil water characteristic curves for tensions ranging from 0 to 400 cm were determined on a volume basis using a pressure cell apparatus (Klute, 1986). Water contents for tensions of 1000 cm and 15000 cm were determined using a pressure plate apparatus with disturbed samples collected separately from the intact samples. At the completion of these tests, the samples were placed in cans, weighed, oven-dried at 105^{o} C for 24 hours, and reweighed to determine water content. Bulk density was computed using the oven-dry weight and inner volume of the pipe section. Particle density was measured on organic soil samples using an air pycnometer.

RESULTS AND DISCUSSION

Bulk Density

Bulk density was very different between the organic soils near the center of the bays and that of the mineral soils near the perimeter of the bays. Figure 3.3 shows the relationship between soil bulk density and depth in the profile for the mineral, histic, shallow organic, and deep organic soil types found in Tatum Millpond Bay. As the thickness of the organic layers decreases going from deep organic to mineral soil types, the bulk density tends to increase at a given depth due to the larger percentage of mineral soil material. The bulk density of the mineral soil at Tatum Millpond Bay changes drastically at about the 40 cm depth, indicating a transition from an organic soil layer to the mineral soil layer. Bulk densities in the mucky mineral and mineral horizons are 0.64 g cm^{-3} and 1.4 g cm^{-3} on average across the three reference bays (Table 3.1).

The deep organic soils tend to have very low bulk densities throughout the soil profile that increase slightly with depth. The increase in bulk density with depth is evident in all four soil types. It is likely due to changes in the degree of decomposition of the organic soil material and increasing mineral soil particle percentage, both of which increase with depth. The bulk densities for the fibric (Oi), hemic (Oe), and sapric (Oa) organic soil layers combined over the three reference bays are 0.15 g cm^{-3}, 0.16 g cm^{-3}, and 0.17 g cm^{-3}, respectively (Table 3.1). Boelter (1969) found that the ranges in bulk density of fibric, hemic, and sapric organic materials for northern Minnesota peats were 0.01 to 0.07 g cm^{-3}, 0.07 to 0.20 g cm^{-3}, and greater than 0.20 g cm^{-3}, respectively. The values for the sapric organic horizons are higher than those measured for the Carolina Bay soils for the same degree of decomposition, likely due to the large pores in the form of root channels exhibited

in the Carolina Bay organic soils. Further, vegetation type can affect bulk density. Moss peat was found to have a lower bulk density than fen peat due partly to the degree of decomposition, but also due to lower ash content (Brandyk et al., 2002). The vegetation at the northern Minnesota site was primarily moss and herbaceous peat while that of the Carolina Bays is primarily woody peat and muck.

Ewing (2003) found the bulk density of organic soil layers in a drained Carolina Bay that was managed for agriculture ranged from 0.48 g cm^{-3} to 1.2 g cm^{-3}. These bulk densities are significantly higher than that of the naturally vegetated undrained Carolina Bays, likely due to the loss of the undecomposed surface horizons, removal of woody debris from the soil profile, subsidence due to oxidation of the drained organic matter, and compaction during management as an agricultural field.

In general, the bulk densities of the four soil types are similar among the three reference bays (Fig. 3.4). For the mineral soils, there is an offset in depth among the three bays due to different thicknesses of organic surface horizons.

Particle Density

Particle density was measured for organic soil materials only. While mineral soil particle densities average approximately 2.65 g cm^{-3} (Hillel, 2004), those of organic soil materials are much lower. Okruszko (1971) found that the particle density of organic soil materials averages 1.5 g cm^{-3}, ranging from 1.3 to 1.6 g cm^{-3}. Particle densities for the natural Carolina Bay organic soils averaged approximately 1.5 g cm^{-3} with very little variation amongst the Oi, Oe, and Oa soil horizons (Table 3.1). Particle density is dependent on ash content, which varies according to the vegetation type that supplied the decomposed

organic matter (Brandyk et al., 2002). Okruszko (1971) discovered a linear relationship between particle density and ash content in 2996 samples, reporting an r value of 0.96.

Total Porosity

Total porosity was determined by estimating the water content in the soil at saturation. In organic soils, water can be held between soil particles but also within the particles themselves (Boelter, 1964). Water content estimates, and thus total porosity estimates made in this study include both of these states of soil water.

The total porosity of the four soil types at Tatum Millpond Bay for various depths is shown in Figure 3.5. Like bulk density, the total porosity of the organic soil near the centers of the bays is very different from that of the mineral soils along the bay periphery. For a given depth in the soil profile, the total porosity tends to be lower in the mineral soils than the organic soils. The deep organic soils showed a relatively constant total porosity throughout the soil profile, averaging approximately 0.93 cm^3 cm^{-3}. The shallow organic, histic, and mineral soils have total porosities that tend to decrease with depth (Fig. 3.5).

The total porosities of the Carolina Bay organic soil horizons fall in the range of others previously studied. Like bulk density, total porosity in organic soils depends on the degree of decomposition of the organic matter as well as the type of vegetation found at the site (Boelter, 1964). The total porosities of the fibric (Oi), hemic (Oe), and sapric (Oa) horizons averaged across the three reference bays were 0.90, 0.89, and 0.89 cm^3 cm^{-3}, respectively (Table 3.1). Boelter (1969) found that the total porosity of northern Minnesota peats was greater than 0.90 cm^3 cm^{-3} for fibric, 0.85 to 0.90 cm^3 cm^{-3} for hemic, and less than 0.85 cm^3 cm^{-3} for sapric organic soils. The sapric organic soils in the Carolina bays tend to have higher total porosities than that of the northern Minnesota peats for the same degree of

decomposition. This could again be a result of vegetation differences and/or the presence of very large pores in these horizons at the Carolina Bays. Ewing (2003) found that the total porosities of organic soil horizons in a drained Carolina Bay were significantly less than that measured in the reference bays, providing further evidence that management of organic soils can alter their physical properties from that of their natural counterparts. Total porosities for sapric horizons of Dare, Pungo, and Ponzer organic soils that were drained and intensively managed for silviculture in eastern NC were reported as 0.73, 0.69, and 0.63 $cm^3\ cm^{-3}$, respectively (Amatya, 1993). Though under forest vegetation, the total porosities of these soils are significantly less than that of natural undrained and unmanaged Carolina Bay organic soils.

The mineral soil horizons exhibited much lower total porosities than the organic surface horizons overlying them. In Figure 3.5, the transition from an organic surface horizon to the mineral subsurface horizons is evident in the total porosity for the mineral and histic soil types at the 25 to 60 cm depth. The total porosities of the mucky mineral and mineral horizons averaged across the three reference bays were 0.73 and 0.44 $cm^3\ cm^{-3}$, respectively. This coincides with published total porosity data for mineral soils in the range of 0.45 to 0.55 $cm^3\ cm^{-3}$ (Collins and Kuelhl, 2001).

The total porosities for the four soil types were similar across the three reference bays as shown in Figure 3.6. Like bulk density, there is an offset in the curves for the mineral soils as a result of varying thicknesses of surface organic layers.

Saturated Hydraulic Conductivity

There was a general decrease in saturated hydraulic conductivity with depth in the laboratory conductivity measurements on Tatum Millpond Bay cores for all four soil types

(Fig. 3.7). However, there does not appear to be a similar trend in conductivity among the four soil types as in the case of bulk density and total porosity. This is likely due to the high variability in organic matter decomposition, variability in pore size and connectivity, and mineral soil texture. The hydraulic conductivities of the four soil types were similar among the three bays (Fig. 3.8), despite the known sources of variability. Conductivity was more variable across the three bays for the less decomposed organic layers near the surface (Fig. 3.8), and less variable for the more decomposed subsurface organic layers, which is consistent with the findings of Boelter (1969).

The hydraulic conductivities of fibric organic (Oi), hemic organic (Oe), and sapric organic (Oa) soil horizons as measured in the laboratory and averaged across the three reference bays were 20.5, 12, and 3.0 cm hr^{-1}, respectively (Table 3.2). Boelter (1969) found that the hydraulic conductivities of fibric, hemic, and sapric organic peat materials in northern Minnesota bogs were greater than 6.5, 0.08 to 6.5, and less than 0.08 cm hr^{-1}, respectively. It follows that since the bulk density of the Carolina Bay organic soils was lower than that of Boelter's Minnesota peat, and the total porosity was higher, the conductivity of the Carolina Bay organic soils would have higher hydraulic conductivities, which proves to be the case.

The saturated hydraulic conductivities as measured in the field were 52% greater on average than those measured in the laboratory (Table 3.2). Boelter (1965) found the opposite to be true, citing leakage between the sample and sample cylinder for the laboratory measured conductivities as the cause. This trend could be due to the fact that the laboratory method measured vertical hydraulic conductivity, while the field method measured horizontal conductivity. However, Boelter (1965) found that there was no significant

difference in vertical and horizontal conductivities in any of the peats that were measured. It is more likely that the large interconnected pores in the Carolina Bay soils were truncated when samples were collected for laboratory analysis. As a result, water must flow through the soil medium for the laboratory conductivity measurements, which would result in a lower conductivity than that measured in the field, where water is free to flow through the large interconnected pores. The conductivity measurements made in the field, therefore, are considered to be more representative of the field effective conductivity than are the laboratory measurements.

Soil Water Characteristic Curves

The soil water characteristic curve shows the relationship between the amount of water stored in a soil and the amount of suction, or tension, applied to that soil. As suction on a soil increases, the amount of water retained in the soil decreases. The shape of the curve for a given soil will depend on the pore size distribution. Soils with a high percentage of large pores will lose more water at lower suctions than will soils with a high percentage of smaller pores. The pore size distribution depends on soil texture in the case of mineral soils, and on degree of decomposition in the case of organic soils, as well as bulk density and soil structure. Clayey mineral soils will have smaller pores than a sandy soil, while undecomposed fibric organic (Oi) soils will have larger pores than well decomposed sapric organic (Oa) soils.

The soil water characteristic curves for the various horizons of a deep organic soil and a mineral soil at Tatum Millpond Bay are shown in Figure 3.9. The fibric organic (Oi) and hemic organic (Oe) horizons of the deep organic soil had similar water contents at saturation, roughly 0.93 $cm^3\ cm^{-3}$. The sapric organic (Oa) horizon had water content slightly lower at

saturation, 0.84 cm^3 cm^{-3}. This trend is consistent with the findings of Boelter (1969). The Oi horizon of this deep organic soil loses a significant amount of water at low tensions, and the Oe horizon slightly less so, indicating relatively large pores in these soil layers. The Oa horizon loses the least amount of water at low tensions, retaining 0.57 cm^3 of water per cm^3 of soil at tensions near 400 cm of water, an indication of a larger percentage of smaller pores in the soil matrix.

The mineral soil horizons of the mineral soil type at Tatum Millpond Bay have water contents of approximately 0.42 cm^3 cm^{-3} at saturation, significantly less than that of the overlying Oi horizon (Fig. 3.9). The mucky sandy loam horizon loses about ½ of this water content at soil water tensions greater than -50 cm, indicating large pores in the profile likely a result of relic root channels and other such voids in the soil. The underlying sand horizon retains much more of this water content at higher tensions, an indication of much smaller pores.

The soil water characteristic curves of the various organic and mineral soil horizons encountered at the reference bays averaged over all cores taken at all three bays are shown in Figures 3.10 and 3.11, respectively. Soil textures of the mucky mineral and mineral horizons include sandy loam, loamy sand, and sand. The water content at saturation for the organic horizons are 0.90, 0.89, and 0.89 cm^3 cm^{-3} for fibric, hemic, and sapric organic soils, respectively. Again, Boelter (1969) found that water contents at saturation for northern Minnesota peats were greater than 0.90, 0.85 to 0.90, and less than 0.85 cm^3 cm^{-3} for the same levels of decomposition. Based on these data, it appears that the sapric Carolina Bay organic soils have greater water contents at saturation than do the Minnesota peats, indicating higher total porosities. The water contents at a soil water pressure head of -100 cm for the

Carolina Bay organic horizons are 0.39, 0.46, and 0.57 cm^3 cm^{-3} for fibric, hemic, and sapric organic soils, respectively. Boelter's study reflected water contents of less than 0.48, 0.48 to 0.70, and greater than 0.70 cm^3 cm^{-3} for the same levels of decomposition at the same tension. The water contents for the hemic and sapric organic horizons of the Carolina Bay soils at this tension are lower than that of the Minnesota peats, indicating that more water was lost at lower tensions, a reflection of a larger percentage of large pores.

Amatya (1993) found that the water contents at saturation for drained and managed sapric Dare and Pungo mucks were 0.73 and 0.69 cm^3 cm^{-3}, respectively, and the water contents at 0.1 bar were 0.68 and 0.55 cm^3 cm^{-3}, respectively. The Carolina Bay sapric organic soil water content at 0.1 bar falls between that of these two soils, indicating an equivalent amount of smaller sized pores. However, the water content at saturation is much higher, indicating higher total porosity and also a greater number of large sized pores. It appears that the effects of management have reduced the abundance of large pores in this soil material relative to natural, undrained sapric organic soils.

Volumes of equivalent cylindrical pore diameters of the natural Carolina Bay soils, as estimated by the capillary rise equation (Hillel, 2004), are shown in Figure 3.12. These data provide further evidence that there is an abundance of large pores in the Oi horizon, 37% of total pore volume has equivalent diameters greater than 0.297 mm, relative to the more decomposed Oe and Oa horizons at 27% and 16%, respectively. The Oa horizon has a larger percentage of very small pores, 55% of total pore volume has equivalent diameters less than 0.007 mm, than less decomposed organic horizons. For the mineral soils, mucky mineral horizons have a larger volume of smaller pores than do the mineral horizons (Fig. 3.12).

This is likely due to the translocation of decomposed organic matter to the larger pore spaces between mineral particles, thus dividing the large pore into several smaller sized pores.

Plant available water is the amount of water held in a soil that can not be drained by gravity, and is available for plant roots to absorb (Lilly, 1981). Quantitatively, it is usually defined as the difference in the water content between field capacity (0.3 bars of soil water tension) and the plant wilting point (15 bars tension), expressed on a percentage volume basis. The amount of plant available water in a soil depends on the texture, organic matter content, the state of decomposition of the organic matter, and pore size distribution of the soil. It is generally known that plant available water increases as the amount of organic matter increases (Lilly, 1981). Furthermore, data presented by Boelter (1969) indicated that available water increases as the degree of decomposition increases.

Plant available water for organic soil horizons in the natural Carolina Bay soils were 41% and 42% by volume for the Oe, and Oa horizons, respectively (Table 3.2). No data were collected for the Oi horizons due difficulty in measuring water content at 15 bars with the fibrous soil samples. These data reveal that the increasing plant available water with increasing levels of organic matter decomposition observed by Boelter also applies to the Carolina Bay organic soils. Plant available water for the mucky mineral and mineral soil horizons were 41% and 19% by volume, respectively (Table 3.2). The well decomposed Oa organic horizons have more plant available water than do the mineral soil horizons, providing further validity to the previously observed trend of increasing plant available water with increasing organic matter content.

Plant available water is a somewhat ambiguous quantity in the context of the natural Carolina Bays. Water table depths rarely exceeded 30 cm below the surface in the organic

soil horizons, which corresponds to a maximum tension of 0.03 bar if it is assumed that the soil above the water table is drained to equilibrium. As a result, the soils in the natural Carolina Bays rarely, if ever, were drained to field capacity, let alone drained to soil water tensions in the range considered in plant available water calculations. However, calculating plant available water is useful in making comparisons with soils of different organic composition and management strategy.

Estimating Organic Soil Hydrologic Properties from more easily obtained data

Due to the difficulty in obtaining undisturbed soil samples in natural Carolina Bays, as well as the expensive laboratory measurements required, it would be desirable to have the ability to estimate some of the hydrologic properties of these soils using much more readily obtainable data. For instance, total porosity can be estimated by the following relation if the bulk density and particle densities are known.

$$f = 1 - \frac{\rho_b}{\rho_p}$$

In this equation, f is the total porosity, ρ_b is the bulk density, and ρ_p is the particle density of the soil. The 1.51 g cm^{-3} particle density for organic matter in the natural Carolina Bays that was estimated in this study can be used to determine total porosity if the bulk density of a particular soil has been determined. Using this particle density to predict the total porosity of 49 organic soil samples collected in the reference bays results in an R^2 value of 0.65 for a scatterplot of predicted versus measured total porosities (Fig. 3.13).

Boelter (1969) found that the soil water characteristic curve could be accurately predicted based on curvilinear regression equations relating bulk density to soil water content at a particular tension. A similar set of equations was generated for the Oi, Oe, and Oa

horizons of natural Carolina Bay soils. The general form of the regression equation at each tension is:

$$\theta = A \times \rho_b^2 + B \times \rho_b + C$$

In this equation, θ is the soil water content at that tension, ρ_b is the bulk density, and A, B, and C are regression coefficients summarized in Table 3. R^2 values for the regression equations at each tension are low for the Oe and Oa horizons (Table 3.3). However, when comparing all of the measured water contents at the various tensions to those predicted by the regression equations, R^2 values for the Oi, Oe, and Oa horizons are 0.85, 0.63, and 0.48, respectively, for scatterplots of predicted water content versus measured water content (Fig. 3.14). This indicates that this model does fairly well in predicting water content for these horizons, particularly for the Oi and Oe horizons.

Saturated hydraulic conductivity is a soil property that is highly variable due to the effects of compaction, macropores, sample size, temperature, and entrapped air (Ahuja et al., 1999). Ahuja et al. (1989) found that hydraulic conductivity is closely related to effective porosity, which is the difference between total porosity and the water content at 1/3 bar. The relationship between saturated hydraulic conductivity and effective porosity is expressed using the Kozeny-Carman equation (Ahuja et al., 1999):

$$K_{sat} = B\phi_e^n$$

In this equation, K_{sat} is the saturated hydraulic conductivity, ϕ_e is the effective porosity, and B and n are constants. This relation was used with good success when evaluating the hydraulic conductivities of 473 data points from nine soils (Ahuja et al., 1989).

In this study, values of B and n were estimated using in situ saturated hydraulic conductivity measurements for the Oe and Oa organic soil horizons of the natural Carolina Bay soils. Unfortunately, there were no samples from Oi horizons for which both an in situ conductivity measurement and soil water characteristic data were measured. Values for B and n were estimated by trial and error methods, and the resulting quantities were 360 and 2.4689, respectively, for the Oe horizons, and 35 and 2.2137, respectively, for the Oa horizons. Measured and predicted saturated hydraulic conductivity values for samples of Oe and Oa horizons using the Kozeny-Carman equation with measured soil water characteristic data are shown in Table 3.4. This equation predicts hydraulic conductivity reasonably well given the limit amount of data. For each horizon type, there were some points for which the equation predicts hydraulic conductivity poorly. With a larger sample of conductivity and soil water characteristic measurements, better estimates of B and n could be found leading to better and more consistent predictions of hydraulic conductivity in these soils.

CONCLUSIONS

The physical properties of organic soils depend on vegetation type, management, hydrology, and degree of decomposition of organic matter. Organic soil horizons found in natural Carolina Bays tend to have low bulk densities, high total porosities, and high saturated hydraulic conductivities when compared to northern Minnesota peats and managed organic soils in North Carolina. Soil water characteristic data collected in this study reveal an abundance of large pores in many of the soil horizons, which is likely the reason for these observations. In general, bulk density tended to increase with depth in the soil profile, while total porosity, saturated hydraulic conductivity, and pore size all tended to decrease with depth.

The natural Carolina Bay soil physical properties are different from the northern Minnesota peats mostly due to differences in vegetation type. The Minnesota peats were mostly of moss composition, while the Carolina bay organic soils were formed from forest vegetation. The abundance of trees creates a vast network of relic root channels in the soil that create large pores, lower bulk density, and increase hydraulic conductivity. The natural Carolina Bay soil physical properties differ from managed North Carolina organic soils due to the effects of drainage on organic soil properties and removal of surface horizons during land preparation. The organic soils in the natural Carolina bays were in many cases underwater most of the time during this study. It is possible that the organic materials at these sites at least partially "float" in the ponded conditions, which could further lead to greater porosity relative to other organic soils where the water table is below the surface.

Physical properties of the reference bay soils are similar across the three bays for similar soil types. As a result, we believe that these data could be used for other natural Carolina Bay sites with similar soils, hydrology, and vegetation. The regression equations formulated in this study will be helpful to others in need of soil water characteristic data for these soils, but who do not have the ability to measure them in the laboratory. The results of this study have significant importance in understanding the natural hydrology of Carolina Bays and in predicting the hydrology of wetland restoration sites.

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Table 3.1. Laboratory bulk density, particle density, and total porosity measurements conducted on Carolina Bay soils across all three reference bays.

Soil	Organic	Bulk Density			Particle Density			Total Porosity		
Material	Decomposition	n	mean	Std error	n	mean	Std error	n	mean	Std error
			---g cm^{-3}---			---g cm^{-3}---			---cm^3 cm^{-3}---	
Organic	Fibric (Peat)	6	0.15	.04	5	1.6	0.11	6	0.90	0.02
Organic	Hemic (Mucky Peat)	18	0.16	.03	15	1.5	0.06	18	0.89	0.01
Organic	Sapric (Muck)	25	0.17	.02	20	1.5	0.05	25	0.89	0.01
Mucky Mineral	-	42	0.64	.05		†ND		41	0.73	0.02
Mineral	-	31	1.4	.04		†ND		30	0.44	0.01

†ND Particle density was not measured on mineral soil types.

Table 3.2. Plant available water, laboratory hydraulic conductivity, and in situ hydraulic conductivity measurements conducted on Carolina Bay soils across all three reference bays.

Soil	Organic	Plant Available Water			Saturated Hydraulic Conductivity: Laboratory			Saturated Hydraulic Conductivity: In situ		
Material	Decomposition	n	mean	Std error	n	mean	Std error	n	mean	Std error
			---% by Vol.---			---cm hr^{-1}---			---cm hr^{-1}---	
Organic	Fibric (Peat)		†ND		3	20.0	10.0	2	45	4.8
Organic	Hemic (Mucky Peat)	8	41%	5%	11	12	4.0	9	13	5.9
Organic	Sapric (Muck)	7	42%	5%	22	3.0	1.1	4	3.3	2.1
Mucky Mineral	-	7	41%	5%	42	4.2	1.6	9	7.0	2.1
Mineral	-	7	19%	2%	31	4.2	1.4	7	6.4	1.1

†ND Water content at 15 bars for fibric organic soil material could not be measured on pressure plate apparatus due to poor contact between sample and plate.

Table 3.3. Regression equations relating bulk density (ρ_b) to soil water content (θ) at various tensions for the Oi, Oe, and Oa horizons of natural Carolina Bay soils.

	Oi Horizons (n=6)				Oe Horizons (n=18)				Oa Horizons (n=25)			
Tension cm	A	B	C	R^2	A	B	C	R^2	A	B	C	R^2
-400	-6.2996	3.1678	0.0365	0.67	-0.6597	0.6551	0.3045	0.13	-4.2027	2.3222	0.2454	0.23
-200	-7.1555	3.4634	0.0418	0.66	-1.1285	0.9481	0.307	0.15	-4.8176	2.6766	0.2471	0.27
-100	-8.961	4.1059	0.0342	0.49	-1.065	0.8243	0.3706	0.07	-4.1599	2.2367	0.3498	0.16
-80	-9.6623	4.3787	0.0296	0.47	-1.0897	0.8255	0.3924	0.06	-4.3548	2.3048	0.3685	0.16
-45	-10.953	4.8834	0.0283	0.45	-1.3361	0.9443	0.4256	0.06	-4.398	2.3342	0.4097	0.15
-20	-10.46	4.7783	0.0838	0.42	-1.2452	0.886	0.4937	0.05	-4.3823	2.2732	0.4735	0.13
-10	-10.631	4.881	0.1385	0.34	-1.3431	0.849	0.5639	0.04	-4.1344	2.0793	0.5424	0.11
0	-2.1501	0.2348	0.9314	0.99	0.6082	-0.7576	0.9921	0.73	0.9834	-0.9447	1.0072	0.61

Table 3.4. Field measured and predicted saturated hydraulic conductivity values for samples of the Oe and Oa horizons of natural Carolina Bay soils.

Oe Horizons				
Depth	Location	ϕ_e	Measured K_{sat}	Predicted K_{sat}
15-23	TM2	0.30	18	18
23-31	TM2	0.25	9.2	12
42-50	TM3	0.24	10.9	10.7
64-72	TM6	0.30	0.53	19

Oa Horizons				
Depth	Location	ϕ_e	Measured K_{sat}	Predicted K_{sat}
45-53	CW4	0.25	1.7	1.7
23-31	TM2A	0.17	11	0.72
84-92	TM4	0.25	2.4	1.6
81-89	TM5	0.15	0.50	0.50
80-88	TM6	0.15	0.37	0.55

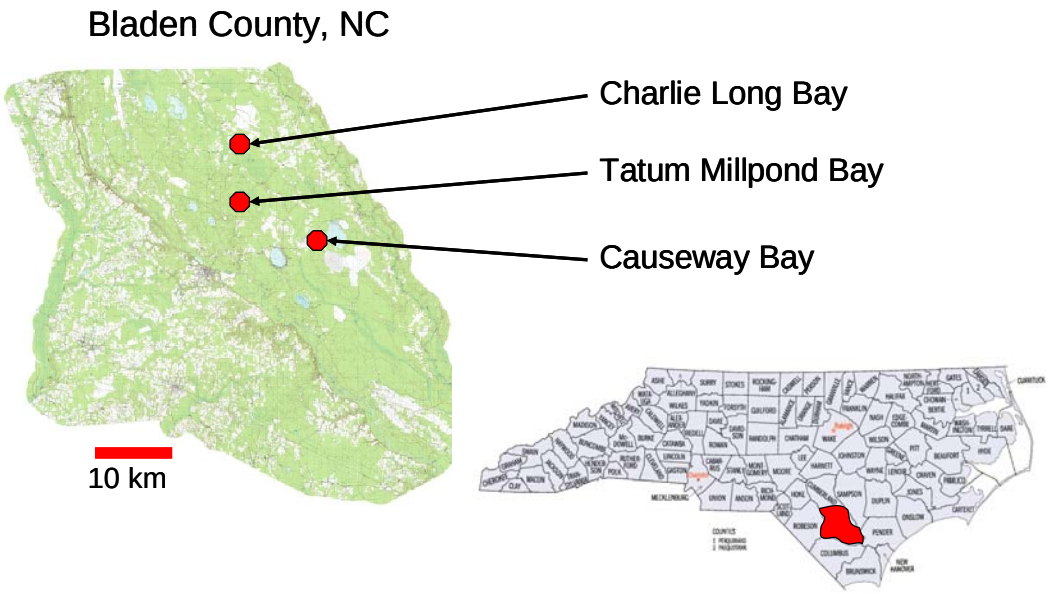


Figure 3.1. Locations of reference Carolina Bays in Bladen county, NC.

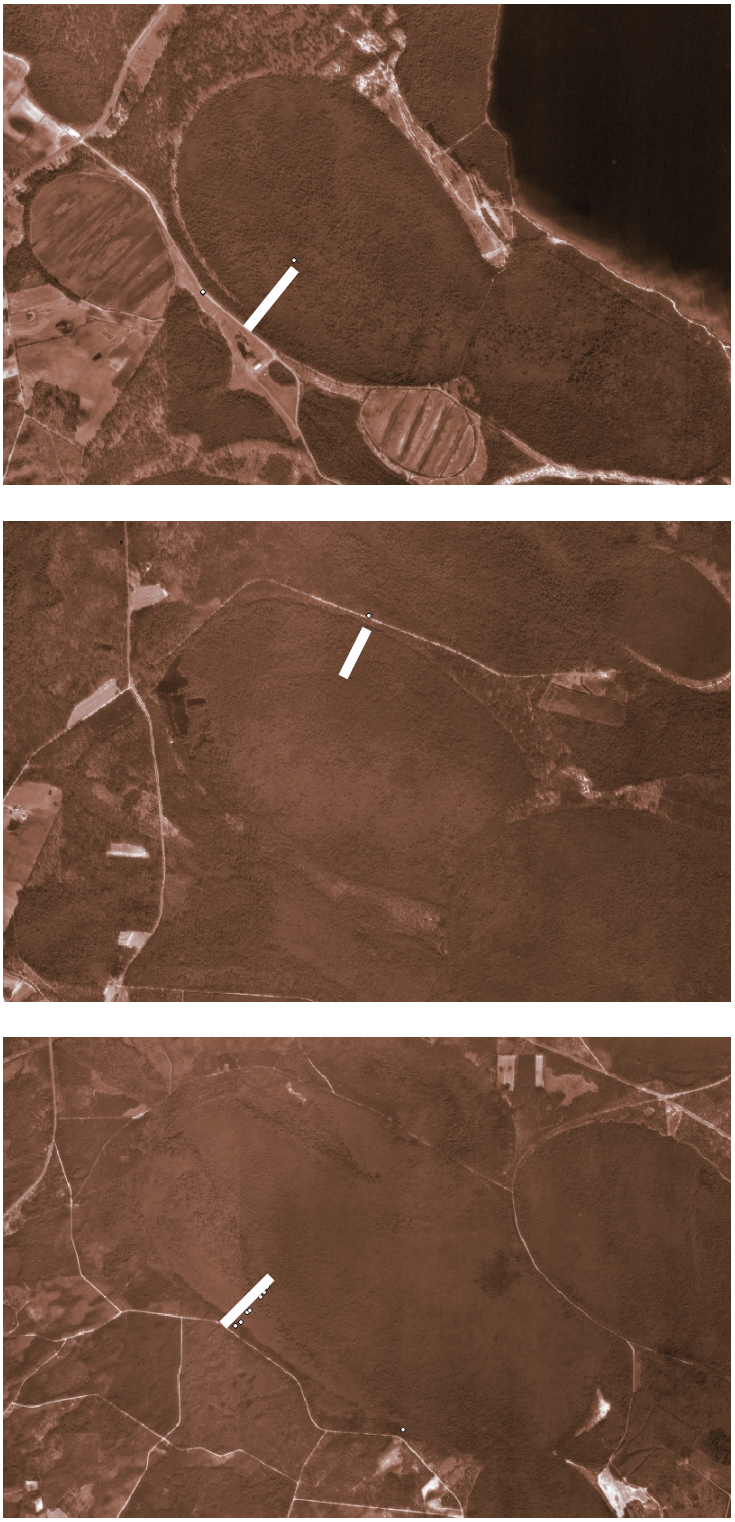


Figure 3.2. Location of transects in Causeway Bay, Charlie Long Millpond Bay, and Tatum Millpond Bay, respectively.

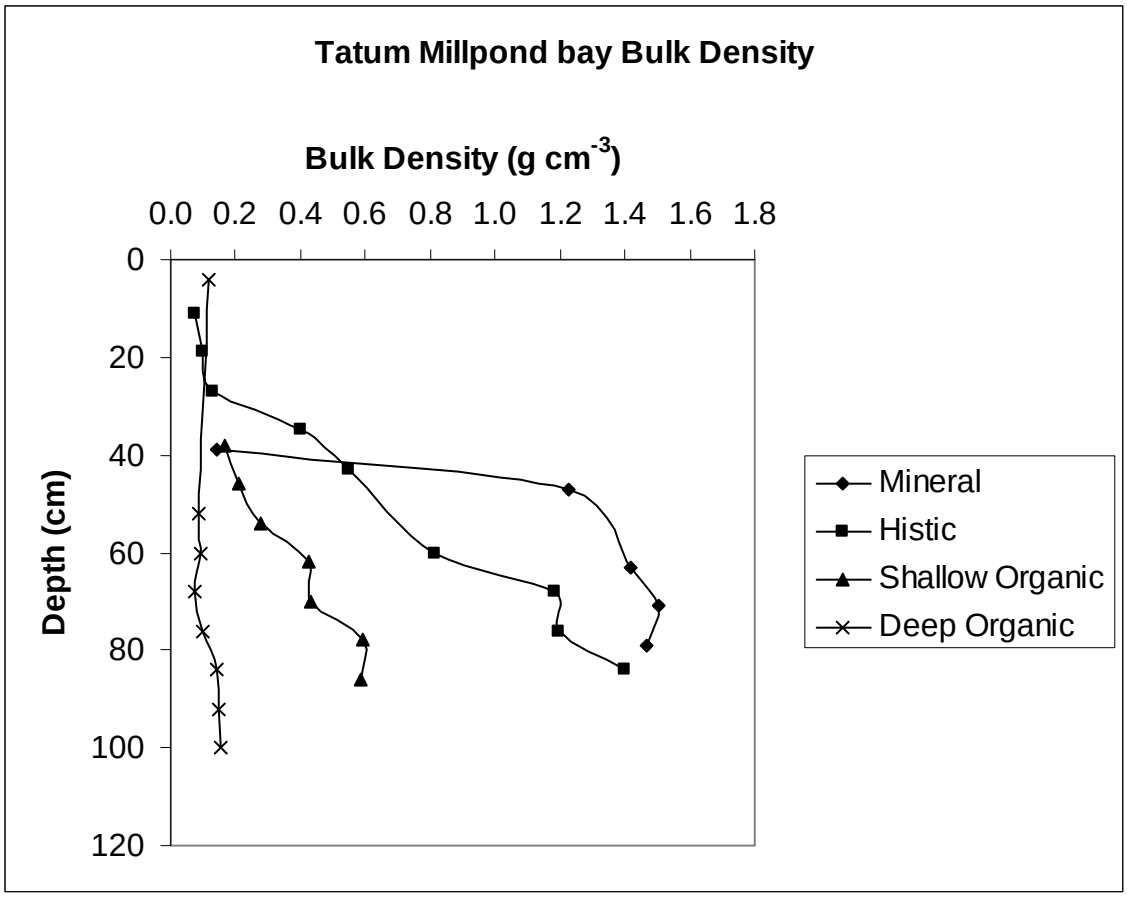


Figure 3.3. Bulk density vs. depth for mineral, histic, shallow organic, and deep organic soils in Tatum Millpond Bay.

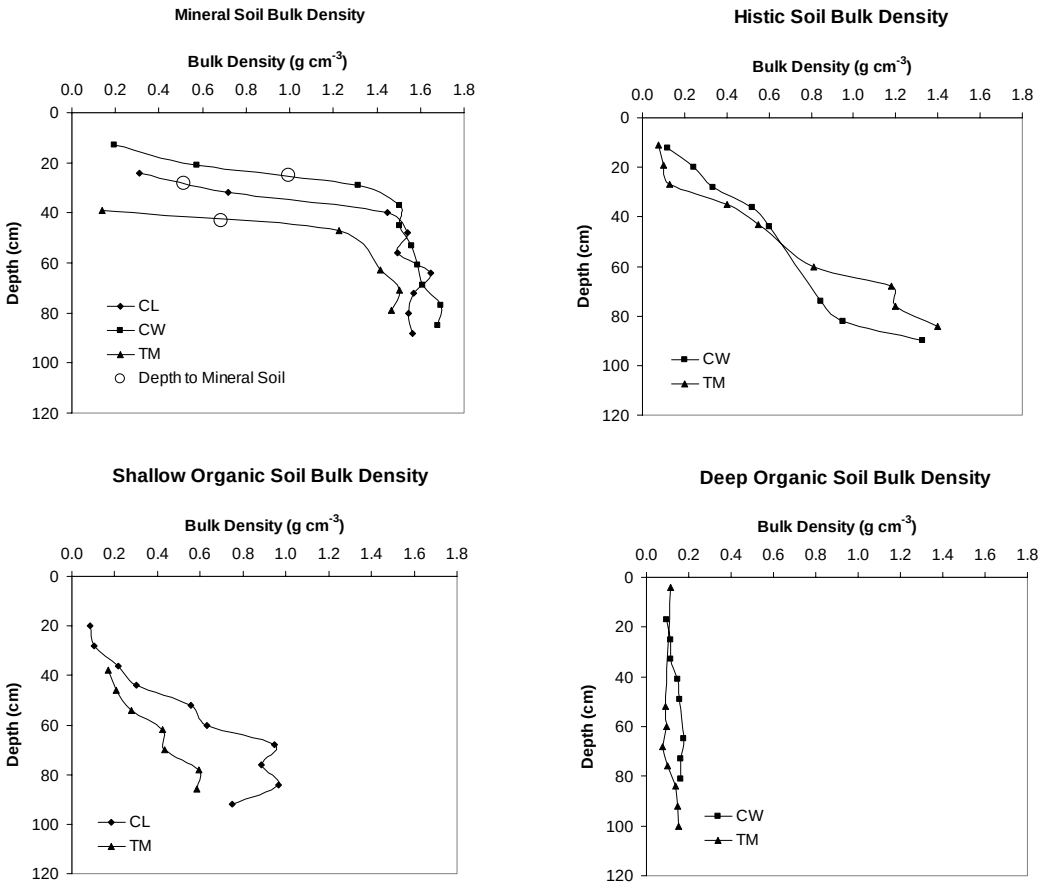


Figure 3.4. Bulk density vs. depth for the four soil types found in the reference bays. CL = Charlie Long Millpond Bay, CW = Causeway Bay, TM = Tatum Millpond Bay.

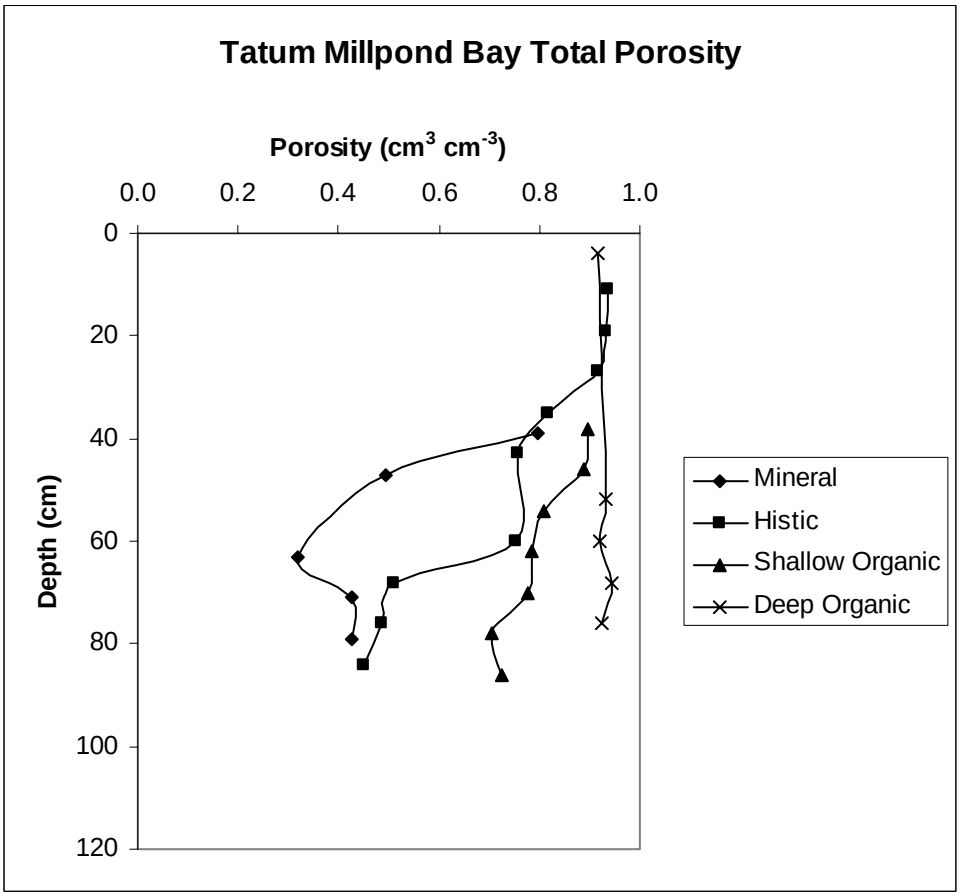


Figure 3.5. Total porosity vs. depth for mineral, histic, shallow organic, and deep organic soils in Tatum Millpond Bay.

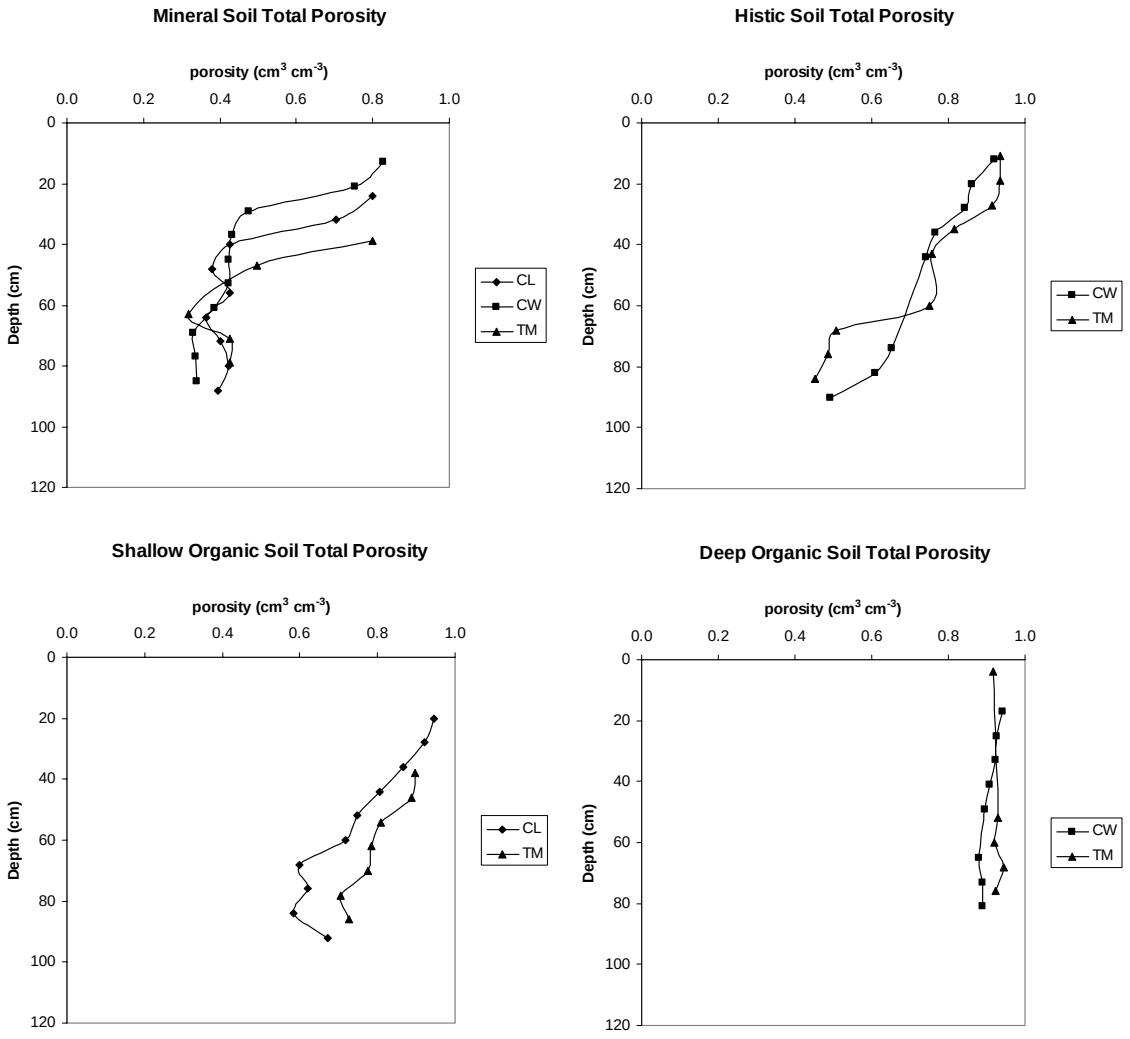


Figure 3.6. Total porosity vs. depth for the four soil types found in the reference bays. CL = Charlie Long Millpond Bay, CW = Causeway Bay, TM = Tatum Millpond Bay.

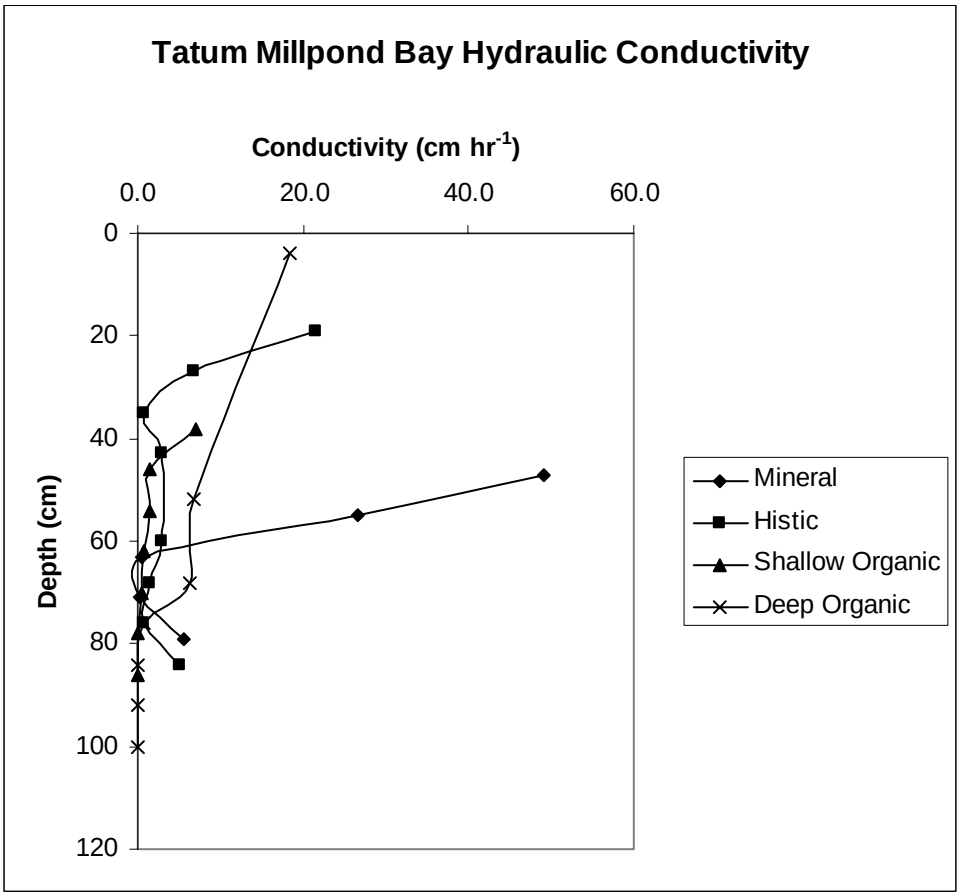


Figure 3.7. Saturated hydraulic conductivity vs. depth for mineral, histic, shallow organic, and deep organic soils in Tatum Millpond Bay as measured in the laboratory.

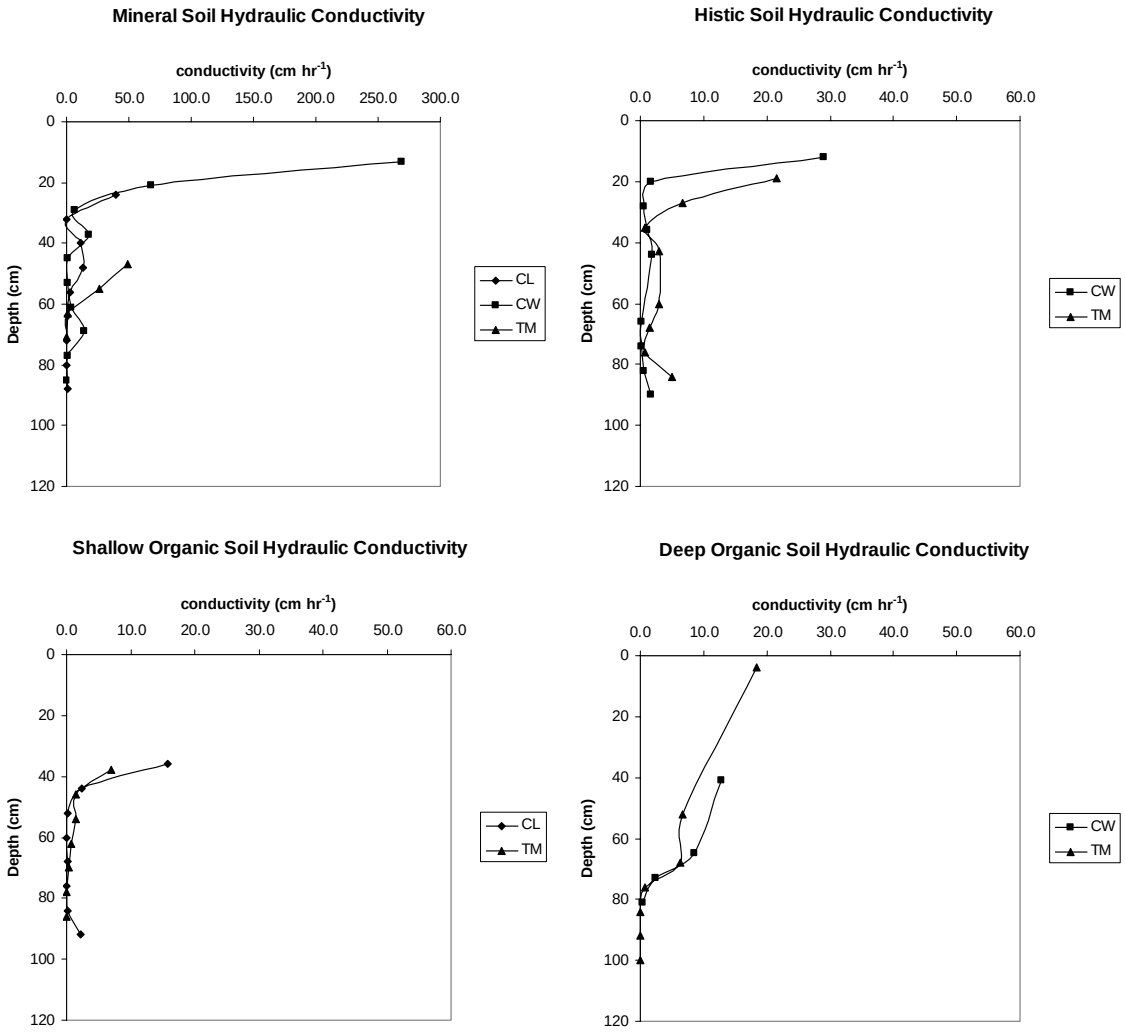
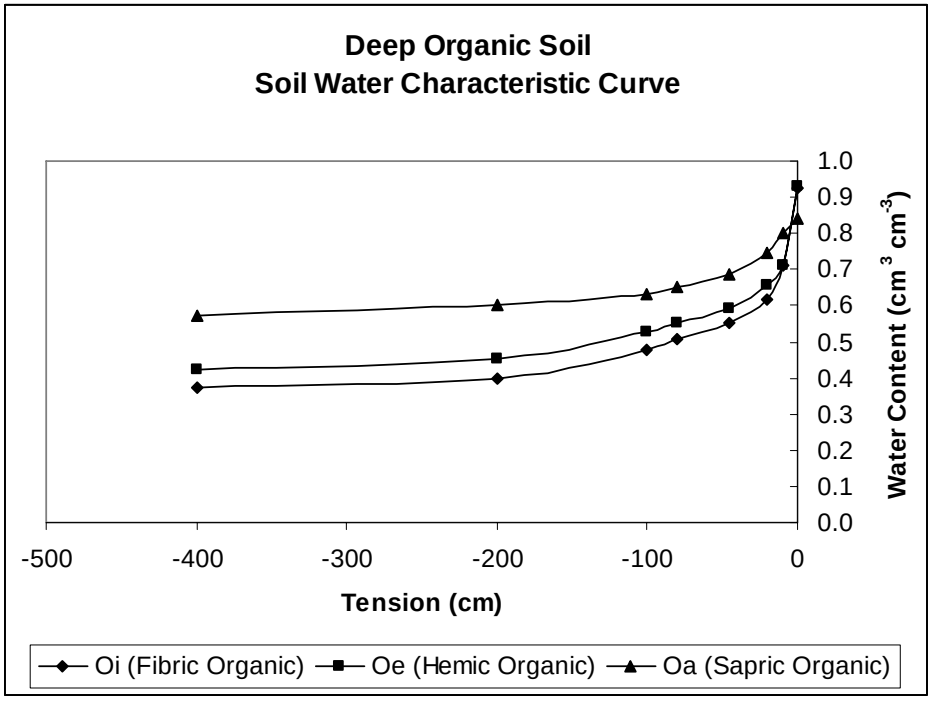


Figure 3.8. Saturated hydraulic conductivity vs. depth for the four soil types found in the reference bays. CL = Charlie Long Millpond Bay, CW = Causeway Bay, TM = Tatum Millpond Bay.



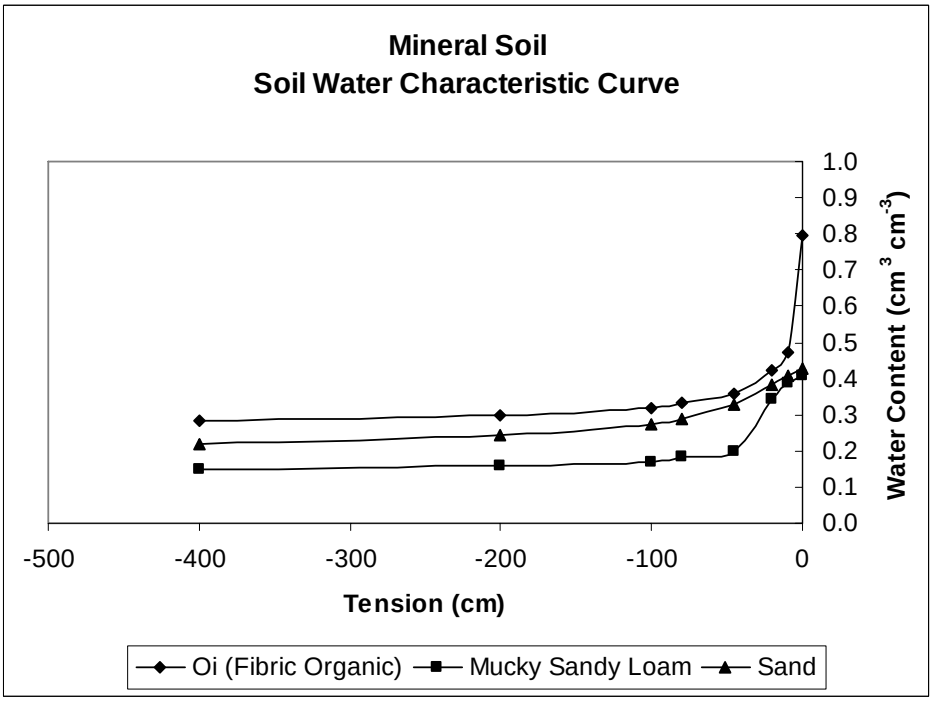


Figure 3.9. Soil water characteristic curves for the various horizons of a deep organic and a mineral soil at Tatum Millpond Bay.

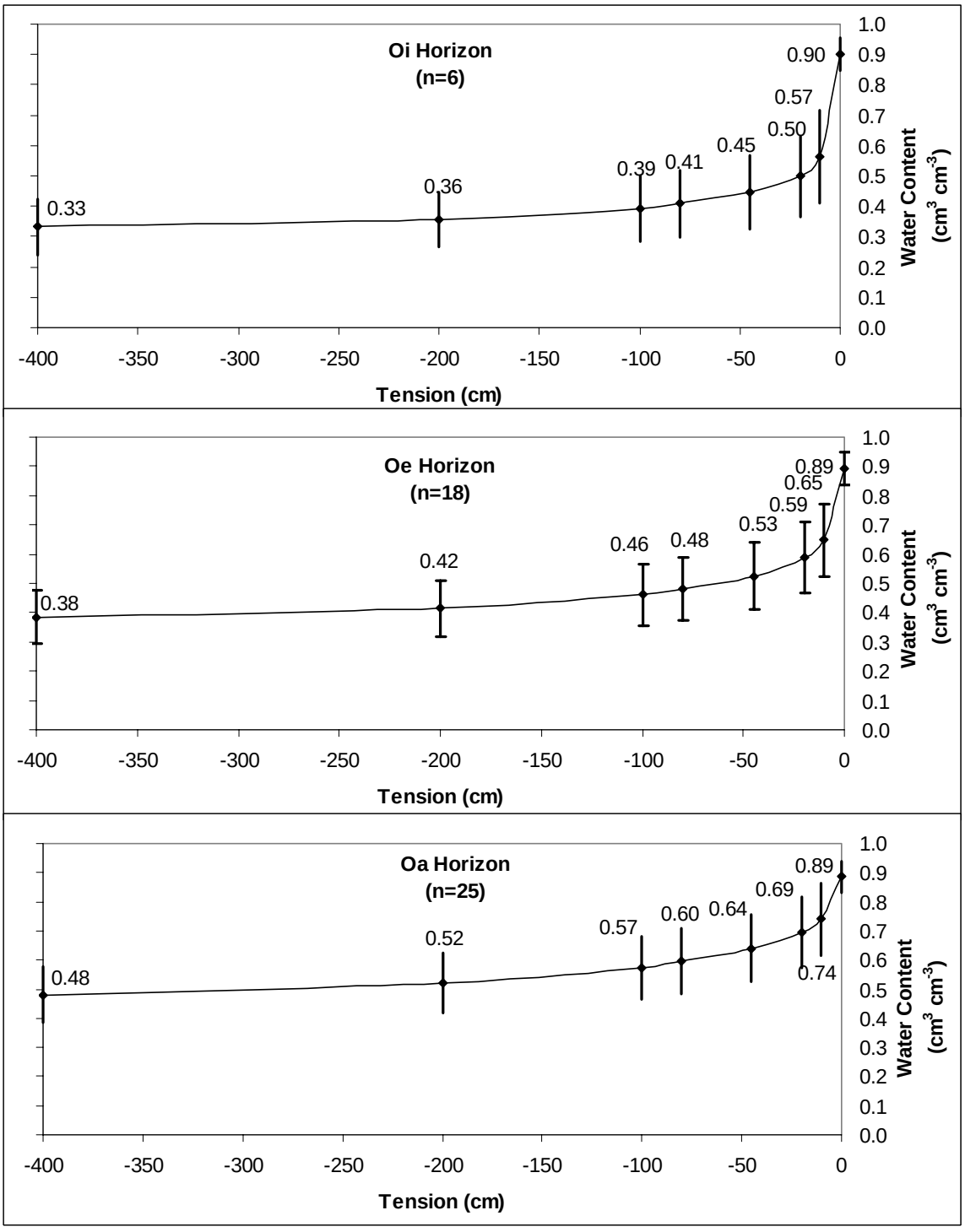
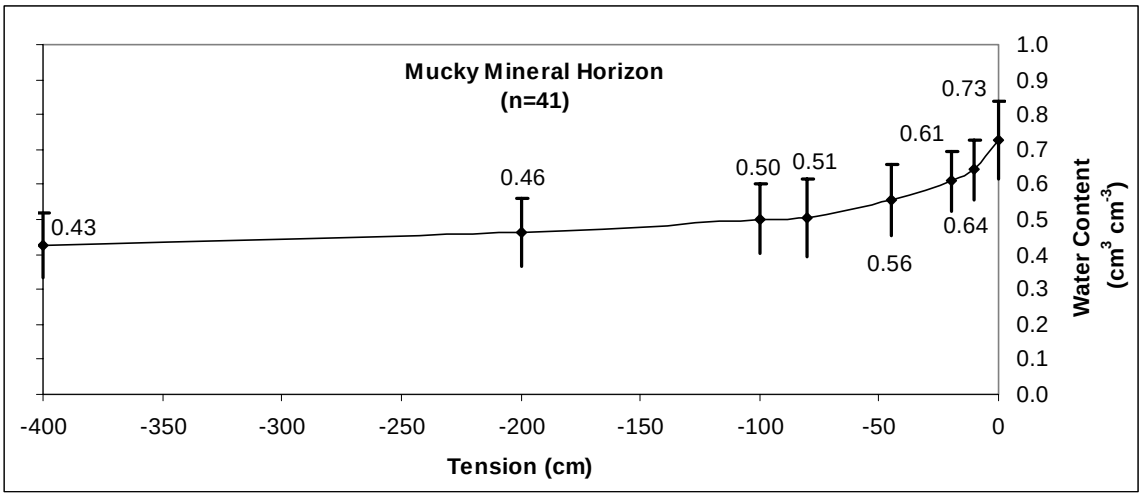


Figure 3.10. Mean soil water characteristic curves for Oi, Oe, and Oa horizons of organic soils encountered in Carolina Bays. Numbers are the average water contents at that tension. Error bars show one standard deviation around the mean.



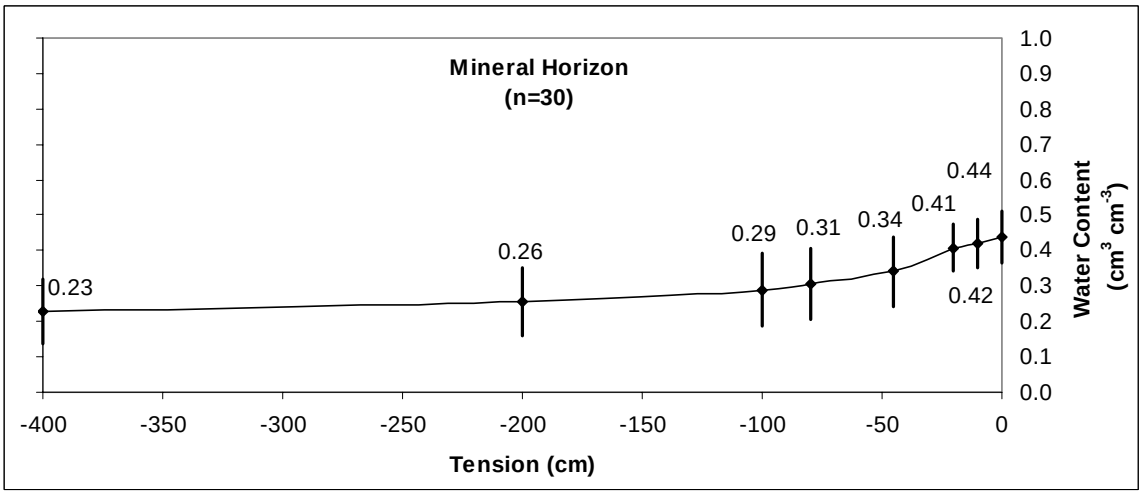


Figure 3.11. Mean soil water characteristic curves for mucky mineral and mineral soil horizons encountered in Carolina Bays. Numbers are the average water contents at that tension. Error bars show one standard deviation around the mean. Soil textures of muck mineral and mineral horizons include sandy loam, loamy sand, and sand.

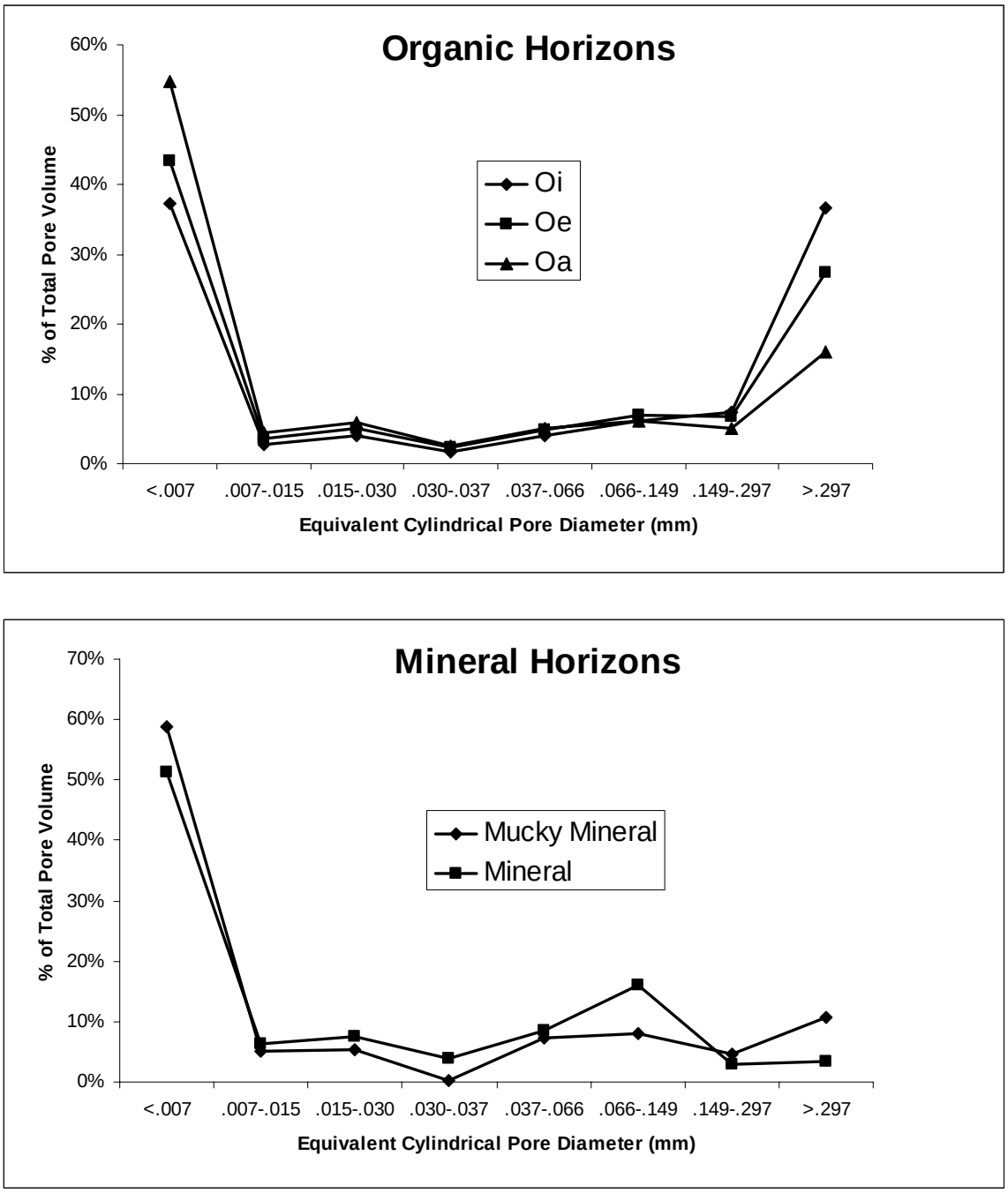


Figure 3.12. Volumes of various sizes of equivalent cylindrical pore diameters expressed as a percentage of total pore volume for organic and mineral soil horizons, averaged over the three bays.

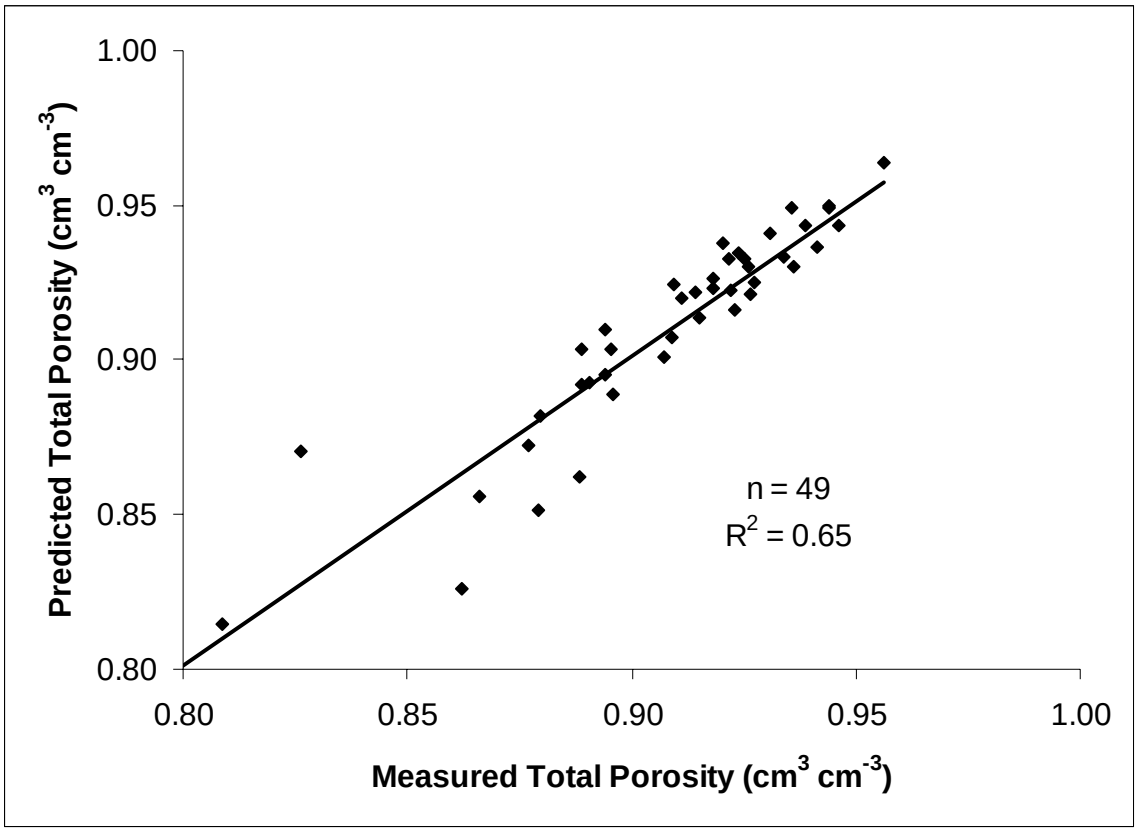


Figure 3.13. Scatterplot of predicted versus measured total porosity of organic soil horizons in natural Carolina Bays.

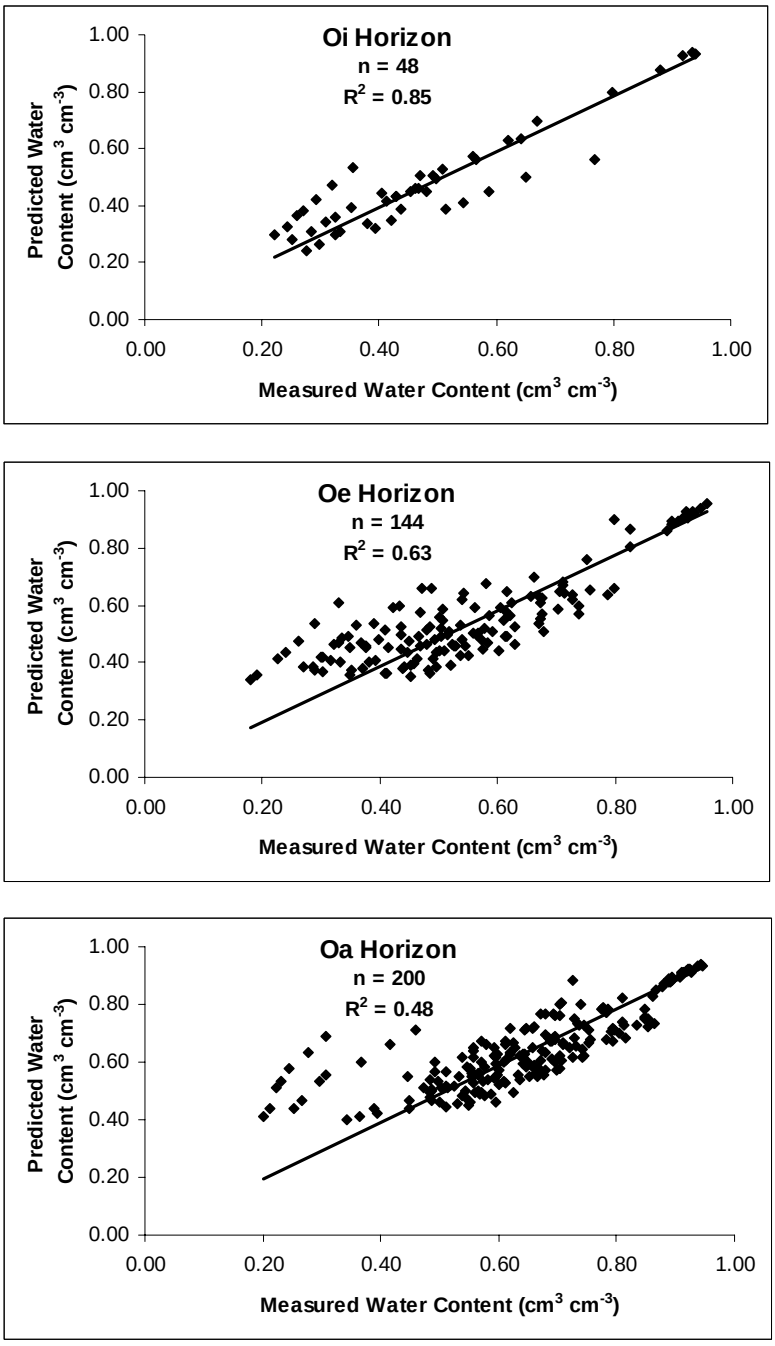


Figure 3.14. Scatter plots of water contents predicted by regression equations versus those measured in the laboratory for the Oi, Oe, and Oa horizons of natural Carolina Bay organic soils at soil water tensions ranging from 0 to 400 cm. R^2 values are the correlation coefficients for a 1:1 line.

CHAPTER 4

SIMULATING THE LONG-TERM HYDROLOGY OF NATURAL CAROLINA BAYS

ABSTRACT

Hydrologic models can be extremely effective tools in designing wetland restoration projects. However, a thorough understanding of the target natural system must be obtained to improve the success rate of these projects. The objective of this study was to develop DRAINMOD hydrologic models to simulate long-term (40-yr) water table depths in three natural Carolina Bay wetlands to quantify their hydrologic variability over time. DRAINMOD models of various locations in the bays were calibrated over a 2 yr period, then 40 yr of historical weather data were used as input for the models to simulate long-term water table depths at those locations in each bay. The models were successful in simulating water table depths at all well locations over the calibration period. Simulation results reveal very shallow water table depths at all of the bays over the 40 yr simulation. Every well location met the wetland hydrology criterion in all years simulated. At many of the wells, the water table elevation appeared to be controlled by the balance between rainfall and evapotranspiration. Groundwater inflow had a significant effect on water table depths at some locations. Groundwater outflow exceeded inflow on an annual basis, but inflow could exceed outflow on a monthly basis, particularly during drier months. The source of the groundwater inflow is not known but it is believed to be a local phenomenon. The water could enter the bays either laterally from adjacent uplands or vertically from confined aquifers below. A confined artesian aquifer below one of the bays was likely the source of inflow for that bay.

INTRODUCTION

Wetlands can provide habitat for wildlife, improve water quality, store floodwaters, and provide recreation for outdoor enthusiasts. Wetlands in the United States are protected under section 404 of the Clean Water Act. The wetland mitigation banking system was developed in response to the Act, such that if a developer destroys a wetland, they must agree to restore, enhance, or create an equal number of wetland acres in compensation.

Carolina Bays are popular candidates for wetland restoration in the southeastern United States. Carolina Bays are elliptical depressions oriented on the landscape such that the major axis of the bay is in the northwest-southeast direction (Prouty, 1952). They are formed in poorly drained coastal plain sediments all along the Atlantic seaboard from northern Florida to New Jersey, but are concentrated in the Carolinas. Their estimated numbers range from 100,000 to 500,000 (Nifong 1998; Prouty 1952), and they can be as small as 90 m along the major axis or as large as 11 km (Prouty, 1952). They tend to have a rim of well drained sandy textured soils that is more pronounced in elevation on the southeastern edge (Sharitz and Gibbons, 1982; Prouty, 1952). Within the sandy rim, the bays have poorly drained and darker colored soils that may be of both mineral and organic composition (Daniels et al., 1999). In some cases, organic soil layers within the bays can reach 4.5 m thick (Ingram and Otte, 1981). There is much debate as to the age of the bays, but the accepted age range is between 10,000-250,000 years old (Sharitz and Gibbons, 1982).

Bruland et al. (2003) studied the hydrology of a Carolina Bay wetland complex in Cumberland county, NC over a 2 yr period, describing the seasonal variation in hydrology as a balance between precipitation and evapotranspiration (ET). During time periods when precipitation exceeded ET, the water table was above the surface, and when ET exceeded

precipitation, the water table was below the surface. Schalles and Shure (1989) also found a strong relationship between precipitation and water level in a Carolina Bay in South Carolina over a 4 yr period, but did note that there may be surface and groundwater connections during wet periods. They asserted that the groundwater exchange must be lateral rather than vertical due to a dense clay aquitard below the bay, and that the lateral exchange only occurs when the water table is above the aquitard. Lide et al. (1995) studied the hydrology of the same Carolina Bay in SC over a 4 yr period and confirmed that there was interaction between water in the bay and that outside the bay, though in their study, they claimed that the interaction occurred in both the vertical and lateral direction. They found that during periods of moderate water table depths, vertical and lateral seepage losses from the bay result in groundwater mounding in the bay and the adjacent area. During periods of high water tables, groundwater inflow occurs that may exceed seepage losses.

Hydrologic models such as DRAINMOD (Skaggs, 1978) and MODFLOW (McDonald and Harbaugh, 1988) are powerful tools that can be used to both understand the hydrology of Carolina Bays and to predict the hydrology of restored or created wetlands. DRAINMOD is a hydrologic modeling package originally developed to simulate agricultural drainage systems in poorly drained soils like those of the Coastal Plain of North Carolina. The model assumes a network of parallel drainage ditches or drain tiles at a given depth and spacing. Based on these parameters, the model determines the relationship between the water table depth and the drainage rate using the Hooghoudt equation. An hourly water balance on a unit area of the soil profile is computed based on inputs of weather (e.g. hourly rainfall and daily maximum and minimum temperature), soil properties, and the drainage network specifications. DRAINMOD has been used extensively for optimizing drainage

systems for agricultural land uses, but it has also been used to simulate the hydrology of natural, undrained wetlands (He et al., 2002; Chescheir et al., 1994). The objective of this study was to develop a DRAINMOD hydrologic model to simulate long-term (40-yr) water table depths in natural Carolina Bay wetlands so that the details of their hydrology could be better understood.

MATERIALS AND METHODS

Juniper Bay, a drained Carolina Bay located in Robeson County, NC, was selected as a wetland restoration site by the North Carolina Department of Transportation (NCDOT). The bay was in agricultural production for as many as 30 yr before being purchased by the NCDOT. As part of the project, three undrained and naturally vegetated Carolina Bays were selected as reference sites for the restoration. DRAINMOD hydrologic models were developed to understand and quantify the long-term hydrology of the reference sites.

Site Descriptions

The reference bays, Charlie Long Millpond Bay (204 ha), Tatum Millpond Bay (808 ha), and Causeway Bay (145 ha), are located in Bladen County NC, adjacent to Robeson County. They are all in or near Bladen Lakes State Forest, at approximately 34^{o}40’59” N and 78^{o}34’54” W (Fig. 4.1) in the Cape Fear River flood plain soil system (Daniels et al., 1999). The area has a high density of Carolina Bays positioned on abandoned flood plains of the Cape Fear River.

Tatum Millpond Bay and Charlie Long Millpond Bay have both been managed by the N.C. Division of Forest Resources since 1938, and have not been extensively burned in the last 65 to 70 yr (Ewing, 2003). Causeway Bay, which is located on privately owned land, also has not been burned in the last 65 to 70 yr. In the past, Tatum Millpond Bay was

selectively logged for Atlantic White Cedar (*Chamaecyparis thyoides* L.) between 1938 and 1954 (Lees, 2004). Charlie Long Millpond Bay reportedly has never been logged, though it was used to practice fireline construction in the 1970s (Ewing, 2003). Past management practices in Causeway Bay are unclear, but it is known that the last timber harvest occurred on the northeast end in the 1960s (Ewing, 2003). Charlie Long Millpond Bay has a small impoundment on the northwest end that is outfitted with a control structure (Fig. 4.2). It is actively managed, raising the water level in the impoundment in mid-September, and lowering it again in mid-March. It is not known how long the management of the impoundment has occurred. Other than this feature, the hydrology of the reference bays has not been extensively altered by drainage.

Soils types in the reference bays typically transition from mostly mineral composition nearest the bay perimeter to mostly organic composition in the center. Torhunta (Coarse-loamy, siliceous, active, acid, thermic, Typic Humaquepts), Lynn Haven (Sandy, siliceous, thermic, Typic Alaquods), and Leon (Sandy, siliceous, thermic, Aeric, Alaquods) soil series are found along the perimeter (Leab, 1990). Meanwhile, Pamlico (Sandy or Sandy-skeletal, siliceous, dysic, thermic, Terric Haplosaprists) and Croatan (Loamy, siliceous, dysic, thermic, Terric Haplosaprists) soil series can be found near the centers of the bays (Leab, 1990).

The soils at the reference bays were described to a depth of 1 m by Ewing (2003), and divided into four classes by the depth of organic material as indicated by the percentage of organic carbon. Mineral soils had an organic layer less than 20 cm thick, histic soils 20 to 40 cm thick, shallow organic soils 40 to 60 cm thick, and deep organic soils had organic layers greater than 60 cm thick. For all soils at the reference bays, a 10 to 20 cm thick fibric

organic horizon (Oi) composed of root mat and undecomposed leaf litter was present on the surface. In the case of the mineral soils, this layer was underlain by sandy textured mineral horizons. The histic soils had approximately 20 cm of highly decomposed sapric organic matter (Oa) between the surface organic layer and the mineral subsurface. The shallow and deep organic soils had a 15 to 30 cm thick, moderately decomposed hemic organic layer (Oe) below the surface layer, followed by a 20 to more than 60 cm thick sapric organic layer, below which was sandy textured mineral soil. Soil textures of the mineral horizons include sandy loam, loamy sand, and sand.

Lees (2004) studied the plant communities that were established in the reference bays. Charlie Long Millpond Bay and Causeway Bay generally exhibited Pond Pine Woodland plant communities nearest the perimeter and High Pocosin plant communities nearest the center of the bays, as defined by the classification system developed by Schafale and Weakley (1990). Tatum Millpond Bay transitioned from Pond Pine Woodland, to Nonriverine Swamp Forest, to High Pocosin, and finally to Bay Forest from the periphery to the center of the bay. These plant communities differ in vegetation species composition, relative abundance of the various species, and the size and stature of the vegetation. Typical tree species include Pond Pine (*Pinus serotina* L.), Swamp Tupelo (*Nyssa Biflora* L.), Loblolly Bay (*Gordonia lasianthus* L.), Sweetbay (*Magnolia virginiana* L.), and Swamp Red Bay (*Persea palustris* L.) The understory consisted of Gallberry (*Ilex coriacea* L.), Giant Cane (*Arundinaria gigantean* L.), Fetterbush (*Lyonia lucida* L.), Coastal Sweet-pepperbush (*Clethera alnifolia* L.), Highbush Blueberry (*Vaccinium corymbosum* L.), and Green Briar (*Smilax Laurifolia* L.) (Lees, 2004).

The overall methodology used in this study was as follows. First, water table depths and rainfall data were recorded at each bay over a 2 yr period from April 2003 to May 2005 for DRAINMOD model calibration. Concurrent with the collection of these data, estimates of ET over the calibration period were calculated and soil property data required by the model were collected from intact cores taken from the bays. Next, the models were calibrated against the water table data collected in the field over the 2 yr period. Once the models were satisfactorily calibrated, 40 yr of historical weather data were used as input for the models to simulate long term water table depths in each bay.

Calibration data collection

Access trails (straight-line transects) were cut through the natural vegetation roughly along the minor axes of the bays from the perimeter to the center (Figs. 4.2 to 4.4). Along each transect, RDS water level recording wells (Remote Data Systems, Inc., Wilmington, NC) were installed to a depth of 1 m according to US Army Corps of Engineers' specifications (Sprecher, 1993). Four wells were installed in Causeway Bay and Charlie Long Millpond Bay, while seven were installed at Tatum Millpond Bay. Each well recorded water table depths on an hourly basis over the 2 yr calibration period.

Weather data collection

One Davis tipping bucket rain gauge (Davis Instruments, Hayward, CA) was installed near the perimeter of each bay (Figs. 4.2 to 4.4). The gauges were installed at a height of approximately 1 m above the surface, and at a distance from surrounding vegetation at least equal to the height of the vegetation to minimize the rain shadow effect (Chang, 2003). In addition, manual rain gauges were installed in close proximity to the tipping bucket gauges for tipping bucket gauge calibration and to use as backup should the tipping bucket gauge

fail. The data recorded by the tipping bucket rain gauges were summarized on an hourly basis for DRAINMOD input for the 2 yr calibration period. Other weather data such as air temperature, relative humidity, wind speed, solar radiation, and barometric pressure that were used in ET estimation were collected from the Turnbull Creek N.C. Division of Forest Resources weather station in Bladen Lakes State Forest. The weather station was located at distances of approximately 12.0, 5.3, and 14.5 km from Charlie Long Millpond Bay, Tatum Millpond Bay, and Causeway Bay, respectively (Fig. 4.1).

Historical weather data have been collected for various locations in the Coastal Plain of NC. Typically these data are limited to daily rainfall and daily maximum and minimum temperature. The DRAINMOD model requires hourly rainfall data so that the effects of storm intensity can be considered. The DRAINMOD software package provides a utility that disaggregates historical daily rainfall data into hourly data based on inputs of average starting hour of storm events and average duration. Using the 2 yr of hourly rainfall data collected during the calibration period, the average starting time for storm events was estimated to be 10:00 am, with an average duration of 4 h. Historical weather data used for the long-term DRAINMOD simulations were obtained from the State Climate Office of NC for Fayetteville, NC from 1964 to 2004. Fayetteville is located approximately 50 km from the reference bays.

Evapotranspiration Estimation

The DRAINMOD software package has the ability to input a file of measured potential evapotranspiration (PET) for hydrologic simulations. However, PET is difficult and expensive to measure on a watershed scale and thus was not measured during the calibration period, and certainly not over the past 40 yr. Alternatively, DRAINMOD can

calculate PET using the Thornthwaite equation (Thornthwaite, 1948). This equation calculates PET based on average air temperature and latitude data, making it an attractive option for estimating PET for historical studies where weather data are limited. However, PET estimates made using the Thornthwaite equation are not considered to be very accurate (Nokes, 1995), particularly for winter months. DRAINMOD partially overcomes this limitation by allowing the user to enter monthly correction factors into the model to adjust the Thornthwaite PET estimates based on PET estimates calculated from more accepted means, such as the Penman-Monteith equation (Monteith, 1965).

PET is assumed to be the sum of dry transpiration from the vegetation and evaporation from the soil. For this study, potential dry transpiration, PT_d, was calculated by the Penman-Monteith equation as:

$$PT_d = \frac{1}{L_v}\left[\frac{\Delta R_n + \frac{C_p \rho_a (e_s - e_a)}{r_a}}{\Delta + \frac{\gamma(1 + r_s)}{r_a}}\right] \quad [1]$$

Where L_v is the latent heat of vaporization, Δ is the saturation vapor pressure gradient, R_n is the net radiation, C_p is the specific heat of air, ρ_a is the air density, e_s-e_a is the vapor pressure deficit, and γ is the psychrometric constant. All of these quantities were calculated based on weather data collected at the Turnbull Creek weather station.

The aerodynamic resistance, r_a, quantifies boundary layer resistance and is calculated as:

$$r_a = \frac{\ln\left[\frac{z-d}{z_o}\right]^2}{k^2 u_z} \quad [2]$$

Where d is the displacement height, z is the height 2 m above the forest canopy, and z_o is the roughness length. All of these quantities are calculated based on the height of the tree canopy. Meanwhile, k is a constant known as the von Karman's coefficient, and u_z is the wind speed measured at z. Wind speed was obtained from the Turnbull Creek weather station. The canopy height of the vegetation at the reference bays is quite variable. Even among the same species, vegetation height varies by plant community (Schafale, 1990). For this study, an average canopy height of 9 m was assumed based on observation at the three reference bays.

The surface resistance, r_s, quantifies stomatal resistance of the vegetation and is calculated as:

$$r_s = \frac{r_l}{LAI} \qquad [3]$$

Where r_l is the bulk stomatal resistance of the forest canopy, and LAI is the leaf area index, both of which depend on the vegetation type and density. Very little is known about these parameters for natural wetland vegetation in the southeastern US. Amatya (1993) successfully simulated the hydrology of a wetland site in Carteret county, NC for a natural mixed stand of pond pine, loblolly pine, and some hardwood species. In this study, LAI was estimated by taking point measurements several times during a year using a LICOR-2000 (1991) instrument (Fig. 4.5). Since these species were similar to those of the natural Carolina bay plant communities, it was assumed that the LAI for the Carolina Bay vegetation was comparable. Also in this study, hourly stomatal resistance for the natural forest stand was estimated using an empirically based prediction equation (Amatya, 1993):

$$\ln\left(\frac{1}{r_l}\right) = a + b \times (e_s - e_a) + d \times R_n + f \times T^3 + g \times \text{winter} \qquad [4]$$

where T is the hourly average air temperature, and a, b, d, f, and g are regression coefficients equal to -3.305, -0.000307, 0.000454, 0.0000267, and -0.153, respectively, as determined from porometer data collected at the site. Winter was set equal to one for days-of-year 304 to 121, and zero for all other days. It was assumed that this relationship would adequately predict stomatal resistance for the natural Carolina Bay vegetation.

Evaporation from the soil was estimated using the Thornthwaite equation, taking into account the effects of canopy closure using the methods of McKenna and Nutter (1984) as described by McCarthy (1992) such that:

$$PE_{soil} = PE_{thornthwaite} \times e^{-0.4 \times LAI} \quad [5]$$

To determine the monthly PET correction factors for the DRAINMOD models, the hourly stomatal resistance was first calculated with Eq. [4], using weather data collected at the Turnbull Creek weather station. These data were then averaged each day to get an average stomatal resistance for that day. Using the average daily stomatal resistance, daily dry canopy transpiration was calculated using Eq. [1]. Daily soil evaporation was then calculated using the Thornthwaite equation. The daily dry canopy transpiration and daily soil evaporation were combined to estimate the daily PET. Finally, the monthly correction factors were determined by first calculating the ratio between the cumulative monthly PET estimated using the equations above and that estimated by DRAINMOD using the Thornthwaite equation for years 2003 to 2005. The monthly correction factors calculated for each month were averaged across the 2 yr calibration period to estimate the monthly correction factor.

At forested sites, the effects of rainfall interception by the canopy serve to complicate estimation of PET both during and following rainfall events. It has been estimated that 10 to 20% of total annual precipitation is lost by canopy interception (Chang, 2003). Amatya et al. (1996) and McCarthy et al. (1992) accounted for interception as well as its effects on transpiration while simulating hydrology in the NC Coastal Plain by using the following approach. During a rainfall event, some water reaches the ground without touching the canopy (throughfall). The remainder of the water, canopy drip, is intercepted by the canopy and either falls to the ground directly or as stemflow. Canopy drip is assumed to occur only after the storage capacity of the canopy has been reached. When the storm event has concluded, no transpiration occurs until a portion of the water held in the canopy has evaporated. Eventually, both evaporation from the canopy and transpiration can occur simultaneously until water stored in the canopy has been completely removed, at which point canopy evaporation ceases.

DRAINMOD handles ET during rainfall events by setting ET equal to zero for any hour during which rainfall occurs. ET will resume the first hour for which there is no rainfall. As a result, DRAINMOD predicts that more water infiltrates the soil during a storm event than would an approach that considers canopy interception. However, DRAINMOD will immediately resume ET the first hour after a rainfall event whereas the canopy interception approach does not completely resume ET until the water stored in the canopy has evaporated. For this study, it was assumed that consideration of canopy interception was not required because the additional water that infiltrated the soil was approximately offset by the additional water removed by ET processes immediately after the storm. Canopy interception is thus a portion of any ET estimates made by DRAINMOD in this study. This

assumption has been validated by comparing simulated water table depths generated by DRAINMOD and other models that account for canopy interception with no discernable differences found (Skaggs, 2005).

Soil Property Data Collection

The DRAINMOD software requires that soil water characteristic (water retention) data and saturated hydraulic conductivity data be collected for each horizon in the soil profile above an impermeable layer. Using this information, a utility in the software calculates additional soil properties as a function of the position of the water table. The relationship between water table depth and volume drained is used to calculate the change in water table depth when a given amount of water is added or removed (Skaggs, 1981). The relationship between upward flux and the water table depth determines the rate of upward water movement from the water table due to ET processes. Finally, the infiltration parameters determine the rate at which water enters the soil profile during storm events or at other times when water is ponded on the soil surface.

Along each bay transect, an intact soil core was collected to a depth of 1 m in close proximity to each water level recording well. Saturated conditions, dense forest vegetation, fragile organic horizons, and woody debris in the soil profile all served to make the collection of intact soil samples difficult. As a result, the development of a new sampling device was required (Caldwell et al., 2005). This coring device enabled continuous samples of 7.6-cm-diam. by 7.6-cm-long along the 1-m-long soil core to be tested in the laboratory for saturated hydraulic conductivity and soil water characteristic data.

For each soil core, detailed profile descriptions were generated, noting the depths and types of soil horizons. Once the samples were prepared, the saturated hydraulic conductivity

was measured using the constant head method (Klute and Dirksen, 1986). The horizontal saturated hydraulic conductivity was also measured in situ for soil horizons below the water table using the piezometer method (Luthin and Kirkham, 1949). After the saturated hydraulic conductivity measurements were made on the laboratory samples, the soil water characteristic curves for tensions ranging from 0 to 400 cm were determined on a volume basis using a pressure cell apparatus (Klute, 1986). Water contents for tensions of 1000 cm and 15000 cm were determined using a pressure plate apparatus with disturbed samples collected separately from the intact samples. Upon completion of these tests, the samples were placed in cans, weighed, oven-dried at 105^{o} C for 24 h, and reweighed to determine water content.

The DRAINMOD software package requires that the depth to an impermeable layer be determined. A soil horizon is effectively impermeable if its saturated hydraulic conductivity is less than 20% of the layer above. In practice, it is generally assumed that the shallowest clay-textured soil horizon is the impermeable layer. In most locations in the reference bays, determining the depth to an impermeable layer was not possible. The dense vegetation mandated the use of hand augers for soil exploration rather than any mechanized means. The fluid nature of the saturated sands frequently impeded forward progress as it would continuously refill the auger hole. At some locations, these sandy layers extended to depths beyond 3 m, while in others dense clay layers were reached at depths less than 2 m. For the DRAINMOD model input, the depth to the impermeable layer was set either at the depth it was found, or at the maximum depth reached during soil exploration. It was assumed that any errors associated with the depth to impermeable layer parameter would be accounted for in other parameters that were adjusted during the model calibration process.

Model Calibration

The DRAINMOD model assumes a drainage system consisting of parallel drain tiles (Fig. 4.6). No such drainage system existed at the natural reference bays. However, work done by He et al. (2002) and others have found that the subsurface drainage in a natural landscape can be simulated using DRAINMOD by adjusting the drainage system dimensions to calibrate the model to measured water table depths. For any hydrologic system, be it a natural wetland or an artificially drained agricultural field, there exists a relationship between the water table depth and the drainage flow rate out of the system. Adjusting the drainage system parameters in DRAINMOD essentially changes the shape of the curve between the water table depth and the drainage rate as predicted by the Hooghoudt equation, thereby approximating the natural relationship between these quantities that exists at the site being modeled. The drainage rate in the Hooghoudt equation is a function of the drain depth, spacing, and the hydraulic conductivities of the various soil layers in the profile. For this study, the drain depth, b, spacing, L, and surface storage, s, were adjusted such that the difference between simulated and measured water table depths over the calibration period was minimized. This calibration process enabled the natural relationship between water table depth and drainage rate at the reference bays to be determined. For all models, the effective drain radius was assumed to be 1.5 cm, and the Kirkham's depth for flow to drains was assumed to be 50% of the surface storage.

DRAINMOD also allows simulation of deep seepage through the impermeable layer to the confined aquifer below. Depending on the hydraulic head in the confined aquifer, seepage across the impermeable layer will either enter or exit the surficial aquifer system. A confined aquifer below a dense clay layer was discovered near well no. 2 at Charlie Long

Millpond Bay that had a hydraulic head greater than that above the clay layer, providing a gradient for upward water movement into the bay. For models in this bay, the saturated hydraulic conductivity of the clay layer (i.e. impermeable layer) was an additional variable that was adjusted during model calibration. Piezometers installed in the confined aquifer provided pressure head data at these locations.

Two different metrics were used to quantify the success of the models in simulating water table depths over the calibration period. First, the average absolute deviation between simulated and measured daily water table depths was calculated as:

$$\alpha = \frac{\sum \left| Y_m - Y_p \right|}{n} \qquad [6]$$

where Y_m is the measured water table depth on a particular day, Y_p is the predicted water table depth as simulated using DRAINMOD, and n is the total number of days during the calibration period. The second metric was the coefficient of determination, R^2. This quantity describes the proportion of the total variance in the measured water table depths that can be explained by the models (Legates and McCabe, 1999). It was obtained by calculating the coefficient of determination of a line of slope equal to 1 for the predicted water table depths plotted against those measured in the field.

Fifteen sets of DRAINMOD model inputs were generated with each corresponding to one of the well locations in the three bays. The model was calibrated for each location by first assuming a drain depth and surface storage depth. The drain spacing was iterated until α was minimized and R^2 was maximized, which generally occurred at the same drain spacing. This process was repeated, iterating the drain depth next and the surface storage depth last. For sites where seepage into the surficial aquifer from the confined aquifer below was

deemed significant, the saturated hydraulic conductivity of the impermeable layer was iterated in conjunction with each of these variables. Once the rough estimates of the calibration variables were established, they were again iterated to insure that there were no interaction effects that could negatively impact the model calibration. Once the models were calibrated, the 40 yr weather record was read into the models to generate long-term water table data for each well location.

At Charlie Long Millpond bay, it was necessary to simulate the managed control structure at the northwest end of the bay for model calibration. This was modeled in DRAINMOD as controlled drainage, where the weir level was raised to a particular elevation on a particular date, and then lowered again at another date. In this mode, the water level in the bay must exceed the elevation of the weir for any subsurface drainage to occur. As a result, controlled drainage significantly reduces subsurface drainage during the time period the weir elevation is raised. The dates of raising and lowering the weir level and the elevation of the weir were additional calibration parameters for the Charlie Long Millpond models since these parameters were not known. For the 40 yr simulations, it was assumed that the control structure was unmanaged, allowing free drainage from the bay all year.

RESULTS AND DISCUSSION

Model Input Data

Rainfall

Monthly rainfall data recorded at the three reference bays during the model calibration period are shown in Figure 4.7. Historical rainfall data were also collected from the 1971 to 2000 climate record at Elizabethtown Lock, NC, in close proximity to the reference bays (USDA, 2002). The area shown in gray in Figure 4.7 is the range in normal

rainfall based on the Elizabethtown Lock historical rainfall data. Normal rainfall is typically defined as the arithmetic mean rainfall computed over three consecutive decades (WMO, 1989). Unfortunately, by this definition, no time period would ever have "normal" rainfall. It would always be either higher or lower than normal. For this study, it was desired to determine a range of rainfall rather than a single value to determine whether a given time period exhibited normal rainfall. As a result, the implied definition of normal rainfall outlined in the Hydric Soil Technical Standard was implemented (USDA, 2005). The lower limit of normal rainfall in this case is defined such that there is a 30% chance that there will be rainfall *less* than this amount during a given time period, based on recorded historical precipitation. Similarly, the upper limit of normal rainfall is defined such that there is a 30% chance that there will be rainfall *greater* than this amount. As shown in Figure 4.7, there was some variability in rainfall amounts recorded at the three bays. However, there was no consistent trend indicating that rainfall at one location was greater than that of the other sites. Rainfall recorded during the month of July 2003 was significantly higher than normal, with 30, 23, and 38 cm recorded at Charlie Long Millpond Bay, Causeway Bay, and Tatum Millpond Bay, respectively, compared to the normal range of 12 to 18 cm. This was caused primarily by a storm that occurred on July 2nd and 3rd, which delivered 10.7, 11.2, and 9.5 cm of rainfall to Charlie Long Millpond Bay, Causeway Bay, and Tatum Millpond Bay, respectively. This storm was not associated with any hurricane or tropical storm activity. August 2004 was another month with higher than normal rainfall, this time due to the effects of Hurricane Charley from the 14th to the 16th.

Normal annual rainfall in Bladen county, NC ranged from 101.1 to 125.8 cm as shown in Table 4.1 (USDA, 2002). Rainfall during 2003 was above normal at Charlie Long

Millpond Bay and Causeway Bay, and in the normal range at Tatum Millpond Bay. 2004 was a normal year for rainfall at Causeway Bay and Tatum Millpond Bay, but slightly lower than normal at Charlie Long Millpond Bay. The early part of 2005 that was part of the model calibration period was a drier than normal year for rainfall at all three reference bays. Variability in rainfall between bays is apparent but there is no consistent trend among the bays. At Charlie Long Millpond Bay, rainfall was 2% and 15% greater than that of Causeway Bay and Tatum Millpond Bay, respectively, during 2003. However, it was 10% and 11% lower in 2004, and 10% and 12% lower in 2005.

The rainfall data from Fayetteville, NC, that was used in the 40 yr model simulations revealed normal rainfall in the range from 106.7 to 123.9 cm, within a few centimeters of that measured at Elizabethtown Lock which was closer to the reference bays. This provided good confidence that the Fayetteville rainfall data were acceptable for use in the long-term model simulations. These data indicate that periods of drought occurred on an approximate 5 yr recurrence interval start in 1970 (Fig. 4.8). The year 2003, which was part of the model calibration period, had the highest rainfall over the 40 yr record.

Measured Water Table Depths

During the model calibration period, the average water table depths at Charlie Long Millpond Bay, Causeway Bay, and Tatum Millpond Bay were 9.0, 6.3, and 2.2 cm, respectively (Fig. 4.9). Water tables were very near or above the soil surface during the latter half of 2003 due to the high level of rainfall during that year. Water tables remained at these levels until the summer months of 2004, a year of normal rainfall, when ET demands were highest.

The relationship among water table depths at the three bays is likely due to the relative elevations of the bays on the landscape. LIDAR elevation data (NCDOT, 2004) reveal that the average elevations of the wells at each of the reference bays are 27.7, 24.6, and 24.1 m above mean sea level for Charlie Long Millpond Bay, Causeway Bay, and Tatum Millpond Bay, respectively. Tatum Millpond Bay, the wettest of the three bays is also located at the lowest elevation. Charlie Long Millpond Bay, the driest of the three, is located at the highest elevation.

Evapotranspiration

ET is a significant portion of the water balance in the natural Carolina Bays. In 2004, total potential evapotranspiration (PET) amounted to 67% of the total rainfall that fell that year. The significance of PET on the hydrology of the reference bays is evident when changes in water table depths are plotted with monthly rainfall and PET (Fig. 4.10). When PET exceeds monthly rainfall, the water table is drawn down. When precipitation exceeds PET, the water table rises, remains constant, or is drawn down more slowly, depending on the amount of excess rainfall relative to PET.

Effective rooting depths of the natural vegetation at the reference bays were assumed to be 45 cm below the soil surface based on observation at the sites. Since the water table depths at the bays were generally within 50 cm of the soil surface during the calibration period, soil water was not limiting ET at any of the modeled well locations. As a result, actual ET (AET) was assumed to be equal to the potential ET. In fact, AET was equal to PET at all times during the 40 yr simulation as well. Shallow water tables, deep rooting depths, high saturated hydraulic conductivities, and high plant available water in the reference bay soils all served to insure that the PET demand was met.

Since the vegetation height in the reference bays is so variable, it was desirable to determine how sensitive Penman-Monteith PET estimates are to vegetation height. Beven (1979) reported that PET is not very sensitive to changes in the aerodynamic resistance term (r_a), the term in the Penman-Monteith PET equation that accounts for vegetation height, but is very sensitive to changes in the surface resistance term (r_s). To verify this, PET was calculated using vegetation heights of 5 and 15 m, and percent differences in PET estimates from a 9 m height, the height assumed in PET estimates for the Thornthwaite monthly correction factor calculation, were calculated for the year 2004 (Fig. 4.11). For the 5 m height, PET was less than that of the 9 m height during the winter months, but greater during the summer. The opposite trend was true for the 15 m height. However, when averaged over the entire year, percent differences were very low, 1.1% and -0.8% for the 5m and 15 m heights, respectively. It was concluded that for a long-term hydrologic study such as this, the effects of vegetation height on PET are negligible.

The Thornthwaite method of estimating PET used by DRAINMOD tends to underestimate PET during the winter months and overestimate during the summer months relative to the Penman-Monteith method (Amatya et al., 1995). As a result, the monthly Thornthwaite correction factors calculated for the DRAINMOD models are greater than unity during the winter months, and less during the summer (Table 4.2). The monthly corrected DRAINMOD Thornthwaite PET correlated very well ($R^2 = 0.97$) with monthly PET estimated by the Penman-Monteith equation over the calibration period (Fig. 4.12).

Soil Data

Soil types, profile descriptions, and saturated hydraulic conductivity (K_{sat}) values estimated by the piezometer method for all modeled well locations in the reference bays are

shown in Table 4.3. The conductivity values estimated for the organic soil horizons in this study are higher than those for others in the literature (Amatya, 1993; Boelter, 1969). This is likely due to the high total porosity, abundance of larger pores, and low bulk density exhibited by these soils, a result of the effects of vegetation type and the management of other soils in agricultural or silvicultural land uses.

Average soil water characteristic curves for the various types of soil horizons reveal the existence of an abundance of large pores in the surface organic horizons (Fig. 4.13). Plant available water for organic soil horizons in the natural Carolina Bay soils were 41% and 42% by volume for the Oe, and Oa horizons, respectively. No data were collected for the Oi horizons due to the difficulty in measuring water content at 15 bars with the fibrous soil samples. Plant available water for the mucky mineral and mineral soil horizons were 41% and 19% by volume, respectively. These relatively high values of plant available water partially explain why the soils in the reference bays were able to supply the ET demand, allowing AET to equal PET.

Soil water characteristic curves and K_{sat} values derived from soil cores collected at each well were used in the DRAINMOD models of those locations to calculate the relationships between volume drained and upward flux versus water table depth, as well as the Green-Ampt infiltration parameters. Averages of the volume drained and upward flux versus water table depth relationships for the four soil types are shown in Figure 4.14. The effect of the depth of organic layers on the volume drained versus water table depth relationship is clearly evident in these curves. The change in slope of the volume drained curve occurs at a boundary between horizons in the soil profile. The location of this change in slope occurred at organic/mineral soil transitions at depths of approximately 20, 30, 45,

and 75 cm for mineral, histic, shallow organic, and deep organic soils, respectively. This corresponds well to the organic layer depths that define these soil types.

Groundwater Inflow

Near well location no. 2 in Charlie Long Millpond Bay, a 55 cm thick, dense clay layer was found underlying 170 cm of organic and sandy mineral soil materials (Fig. 4.15). Below this clay layer, another sandy layer was found. The hydraulic head measured with a piezometer in this confined sandy aquifer was higher than that in the unconfined aquifer system above (Fig. 4.16), providing potential for vertical water flux into the bay. In fact, the water level in the piezometer was consistently above the soil surface in the bay, making this an artesian aquifer. This system appeared to be continuous along the transect cut through the bay. The location of the source area for this confined artesian aquifer is not known. However, the pressure head in the aquifer correlates well with rainfall recorded at the bay (R^2 = 0.87), so it must not be at too great a distance.

Inspection of hourly water table depths from the four well locations in Charlie Long Millpond Bay revealed that indeed, groundwater appears to be entering the bay. Distinct diurnal water table fluctuations were observed at three of the four wells in the bay such that the water table was drawn down during the day when ET demands are highest, rising again at night due to an influx of groundwater (Fig. 4.17). This groundwater inflow is presumed to originate from the confined aquifer below the bay, traveling vertically through the clay layer into the unconfined surficial aquifer, but it could also enter the bay laterally from adjacent uplands.

No such confined aquifer system was discovered at Causeway Bay or Tatum Millpond Bay, though this does not mean that they are not present. Limited by hand augers

for soil exploration, the deepest excavations achieved were 2 to 2.5 m with no sign of a confining clay layer. Inspection of hourly water table depths at these bays revealed minor diurnal fluctuations at one of the four wells in Causeway Bay, and major fluctuations at one of the seven wells in Tatum Millpond Bay (Fig. 4.18), indicating some influx of groundwater from either the vertical or lateral direction, or both. Both of the wells that showed the diurnal water table fluctuations were located nearest the bay perimeter in mineral soil types. Mineral soil horizons have a lower drainable porosity than do organic horizons. As a result, adding or removing an equivalent amount of water from these two soils would raise or lower the water table to a greater extent in the mineral soil than in the organic soil. This is illustrated in Figure 4.19, where the diurnal water table fluctuations are easily discernable when the water table was in the mineral soil horizon at well no. 1A in Tatum Millpond Bay, but not so when it was in the very porous organic surface horizon. Therefore, it should not be concluded that because the diurnal water table fluctuations are not apparent at wells located toward the centers of the bays in organic soils, there is no groundwater input at these locations.

Preliminary DRAINMOD simulations for the wells in Charlie Long Millpond Bay revealed the necessity of adding a deep seepage component to these models to account for groundwater input. DRAINMOD inputs for the deep seepage component include the thickness of the restrictive layer, the conductivity of the restrictive layer, and the pressure head in the confined aquifer below the restrictive layer. This pressure head is assumed to be constant, but for the confined aquifer below Charlie Long Millpond Bay it is clearly not (Fig. 4.16).

To address this problem, the DRAINMOD software was modified to allow the user to input a file containing daily pressure head data for the confined aquifer. The pressure head in

the confined aquifer then must be predicted based on inputs of rainfall and temperature, since those are the only data available for the 40 yr simulations. It was assumed that the structure of the confined aquifer/Carolina Bay system was similar to that shown in Figure 4.20. Somewhere near the bay, there was an upland area that received rainfall similar to that at the bay. The unconfined aquifer at the upland was separated from that of the bay by a restricting clay layer that was either discontinuous near the upland or ends at the surface. Drainage of the upland aquifer was restricted by the clay layer above and by another restrictive layer below. Vegetative cover at the upland was assumed to be similar to that in the bay and thus ET is assumed to be equivalent. The water table depth at the upland, and hence the pressure head in the confined aquifer below the bay, can then be predicted by performing a water balance on the upland source area.

The drainable porosity of the soils in the upland area was estimated by first measuring the response in pressure head in the confined aquifer below the bay to rainfall events greater than 2 cm d^{-1}. This minimum rainfall was established to ensure that the effects of the rainfall event on water table response were much greater than the effects of subsurface drainage. Next, a linear regression equation was developed to estimate the drainable porosity as a function of water table depth in the upland, or pressure head in the confined aquifer (Eq. 7):

$$f = 0.0016 \times H - 0.1323 \quad [7]$$

Where f is the upland soil drainable porosity ($cm^3\ cm^{-3}$) and H is the pressure head in the confined aquifer (cm).

For simplicity, it was assumed that there was no surface drainage from the upland area so the remainder of the water balance is then subsurface drainage. The drainage was calculated for each day using the water balance equation for the upland from mid-February

2004 to the end of April 2005. To have the ability to predict the drainage of the upland, a linear regression equation was developed to estimate drainage based on the pressure head in the confined aquifer (Eq. 8):

$$D = 0.0044 \times H - 1.0329 \quad [8]$$

Where D is the daily subsurface drainage (cm d^{-1}).

Using the rainfall, ET, drainage, and drainable porosity data, the daily change in pressure head in the confined aquifer was predicted using the water balance equation. This was accomplished by first assuming an initial pressure head, and then the subsurface drainage and the drainable porosity of the upland soil was calculated based on this pressure head. For the next day, the pressure head was calculated based on the rainfall, ET, drainage, and drainable porosity of the previous day. This model for the pressure head in the confined aquifer worked very well over the calibration period (Fig. 4.21), providing a means of predicting the pressure head in the confined aquifer as a function of daily rainfall and daily maximum and minimum air temperature for the 40 yr simulations.

Model Calibration

Calibration metrics for the 15 DRAINMOD models in the reference bays are shown in Table 4.4. Plots of measured and simulated water table depths for Charlie Long Millpond Bay, Causeway Bay, and Tatum Millpond Bay over the calibration period are shown in Figures 4.22, 4.23, and 4.24, respectively. Overall, the DRAINMOD simulated water table depths correlated very well with those measured at the reference bays. This was helped in part by the very shallow water table depths over the calibration period, which served to minimize deviations between simulated and measured data.

By adjusting the drain depth and spacing during the calibration process, the natural relationship between the water table depth and drainage flow rate was approximated. Figure 4.25 shows this relationship for the four well locations in Charlie Long Millpond Bay. The x-intercept in these curves is set by the drain depth parameter. The y-intercept and the shape of these curves are determined by the drain depth, spacing, and the conductivities of the various soil layers in the profile. The drainage rates of well locations 3 and 4 are higher than that of wells 1 and 2 for water table depths near the ground surface. This is likely because wells 3 and 4 are located at higher elevations than 1 and 2, thus they have higher drainage rates. Well no. 1 has very low drainage rates relative to the other wells, and if the water table is greater than 5 cm below the ground surface, no drainage occurs at all. The DRAINMOD parameters quantified as a result of the model calibration process for each of the well locations are shown in Table 4.5.

Between July and October 2003, simulated water tables at the wells in Charlie Long Millpond Bay were much deeper than those measured in the field. This was the time period for which greater than normal rainfall occurred at all of the bays. Apparently, there was some mechanism that caused additional water to enter the bay that was not captured by the models. The piezometer measuring pressure head in the confined aquifer below the bay was not installed until February, 2004 so simulated pressure heads during this time were not verified by field measurement. It is possible that the simulated pressure head in the confined aquifer was not high enough, or perhaps additional groundwater inflow to the bay was occurring laterally. Additional DRAINMOD simulations were executed to determine the pressure head required to calibrate the models during this time period, revealing an increase in pressure head of approximately 80% over the average pressure head in 2004 (Fig. 4.26).

A possible explanation for a phenomenon such as this is that some aspect of the upland source area for the confined aquifer changed causing the pressure head to reach these levels. Downed trees or beaver activity could have temporarily altered the hydrology of this site causing the unusually high pressure heads. Since 2003 had the highest rainfall over the past 40 yr, it was assumed that this was an isolated event that may be neglected for the long-term simulations.

To effectively calibrate the models of well locations no. 1A at Tatum Millpond Bay and no. 1 at Causeway Bay, it was necessary to add deep seepage to these models as well. These were the well locations nearest the perimeters of the bays that exhibited diurnal water table fluctuations, indicating an influx of groundwater (Fig. 4.18). It was assumed that the confined aquifer system observed at Charlie Long Millpond Bay would adequately approximate the mechanism providing groundwater input at these well locations. In reality, however, the groundwater could enter the areas near the wells from the lateral direction in addition to, or instead of the vertical direction.

The remaining modeled well locations in Tatum Millpond Bay exhibited water tables above the surface for most of the calibration period. This did not provide good confidence that the models will correctly simulate water table depths during drier years. Water table depths measured at the bay, and rainfall measured at the Turnbull Creek weather station in 2002 (prior to the calibration period) were used to test the model for a year of less than normal rainfall (Fig. 4.8). Water table depths were measured at the bay during this time, but rainfall was not recorded until 2003. The models performed reasonably well in simulating water table depths, especially given the error caused by using rainfall data measured at a distant source (Fig. 4.27).

Model Simulation Results

Water Table Depths

A summary of the long-term simulated water table depth data for each well location is shown in Table 4.6. Long-term water table depths averaged across all wells for the three reference bays were 15.8 and 6.8 cm below the surface at Charlie Long Millpond Bay and Causeway Bay, respectively, and 2.4 cm above the surface at Tatum Millpond Bay. In general, the deepest water tables are found at well locations nearest the perimeters of the bays due to the higher elevations along the sandy rim. Water tables along the perimeters of the bays were deeper than 45 cm for 8 to 14% of the total number of days during the 40 yr simulation. Maximum water table depths of 154.9, 107.9, and 89.6 cm for Charlie Long Millpond Bay, Causeway Bay, and Tatum Millpond Bay, respectively, occurred during an exceptionally dry period in 1993. Tatum Millpond Bay was by far the wettest of the three reference bays. In some locations at this bay, water was ponded on the surface for 87% of the total days of the 40 yr simulation.

For a site to meet wetland hydrology requirements, the water table must be continuously within 30 cm of the surface for a duration of at least 5% of the growing season in most years (greater than 50%) (Environmental Laboratory, 1987). The growing season is defined as the time period between the average last day in the spring in which the low temperature was below -2^{o} C to the average first day in the fall that this temperature is reached. In Bladen county, NC, the growing season begins on March 20th and ends on November 16th, a total of 240 d (USDA, 2002). Therefore the required number of consecutive days during the growing season for which the water table must be within 30 cm of the surface is 12 d. The minimum number of consecutive days that the hydrology criterion

was met at the reference bays over the 40 yr simulation was 28 d. Wetland hydrology therefore, was present at each modeled well location every single year over the past 40 yr.

Water Balance Components

Though the DRAINMOD models were calibrated to simulate water table depths and not specific components of the hydrologic water balance, a good deal of information on the hydrology of natural Carolina Bays can be obtained by studying the simulated water balances predicted by DRAINMOD. The water balance equation is shown in equation [9].

$$\Delta S = P - ET - RO - GO + GI \quad [9]$$

Where ΔS is the change in water storage, P is precipitation, ET is evapotranspiration, RO is the surface runoff, GO is the groundwater outflow, and GI is the groundwater inflow.

For long-term simulations, the change in storage, ΔS, tends to be small compared to the other components of the water balance equation. Indeed, over the 40 yr DRAINMOD simulations, the change in storage was less than 10 cm compared to over 4700 cm of total rainfall. For this reason, the change in storage term will be neglected from discussions of water balances in the reference bays. The surface runoff term quantifies the amount of water that was lost from the system when the surface storage depth of the soil was exceeded. Groundwater outflow is the amount of water lost through the drainage system network in DRAINMOD. Groundwater inflow is the amount of water that entered the system vertically through the impermeable layer separating the surficial unconfined aquifer from the confined aquifer below.

The average annual components of the water balance equation for each well location in the reference bays over the 40 yr simulation are shown in Table 4.7. Evapotranspiration was by far the largest water loss component. On average, ET amounted to 43 to 64% of the

total water input on an annual basis. Total water input is the sum of the rainfall and deep seepage (groundwater inflow) components. On a monthly basis, ET could be equal to or greater than precipitation, resulting in a decline in water table elevations for that month. Surface runoff was typically low, ranging from 2 to 34% of total water input.

Runoff was lower at well locations nearest the perimeter of the bays, a result of deeper water tables that allow more rainfall to infiltrate the soil rather than running off when the surface storage depth was exceeded. Runoff from these types of wetlands generally occurs as sheet flow over broad stretches rather than channelized flow in streams or ditches (Ash et al., 1983). Sheet flow occurs just below the litter layer following small but relatively discrete channels. The surface layer of these organic soils, commonly called “root mat”, is a zone of dense plant roots and partially decomposed organic material that has a very high hydraulic conductivity. Runoff from one area of a bay may then provide an input in the form of surface run-on or groundwater inflow to another location down gradient in the bay. In Charlie Long Millpond Bay and Tatum Millpond Bay, surface flow outlets exist that could carry any surface runoff out of the bay. Subtle linear features are visible in the color infrared aerial photographs of Charlie Long Millpond Bay (Fig. 4.2) moving roughly parallel to the bay perimeter along the northern and southern edges. These features could be small channels that carry surface water around the edges of the bay to the impoundment and drainage outlet in the southwestern portion of the bay.

Deep seepage (groundwater inflow) ranged from 4 to 33% of the total water input for those sites which required deep seepage for model calibration. Again, this groundwater inflow was modeled as seepage across a restrictive layer between the unconfined aquifer at the surface and a confined aquifer below the restrictive layer. Seepage across the restrictive

layer could be either upward or downward depending on the hydraulic heads above and below the restrictive layer. However, in all cases for this study, the seepage always occurred vertically upward from the confined aquifer to the unconfined aquifer at the surface. Subsurface drainage (groundwater outflow) for these locations ranged from 25 to 48% of total water input, much higher than that of well locations without groundwater inflow. Groundwater outflow exceeded inflow on an annual basis, but like ET, the relationship varies when studied on a monthly basis, particularly in drier years (Fig. 4.28). In this case, groundwater inflow exceeded groundwater outflow at Charlie Long Millpond Bay well no. 3 during the summer months of 1993. This is because as the water table in the bay is lowered, the head driving water flux through the subsurface virtual drains is reduced, thereby reducing the amount of groundwater outflow. At the same time, since the head at the top of the impermeable layer is reduced, there is a larger gradient for groundwater inflow to occur from the underlying confined aquifer, increasing the amount of groundwater inflow. As a result, a net influx of groundwater to these locations occurs, providing a buffer to maintain water table elevations during these dry periods.

Charlie Long Millpond Bay Hydrology

Groundwater inflow is a significant component of the hydrology at Charlie Long Millpond Bay. The DRAINMOD simulations suggest that inflow may account for as much as 33% of the total water input. Groundwater outflow exceeds inflow on an annual basis, but during dry periods, inflow can exceed outflow helping to maintain relatively shallow water table depths. Surface runoff is low at this bay, primarily a result of deeper water table depths relative to the other reference bays. Having average water table depths 16 cm below the

surface allows rainfall to infiltrate the soil rather than running off when the surface storage depth is exceeded.

Relative surface elevations at the four wells in Charlie Long Millpond Bay are shown in Figure 4.29. These elevations were measured using a CMT Z33 survey grade, real-time kinematic GPS unit (CMT Inc., Corvallis, OR). The advertised static vertical accuracy for this GPS unit is 1.7 cm + 1 ppm. Using these data, it is apparent that the average annual net groundwater flux as simulated in DRAINMOD over the 40 yr study, correlates well with relative surface elevation and average water table elevation measured at Charlie Long Millpond Bay (Fig. 4.30). For higher surface and water table elevations, there was greater groundwater outflow (more negative) than was found at lower elevations. The higher elevations have a higher gradient to drive water to leave the system, making groundwater outflow higher. The lower elevations have lower gradients, which causes drainage to be lower. This relationship helps to validate the results of the long-term DRAINMOD simulations using other field measured data.

The surface elevation data were used to determine whether hydraulic gradients exist between the well locations along the bay transect. Figure 4.31 shows the water table elevations measured on site for 8/15/02, a dry period, 3/26/04, a wet period, and 7/19/04, a period of wetness between the other two. During the dry period, the water table is essentially flat along the transect with very slight gradients from well no. 1 to well no. 2, and from well no. 4 to well no. 3. During the wet period (3/26/04) these gradients increase but are still quite low. Also during the wet period, an additional gradient is established between well no. 3 and well no. 2. These gradients could provide lateral flow from wells no. 1, no. 3, and no. 4 to well no. 2 during wet periods, though the gradients are still fairly low. Drainage out of

the bay may be occurring near well no. 2, and since the water table elevation there seems to have a relative minimum elevation, the drainage outlet from the bay may not allow further drainage for deeper water table elevations. During dry periods, the gradients along the bay transect are reduced by an order of magnitude, making lateral groundwater movement along the transect even more unlikely.

Given that the water table elevation near well no. 4 can be higher than the ground surface near well no. 2, where the confined artesian aquifer was discovered, it is possible that the source area providing the pressure head in this aquifer is within the bay itself rather than outside as previously thought. The water level elevation in the piezometer in the confined aquifer tracks very closely with the water table elevation recorded in well no. 4 (Fig. 4.32). There is an offset between the two curves of approximately 35 cm that could indicate that the source area is slightly lower in elevation than well no. 4. When the water table elevation data from well no. 4 were adjusted by 35 cm, there was good correlation between the water level in this well and the pressure head in the confined aquifer near well no. 2 ($R^2 = 0.86$).

An alternative explanation for the pressure head in the confined aquifer could be that the clay layer separating the unconfined aquifer from the confined aquifer is discontinuous across the bay. Rainfall infiltrating the soil in an area without the clay layer present remains at a higher elevation than the ground surface in other locations within the bay due to low lateral hydraulic gradients. This water then causes a pressure head to develop beneath the clay layer at lower elevations. The vertical gradient through the clay layer is greater than that of the lateral gradient across the bay due a shorter travel distance. Depending on the relative conductivities of the clay layer and the soils above, the water from the source area will travel

laterally along the bay transect, vertically through the clay layer, or both, to locations at lower elevations.

The control structure located on the northwest side of Charlie Long Millpond Bay effectively creates a pond up-stream when the water level is raised, which is then used for duck hunting. From on site observation it was determined that the elevation of the water level was raised in the fall and lowered again the following spring. During the DRAINMOD model calibration process, the exact dates of March 17 and September 17 were estimated for the lowering and raising of the water level, respectively. The effects of the control structure on simulated water table depths at the four wells are shown in figure 4.33. Water tables at wells no. 2, no. 3, and no. 4 were raised by an average of 16, 10, and 14 cm, respectively, during the time period from September 17, 2004 to March 17, 2005. The virtual drain depth at well no. 1 was only 5 cm below the soil surface, enabling water to be drained only if the water table was less than 5 cm deep. This occurred during a small portion of the controlled drainage period, so the control structure had very little effect on the water table at that location.

Causeway Bay Hydrology

Like the well locations in Charlie Long Millpond Bay, well no. 1 in Causeway Bay exhibited evidence of groundwater inflow. On average, 10% of the total water input per year at this well consisted of groundwater inflow. Also like the wells in Charlie Long Millpond Bay, deeper water table depths at this well location allowed more water to infiltrate the soil, reducing the surface runoff component of the water balance. The remainder of the well locations in Causeway Bay did not show evidence of groundwater inflow. They also showed virtually no groundwater outflow in their water balances either. Due to the lack of drainage,

water tables at these wells were ponded on the surface 67 to 78% of the time. As a result, water at these locations was ponded at depths closer to that of the surface storage depth, causing these well locations to have greater surface runoff, ranging from 29 to 34% of total water input.

Tatum Millpond Bay Hydrology

Eighteen percent of the total water input at Tatum Millpond Bay well no. 1A is derived from groundwater inflow. It is presumed that this groundwater enters the area either laterally through the surficial unconfined aquifer or vertically through confining layers from confined aquifers below. No GPS surface elevation data were collected at this site, but maps of LIDAR elevation data (NCDOT, 2004) indicate an area of higher elevation along the major axis of the bay and just to the south of the bay (Fig. 4.34). Like Charlie Long Bay, these nearby areas of higher elevation may be the source of the groundwater inflow at this well location. The average water table depth at well no. 1A was 12 cm below the surface, which should allow water to infiltrate the soil the majority of the time rather than running off. However, low surface storage caused water to run off anytime the water table rose to the surface. As a result, there was a relatively high runoff component of the water balance amounting to 31.8 cm per year, on average.

The remainder of the wells in this bay did not show evidence of groundwater inflow. They were among the wettest well locations in the three bays, with average water table depths above the surface. In fact, these sites were ponded 79 to 86% of the time, in spite of losing 20 to 24 cm per year in groundwater outflow. This was due primarily to high surface storage depths allowing water to pond on the surface to infiltrate the soil at a later date.

SUMMARY AND CONCLUSIONS

The DRAINMOD hydrologic modeling software package was used to simulate long-term water table depths in three naturally vegetated Carolina Bays. Water table depths were measured over a 2 yr period at 15 well locations across the three bays. Soil property data were measured from intact cores collected near each well location. Monthly Thornthwaite evapotranspiration correction factors were determined by estimating potential evapotranspiration using the Penman-Monteith equation and weather data collected at a nearby weather station. Using these inputs, the DRAINMOD models were calibrated by comparing simulated water table depths to those measured over the 2 yr period. Since the sites had no artificial drainage, virtual drainage system parameters such as drain depth and spacing, were adjusted to achieve the best correlation between simulated and measured water table depths. Once the models were adequately calibrated, a 40 yr weather record was used as input for the models so that long-term water table depths could be simulated, and the hydrology of the bays could be better understood.

The DRAINMOD models were successful in simulating water table depths at all well locations over the 2 yr calibration period. Though rainfall during part of this time was above normal, the models performed reasonably well when tested with data collected during a much drier year. Simulation results reveal very shallow water table depths at all of the bays over the 40 yr simulation. Every well location met the wetland hydrology criterion in all years simulated. Tatum Millpond Bay had the shallowest water table depths, with six of the well locations in this bay having 40 yr average water table depths above the soil surface. Charlie Long Millpond Bay had the deepest water table depths, likely a result of being at a higher elevation than the other bays.

Evapotranspiration was the largest output in the water balance at all well locations. At many of the wells, the water table elevation appeared to be controlled by the balance between rainfall and evapotranspiration. During periods when evapotranspiration exceeded rainfall, the water table depth increased. When rainfall exceeded evapotranspiration, the water table depth decreased. At other well locations however, additional water input in the form of groundwater inflow had a significant effect on water table depths. Three of the four wells at Charlie Long Millpond Bay and one well at each of the other bays exhibited diurnal water table fluctuations indicating an influx in groundwater. These fluctuations were caused by the effects of evapotranspiration deepening the water table during the day, and groundwater inflow raising it again overnight. Groundwater outflow exceeded inflow on an annual basis, but inflow could exceed outflow on a monthly basis, particularly during drier months. The source of the groundwater inflow is not known but it is believed to be a local phenomenon. The water could enter the bays either laterally from adjacent uplands or vertically from confined aquifers below. A confined artesian aquifer below Charlie Long Millpond Bay was likely the source of inflow for that bay. Surface elevations within the bay indicate that the source area for this confined aquifer could be within the bay itself, in an area of higher elevation that lacks the confining layer below. Very low lateral gradients cause water to perch at these higher elevations, which then create a pressure head beneath the confining layer at lower elevations. The results of this study can be used to better understand the hydrology of natural Carolina Bays, improving the success of restoration projects of similar sites.

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Table 4.1. Annual rainfall data recorded at reference bays during calibration period.

Bay	Total rainfall during year (cm)		
	2003[a]	2004	2005[b]
Charlie Long Millpond	137.0	100.1	33.5
Causeway	134.3	110.8	37.1
Tatum Millpond	119.1	113.0	37.9
Normal		101.1 – 125.8	

[a] Rain gauges were not installed until April, 2003. Rainfall data between January 2003 and March 2003 were taken from Turnbull Creek weather station.

[b] 2005 rainfall data only includes that recorded from January 2005 to May 2005.

Table 4.2. Monthly PET correction factors used in DRAINMOD simulations.

Month	Correction Factor
January	1.88
February	2.33
March	1.64
April	0.90
May	0.80
June	0.77
July	0.83
August	0.83
September	0.91
October	0.91
November	1.03
December	1.85

Table 4.3. Soil property data for each modeled well location in the reference bays.

Bay	Well Location	Soil Type	Texture	Depth	K_{sat}
				cm	cm hr^{-1}
Charlie Long Millpond	1	Mineral	Oi	28	40.0
			mLS	36	6.5
			S	92	3.9
	2	Mineral	Oi	16	34
			mLS	61	16
			S	93	7.0
	3	Shallow Organic	Oi	12	37
			Oe	37	7.8
			mSL	85	1.1
			SL	101	1.0
	4	Shallow Organic	Oi	15	37
			Oa	40	8.6
			mSL	94	0.25
Causeway	1	Mineral	Oi	9	180
			Oe	25	24
			S	81	7.4
			LS	89	10.5
	2	Histic	Oi	15	310
			mLS	40	19
			mS	70	4.9
			S	94	6.5
	3	Deep Organic	Oi	16	50.3
			Oa	27	7.9
			mLS	67	3.1
	4	Deep Organic	Oi	21	180
			Oe	45	1.7
			Oa	85	3.1
Tatum Millpond	1A	Mineral	Oi	20	24
			mSL	59	5.1
			S	91	6.4
	2	Histic	Oi	15	19
			Oe	31	9.2
			mLS	64	6.5
			S	88	8.8
	2A	Histic	Oi	23	11
			Oa	39	2.3
			mLS	71	2.3
	3	Shallow Organic	Oi	34	40.7
			Oe	50	14
			Oa	74	14
			mSL	90	3.3

Table 4.3 (continued)

Bay	Well Location	Soil Type	Texture	Depth cm	K_{sat} cm hr^{-1}
Tatum Millpond	4	Deep Organic	Oi	16	24
			Oe	68	3.4
			Oa	108	2.4
	5	Deep Organic	Oi	9	24
			Oe	65	31
			Oa	105	0.50
	6	Deep Organic	Oi	8	24
			Oe1	35	7.5
			Oe2	80	0.53
			Oa	104	0.37

Table 4.4. Calibration metrics for DRAINMOD models of the 15 modeled well locations in the reference bays.

Bay	Well Location	α	R^2
		cm	
Charlie Long Millpond	1	4.1	0.52
	2	3.3	0.86
	3	4.9	0.33
	4	6.1	0.43
Causeway	1	4.3	0.68
	2	1.5	0.76
	3	0.5	0.78
	4	0.9	0.70
Tatum Millpond	1A	5.5	0.29
	2	0.3	0.68
	2A	1.1	0.47
	3	0.2	0.53
	4	0.7	
	5	1.4	0.53
	6	0.4	0.67

Table 4.5. DRAINMOD model parameters estimated during model calibration.

Bay	Well Location	Drain Depth	Drain Spacing	Surface Storage	Depth to Impermeable Layer	Thickness of Impermeable Layer	Conductivity of Impermeable Layer
		cm	cm	cm	cm	cm	cm hr^{-1}
Charlie Long Millpond	1	5	13000	4.5	170	55	0.00058
	2	85	10000	1.1	170	55	0.0044
	3	95	5500	2.0	183	112	0.0098
	4	65	3150	0.7	170	55	0.0029
Causeway	1	20	3500	0.1	170	55	0.0013
	2	10	999999	4.2	170	ND†	ND†
	3	45	440000	7.25	170	ND†	ND†
	4	40	999999	6.1	170	ND†	ND†
Tatum Millpond	1A	55	9000	0.1	170	55	0.0028
	2	70	334000	15	170	ND†	ND†
	2A	65	107000	14	170	ND†	ND†
	3	65	496500	16	170	ND†	ND†
	4	55	150000	16	170	ND†	ND†
	5	55	355000	12	170	ND†	ND†
	6	55	90400	14	170	ND†	ND†

ND† Not determined. No groundwater inflow required to calibrate these models.

Table 4.6. Summary of simulated long-term (40 yr) water table depths for the various well locations in the reference bays. Positive water table depths indicate the water table was above the surface.

Bay	Well location	Distance from bay perimeter	Average water table depth	Maximum water table depth	% of total days ponded	% of total days > 45 cm	Minimum consecutive days per year WTD<=30 cm during growing season
		m	cm	cm	%	%	days
Charlie Long Millpond	1	71.6	-11.1	-154.9	58%	8%	49
	2	135.5	-15.1	-70.9	16%	7%	41
	3	157.1	-11.9	-58.4	24%	1%	54
	4	299.0	-24.9	-97.4	0%	9%	28
Causeway	1	53.6	-23.0	-107.9	0%	14%	36
	2	90.5	-4.2	-98.8	67%	3%	91
	3	131.7	0.6	-49.8	78%	0%	117
	4	369.6	-0.6	-46.3	75%	0%	118
Tatum Millpond	1A	60.0	-12.1	-89.6	4%	8%	44
	2	92.2	5.7	-47.5	84%	0%	112
	2A	192.5	3.2	-62.3	81%	1%	93
	3	217.0	6.7	-54.7	87%	0%	107
	4	365.4	7.0	-32.7	86%	0%	166
	5	410.3	1.9	-54.7	79%	1%	91
	6	461.1	4.4	-45.6	84%	0%	42

Table 4.7. Average annual water balance components for the modeled well locations in the reference bays over the 40 yr DRAINMOD simulations. For all models, the average annual rainfall was 118 cm and ET was 75.8 cm.

Bay	Well Location	Outputs		Inputs
		Runoff	Groundwater Outflow (GO)	Groundwater Inflow (GI)
		cm	cm	cm
Charlie Long Millpond	1	11.1	35.7	4.71
	2	18.6	71.5	47.9
	3	15.0	84.7	57.5
	4	3.66	71.8	33.2
Causeway	1	13.8	41.3	12.9
	2	39.6	2.47	0
	3	34.7	7.31	0
	4	36.7	5.23	0
Tatum Millpond	1A	31.8	36.8	26.6
	2	20.0	21.9	0
	2A	18.2	23.7	0
	3	20.7	21.2	0
	4	19.6	22.3	0
	5	21.2	20.8	0
	6	22.1	19.8	0

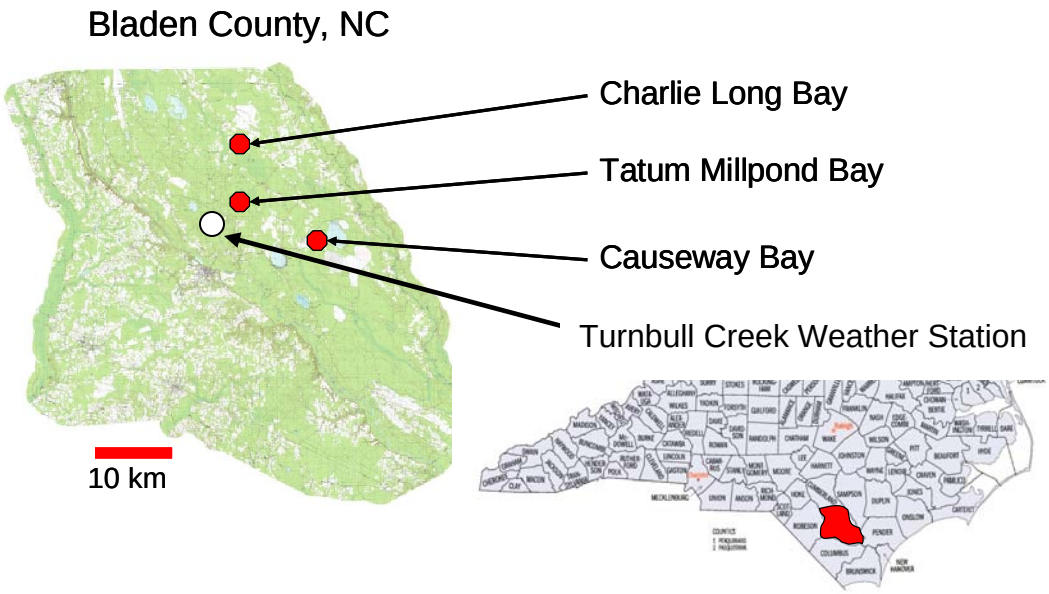


Figure 4.1. Locations of reference Carolina Bays in Bladen County, NC.

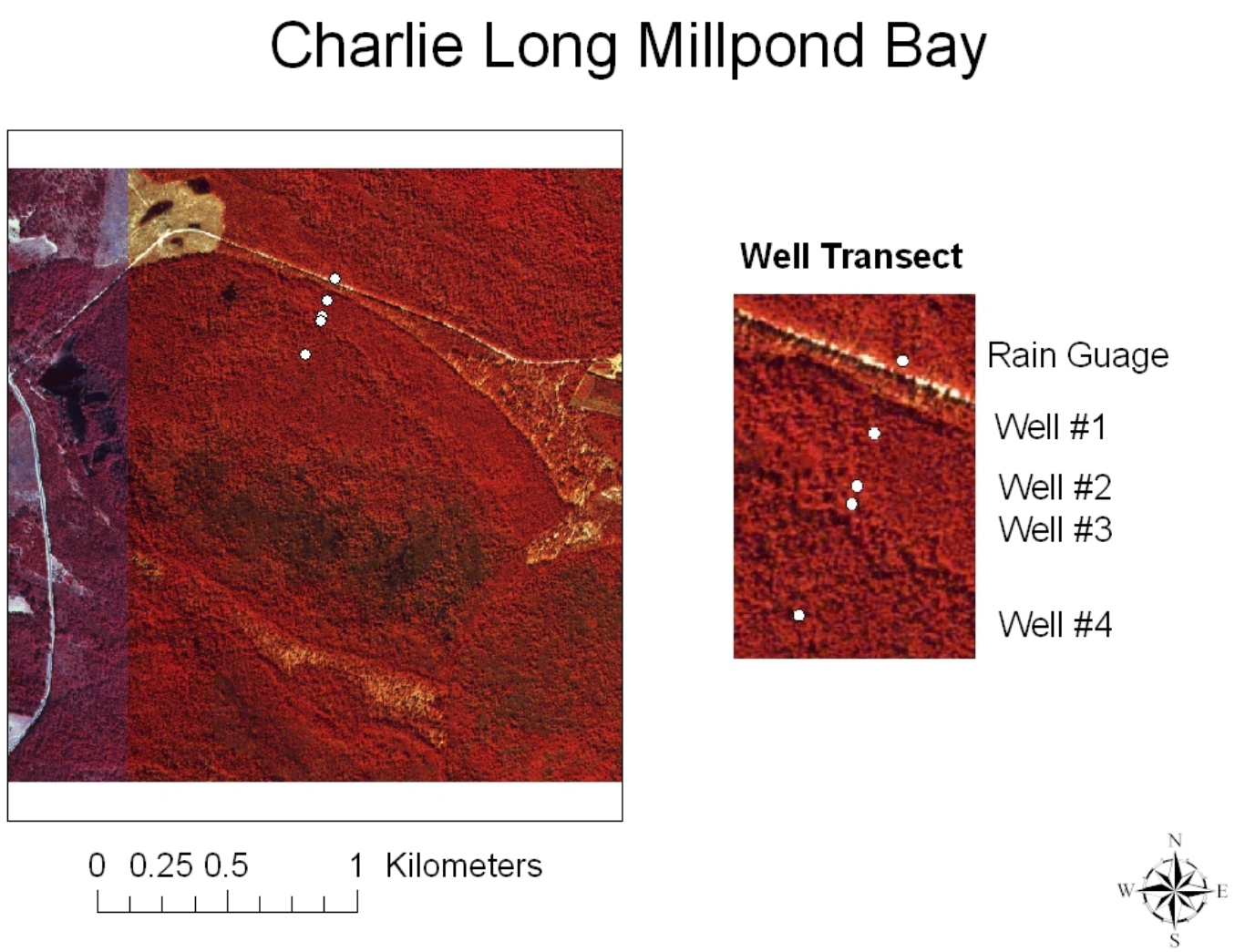


Figure 4.2. Location of transects, wells, and rain gauges in Charlie Long Millpond Bay. Locations determined by GPS.

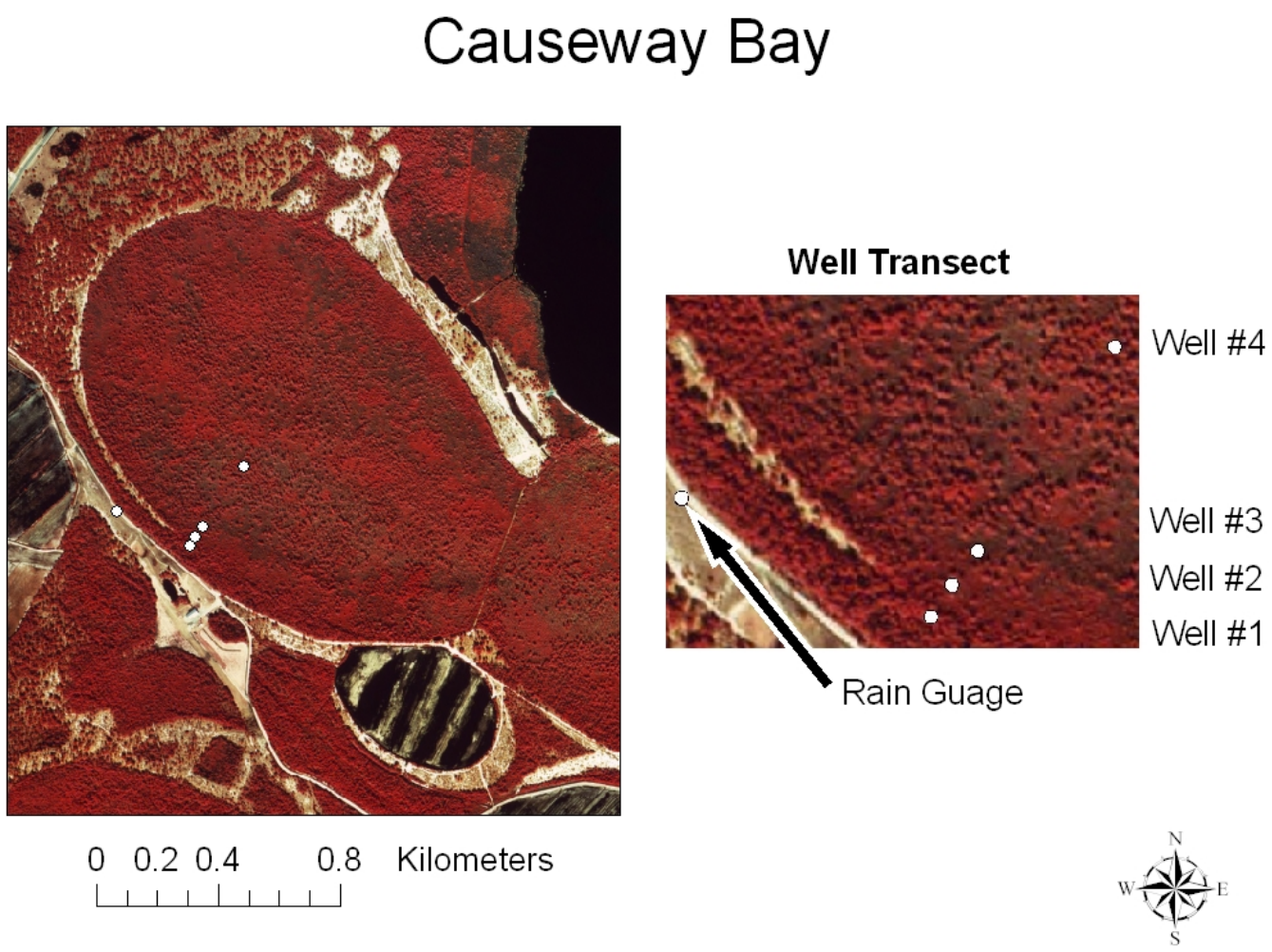


Figure 4.3. Location of transects, wells, and rain gauges in Causeway Bay.

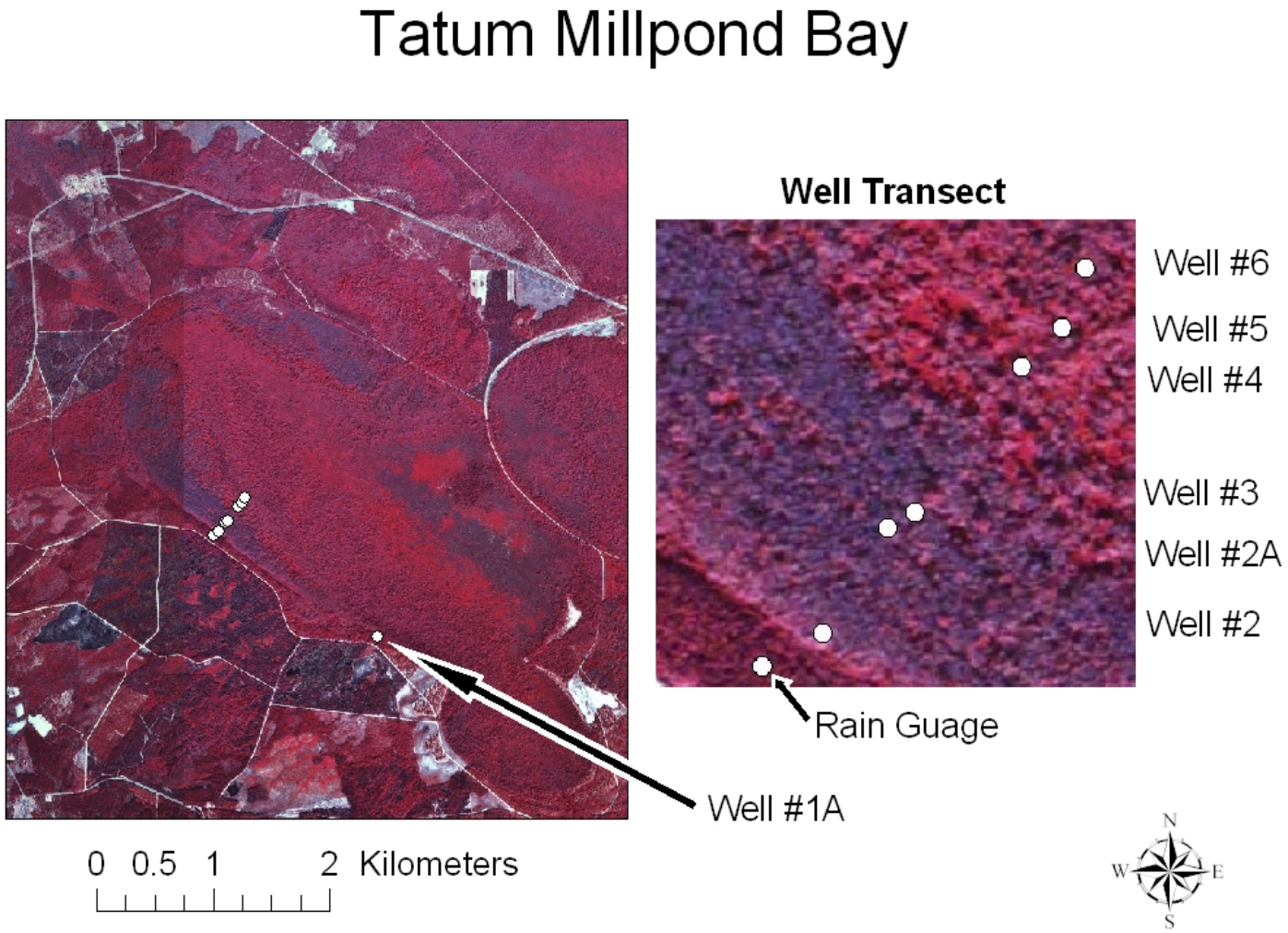


Figure 4.4. Location of transects, wells, and rain gauges in Tatum Millpond Bay.

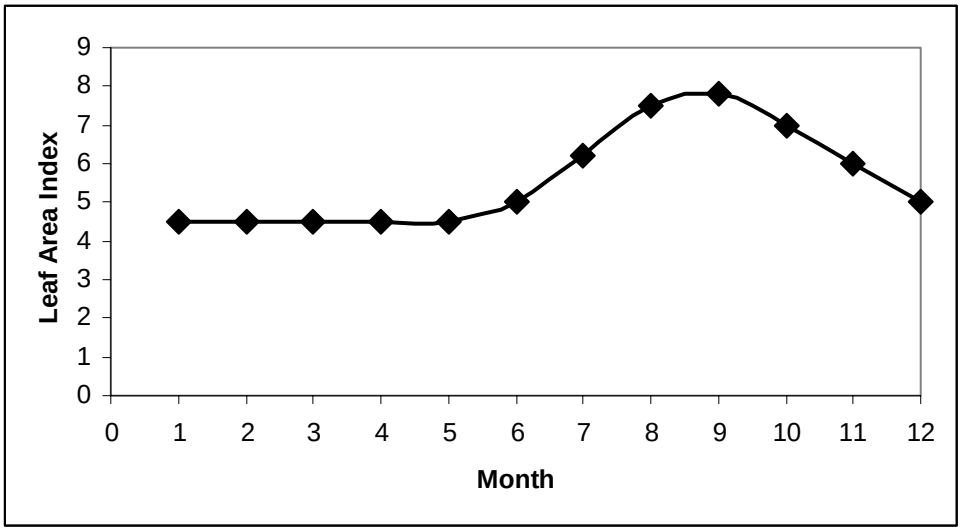


Figure 4.5. Leaf area index (LAI) values assumed for PET calculations with the Penman-Monteith equation. Adapted from Amatya (1993).

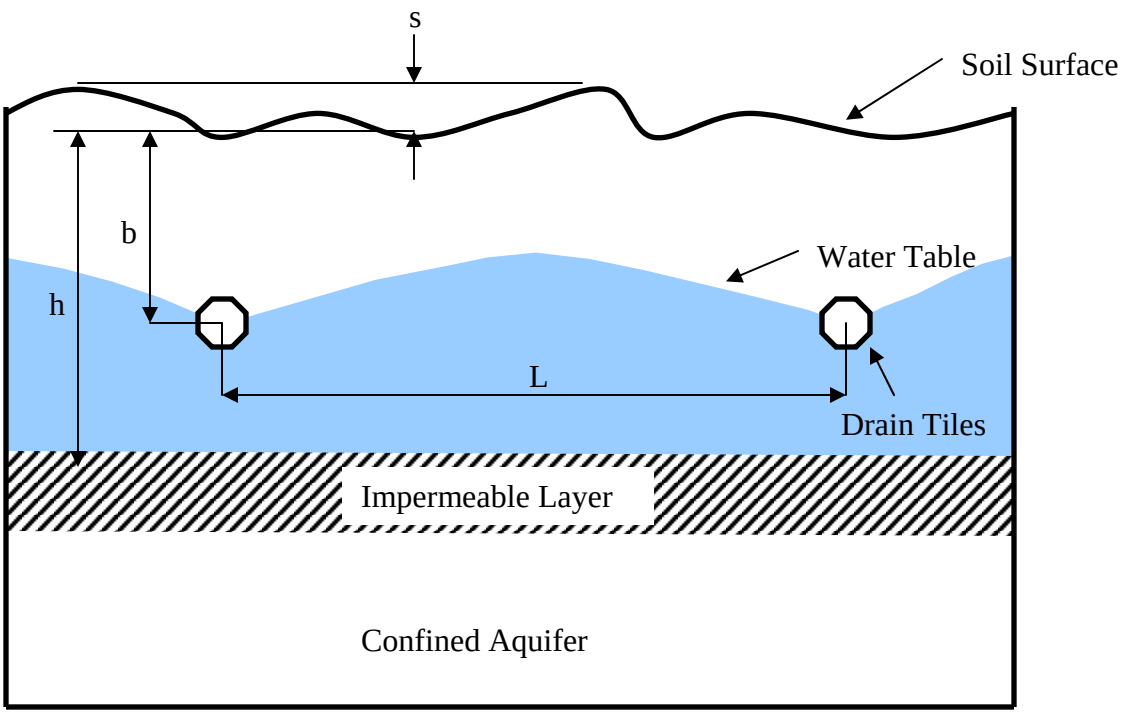


Figure 4.6. Schematic diagram of the DRAINMOD drainage system. Dimensions include the drain depth, b, drain spacing, L, depth to impermeable layer, h, and surface storage, s.

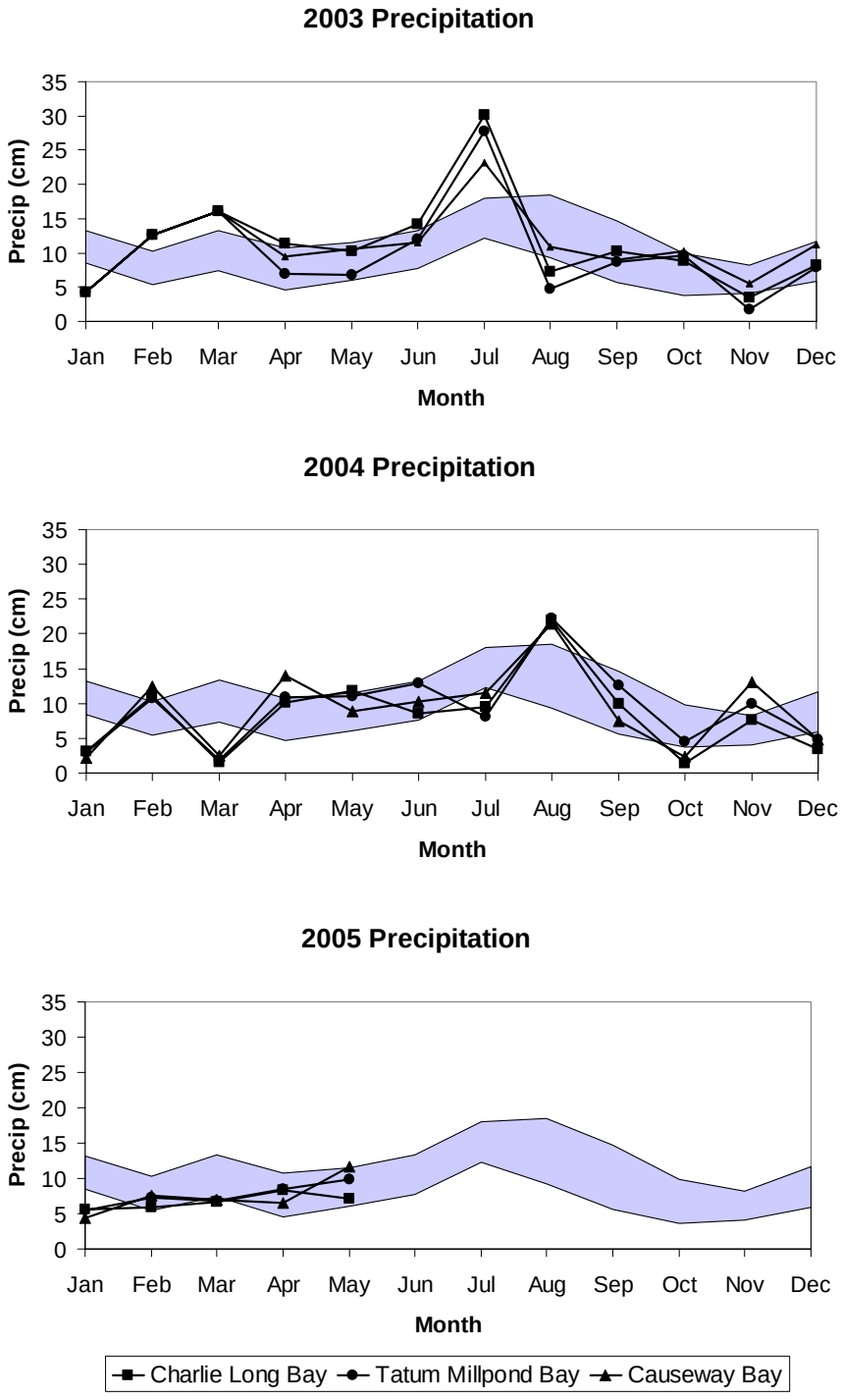


Figure 4.7. Monthly rainfall recorded at reference bays during the 2003 to 2005 calibration period. Normal rainfall is represented by the area in gray.

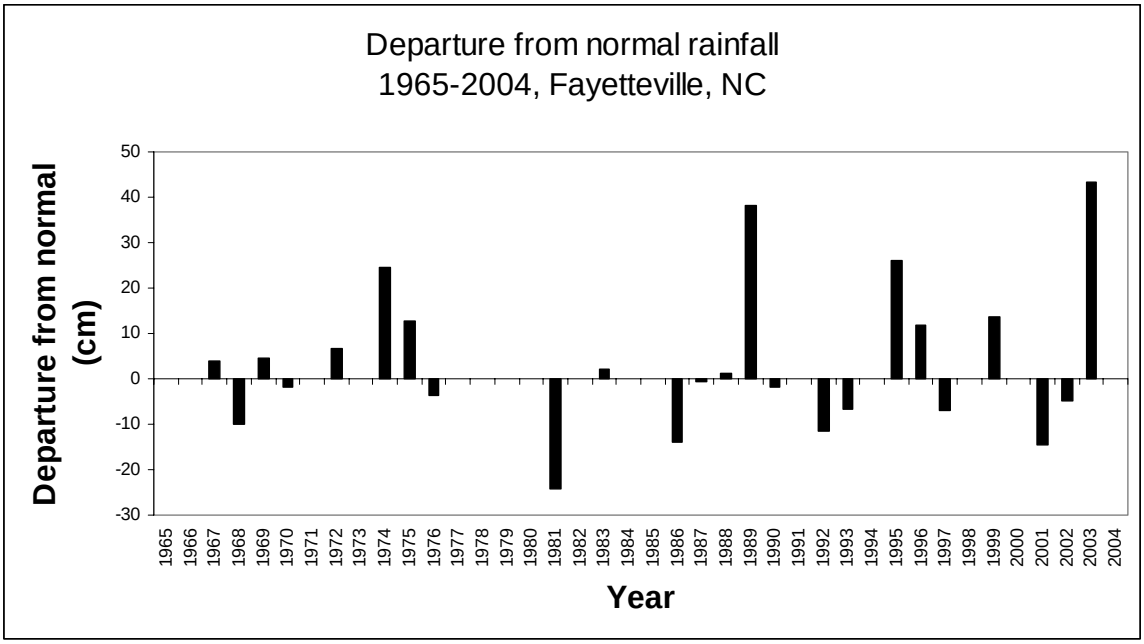


Figure 4.8. Departure from the normal range of rainfall in the long-term weather data used for model simulations.

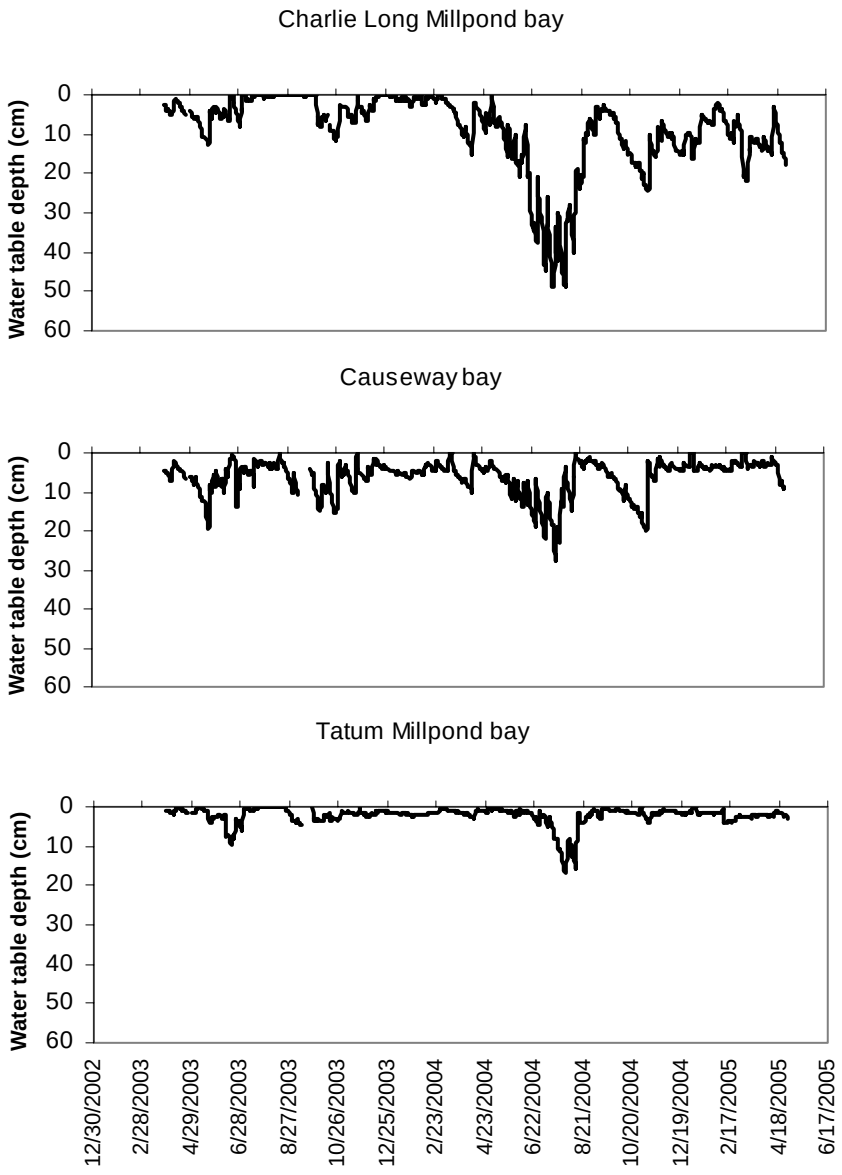


Figure 4.9. Water table depths during the calibration period averaged across all well locations at the reference bays.

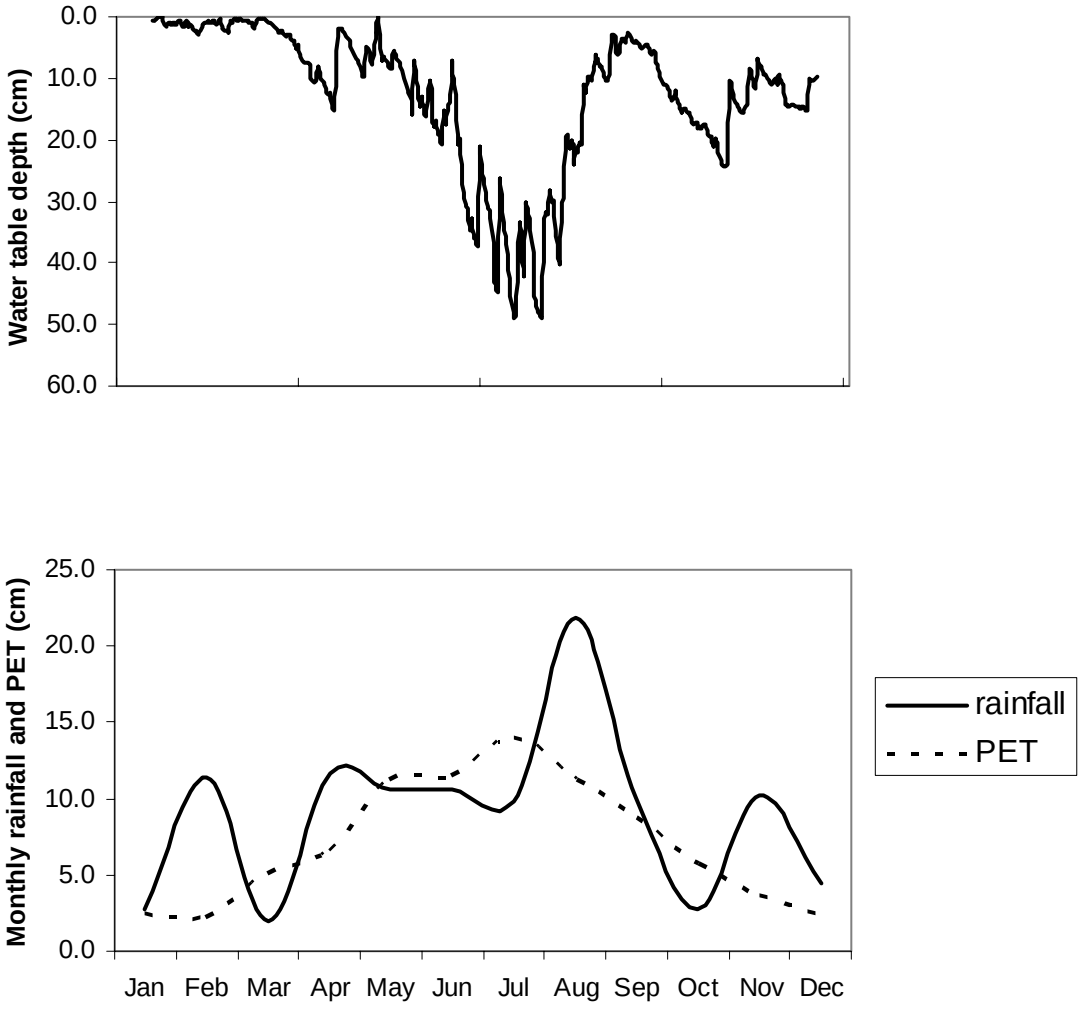


Figure 4.10. 2004 rainfall, PET, and measured water table depth averaged across the four wells in Charlie Long Millpond Bay.

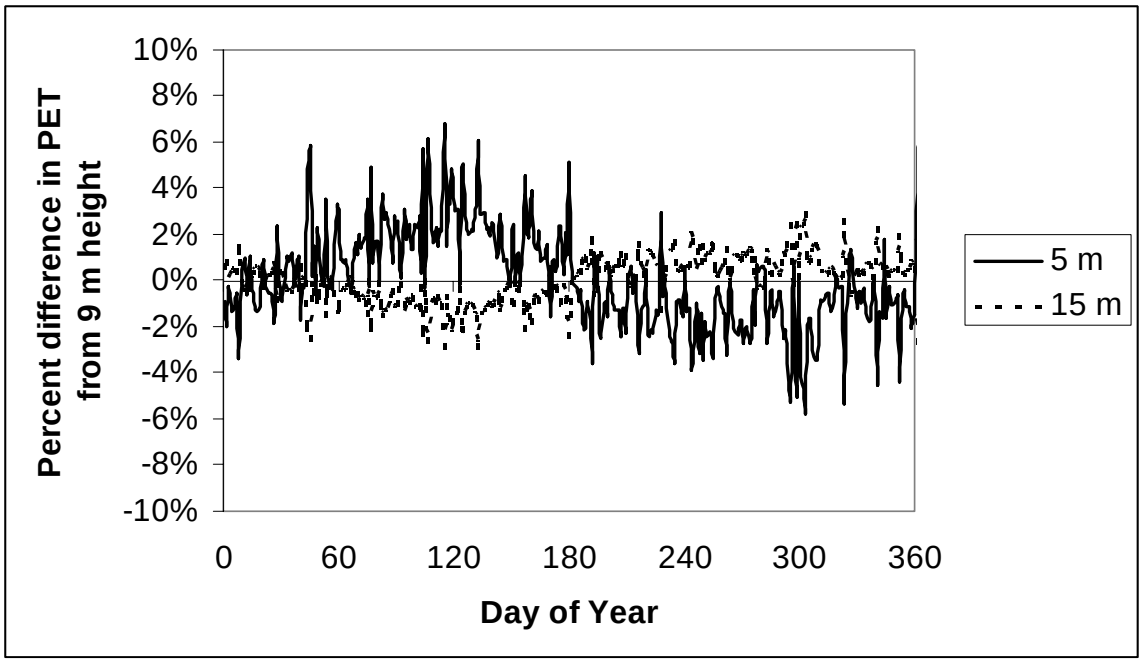


Figure 4.11. Percent difference from 9 m canopy height in 2004 Penman-Monteith PET estimates.

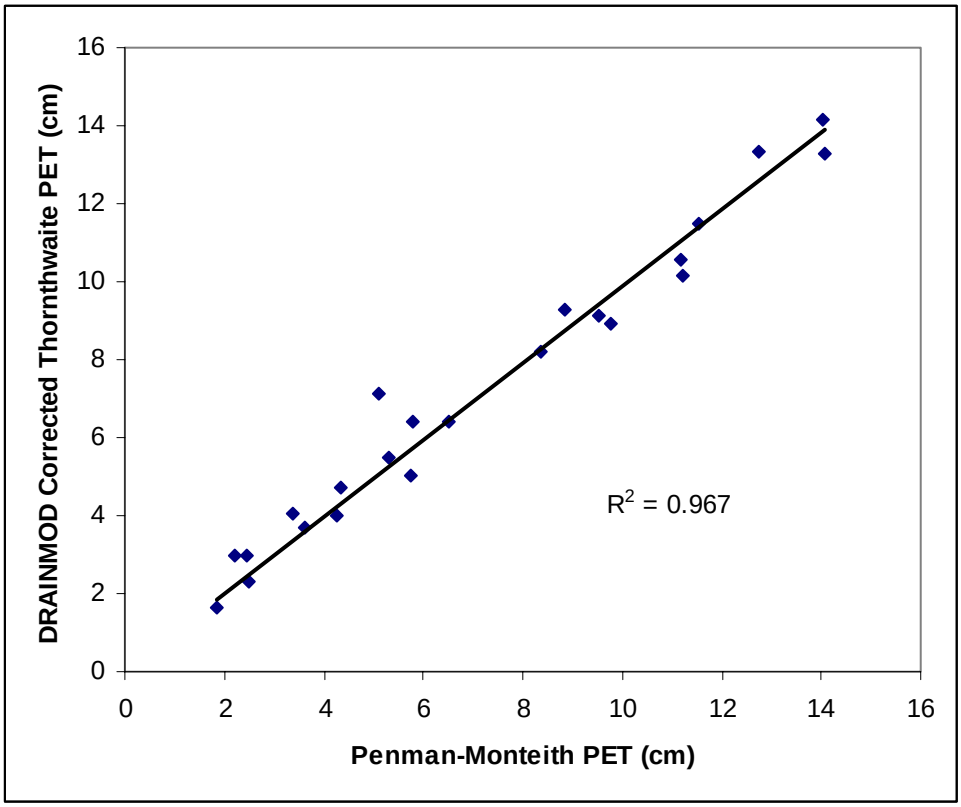


Figure 4.12. Scatterplot of monthly DRAINMOD PET predictions versus Penman-Monteith PET estimates during calibration period.

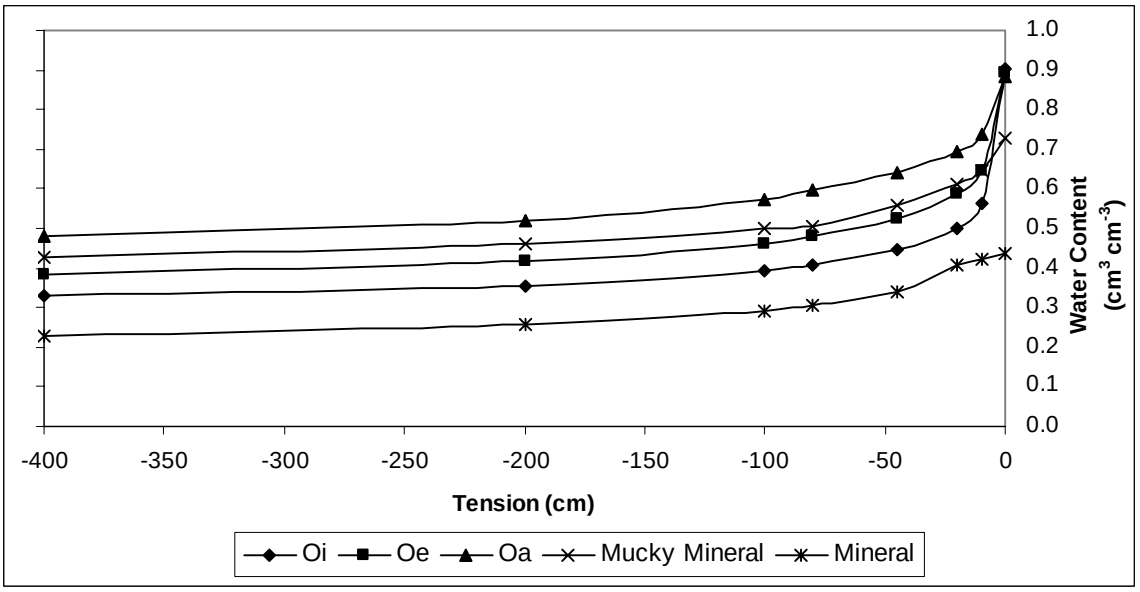


Figure 4.13. Mean soil water characteristic curves for the various types of soil horizons in the reference bays.

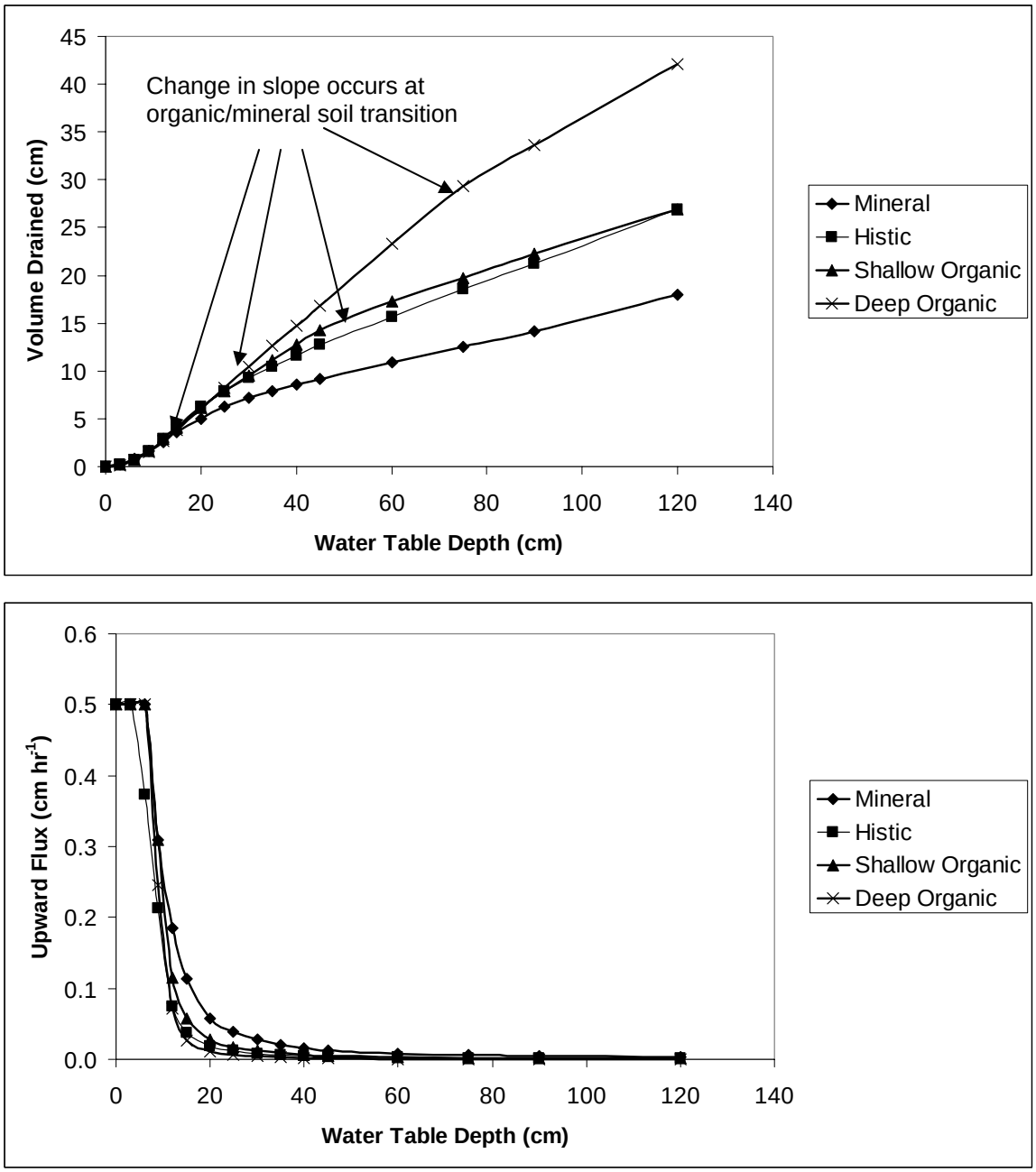


Figure 4.14. Volume drained and upward flux versus water table depth averaged across similar soil types found in the reference bays.

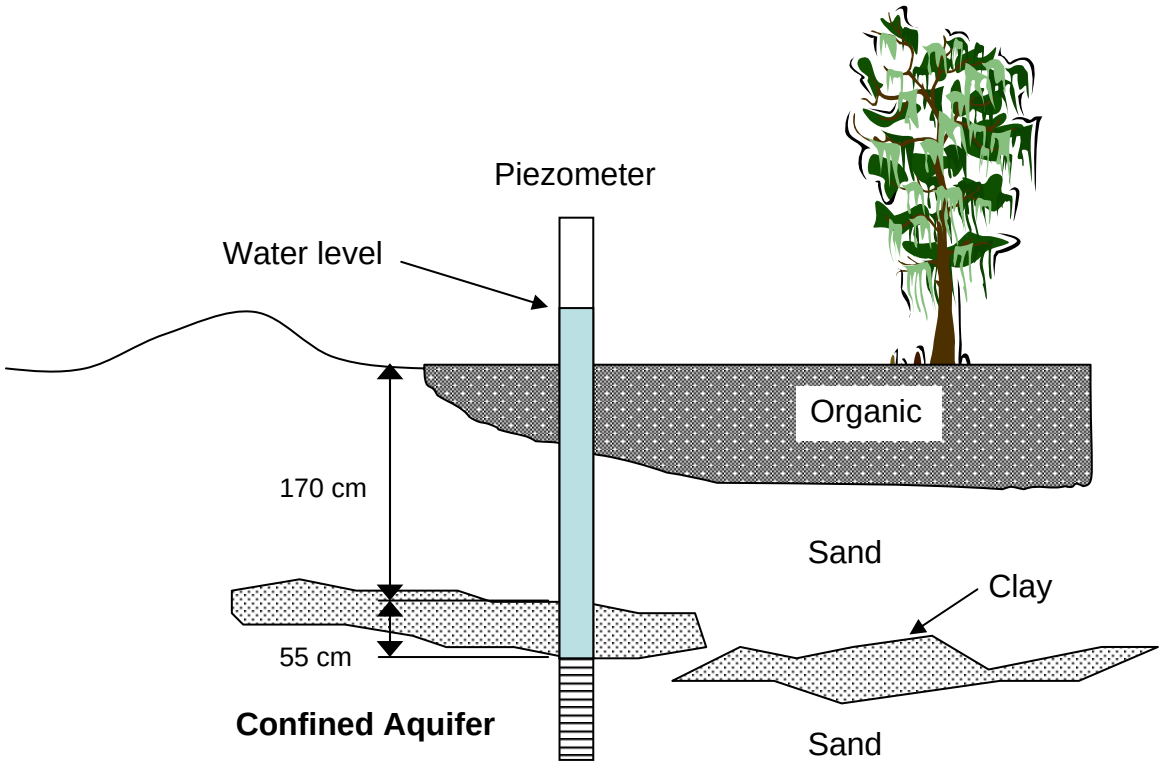


Figure 4.15. Schematic diagram of the confined aquifer system at Charlie Long Millpond Bay.

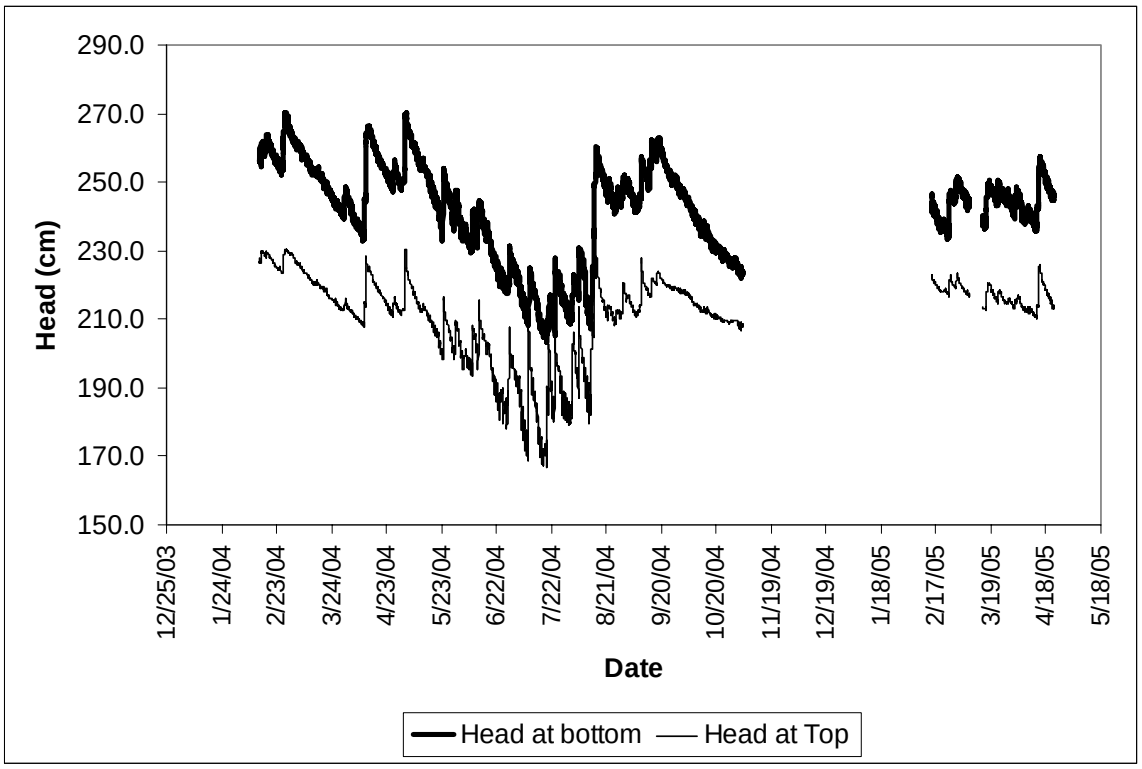


Figure 4.16. Hydraulic heads above and below confining layer below Charlie Long Millpond Bay near well no. 2.

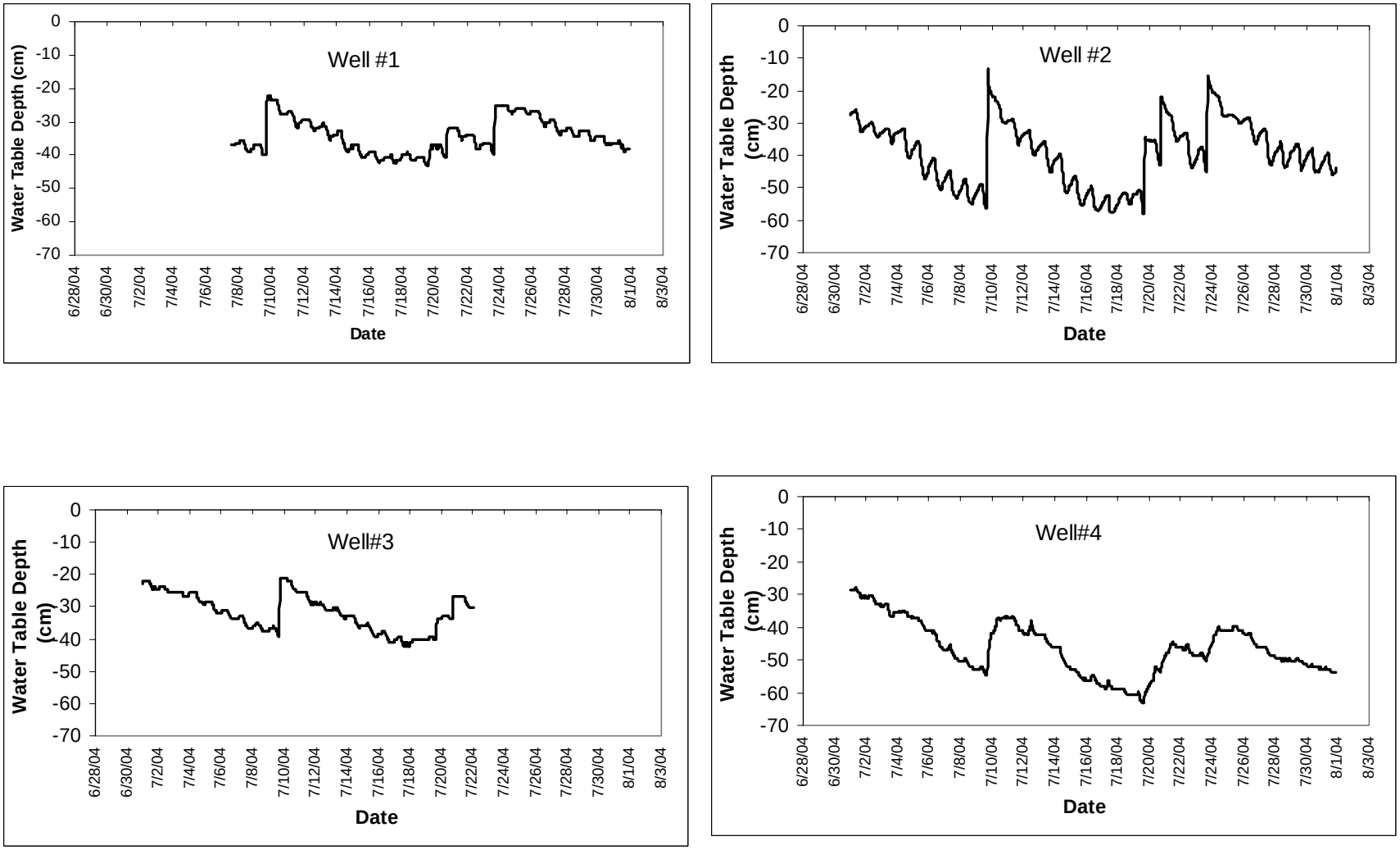
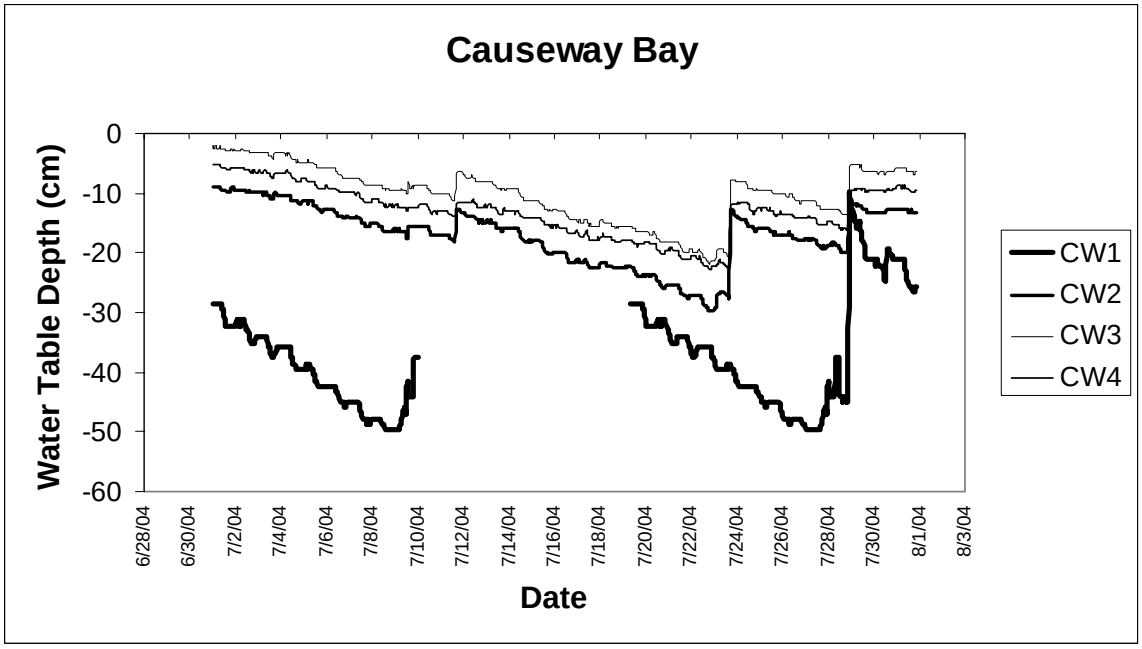


Figure 4.17. Diurnal water table fluctuations measured at wells in Charlie Long Millpond Bay.



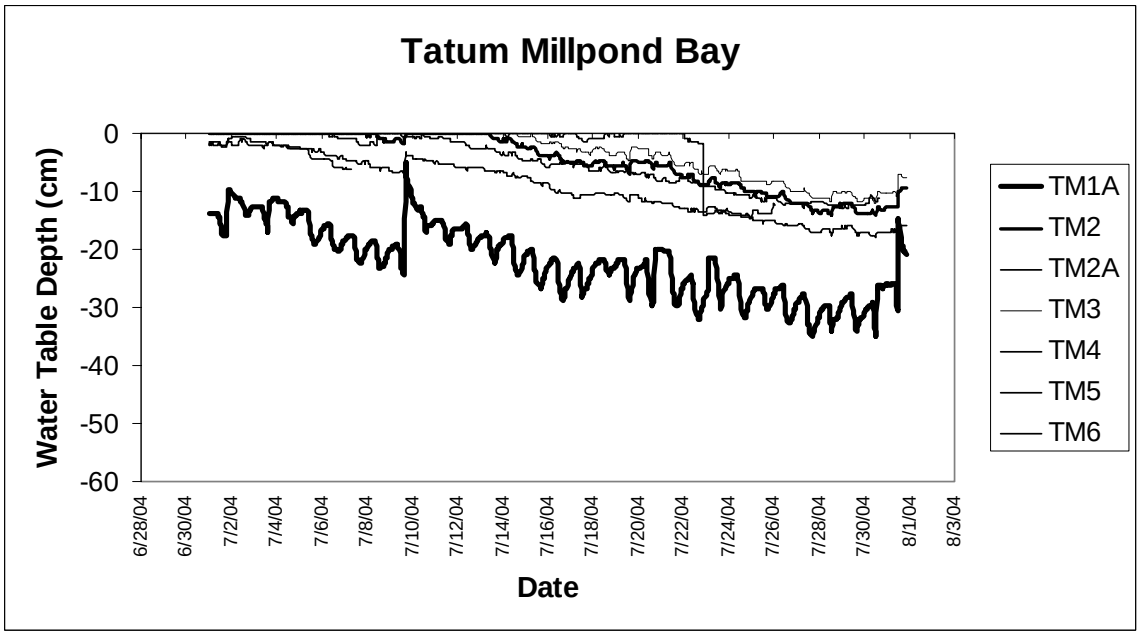


Figure 4.18. Diurnal water table fluctuations at wells in Causeway Bay and Tatum Millpond Bay.

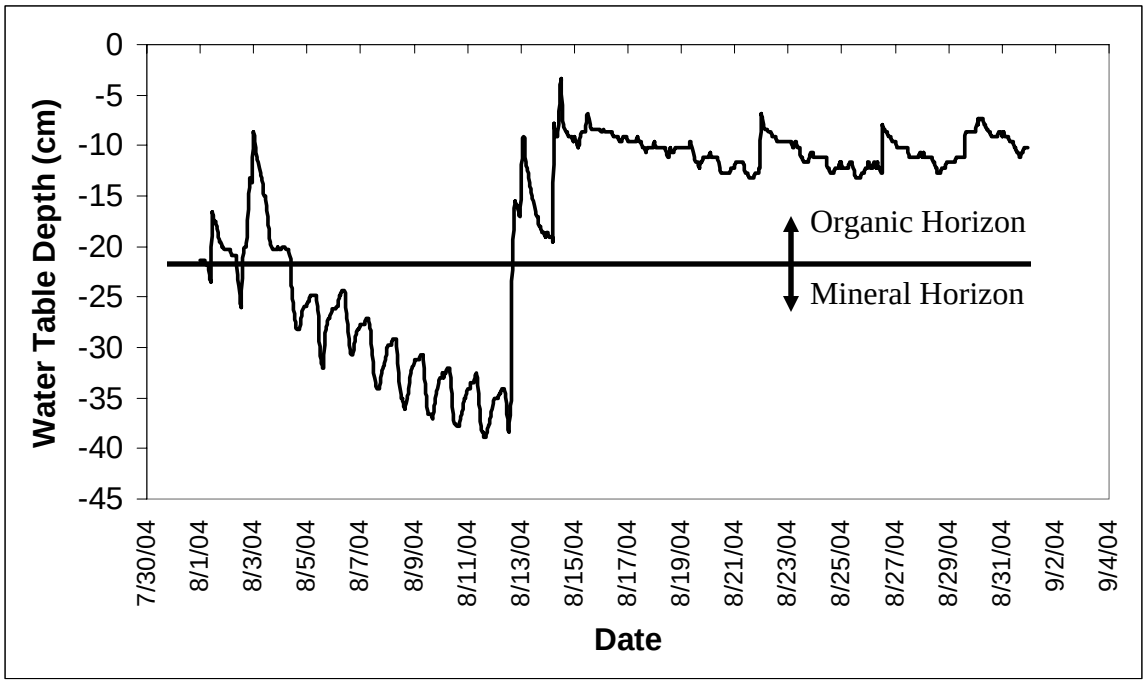


Figure 4.19. Diurnal water table fluctuations in the mineral and organic soil horizons at well no. 1A in Tatum Millpond Bay.

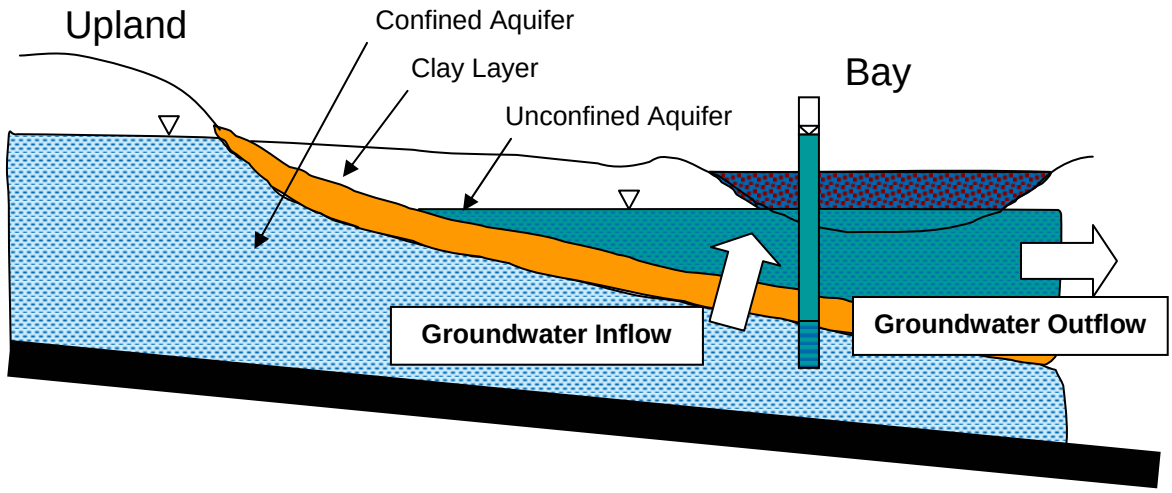


Figure 4.20. Conceptual schematic diagram of the confined aquifer/Carolina Bay system beneath Charlie Long Millpond Bay.

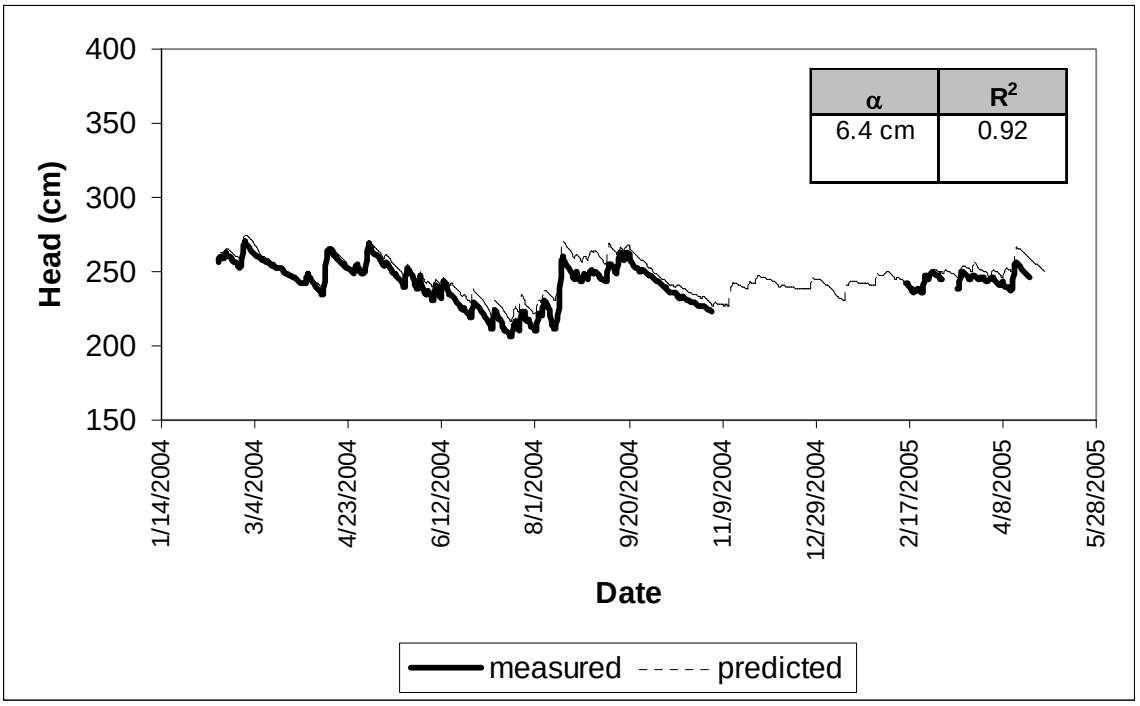


Figure 4.21. Measured and predicted pressure head in the confined aquifer below Charlie Long Millpond Bay.

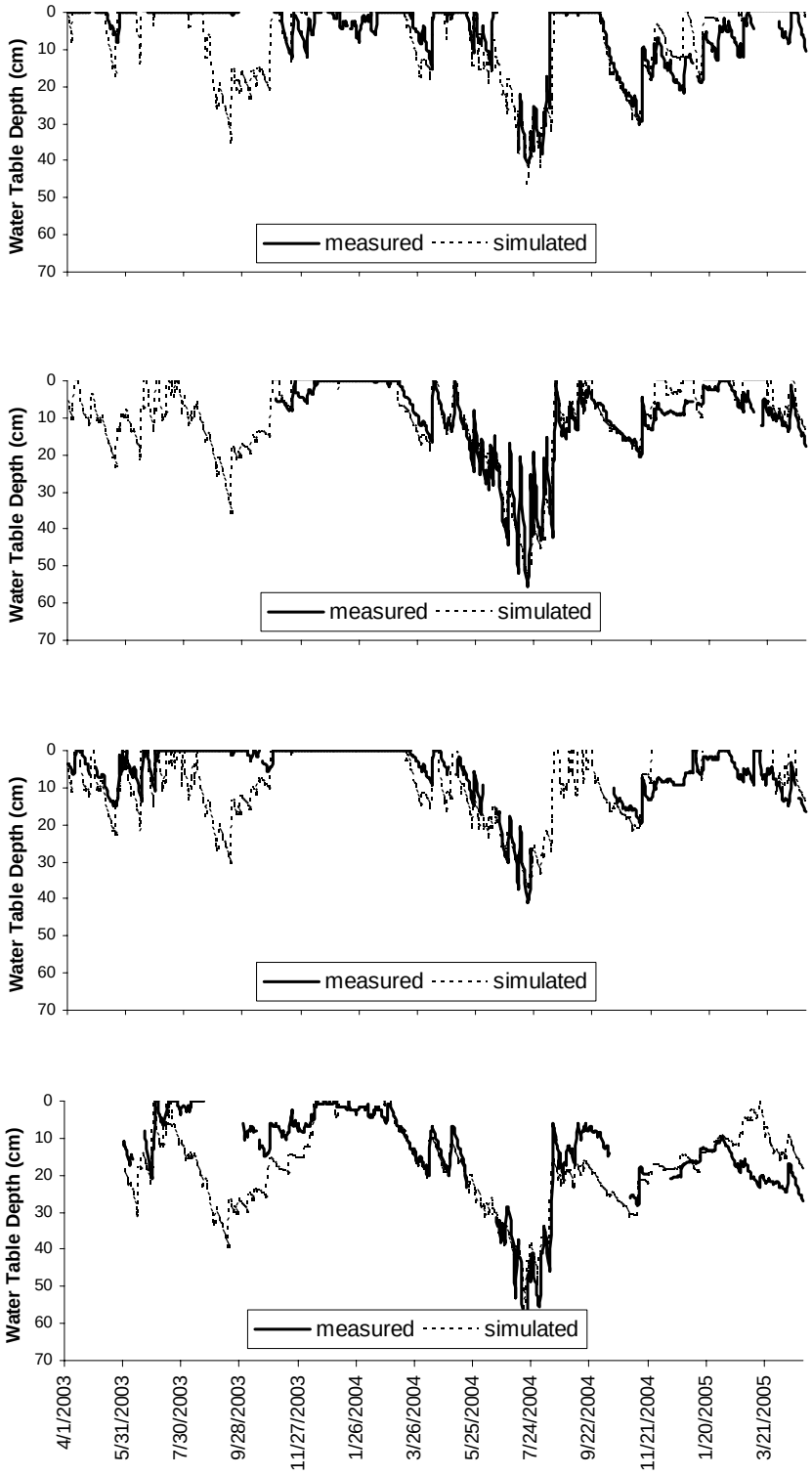


Figure 4.22. Measured and simulated water table depths at Charlie Long Millpond Bay during the calibration period.

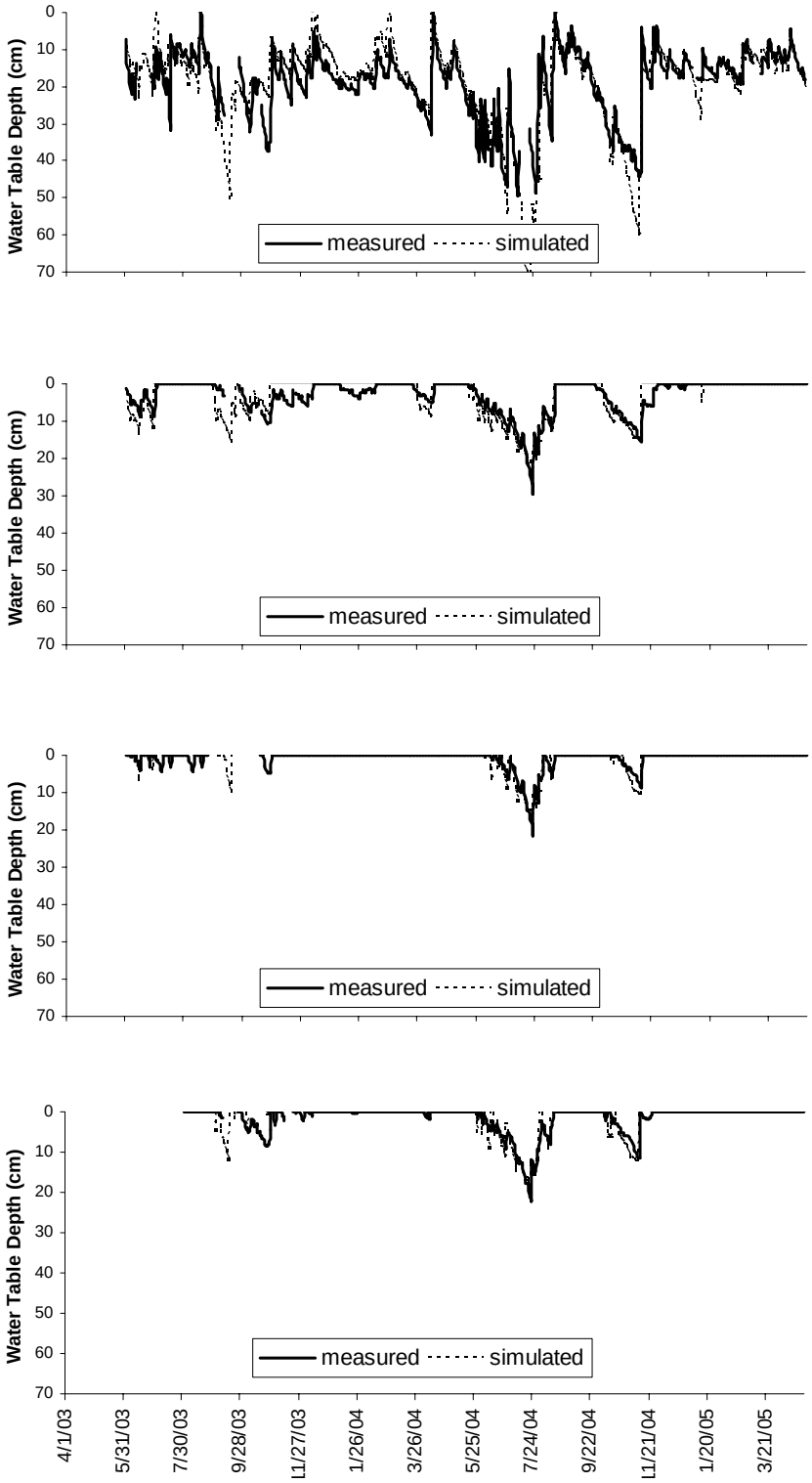


Figure 4.23. Measured and simulated water table depths at Causeway Bay during the calibration period.

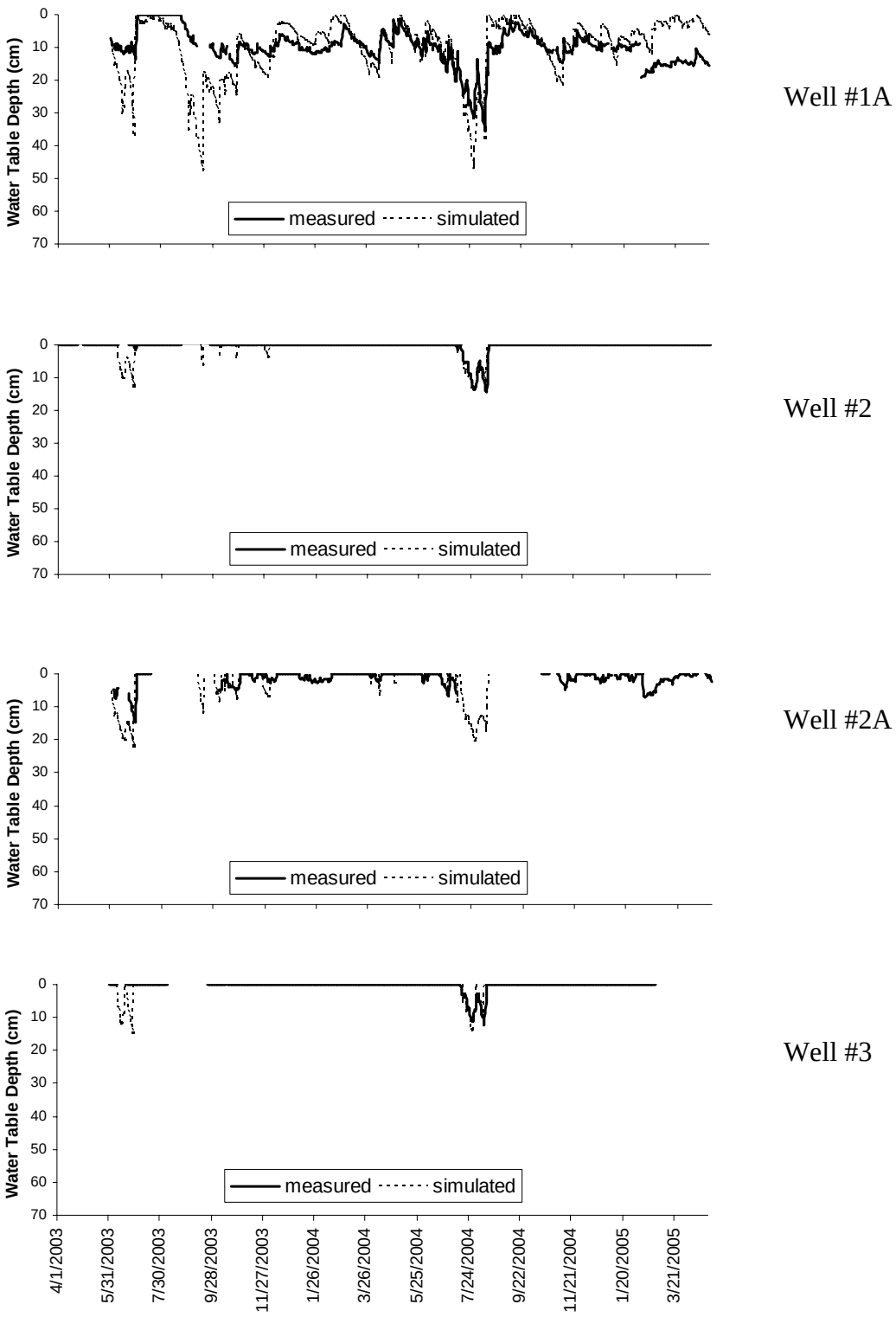
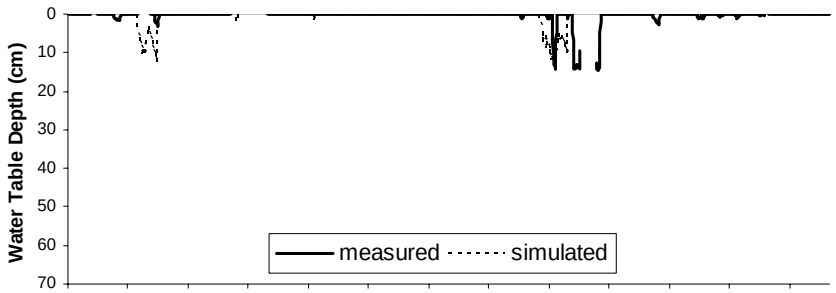
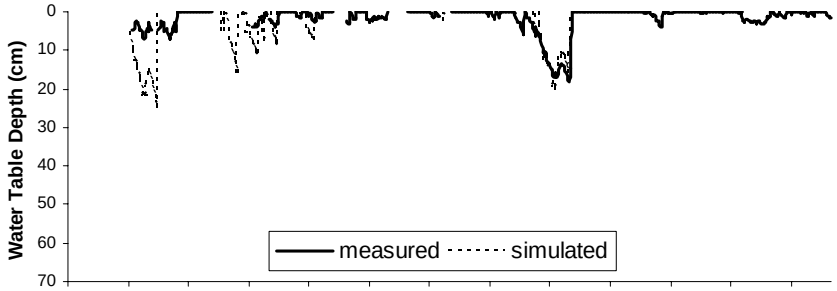


Figure 4.24. Measured and simulated water table depths at Tatum Millpond Bay during the calibration period.

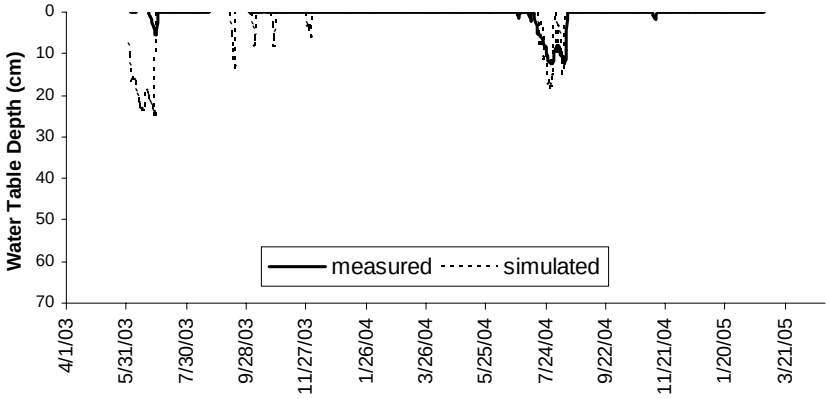
Figure 4.24 (continued)



Well #4



Well #5



Well #6

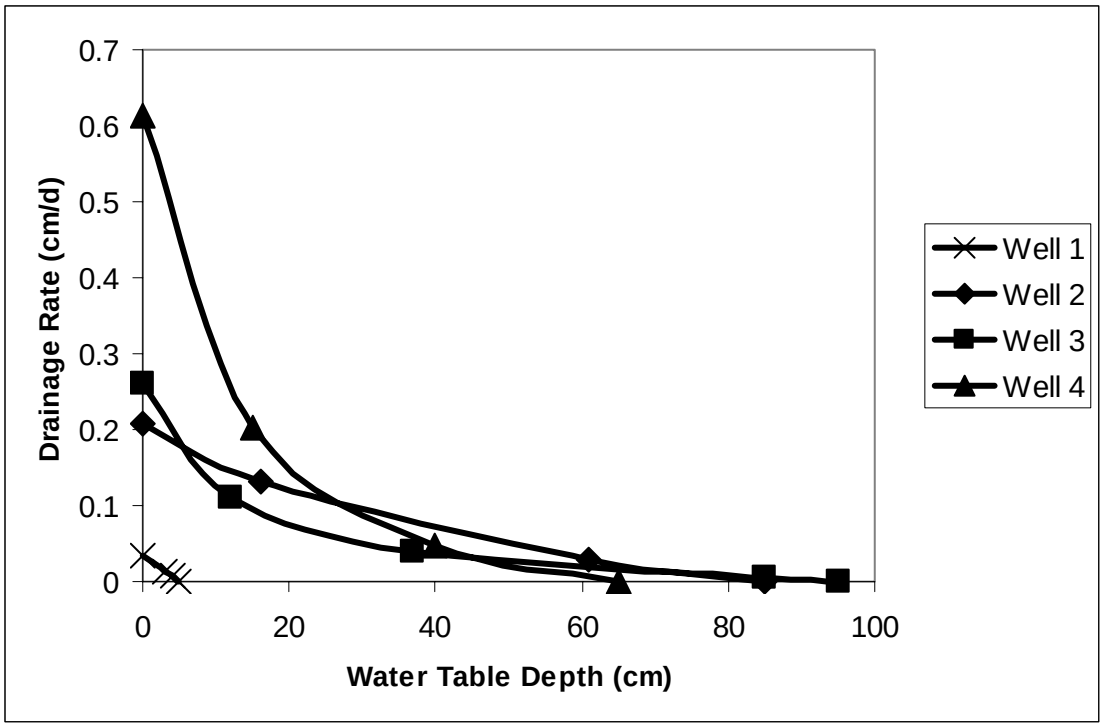


Figure 4.25. Relationship between drainage rate and water table depth for the four well locations in Charlie Long Millpond Bay as determined in the DRAINMOD model calibration process.

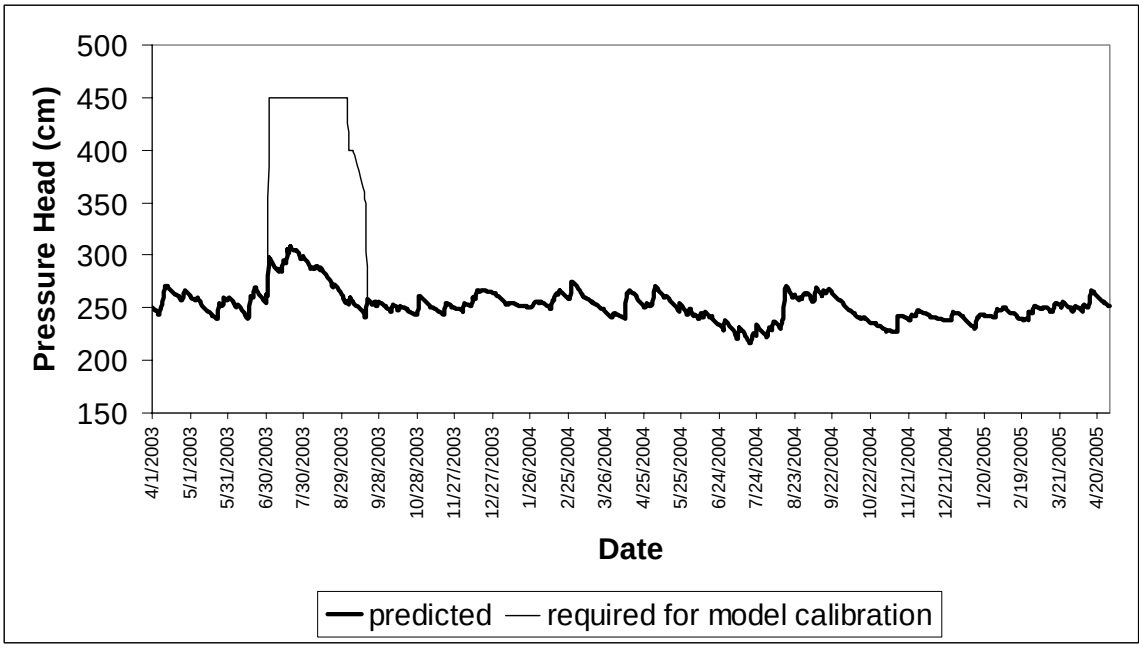


Figure 4.26. Charlie Long Millpond Bay confined aquifer pressure head during calibration period. Data shown are pressure heads predicted by the pressure head prediction model, and that which would be required to calibrate the models for this bay between July and October, 2003.

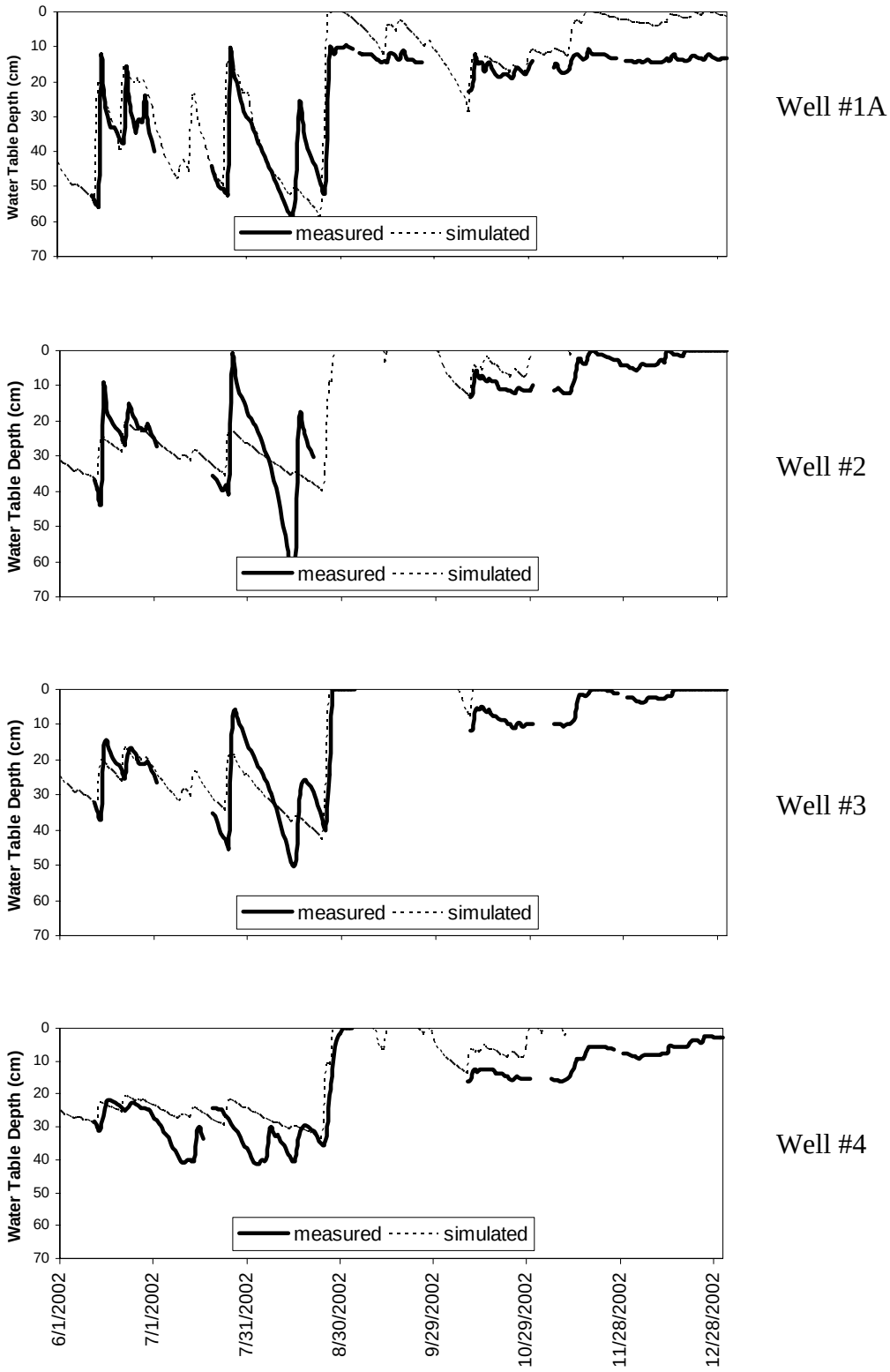


Figure 4.27. Measured and simulated water table depths at Tatum Millpond Bay during 2002, a dry year not included in the model calibration period.

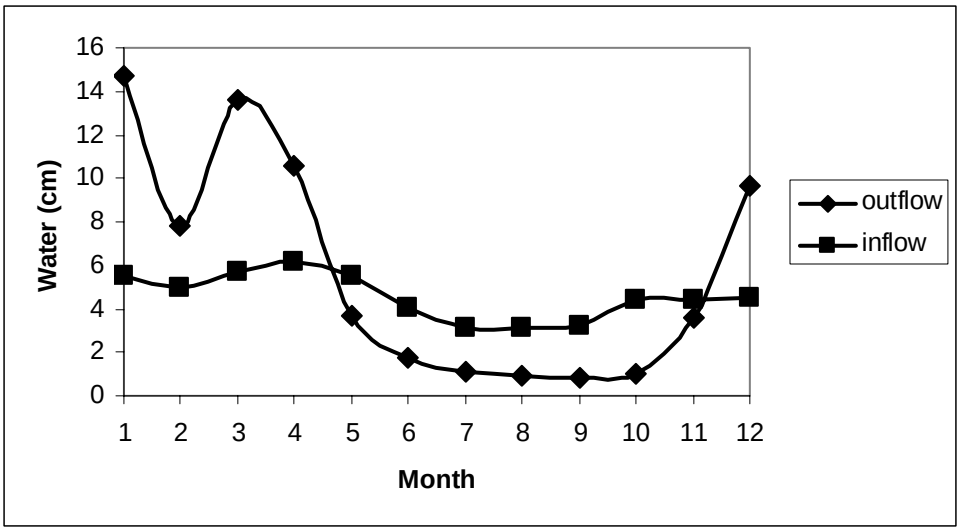


Figure 4.28. Simulated monthly groundwater inflow and outflow at Charlie Long Millpond Bay well no. 3 during 1993.

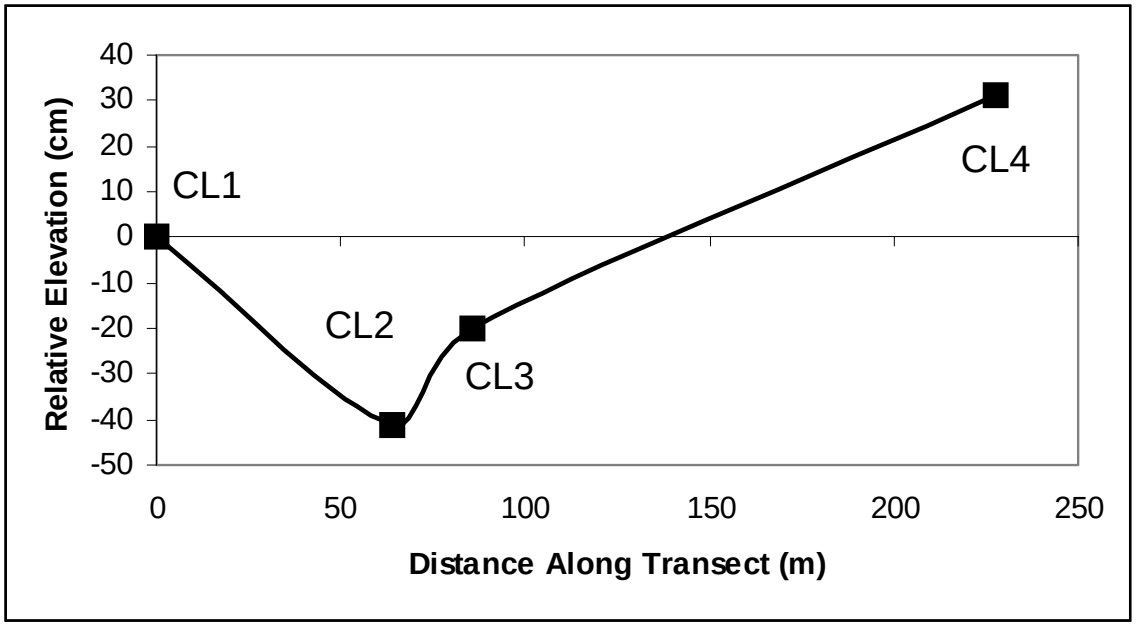
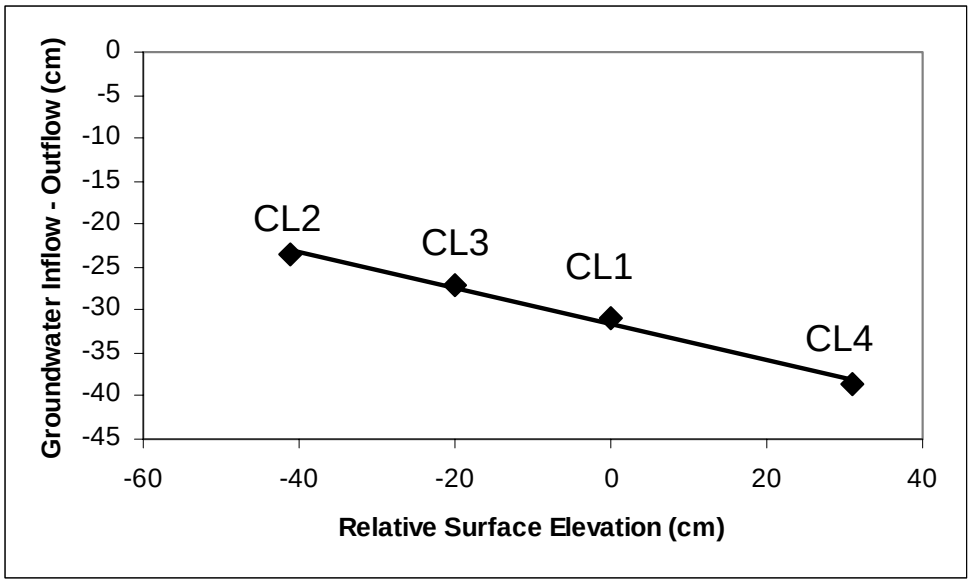


Figure 4.29. Relative surface elevations of well locations in Charlie Long Millpond Bay.



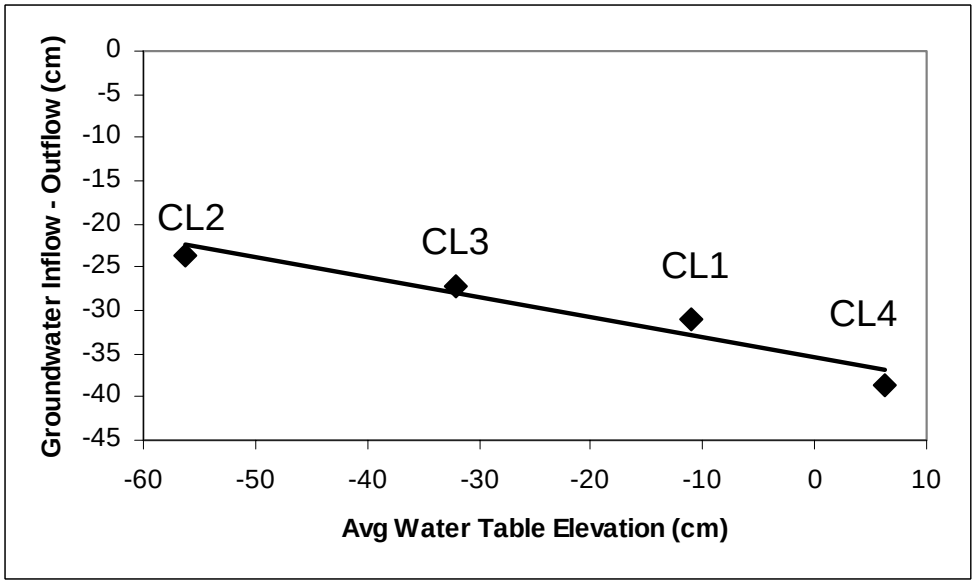


Figure 4.30. Average annual net groundwater flux versus surface elevation and average water table elevation at Charlie Long Millpond Bay.

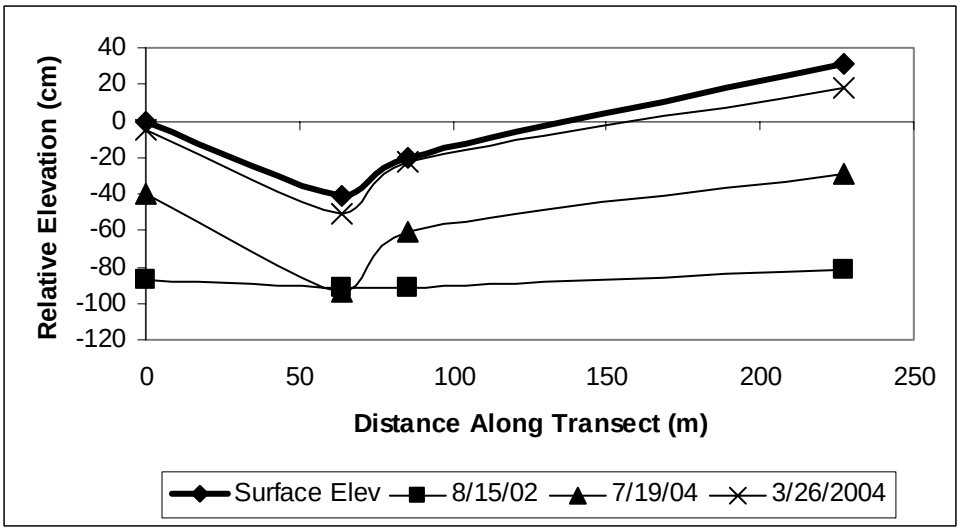


Figure 4.31. Ground surface and water table elevations on various dates across the Charlie Long Millpond Bay transect.

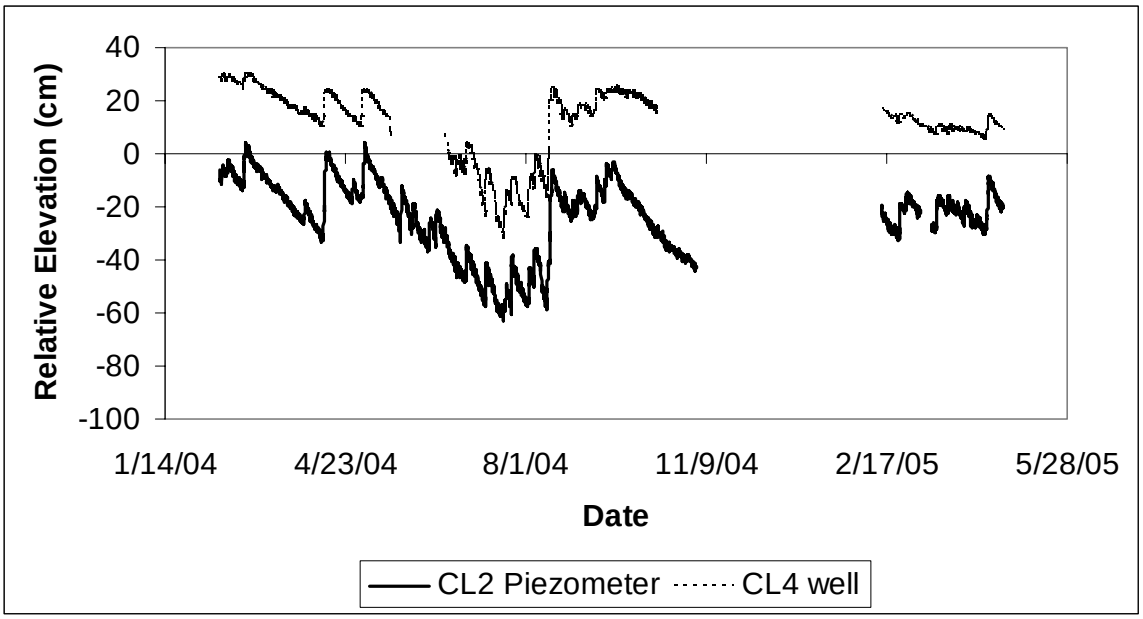
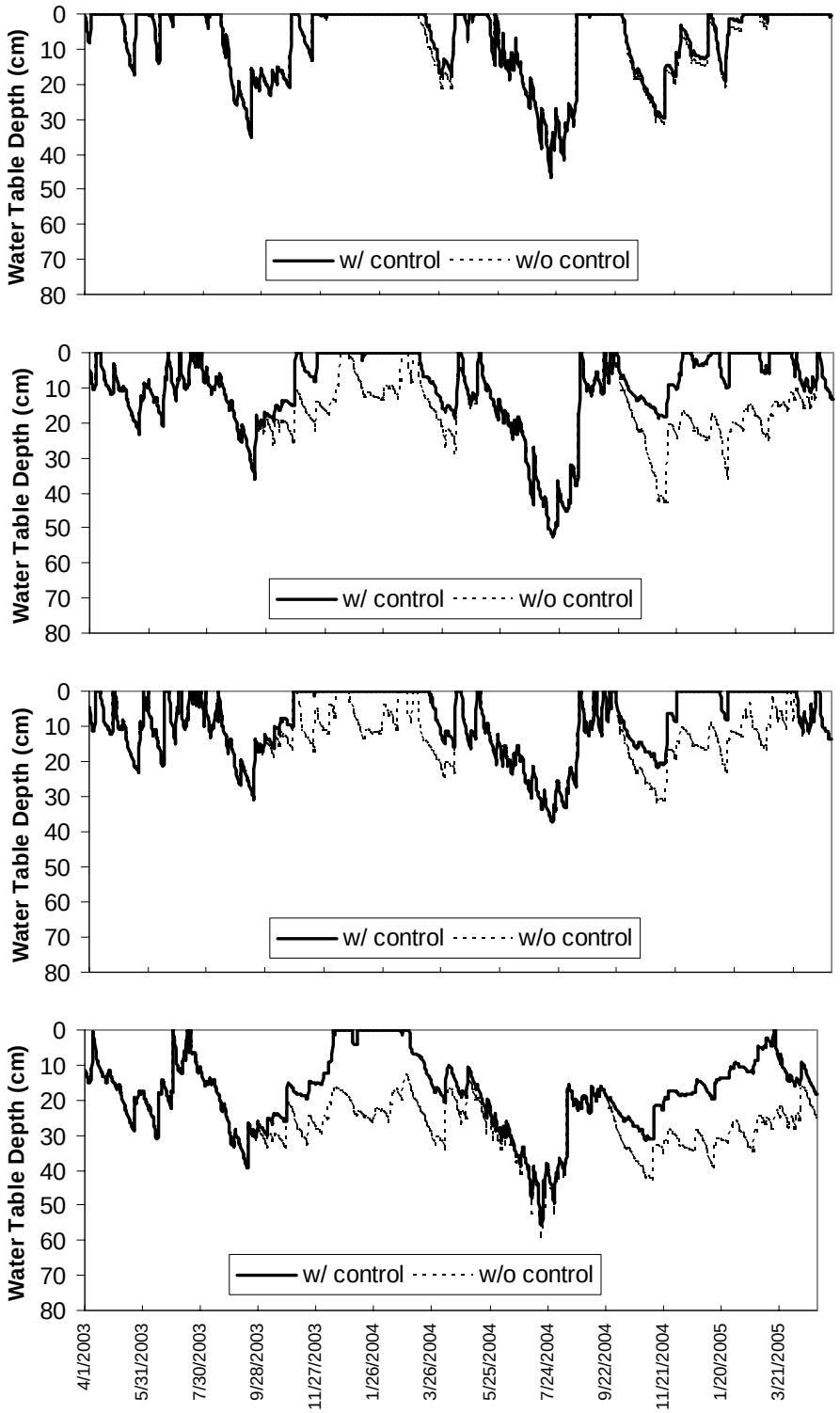


Figure 4.32. Water elevation in the confined aquifer piezometer near Charlie Long Bay well no. 2 and the water elevation measured in well no. 4.



Well #1

Well #2

Well #3

Well #4

Figure 4.33. Effects of the water table control structure on water table elevations at Charlie Long Millpond Bay.

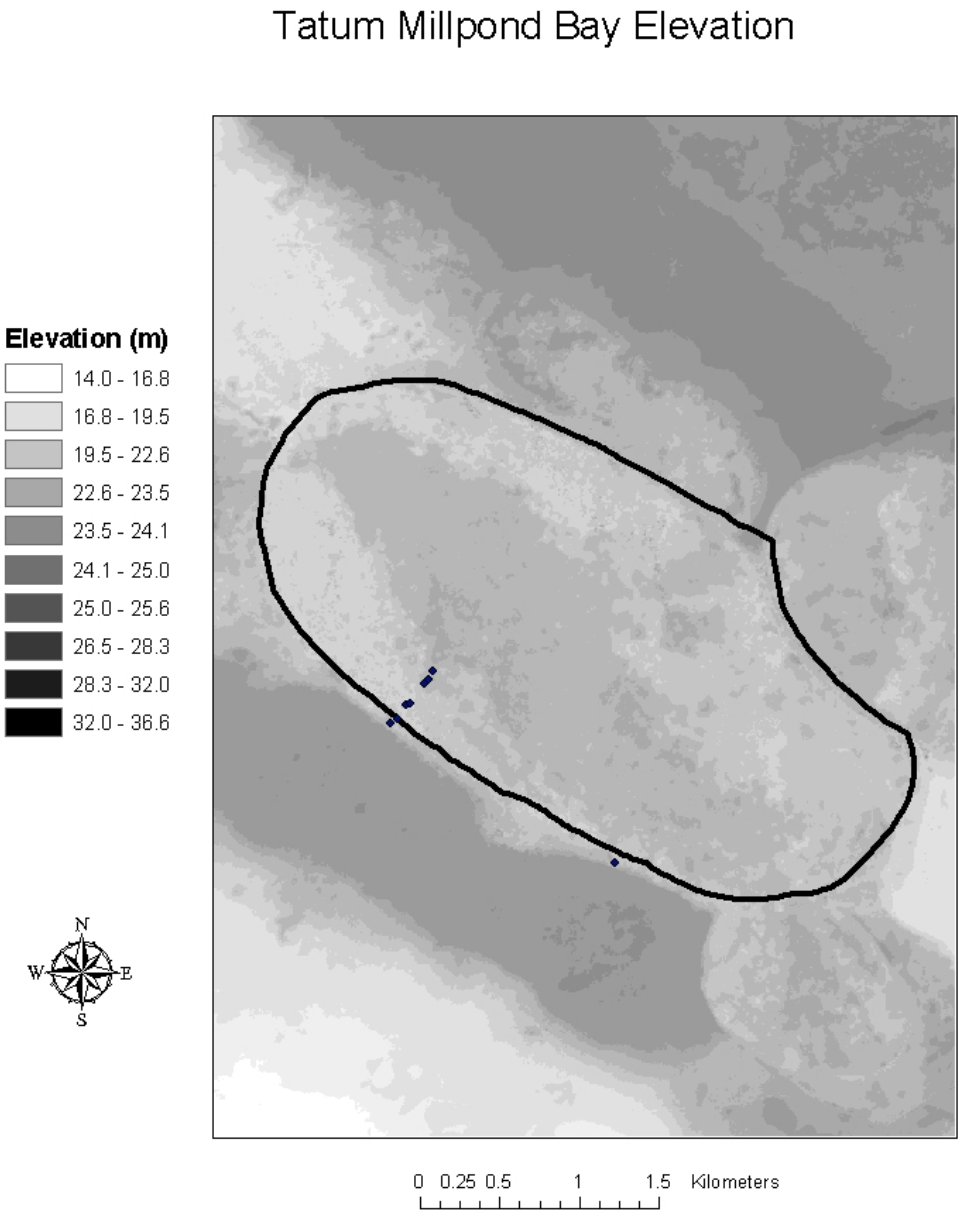


Figure 4.34. Surface elevation map of Tatum Millpond Bay showing area of high elevation along major axis of the bay and just to the south of the bay.

CHAPTER 5

CHARACTERIZING THE LONG-TERM HYDROLOGY OF FOUR CAROLINA BAY PLANT COMMUNITIES

ABSTRACT

Successful restoration of a wetland requires that wetland vegetation be established at the site. Unfortunately, the planted vegetation frequently does not survive in the environment created by the restoration due to an overabundance of water, or insufficient water in the soil. This is primarily due to a lack of detailed long term quantitative data describing the hydrologic requirements of natural wetland plant communities. The objective of this study was to compare the long-term (40 yr) hydrology associated with the Pond Pine Woodland (PPW), Nonriverine Swamp Forest (NRSF), High Pocosin (HP), and Bay Forest (BF) plant communities found in three undisturbed Carolina Bays on the North Carolina Coastal Plain. This objective was achieved by simulating water table depths in the various plant communities in the bays over a 40 yr period with calibrated DRAINMOD hydrologic models. The hydrology of the PPW community differed significantly from that of the NRSF, HP, and BF communities in that water tables were deeper in the soil profile, water was ponded on the surface less often and for shorter durations, and the water table dropped to mineral soil horizons more frequently for extended periods of time. Further, the PPW received an average of 15% of its water input from groundwater inflow, whereas the other communities did not exhibit groundwater inflow. The hydrology of the NRSF, HP, and BF communities were very similar. The water table in the NRSF and HP occasionally dropped to mineral soil horizons, which may provide them with additional fertility relative to BF. The results of this study will enable wetland restoration engineers to better approximate the natural hydrology of these plant communities at a restoration site, thereby improving vegetation establishment success.

INTRODUCTION

Wetlands can provide habitat for wildlife, improve water quality, store floodwaters, and provide recreation for outdoor enthusiasts. Wetlands in the United States are protected under section 404 of the Clean Water Act. The wetland mitigation banking system was developed in response to the Act, such that if a developer destroys a wetland, he or she must agree to restore, enhance, or create an equal number of wetland acres in compensation.

Carolina Bays are popular candidates for wetland restoration in the southeastern United States. Carolina Bays are elliptical depressions oriented on the landscape such that the major axis of the bay is in the northwest-southeast direction (Prouty, 1952). They are formed in poorly drained Coastal Plain sediments, and occur along the Atlantic seaboard from northern Florida to New Jersey, but are concentrated in the Carolinas. Their estimated numbers range from 100,000 to 500,000 (Nifong 1998; Prouty 1952), and they can be as small as 90 m along the major axis or as large as 11 km (Prouty, 1952). They tend to have a rim of well drained sandy textured soils that is more pronounced in elevation on the southeastern edge (Sharitz and Gibbons, 1982; Prouty, 1952). Within the sandy rim, the bays have poorly drained and darker colored soils that may be of both mineral and organic composition (Daniels et al., 1999). In some cases, organic soil layers within the bays can reach 4.5 m thick (Ingram and Otte, 1981). There is much debate as to the age of the bays, but the accepted age range is between 10,000-250,000 years old (Sharitz and Gibbons, 1982).

Successful restoration of a wetland requires re-establishing three wetland components: wetland soils, wetland hydrology, and wetland vegetation. In most cases, a specific wetland plant community is selected as the target ecosystem, and plant species associated with that community are planted at the restoration site. Unfortunately, the

hydrologic regime of restored wetlands frequently cannot adequately sustain these communities (Dennison and Schmid, 1997). This is sometimes a result of improper hydrologic design, but in many cases it is due to a lack of understanding of the hydrology required by these plant communities. To insure that at least some vegetation survives, wetland engineers will frequently plant a variety of vegetation at a site with a wide range of hydrologic requirements in hopes that the hydrologic conditions of a restored wetland will be able to support some of the planted species (Morgan and Roberts, 2003). This practice, though effective in some cases, is inefficient and has no guarantee of success. Quantitative scientific data describing the hydrology of various plant communities could allow much more efficient and successful establishment of wetland vegetation at a restoration site. However, most of the information found in the literature concerning these hydrologic requirements is described in qualitative terms. Expressions such as "seasonally or frequently flooded or ponded to the surface" are used to describe hydrology. Much more quantitative data describing the required hydrology of plant communities is required so that a system to fulfill those requirements can be designed.

Hydrologic models such as DRAINMOD (Skaggs, 1978) and MODFLOW (McDonald and Harbaugh, 1988) are powerful tools that can be used to both understand the hydrology of Carolina Bays and to predict the hydrology of restored or created wetlands. DRAINMOD is a software package originally developed to simulate agricultural drainage systems in poorly drained soils like that of the Coastal Plain of North Carolina. The model assumes a network of parallel drainage ditches or drain tiles at a given depth and spacing. Based on these parameters, the model determines the relationship between the water table depth and the drainage rate using the Hooghoudt equation. An hourly water balance on a

unit area of the soil profile is computed based on inputs of weather (e.g. hourly rainfall and daily maximum and minimum temperature), soil properties, and the drainage network specifications. DRAINMOD has been used extensively for optimizing drainage systems for agricultural land uses, but it has also been used to simulate the hydrology of natural, undrained wetlands (He et al., 2002; Chescheir et al., 1994).

Juniper Bay, a drained Carolina Bay located in Robeson county, NC, was selected as a wetland restoration site by the North Carolina Department of Transportation (NCDOT). The bay was in agricultural production for as many as 30 yr before being purchased by the NCDOT. As part of the project, three undrained and naturally vegetated Carolina Bays were selected as reference sites for the restoration. Lees (2004) studied the plant communities that were established in the reference bays, finding Pond Pine Woodland (PPW) nearest the perimeters of the bays, and High Pocosin (HP) nearest the centers of the bays. One of the bays also exhibited the Non-riverine Swamp Forest (NRSF) plant community as well as Bay Forest (BF). Environmental factors that are believed to affect plant community establishment include peat accumulation, fire, nutrient levels, hydroperiod, and human use (Sharitz and Gibbons, 1982). For the reference bays, no fires, drainage, or logging have occurred in the past 65 to 70 yr (Ewing, 2003). Lees (2004) found no difference in nutrient availability between PPW, HP, and BF communities in these bays. As a result, it was hypothesized that the driving factor in the establishment of these plant communities is differences in hydrologic regime.

The objective of this study was to compare and quantify the long term hydrology (e.g. 40 yr) of each of these plant communities using DRAINMOD. The results of this study will help to determine whether there are differences in the hydrology of these plant communities

that could explain why they are established in their present locations within the bays. In addition, it will provide quantitative data describing the hydrology of these plant communities so that wetland restoration engineers may better approximate the natural hydrology at a restoration site, thereby improving vegetation establishment success.

SITE DESCRIPTIONS

The reference bays, Charlie Long Millpond Bay (204 ha), Tatum Millpond Bay (808 ha), and Causeway Bay (145 ha), are located in Bladen County NC. They are all in or near Bladen Lakes State Forest, at approximately 34°40'59" N and 78°34'54" W (Fig. 5.1) in the Cape Fear River flood plain soil system (Daniels et al., 1999). The area has a high density of Carolina Bays positioned on abandoned flood plains of the Cape Fear River.

Tatum Millpond Bay and Charlie Long Millpond Bay have both been managed by the N.C. Division of Forest Resources since 1938, and have not been extensively burned in the last 65-70 yr (Ewing, 2003). Causeway Bay, which is located on privately owned land, also has not been burned in the last 65 to 70 yr. In the past, Tatum Millpond Bay was selectively logged for Atlantic White Cedar between 1938 and 1954 (Lees, 2004). Charlie Long Millpond Bay reportedly has never been logged, though it was used to practice fireline construction in the 1970s (Ewing, 2003). Past management practices in Causeway Bay are unclear, but it is known that the last timber harvest occurred on the northeast end in the 1960s (Ewing, 2003).

The soils at the reference bays were described to a depth of 1 m by Ewing (2003), and divided into four classes by the depth of organic material as indicated by the percentage of organic carbon. Mineral soils had an organic layer less than 20 cm thick, histic soils 20 to 40 cm thick, shallow organic soils 40-60 cm thick, and deep organic soils had organic layers

greater than 60 cm thick. Soils types in the reference bays typically transition from mostly mineral composition nearest the bay perimeter to mostly organic composition in the center. Torhunta (Coarse-loamy, siliceous, active, acid, thermic, Typic Humaquepts), Lynn Haven (Sandy, siliceous, thermic, Typic Alaquods), and Leon (Sandy, siliceous, thermic, Aeric, Alaquods) soil series are found along the perimeter (Leab, 1990). Meanwhile, Pamlico (Sandy or Sandy-skeletal, siliceous, dysic, thermic, Terric Haplosaprists) and Croatan (Loamy, siliceous, dysic, thermic, Terric Haplosaprists) soil series can be found near the centers of the bays (Leab, 1990). Soil textures of the mineral horizons include sandy loam, loamy sand, and sand.

Lees (2004) studied the plant communities that were established in the reference bays. Charlie Long Millpond Bay and Causeway Bay generally exhibited PPW plant communities nearest the perimeter and HP plant communities nearest the center of the bays, as defined by the classification system developed by Schafale and Weakley (1990). Tatum Millpond Bay transitioned from PPW, to NRSF, to HP, and finally to BF from the periphery to the center of the bay. Lees (2004) discovered that plant community type occurrence correlates well with the depth of organic soil materials. The following plant community / soil type complexes were established: 1) PPW – mineral soil, 2) PPW – histic/shallow organic soil, 3) NRSF – histic/shallow organic soil, 4) HP – deep organic soil, and 5) BF – deep organic soil. Available soil phosphorus is thought to be the limiting factor in plant growth in pocosin wetlands (Barnes, 1981; Walbridge, 1991). In addition, available phosphorus has been found to be greater in the soils of the NRSF plant community compared to that of its pocosin counterparts (Bridgham and Richardson, 1993; Bruland et al., 2003). Lees (2004) also found that soil phosphorus levels in the NRSF plant community are significantly higher

than that of the other plant communities. However, the difference in soil phosphorus levels was not found to be significant among the PPW, HP, and BF plant communities.

MATERIALS AND METHODS

The overall methodology used in this study can be summarized as follows. First, water table depths and rainfall data were recorded in the various plant communities at each bay over a 2 yr period from April 2003 to May 2005 for DRAINMOD model calibration. Concurrent with the collection of these data, estimates of evapotranspiration (ET) over the calibration period were calculated and soil property data required by the model were collected from intact cores taken from the bays. Next, the models were calibrated against the water table data collected in the field over the 2 yr period. Once the models were satisfactorily calibrated, 40 yr of historical weather data were used as input for the models to simulate long term water table depths in each bay. These data were then studied to characterize and quantify differences in the hydrology of the plant communities.

Calibration Data Collection

Access trails (straight line transects) were cut through the natural vegetation roughly along the minor axes of the bays from the perimeter to the center (Figs. 5.2 to 5.4). Along each transect, RDS water level recording wells (Remote Data Systems, Inc., Wilmington, NC) were installed to a depth of 1 m in each plant community. Each well recorded water table depths on an hourly basis over the 2 yr calibration period. In addition, one Davis tipping-bucket rain gauge (Davis Instruments, Hayward, CA) was installed near the perimeter of each bay. Well locations, approximate plant community boundaries, and depths of organic soil layers along each transect in the reference bays are shown in Figure 5.5.

Evapotranspiration Estimation

DRAINMOD calculates potential evapotranspiration (PET) using the Thornthwaite equation (Thornthwaite, 1948). The user can enter monthly correction factors into the model to adjust the Thornthwaite PET estimates based on PET estimates calculated from more accurate means, such as the Penman-Monteith equation (Monteith, 1965). To determine the monthly correction factors, potential evapotranspiration (PET) during the model calibration period was estimated using the Penman-Monteith equation. Weather data required by this equation such as air temperature, relative humidity, wind speed, solar radiation, and barometric pressure that are used in PET estimation were collected from the Turnbull Creek N.C. Division of Forest Resources weather station in Bladen Lakes State Forest. The weather station was located approximately 12.0, 5.3, and 14.5 km from Charlie Long Millpond Bay, Tatum Millpond Bay, and Causeway Bay, respectively (Fig 5.1). The average vegetation canopy height was assumed to be 9 m, based on observation at the reference bays. Leaf area index was assumed to be similar to that measured by Amatya (1993) for a natural mixed stand of pond pine, loblolly pine, and some hardwood species in a coastal plain wetland. A regression equation used by Amatya (1993) was used in this study to estimate the stomatal resistance of the vegetation. Once the Penman-Monteith PET was calculated for the calibration period, these PET estimates were compared to that calculated with the Thornthwaite equation to calculate the DRAINMOD monthly PET correction factors. PET was assumed to be similar across the vegetation of the four plant communities found in the reference bays. The effective rooting depth of the vegetation for all plant communities was assumed to be 45 cm below the soil surface based on observation at the sites.

Soil Data Collection

The DRAINMOD software requires soil water characteristic (water retention) data and saturated hydraulic conductivity data to be collected for each horizon in the soil profile above an impermeable layer. Along each bay transect, an intact soil core was collected to a depth of 1 m in close proximity to each water level recording well. For each soil core, detailed profile descriptions were generated, noting the depths and types of soil horizons. Once soil samples were prepared, soil water characteristic curves for tensions ranging from 0 to 400 cm were determined on a volume basis using a pressure cell apparatus (Klute, 1986). Water contents for tensions of 1000 cm and 15000 cm were determined using a pressure plate apparatus with disturbed samples collected separately from the intact samples. Upon completion of these tests, the samples were placed in cans, weighed, oven-dried at 105^{o} C for 24 hours, and reweighed to determine water content. The horizontal saturated hydraulic conductivity was measured in situ for soil horizons below the water table using the piezometer method (Luthin and Kirkham, 1949).

Model Calibration

The DRAINMOD model assumes a drainage system consisting of parallel drain tiles (Fig. 5.6). For the natural reference Carolina Bays, no such drainage system exists. However, work done by He et al. (2002) and others have found that the subsurface drainage in a natural landscape can be simulated using DRAINMOD by adjusting the drainage system dimensions to calibrate the model to measured water table depths. For any hydrologic system, be it a natural wetland or an artificially drained agricultural field, there exists a relationship between the water table depth and the drainage flow rate out of the system. Adjusting the drainage system parameters in DRAINMOD essentially changes the shape of

the curve between the water table depth and the drainage rate as predicted by the Hooghoudt equation, thereby approximating the natural relationship between these quantities that exists at the site being modeled. The drainage rate in the Hooghoudt equation is a function of the drain depth, spacing, and the hydraulic conductivities of the various soil layers in the profile. For this study, the drain depth, b, spacing, L, and surface storage, s, were adjusted such that the difference between simulated and measured water table depths over the calibration period was minimized.

DRAINMOD also allows simulation of deep seepage through the impermeable layer to the confined aquifer below. Depending on the hydraulic head in the confined aquifer, seepage across the impermeable layer will either enter or exit the surficial aquifer system. A confined aquifer below a dense clay layer was discovered near well no. 2 at Charlie Long Millpond Bay that had a hydraulic head greater than that above the clay layer, providing a gradient for upward water movement into the bay. For well locations exhibiting groundwater inflow, the saturated hydraulic conductivity of the clay layer (i.e. impermeable layer) was an additional variable that was adjusted for model calibration. Piezometers installed in the confined aquifer provided pressure head data at these locations.

Simulation of Long-term Plant Community Hydrology

The historical weather data used for the long-term DRAINMOD simulations were obtained from the State Climate Office of NC for Fayetteville, NC from 1964 to 2004. Fayetteville is located approximately 50 km from the reference bays. Once the models were calibrated, the 40 yr weather record was read into the models to generate long-term water balances and water table data for each well location in the various plant communities in the reference bays. The water table data simulated for each plant community were reduced by

calculating parameters that quantified the relative wetness of the site (i.e. the amount of time water was ponded on the surface), the relative dryness of the site (the amount of time the water table was below the effective root zone), and the amount of time the water table was below the organic soil horizons in mineral soil materials.

RESULTS AND DISCUSSION

Historical Weather Data

The rainfall data from Fayetteville, NC, that were used in the 40 yr model simulations revealed normal rainfall in the range from 106.7 to 123.9 cm. Normal rainfall is typically defined as the arithmetic mean rainfall computed over three consecutive decades (WMO, 1989). Unfortunately, by this definition, no time period would ever have "normal" rainfall. It would always be either higher or lower than normal. For this study, it was desired to determine a range of rainfall rather than a single value to determine whether a given time period exhibited normal rainfall. As a result, the implied definition of normal rainfall outlined in the Hydric Soil Technical Standard was implemented (USDA, 2005). The lower limit of normal rainfall in this case is defined such that there is a 30% chance that there will be rainfall *less* than this amount during a given time period, based on recorded historical precipitation. Similarly, the upper limit of normal rainfall is defined such that there is a 30% chance that there will be rainfall *greater* than this amount. The historical rainfall data for Fayetteville, NC indicate that periods of below normal rainfall occurred on an approximate five year recurrence interval starting in 1970 (Fig. 5.7). In addition, approximately every 10 yr, there was either a year of extremely low rainfall or two consecutive years of moderately low rainfall. These dry periods may serve to facilitate wildfires on approximately the same

interval, similar to the historical 10 to 30 yr interval noted in pocosin wetlands by McDonald, et al. (1983). The average air temperature over the 40 yr period was 16.1^{o} C.

Soil Data

Soil bulk density and saturated hydraulic conductivity (K_{sat}) values for all modeled well locations in the reference bays are shown in Table 5.1. The bulk densities of the organic soil horizons are very low and are fairly uniform across the three bays for the same soil type. The bulk densities for the fibric (Oi), hemic (Oe), and sapric (Oa) organic soil layers combined over the three reference bays are 0.15 g cm^{-3}, 0.16 g cm^{-3}, and 0.17 g cm^{-3}, respectively. The conductivity values estimated for the soil horizons in this study are relatively high, likely due to the high total porosity, abundance of larger pores, and low bulk density exhibited by these soils. The mucky mineral and mineral soil horizons exhibit higher bulk densities than the organic horizons due to higher mineral soil material composition.

Average soil water characteristic curves for the various types of soil horizons reveal the existence of an abundance of large pores in the surface organic horizons as evidenced by the high water content at zero tension (Fig. 5.8). Plant available water for organic soil horizons in the natural Carolina Bay soils were 41% and 42% by volume for the Oe, and Oa horizons, respectively. No data were collected for the Oi horizons due difficulty in measuring water content at 1.5 MPa with the fibrous soil samples. Plant available water for the mucky mineral and mineral soil horizons were 41% and 19% by volume, respectively. This high level of plant available water helped to insure that sufficient water was available in the soil to meet PET demands throughout the 40 yr model simulations.

Groundwater Inflow

Near well no. 2 in Charlie Long Millpond Bay, a 55 cm thick, dense clay layer was found underlying 170 cm of organic and sandy mineral soil materials (Fig. 5.9). Below this clay layer, another sandy layer was found. The hydraulic head measured with a piezometer in this confined sandy aquifer was higher than that in the unconfined aquifer system above, providing potential for vertical water flux into the bay. In fact, the water level in the piezometer was consistently above the soil surface in the bay, making this an artesian aquifer. The clay layer underlain by a sandy, confined artesian aquifer appeared to be continuous along the transect cut through the bay. The location of the source area for this confined artesian aquifer is not known, but ground surface elevations along the bay transect indicate that the source area could be within the bay itself. The change in pressure head in the aquifer correlates well with rainfall recorded at the bay ($R^2 = 0.87$), so it must not be at too great a distance.

Inspection of hourly water table depths from the four well locations in Charlie Long Millpond Bay revealed that groundwater is entering the bay. Distinct diurnal water table fluctuations were observed at three outermost wells in the bay such that the water table was drawn down during the day when ET demands are highest, rising again at night due to an influx of groundwater (Fig. 5.10). This groundwater inflow is presumed to originate from the confined aquifer below the bay found near well no. 2, traveling vertically through the clay layer into the unconfined surficial aquifer, but it could also enter the bay laterally from adjacent uplands either inside or outside of the bay perimeter. No such confined aquifer system was discovered at Causeway Bay and Tatum Millpond Bay, but similar diurnal water table fluctuations were noted at the wells nearest the perimeters of those bays as well.

It was found that groundwater inflow was required to calibrate the DRAINMOD models for the well locations exhibiting these diurnal water table fluctuations, and that the inflow could be simulated as deep seepage through a restrictive layer below the bays. The magnitude and direction of water flux through the restrictive layer is dependent on the hydraulic heads above and below the clay layer. The pressure head in the confined aquifer below Charlie Long Millpond Bay was quite variable, but it was successfully simulated with an empirical model based on rainfall and ET over the calibration period. Using this model, the daily pressure head in the confined aquifer was simulated over the 40 yr period, and used as input for the DRAINMOD models for the long term simulations.

The influx of groundwater was noted near the perimeter of the three reference bays, which in all cases corresponds to the PPW plant communities. This supports Otte's (1982) theory that there may be nutrient rich groundwater inflow to this plant community that helps support the relatively high above ground plant biomass in this community. The source area for this groundwater inflow could be situated on an elevated organic dome within the bay that is slightly higher in elevation than the PPW. If this area is dominated by the HP plant community, these findings support the notion that HP generally exhibits groundwater outflow. The diurnal water table fluctuations were not evident in the NRSF found in Tatum Millpond Bay, providing evidence that the source of the additional soil phosphorus found in this plant community may not be a result of nutrient enriched groundwater inflow entering the area as is generally thought to be the case (Otte, 1982; Daniel, 1981).

Model Calibration

The water table depths simulated with DRAINMOD correlated very well with those measured at the reference bays during the 2003 to 2005 calibration period. Average absolute

deviations between simulated and measured water table depths ranged from 0.2 to 6.1 cm while R^2 values of simulated versus measured water table depths fell in the 0.29 to 0.86 range. Example plots of measured and simulated water table depths for Causeway Bay over the calibration period are shown in Figure 5.11.

Model Simulation Results

Plant Community Water Balances

The average annual water balance components over the 40 yr simulation for the plant communities in the reference bays are shown in Table 5.2. Evapotranspiration (ET) was by far the largest water loss component. On average, ET amounted to 43% to 64% of the total water input on an annual basis. Total water input is the sum of the rainfall and deep seepage (groundwater inflow) components.

Average annual surface runoff was similar between PPW and NRSF, slightly higher for BF, and greater still for HP. This is likely a result of the relative elevations of the different plant communities. HP and BF occur on deep organic soils, which potentially accumulate organic materials such that the soil surface is elevated relative to surrounding areas. As a result, higher surface runoff will occur in these communities. Despite the fact that surface runoff was similar between PPW and NRSF, the relatively low runoff in these communities occurred for different reasons. In the PPW, the water table rarely rose above the soil surface, so the majority of the rainfall was able to infiltrate the soil rather than running off. In the NRSF, the water table was generally above the soil surface, but a higher amount of surface storage in this community allowed excess rainfall to be stored on the surface instead of running off. Runoff from one area of a bay may provide an input in the form of surface run-on or groundwater inflow to another location down gradient in the bay.

In Charlie Long Millpond Bay and Tatum Millpond Bay, surface flow outlets exist that could carry any surface runoff out of the bay. Subtle linear features are visible in the color infrared aerial photographs of Charlie Long Millpond Bay (Fig. 4.2) moving roughly parallel to the bay perimeter along the northern and southern edges. These features could be small channels that carry surface water around the edges of the bay to the impoundment and drainage outlet in the southwestern portion of the bay.

The PPW plant community received approximately 15% of its average annual water input from groundwater inflow. Groundwater outflow exceeded inflow on an annual basis, but during dry periods groundwater inflow exceeded outflow (Fig. 5.12), helping to keep water tables generally within 30 cm of the surface even during periods of drought. The NRSF, HP, and BF plant communities did not have groundwater inflow in their water balances with one exception. Well no. 3 in the Charlie Long Millpond Bay HP plant community had approximately 33% of the total water input occurring as groundwater inflow. The HP in this bay was a relatively small community, accounting for only about 25 m of the 300 m transect (Fig. 5.5). As a result, the water table levels measured by this well may have reflected a hydrologic regime more indicative of the adjacent PPW than HP. Data for this well are excluded from all average hydrologic parameters for the HP plant community unless otherwise specified. The lack of groundwater inflow to the NRSF indicates that the source of the relatively high nutrient levels in that community, at least in this case, is not due to nutrient rich groundwater flowing through the system as proposed by Otte (1982).

Net drainage (Groundwater outflow – Groundwater inflow) for the PPW community was similar to the groundwater outflow of the NRSF. The HP and BF had lower annual drainage amounts because of the additional water lost as surface runoff in these communities.

However, the distinction between surface runoff and subsurface drainage in these communities is somewhat blurred. Runoff from pocosins occurs as sheet flow over broad stretches rather than streams or ditches (Ash et al., 1983). Sheet flow occurs just below the litter layer, following small but relatively discrete channels. The surface layer of organic soils, commonly called "root mat", is a zone of dense plant roots and partially decomposed organic material that has a very high hydraulic conductivity. As a result, the surface runoff component of the water balance may have actually been lost from the system below the soil surface. The surface runoff from the HP community may have contributed to the groundwater inflow component of adjacent PPW plant communities.

Standard errors for the NRSF and BF plant community water balance components are small compared to that of the PPW and HP communities. The NRSF and BF were only present in Tatum Millpond Bay, whereas the HP and PPW were present at all three reference bays. As a result, the standard error for HP and PPW reflects bay to bay variability as well as the variability within the plant community in one bay.

Plant Community Water Table Depths

HYDROGRAPH STATISTICS

The average, maximum, and standard deviation of the daily water table depths over the 40 yr simulation are shown in Table 5.3. Like the water balance components, the average water table depth at well no. 3 in Charlie Long Millpond Bay appears to be an outlier for the HP community and is thus excluded from average parameters calculated for that community (Fig. 5.13). The NRSF, HP, and BF plant communities had water tables above the surface, on average, over the 40 yr simulation with the HP community ponded to a slightly shallower

depth than the other two communities. Meanwhile, the 40 yr average water table depth for the PPW plant community was 15 cm below the soil surface.

For this study, ponding does not indicate that the entire area is completely flooded with water. At the reference bays, the ground surface can vary in elevation by 15 cm or more on a local scale due to the large amount of microtopography at these sites in the form of natural hummocks and swales. The magnitude of this microtopography appeared to be similar among the various plant communities studied. In general, the local high elevations were occupied by trees, so the wells were installed in the local low elevations due to the difficulty in installing the wells in those areas of very dense tree roots. As a result, the wells recorded water table depths in the areas of locally lower elevation, which could exhibit ponded water while the locally higher elevations did not (Fig. 5.14).

The maximum water table depths occurred during an exceptionally dry period in 1993. During this time, the water table reached a maximum depth of 103 cm in the PPW plant community. For the NRSF, HP, and BF communities, the maximum water table depth was 55, 43, and 50 cm below the surface, respectively. The PPW community exhibited deeper water table depths during this time than the other communities because of the thinner organic soil layers found in this community. In general, the organic soil layers had a higher drainable porosity than mineral soil layers, so the removal of an equal amount of water in these two soil layers would lower the water table to a greater extent in the mineral layer than in the organic.

The standard deviation of the daily water table depths indicate that the PPW plant community has the most variable hydrograph of all of the plant communities, again a result of the lower drainable porosity of the mineral soils in which it is found as compared to the

organic soils associated with the other plant communities. The NRSF and BF communities have similar and intermediately variable hydrographs, and the HP has the least variable hydrograph of all of the communities studied. Although the HP may have a slightly lower average water table depth than the NRSF and BF communities, the daily fluctuation in water table depth is lower, which minimized the maximum water table depth that occurred in 1993.

WATER TABLE DEPTH DISTRIBUTION

The percentage of the total days during the 40 yr simulation for which the water table was at various depths in each plant community is shown in Figure 5.15. Data shown are averaged across the three reference bays for the same plant community. The distribution of water table depths for the NRSF and BF plant communities were very similar; ponded 82 to 84% of the time during the 40 yr simulation, with the water table rarely extending deeper than 45 cm, the effective rooting depth of the vegetation. The HP community was similar to the NRSF and BF communities, but was ponded slightly less often. The PPW plant community was ponded only 24% of the time, had water table depths between 0 and 30 cm below the surface 60% of the time, and 8% of the time the water table was deeper than 45 cm.

PONDING

When a ponding event occurred, the average ponding depth during that event over the 40 yr simulation was similar between the NRSF and BF at 9.5 and 8.3 cm, respectively, slightly less (6.5 cm) for the HP, and 0.8 cm for the PPW (Table 5.4). This is likely a reflection of the amount of surface storage available at each site. The PPW plant communities generally occurred near the perimeters of the reference bays at a relatively high elevation, so there was less storage available to create ponding conditions. The NRSF

community occurred at a relatively low position on the landscape, so there was more storage capacity available. It is generally believed that the HP plant community occurs at relatively high elevations, which facilitates groundwater movement out of rather than in to these communities. However, in the case of the HP communities in the reference bays, there was still sufficient surface storage capacity available to hold an average of 6.5 cm of water on the surface during ponding events. This is likely a result of the highly variable micro-topography at these bays in the form of hummocks and swales caused by the vegetation, which could easily hold water on the surface to these depths.

The average total number of days per year for which water was ponded was similar among the NRSF, HP, and BF plant communities, averaging approximately 307, 291, and 299 d y^{-1}, respectively (Table 5.4). The PPW plant community was ponded for significantly less time, averaging 89 d y^{-1}. The longest consecutive ponding events typically occurred during the winter months when ET demands were lowest, across the break between consecutive years. The average maximum consecutive days of a ponding event over the 40 yr period was found to be similar among the NRSF, HP, and BF communities, at 124, 111, and 104 d, respectively. Meanwhile, the average maximum consecutive days of a ponding event was found to be about 15 d for the PPW plant community. The longest consecutive period of ponding occurred between 1987 and 1990, which was a period of significantly higher than normal rainfall. This ponding event lasted 913, 760, and 907 d for the NRSF, HP, and BF communities, but only 92 d for PPW.

The frequency (i.e. the number of years out of 40) for which water was ponded for various total days per year are shown in Figure 5.16. In 19 of 40 yr, water was ponded for less than 20 total d y^{-1} in the PPW plant community, and for about 10 of these years, water

was never ponded on the surface. The NRSF, HP, and BF communities were ponded 341-365 d y^{-1} 14, 10, and 13 yr out of 40, respectively. In fact, all three of these communities never had a year for which water is not ponded for at least 140 total days.

The percentage of ponding events that lasted for a specific range of consecutive days was determined (Fig. 5.17). For the PPW community, the majority of the ponding events lasted less than 10 consecutive days. In the NRSF and BF communities, almost 50% of the ponding events were also less than 10 consecutive days. For NRSF, HP, and BF communities, approximate 65% of the ponding events were less than 70 d in duration. However, approximately 15% of the ponding events lasted for 200 to 300 consecutive days among these communities.

WATER TABLE BELOW THE EFFECTIVE ROOTING ZONE

In addition to ponding events, dry periods were also evaluated and compared among the four plant communities found in the reference bays. The effective rooting depth of the vegetation in all of the plant communities was assumed to be 45 cm, based on observation at the bays. The PPW community exhibited water table depths deeper than 45 cm approximately 8% of the total days during the 40 yr simulation, while the NRSF, HP, and BF communities had water tables this deep less than 1% of the total days (Fig. 5.15).

On average, the PPW community had water tables deeper than 45 cm approximately 29 total days per year, 13 of which were consecutive (Table 5.5). The NRSF community exhibited deep water tables about one day per year on average, but in reality this only occurred in 2 out of the 40 yr simulated. The HP and BF communities exhibited water tables below the root zone less than one day per year on average. The longest duration of these deep water tables occurred during a dry period in 1993. In 1992 and 1993, there was a

rainfall deficit of 18.3 cm of water below the lower limit of normal rainfall (Fig. 5.7). This caused a total of 108 d of water tables below the root zone in the PPW community that year, 96 of which were consecutive days. The NRSF, HP, and BF communities exhibited 38, 16, and 32 total days, respectively, 37, 13, and 28 of which were consecutive. It appears that the HP community does not dry down to the same extent as the NRSF and BF communities, a reflection of the lower standard deviation of the daily water table depth associated with this community.

The maximum consecutive days per year for which the water table was deeper than 45 cm in each plant community are shown in Figure 5.18. The only year for which the water table depth exceeded 45 cm for the HP community was in 1993. For the remainder of the years, the water table was within 45 cm of the surface. The NRSF and BF communities exhibited water table depths below 45 cm in 2 of the 40 yr, 1986 and 1993. For the PPW plant community, the water table was deeper than 45 cm for at least 10 consecutive days in 13 out of 40 yr, and at least 20 consecutive days in 9 out of 40 yr. On three occasions, the water table was deep for at least 20 consecutive days in two consecutive years. These dry periods occurred roughly every 4 to 6 yr, corresponding to periods of below normal rainfall (Fig. 5.7).

WATER TABLE IN MINERAL SOIL

One of the explanations in the literature for the establishment of some plant communities is the ability of the vegetation to extend roots down into mineral soil horizons during drier periods, thereby accessing potentially higher nutrient reserves in these soil materials (Otte, 1982; Schafale and Weakley, 1990). For this study, the interactions of the water table with the mucky mineral horizons, if present, or mineral soil horizons were

considered. The PPW community had water tables in mineral soil 20% of the total time, the NRSF and HP communities about 1% of the total time, and the BF never exhibited water tables in mineral soil horizons. The PPW community had water tables in mineral soil more of the time that the other communities due to the deeper water table depths found there and the presence of thinner organic soil horizons. The BF community only occurred on deep organic soils (greater than 170 cm), but the maximum water table depth observed in this community was only 50 cm, so the water table never reached mineral soil. The depth of organic soil material was quite variable in the NRSF and HP (Fig. 5.5), causing some well locations in these communities to occasionally exhibit water table depths in mineral soil while the water tables at other well locations never reached these depths.

On average, the PPW community had 73 total days per year during which the water table was in the mineral soil horizons, and on average, there were 37 consecutive days per year with the water table at these depths (Table 5.6). Meanwhile, the NRSF and HP communities averaged about 3 d y^{-1} with the water table in mineral soil, though only about 5 out of the 40 yr simulated exhibited these water table depths. The maximum consecutive days having water table depths in mineral soil occurred during the dry period of 1993, where the PPW had water tables at these depths for 131 consecutive days, and the NRSF and HP communities for 54 and 47 consecutive days, respectively.

The maximum number of consecutive days for which the water table was in mineral soil for each year of the simulation is shown in Figure 5.19. The water table was in mineral soil for at least 60 consecutive days in 9 of the 40 yr in the PPW community. The occurrence of these periods where the vegetation can reach mineral soil was fairly evenly dispersed throughout the 40 year simulation, never going for more than 10 yr without an occurrence.

On the other hand, the NRSF community exhibited water tables in the mineral soil horizons only in 5 of the 40 yr. On average, these occurrences lasted for 19 consecutive days. Similar to the NRSF community, the HP community had water tables in the mineral soil horizons in 6 of the 40 yr, averaging 19 consecutive days. Again, the BF community never exhibited water tables in mineral soil.

Summary

Comparing the hydrology of the Carolina Bay plant communities

The results of this study suggest that the PPW plant community has a significantly different hydrologic regime than the other plant communities studied. The PPW community exhibits groundwater inflow coming from an upland source amounting to approximately 15% of the total water input. The other communities did not exhibit any evidence of groundwater inflow. Water table depths were 15 cm below the surface on average in the PPW community, whereas water was ponded above the surface in the other communities. Ponding conditions existed for only 24% of the 40 yr simulation in the PPW community, whereas the other communities were ponded about 82% of the time. When there was a ponding event, it lasted about 15 consecutive days, on average, in the PPW community and about 110 consecutive days in the other communities. The water table reached mineral soil horizons in the PPW community for at least 30 consecutive days in one out of two years causing plant roots to seek water in these potentially more fertile soil materials, which may be a contributing factor to the location where this community becomes established. The water table reached mineral soil layers at least 10 consecutive days in only one out of ten years for the NRSF and HP communities, and it never reached mineral soil layers in the BF community.

There is very little difference in the hydrologic regime of NRSF, HP and BF communities to explain their spatial establishment within these Carolina Bays. Virtually all aspects of their hydrology are identical. There is some evidence to suggest that the hydrology of the HP community is slightly different from NRSF and BF, but it is difficult to tell based on the sample sizes considered in this investigation. Water table depths in the HP community may be slightly less variable and more moderate than NRSF and BF communities; water may be ponded to a slightly shallower depth for a slightly shorter duration during wet periods, and water tables may remain relatively shallow during dry periods, but when they do recede, they remain at these depths for shorter durations. Further study of these communities that would broaden the sample sizes may determine whether there are hydrologic differences that could explain the establishment of these communities.

The establishment of the NRSF community relative to the HP and BF communities may be a result of available phosphorus in the soil. The soils of the NRSF community exhibited much higher available phosphorus levels than all of the other communities, which may explain why tree species such as *Nyssa biflora* and *Taxodium ascendens* have become established there. The source of this additional phosphorus in the case of the reference bays is not known. There does not appear to be any groundwater inflow to the NRSF community that could transport dissolved minerals to the area. Perhaps sediments deposited prior to the establishment of the NRSF community were rich in phosphorus, enabling the swamp forest trees species to become established. Further study would be required to determine the source of the relatively high levels of soil phosphorus in the NRSF community.

The establishment of HP versus BF may be a result of some past disturbance in the HP community. The HP plant communities in the reference bays had fewer and smaller trees

than the BF communities. There was no statistical difference in available soil phosphorus between HP and BF found in the reference bays (Lees, 2004) to explain these differences in canopy characteristics. The density and stature of the HP canopy may have been caused by a wildfire or by logging practices that took place some time in the past. Over time, the HP community may recover from the disturbance, returning to its original plant community type. However, if the disturbance occurs on a regular basis as in the case of natural wildfire, this community will likely maintain characteristics typical of the HP plant community.

Implications for wetland restoration

While the results of this study are based on model simulations rather than measured field data, and they were collected in a limited number of Carolina Bays, they can provide a foundation for quantifying the environmental conditions associated with the four plant communities studied so that these conditions can be approximated by wetland restoration engineers. In reviewing the various parameters quantifying the hydrologic regime of these plant communities, the differences in the depth, frequency, and duration of ponding events appeared to be most significant. Particularly, the average duration of a ponding event; 15 consecutive days for the PPW community and 110 consecutive days for the NRSF, HP, and BF communities was considered significantly different.

Using these data, design criteria for restoration of these four plant communities was proposed (Table 5.7). The three major factors of PPW, NRSF, and BF plant community establishment considered in this proposal were hydrology, quantified by the average consecutive days of a ponding event, depth of organic soil layers, and soil fertility. The HP plant community was not considered in this proposal because it is believed that this

community is a result of some past disturbance. Thus the HP is a community in transition, recovering from the disturbance and regenerating toward another plant community type.

The design criteria shown in Table 5.7 could be used as follows. Wetland designers could record rainfall and water table depths at various locations on a wetland restoration site over at least a 1 yr period prior to the restoration of hydrology. Next, these data would be used to calibrate DRAINMOD models of each well location at the site. Once the models were calibrated, a 40 yr record of weather data could be used as input for the models, simulating the water table depths of the various well locations on the site *after* the hydrology has been restored by filling ditches, etc. The resulting water table data could then be reduced by calculating the average duration of ponding events over the 40 yr simulation. Each modeled well location could then be evaluated for vegetation establishment based on the predicted hydrologic regime, depth of organic soil layers, and soil fertility.

If it is predicted that a particular site will be ponded for 110 consecutive days on average, the organic soil layers are greater than about 50 cm, and there are high levels of available soil phosphorus, the NRSF plant community would be the suggested community for establishment at that location. The high phosphorus in this case could be a result of soil amendments such as fertilizers added to the soil during past agricultural land use. If the site has the same hydrologic regime and depth of organic soil layers, but much lower levels of available soil phosphorous, the BF community would be the suggested community for establishment at that site. It is unclear as to exactly what level of available soil phosphorus means the difference between the NRSF community and the BF community. Further research is needed to determine the critical level of soil phosphorus for plant community establishment.

On the other hand, if the predicted hydrology of the site only allows about 15 consecutive days per ponding event, on average, the organic soil layers are less than about 50 cm, and there is a low level of available soil phosphorus, the PPW community would be suggested for establishment at that site. The results of this study do not evaluate the case where similar hydrology and organic layer depth exist, but there are higher levels of soil phosphorus. The recommended plant community would likely still be the PPW community or other natural successional vegetation. In these cases where there are high levels of soil phosphorus, it would probably be necessary to control weeds and other competitive species that this higher soil nutrient status may favor such that the planted wetland vegetation may become established.

The importance of the depth of organic soil material will depend on the desired or given hydrologic regime associated with the restoration site of interest. If the hydrologic regime is predicted to have an average of 110 consecutive days per ponding event, it likely will not matter whether the organic soil layers extend more or less than 50 cm below the ground surface. A hydrologic regime with such shallow water tables and frequent ponding would be conducive to the accumulation of organic matter, thus the thickness of the organic layer will increase over time until an equilibrium between the production and decomposition of organic matter is reached. However, if the restoration site in question has a thick layer of organic soil (greater than 50 cm), and the predicted hydrologic regime will have an average of only about 15 consecutive days of ponding per ponding event, loss of organic matter near the surface as a result of oxidation and compaction will serve to lower the elevation of the ground surface over time, and eventually the water table will be much closer to the surface

than originally intended. This could lead to a shift in hydrologic regime from one best suited for the PPW community to one more reminiscent of the NRSF or BF communities.

Implicit in the frequency and duration of ponding events associated with these plant communities is the ability of these sites to store water on the surface. It is apparent that the rough surface microtopography is an important component of the structure of these wetland systems. Observation of these natural plant communities revealed that tree species were generally established on local topographic high elevations, while the local low elevations were frequently filled with standing water. Any restoration of these plant communities should include measures to simulate the natural surface undulations observed at the reference bays. Further, vegetation should be planted on the local high elevations for improved likelihood of survival. The hydrologic regime associated with the proposed design criteria represents that of the established plant community. It is likely that these sites should be somewhat "drier" for a period of time when establishing the new vegetation, both in terms of ponding duration and frequency and average water table depth.

CONCLUSIONS

The hydrologic regime of the PPW plant community differs significantly from that of the NRSF, HP, and BF communities in the reference bays. This community exhibited a significant influx of groundwater while the others did not, though the net groundwater flux was similar to the other communities. It is unclear as to whether this groundwater inflow is critical for PPW community establishment. Further study of the nutrient status of the groundwater in this community compared to that of the other communities could indicate that the groundwater inflow in the PPW community provides additional fertility not available to the other communities.

Water tables were deeper and more variable in the PPW community than the others, ponding less frequently and to shallower depths. This in combination with the thinner organic soil horizons associated with this community allowed the water table to drop into mineral soil horizons frequently and for extended periods of time, enabling the vegetation to extend roots down into these potentially more fertile soils. It is not known whether the ability of plant roots to reach mineral soil layers is important for plant community establishment. In other studies, the BF community has been shown to exhibit higher levels of available soil phosphorus than the HP community (Walbridge, 1991). However, in this study, it was found that the water table occasionally reached mineral soil layers in the HP community, but never in the BF community. Further study would be required to determine whether there differences in available soil phosphorus in the mineral soil layers relative to the overlying organic soil layers.

The hydrologic regime of the NRSF, HP and BF communities were very similar and may in fact be the same. Water tables were above the surface on average, rarely going deeper than the effective rooting depth of the vegetation (45 cm). There is some evidence that suggests that the HP community has slightly lower water tables on average that are slightly less variable than the NRSF and BF communities. Further study of these communities would be necessary to discern any differences. Some locations in the NRSF and HP communities exhibited water tables that dropped into mineral soil horizons on a few occasions, which may allow vegetation in these communities to reach these soil materials of higher nutrient status. The NRSF community exhibited higher levels of soil phosphorus than any of the other communities, which is likely the determining factor of their location within the bays. The source of the additional phosphorus does not appear to be from groundwater

inflow, so it is probably a result of the deposition of sediment with high levels of phosphorus during the formation of the bays.

The relationship between the HP and BF communities may be one of past disturbance. Both communities have similar species composition in the canopy, but the HP community has fewer and smaller trees than the BF community. There is no difference in soil fertility to explain these differences in canopy characteristics. It is possible that a past disturbance such as wildfire or logging destroyed the original canopy in the present day HP community, which is now slowly regenerating. This regenerating canopy may have the appearance of HP with few, scattered, and low stature trees. However, this canopy may one day resume the appearance of a BF community. However, if the disturbance occurs on a regular basis as in the case of natural wildfire, this community will likely maintain characteristics typical of the HP plant community.

Data presented in this study provide a foundation for quantifying the hydrologic needs of the four plant communities studied. Using the proposed design criteria for restoration of wetland plant communities, wetland restoration engineers can either design the required hydrology of a desired plant community into a restoration site, or they can estimate the hydrologic regime of various locations of a site and then determine which plant community to establish in which location. This will likely require that hydrologic models be created to simulate the hydrology of the site, adding to the time and cost involved in a wetland restoration. However, over the long term, the successful establishment of vegetation at the site may outweigh this initial cost.

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Table 5.1. Soil property data for the various soil horizons encountered at the reference bays. Data shown are averaged across similar horizons at all three reference bays. S = sand, SL = sandy loam, LS = loamy sand.

Soil Horizon	Soil Material	Bulk Density			Saturated Hydraulic Conductivity		
		Number of samples	Mean	Standard error	Number of samples	Mean	Standard error
			---g cm^{-3}---			---cm hr^{-1}---	
Oi	Fibric Organic (Peat)	6	0.15	0.04	2	46	4.8
Oe	Hemic Organic (Mucky Peat)	18	0.16	0.03	9	13	5.9
Oa	Sapric Organic (Muck)	25	0.17	0.02	4	3.3	2.1
Mucky Mineral	Mucky Modified S, SL, LS	42	0.64	0.05	9	7.0	2.1
Mineral	S, SL, LS	31	1.40	0.04	7	6.4	1.1

Table 5.2. Simulated long term average annual water balance components for the plant communities in the reference bays. Average annual rainfall and ET for all plant communities were 118 and 75.8 cm, respectively.

Plant Community	Number of Samples	Surface Runoff		Groundwater Outflow		Groundwater Inflow	
		Average	Std. Error	Average	Std. Error	Average	Std. Error
		---cm---		---cm---		---cm---	
Pond Pine Woodland	6	19.7	5.50	43.3	10.6	20.88	7.47
Nonriverine Swamp Forest	3	19.6	0.74	22.3	0.76	0.00	0.00
High Pocosin*	3	30.3	5.39	11.6	5.36	0.00	0.00
Bay Forest	2	21.6	0.46	20.27	0.49	0.00	0.00

* Charlie Long Millpond Bay well no. 3 not included in average water table depth parameters for the high pocosin plant community.

Table 5.3. Hydrograph statistics for the various plant communities found in the reference bays.

Plant Community	Number of Samples	Average water table depth		Maximum water table depth		Standard Deviation of the daily water table depth	
		Average	Standard error	Average	Standard error	Average	Standard error
		---cm---		---cm---		---cm---	
Pond Pine Woodland	6	-15.1	3.17	-103	11.5	17.7	1.60
Nonriverine Swamp Forest	3	5.22	1.05	-54.8	4.28	11.3	0.65
High Pocosin*	3	2.32	2.35	-42.9	5.21	9.60	0.07
Bay Forest	2	3.16	1.29	-50.16	4.53	12.3	0.26

* Charlie Long Millpond Bay well no. 3 not included in average water table depth parameters for the high pocosin plant community.

Table 5.4. Ponding parameters in the various plant communities found in the reference bays.

Plant Community	Number of Samples	Average ponding depth		Average total days ponded per year		Average consecutive days ponded		Maximum consecutive days ponded	
		Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error
		---cm---		---d y^{-1}---		---d---		---d---	
Pond Pine Woodland	6	0.8	0.5	89.0	45.4	14.6	8.72	91.7	53.4
Nonriverine Swamp Forest	3	9.5	0.6	307	6.4	124	18.8	913	2.33
High Pocosin*	3	6.5	1.9	291	12.1	111	20.61	760.0	77.7
Bay Forest	2	8.3	0.8	299	9.1	104	6.40	907	5.00

* Charlie Long Millpond Bay well no. 3 not included in average water table depth parameters for the high pocosin plant community.

Table 5.5. Parameters for water tables below the effective root zone in the various plant communities found in the reference bays.

Plant Community	Number of Samples	Average total days per year with water table depth > 45 cm		Maximum total days per year with water table depth > 45 cm		Average consecutive days per year with water table depth > 45 cm		Maximum consecutive days per year with water table depth > 45 cm	
		Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error
		---d y^{-1}---		---d y^{-1}---		---d y^{-1}---		---d y^{-1}---	
Pond Pine Woodland	6	29.3	5.6	108	22.6	13.0	3.7	96.3	29.5
Nonriverine Swamp Forest	3	1.2	0.6	38.3	16.8	1.1	0.5	36.7	17.1
High Pocosin*	3	0.4	0.3	16.3	13.9	0.3	0.3	12.7	10.3
Bay Forest	2	0.9	0.8	32.0	30.0	0.7	0.7	28.0	26.0

* Charlie Long Millpond Bay well no. 3 not included in average water table depth parameters for the high pocosin plant community.

Table 5.6. Parameters for water tables in mineral soil horizons for the various plant communities found in the reference bays.

Plant Community	Number of Samples	Average total days per year with water table in mineral soil		Maximum total days per year with water table in mineral soil		Average consecutive days per year with water table in mineral soil		Maximum consecutive days per year with water table in mineral soil	
		Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error
		---d y^{-1}---		---d y^{-1}---		---d y^{-1}---		---d y^{-1}---	
Pond Pine Woodland	6	73.2	17.7	168	29.2	36.7	11.6	131	39.9
Nonriverine Swamp Forest	3	2.6	1.3	54.0	27.0	2.4	1.2	53.7	26.8
High Pocosin*	3	3.2	0.6	46.7	22.7	3.0	3.0	46.7	46.7
Bay Forest	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Charlie Long Millpond Bay well no. 3 not included in average water table depth parameters for the high pocosin plant community.

Table 5.7. Proposed design criteria for restoration of selected wetland plant communities.

		Hydrology and soil type	
		Pond 110 d **Organic > 50 cm**	**Pond 15 d** **Organic < 50 cm**
Soil fertility	**High phosphorus** **(Ag field)**	NRSF	
	Low phosphorus	BF	PPW

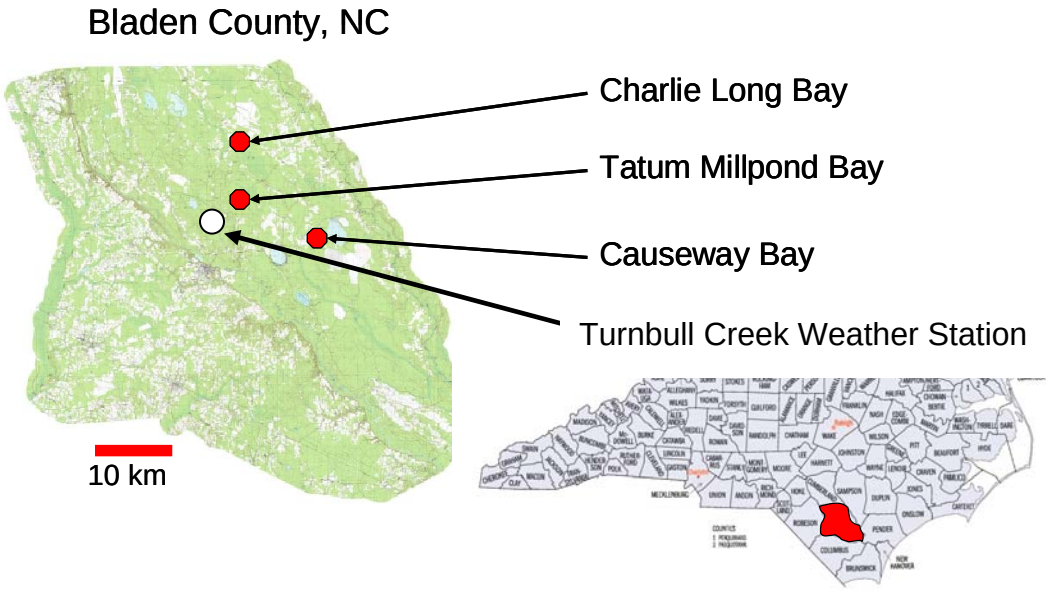

Figure 5.1. Locations of reference Carolina Bays in Bladen County, NC.

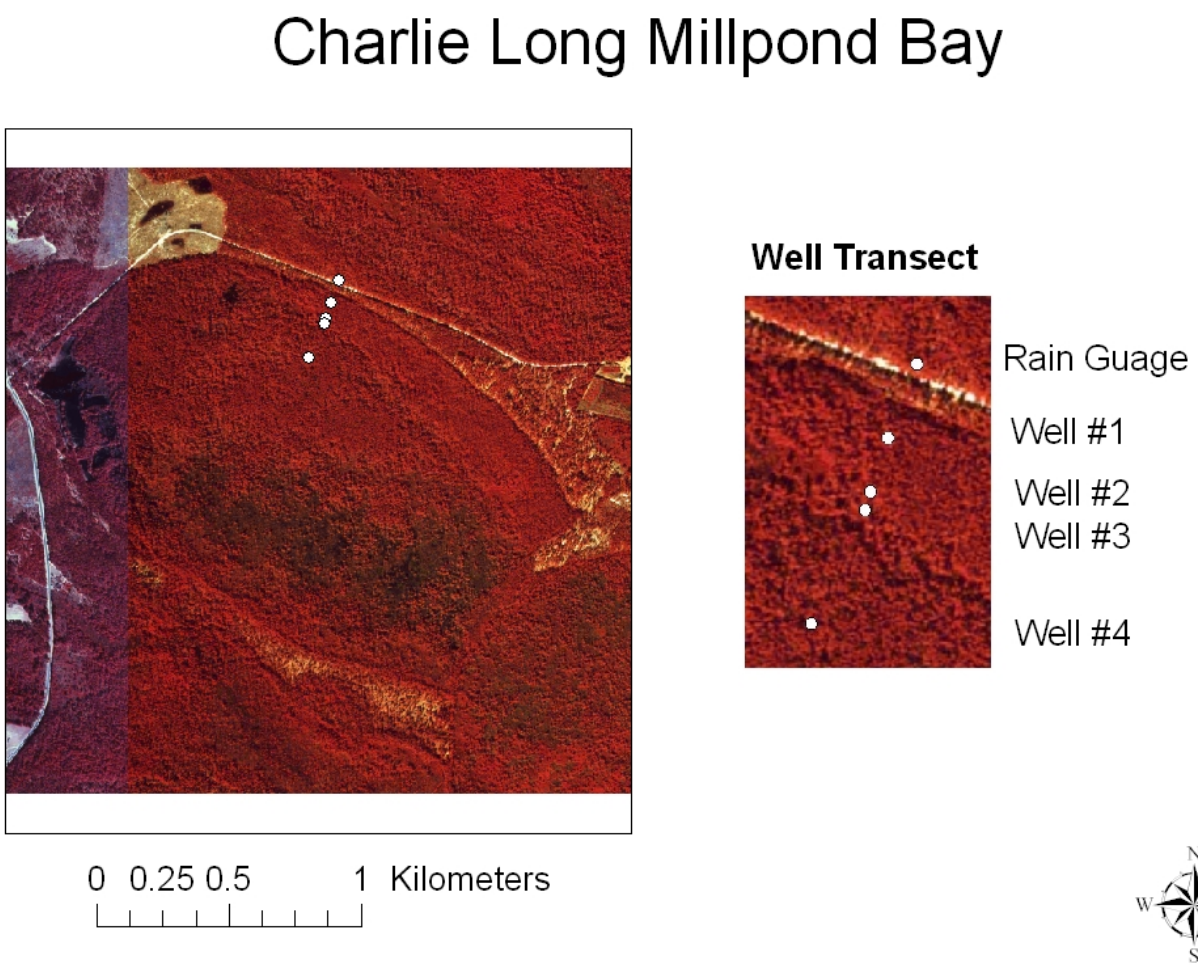

Figure 5.2. Location of transects, wells, and rain gauges in Charlie Long Millpond Bay. Locations determined by GPS.

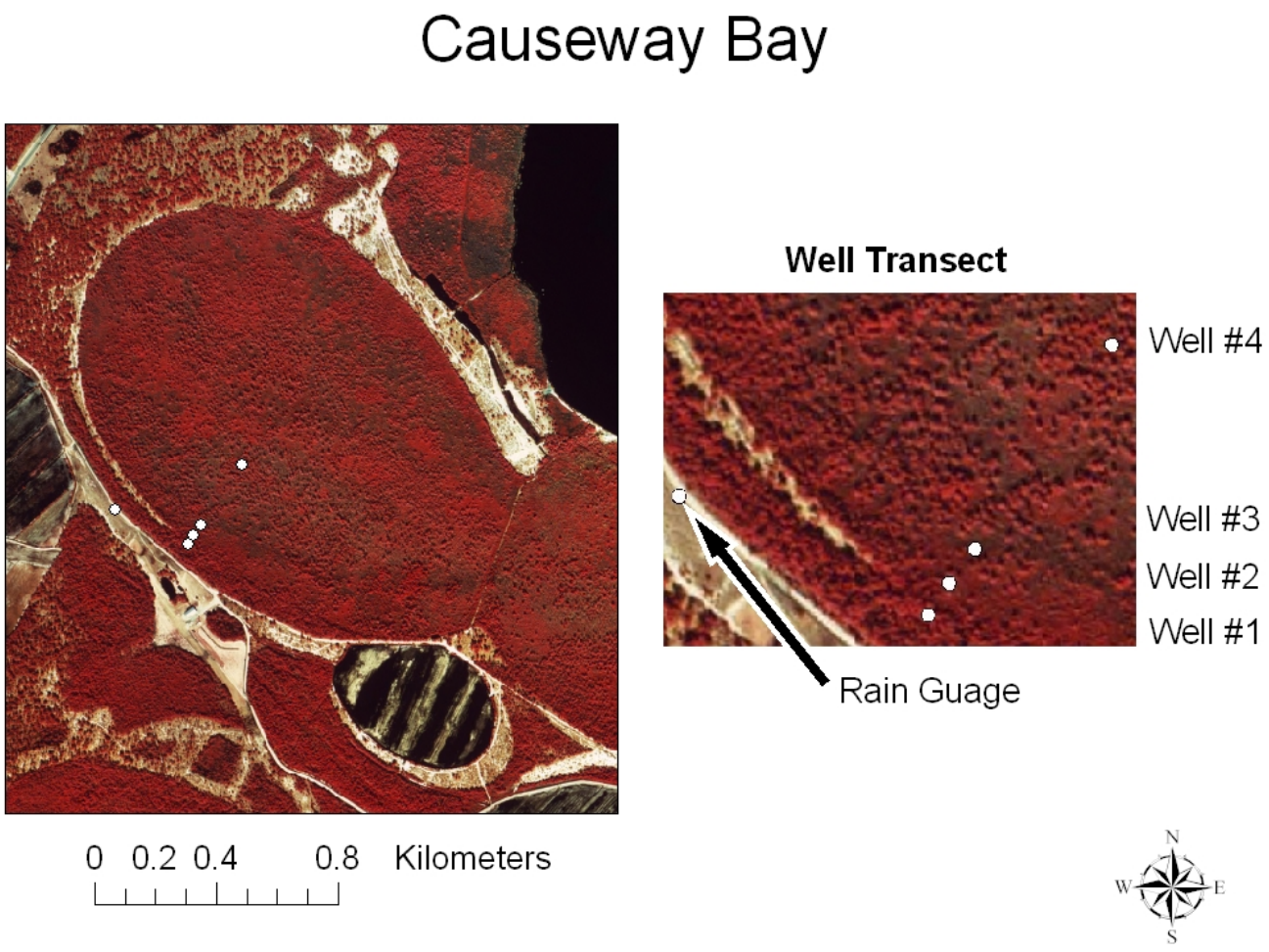

Figure 5.3. Location of transects, wells, and rain gauges in Causeway Bay.

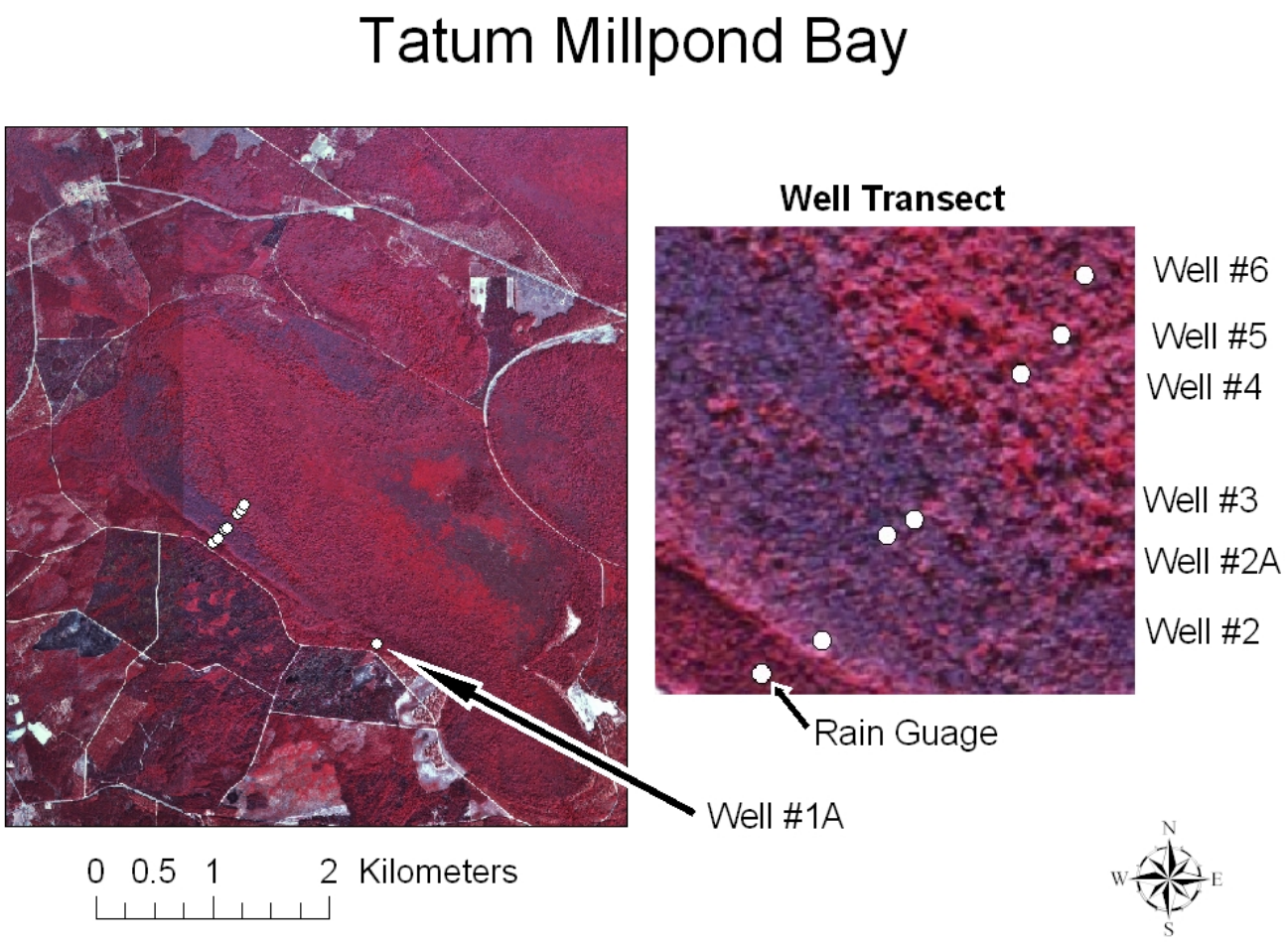

Figure 5.4. Location of transects, wells, and rain gauges in Tatum Millpond Bay

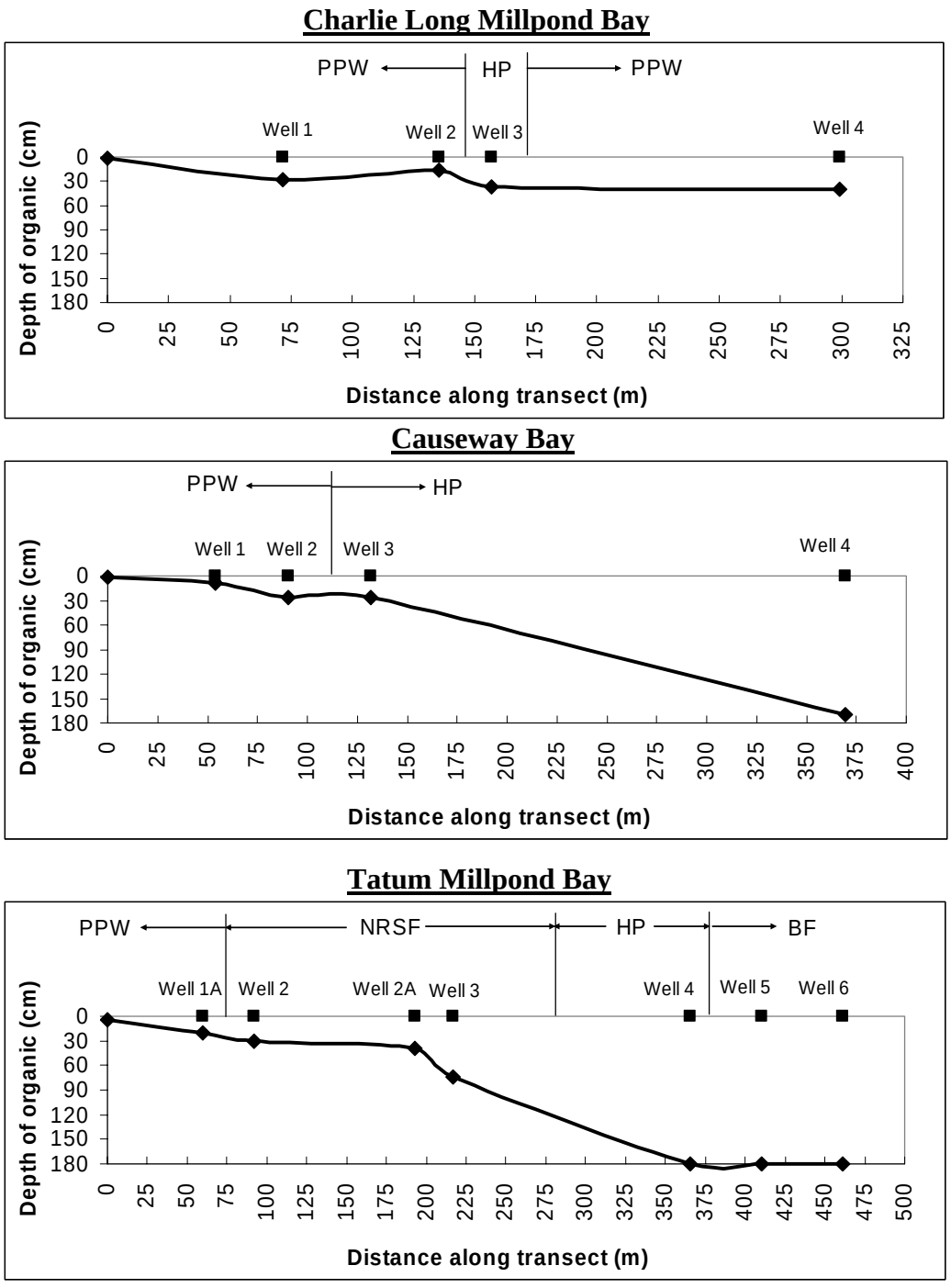

Figure 5.5. Well locations, plant community boundaries, and depths of organic soil layers in each reference bay. Relative surface elevations along the transect are not represented. Depth of organic soil was measured relative to the soil surface at that location.

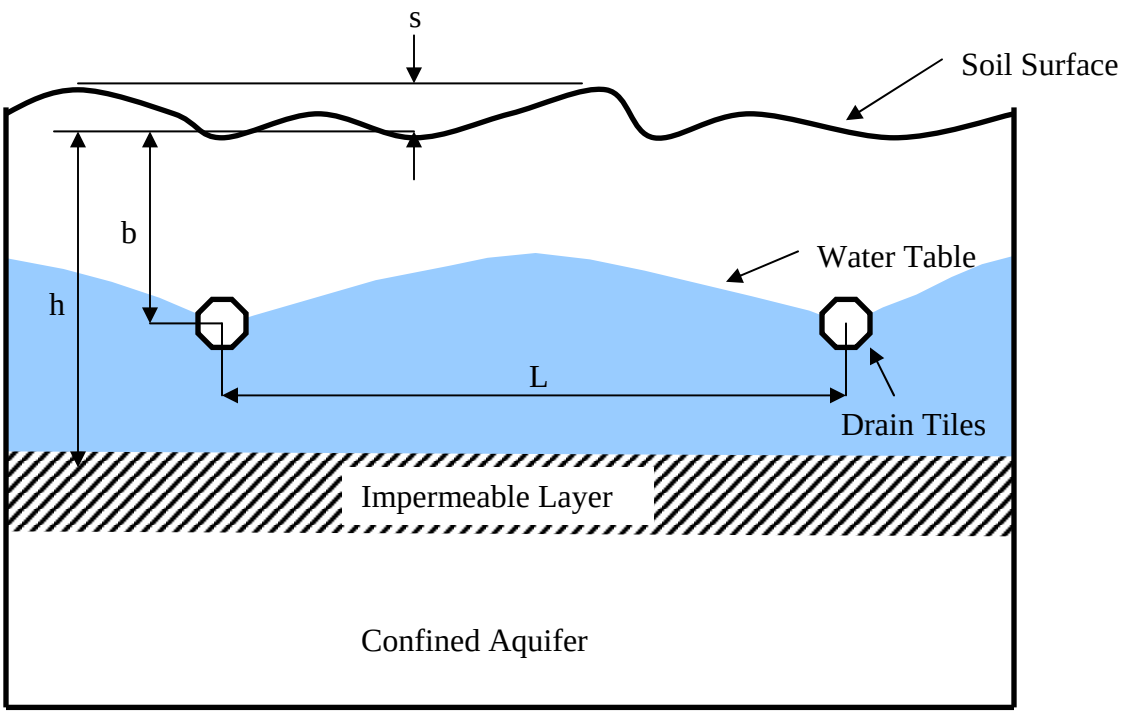

Figure 5.6. Schematic diagram of the DRAINMOD drainage system. Dimensions include the drain depth, b, drain spacing, L, depth to impermeable layer, h, and surface storage, s.

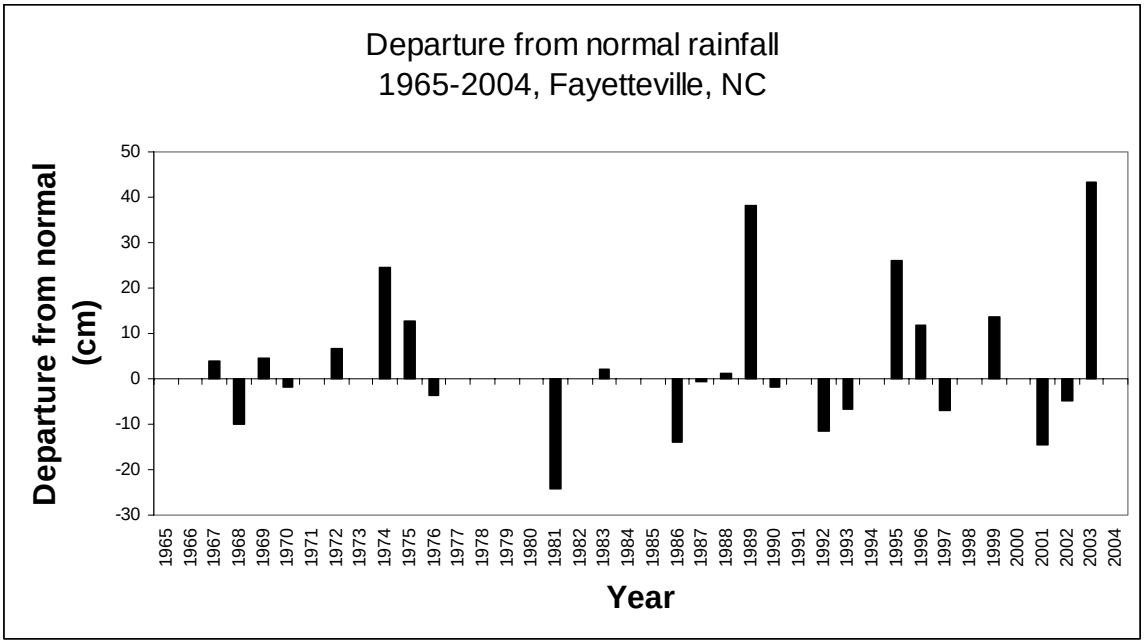

Figure 5.7. Departure from the normal range of rainfall in the long-term weather data used for model simulations.

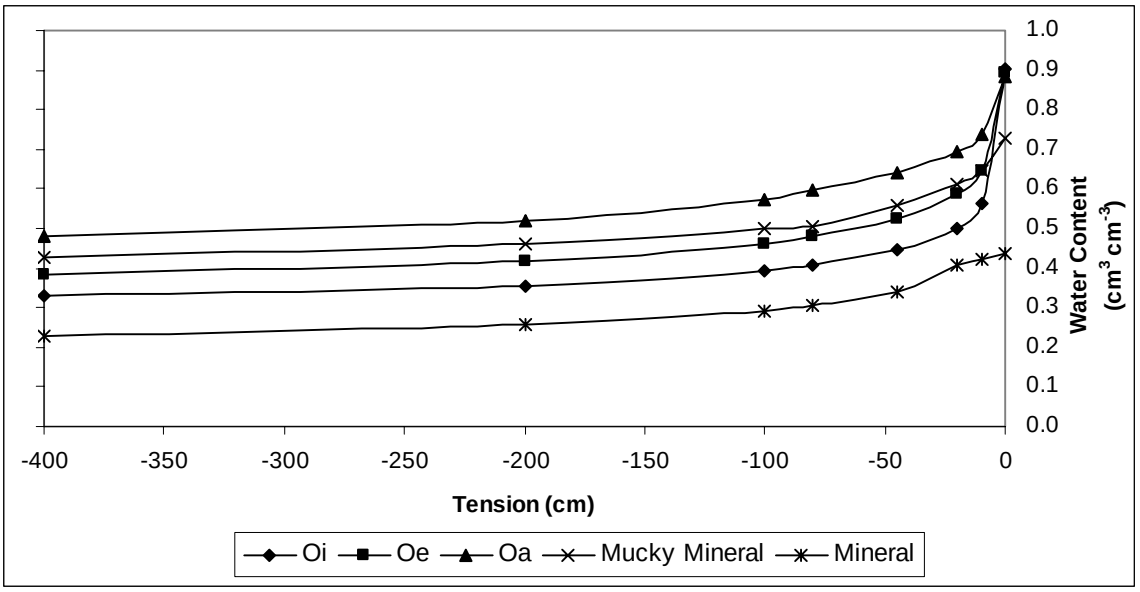

Figure 5.8. Mean soil water characteristic curves for the various types of soil horizons in the reference bays.

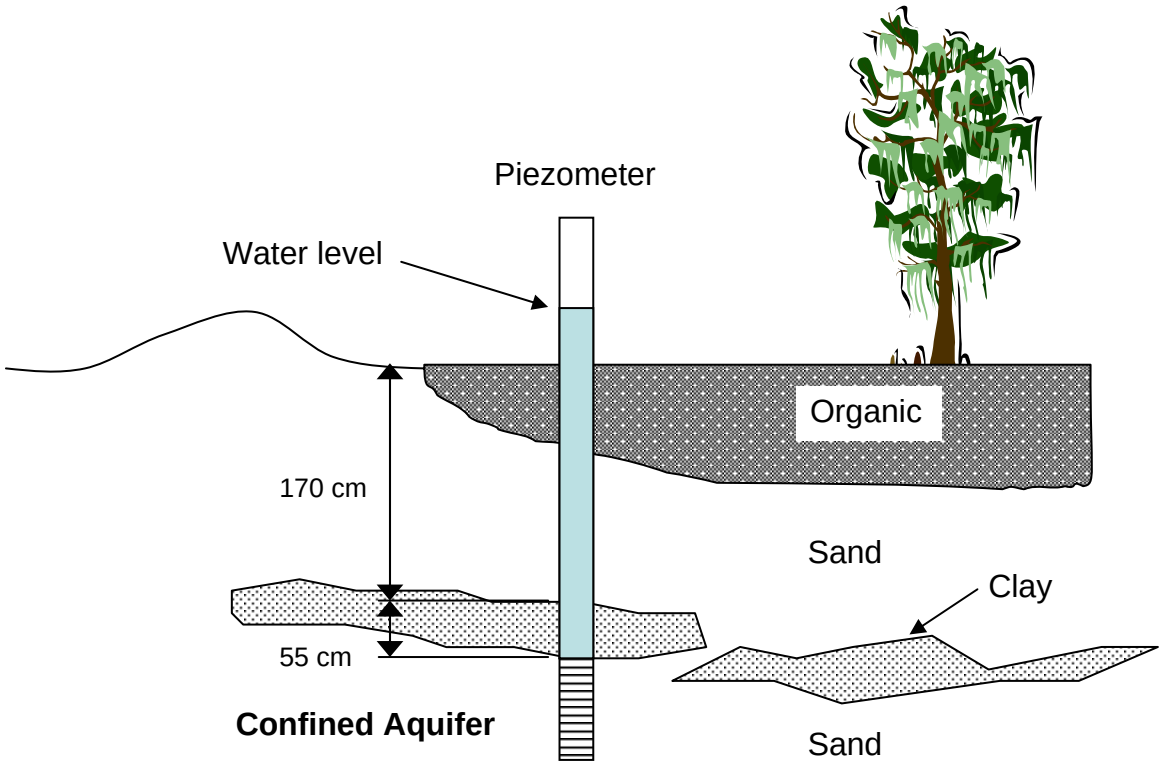

Figure 5.9. Schematic diagram of the confined aquifer system at Charlie Long Millpond Bay.

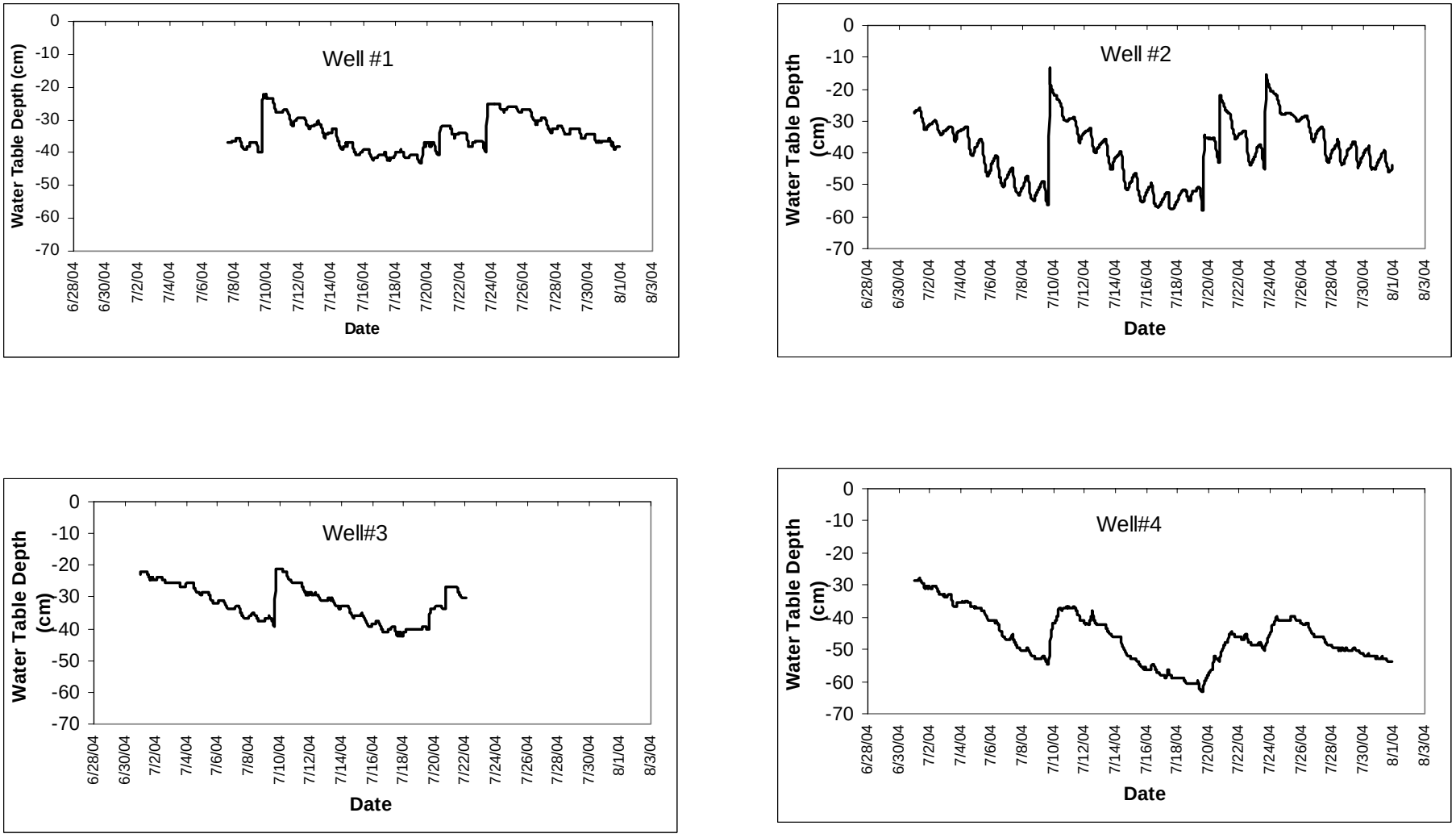

Figure 5.10. Diurnal water table fluctuations measured at wells in Charlie Long Millpond Bay.

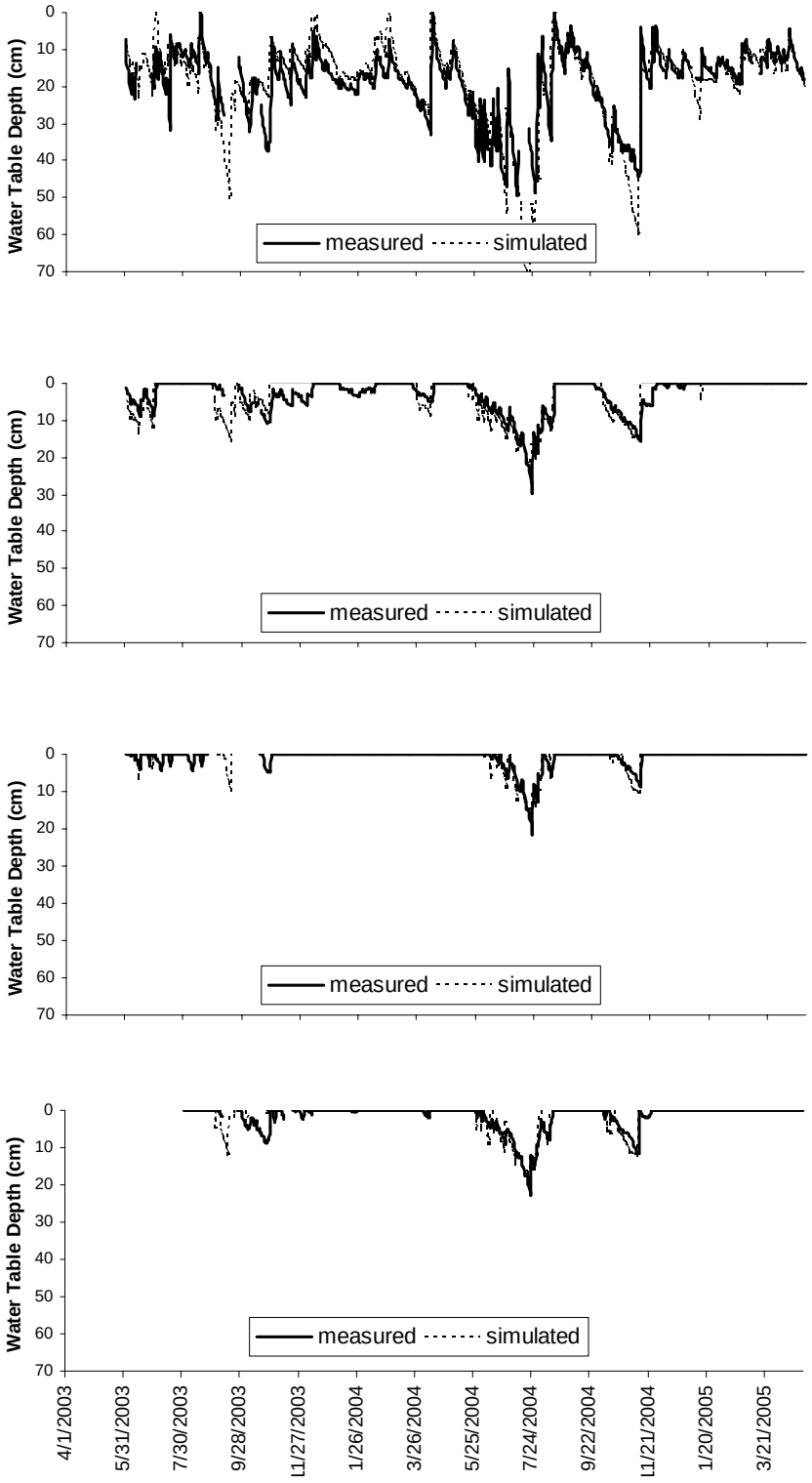

Figure 5.11. Measured and simulated water table depths at Causeway Bay during the calibration period.

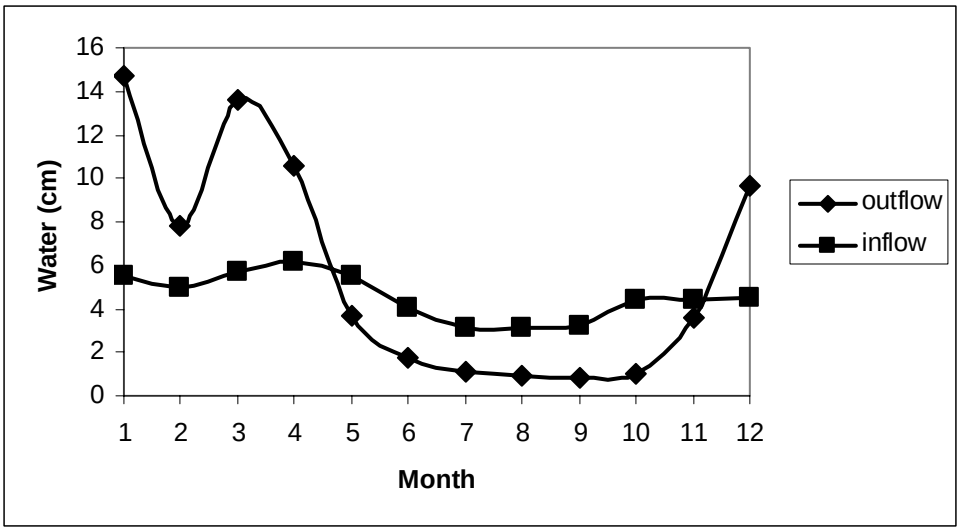

Figure 5.12. Simulated monthly groundwater inflow and outflow at Charlie Long Millpond Bay well no. 3 during 1993.

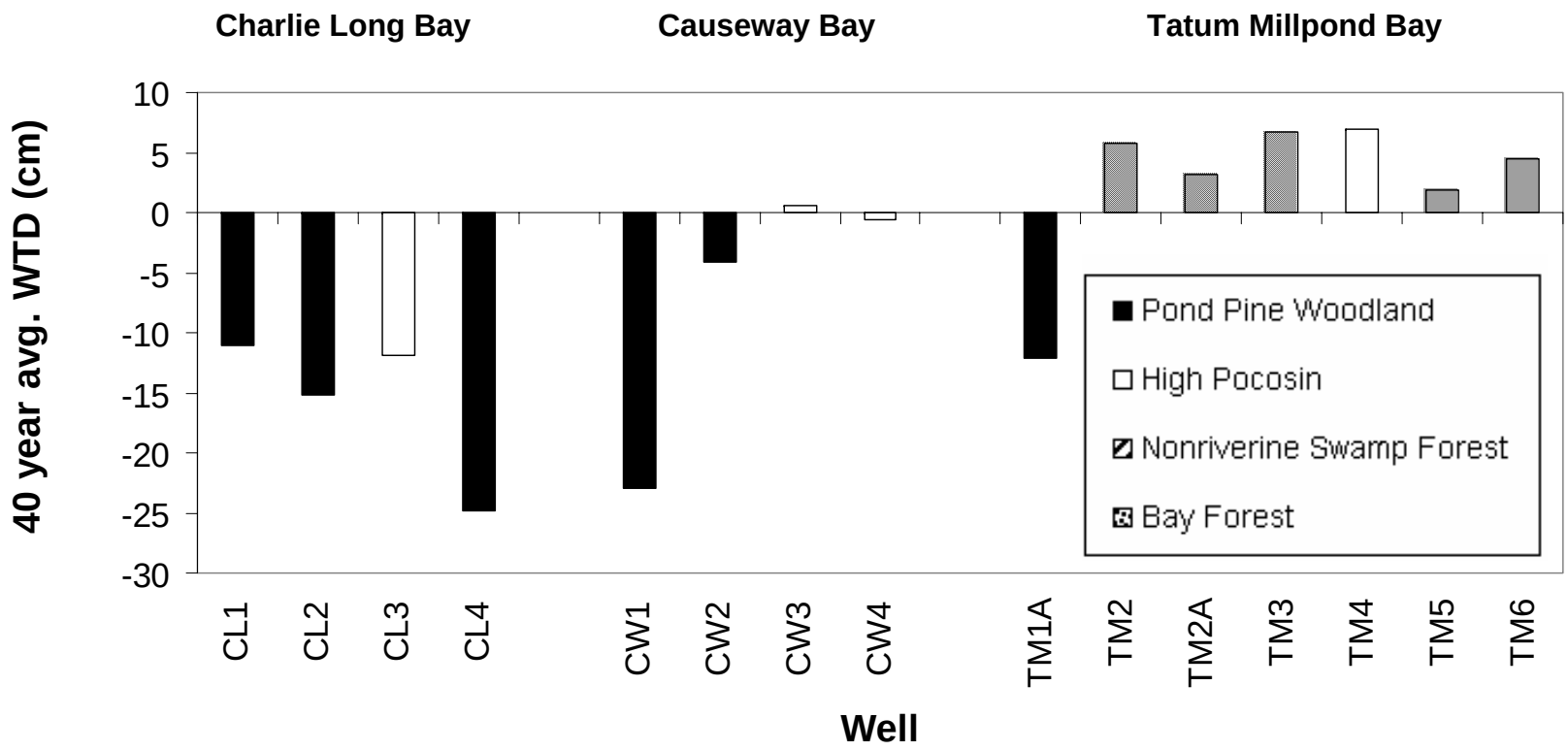

Figure 5.13. Average water table depths over the 40 yr simulation for each well location in the reference bays. Charlie Long Millpond Bay well no. 3 not included in the average calculations for the high pocosin plant community.

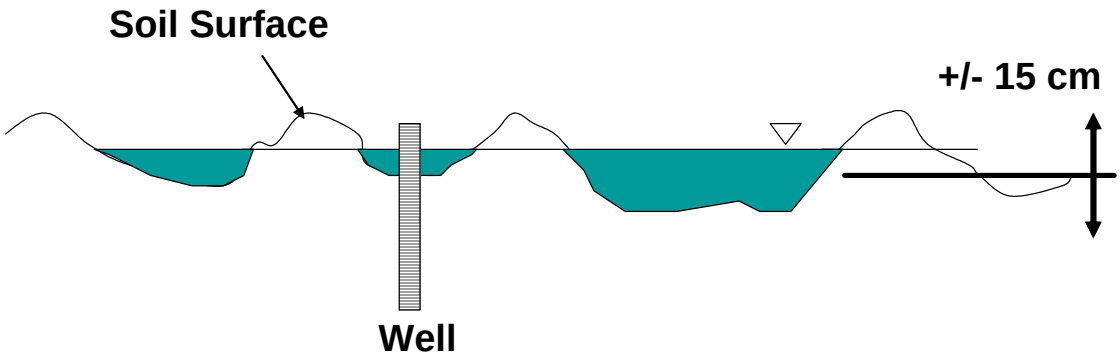

Figure 5.14. Schematic representation of the microtopography observed at the reference bays. Locally higher elevations were typically occupied by trees. As a result, wells were installed in locally lower elevations. The hydrology recorded by the wells represents that of the locally lower elevations.

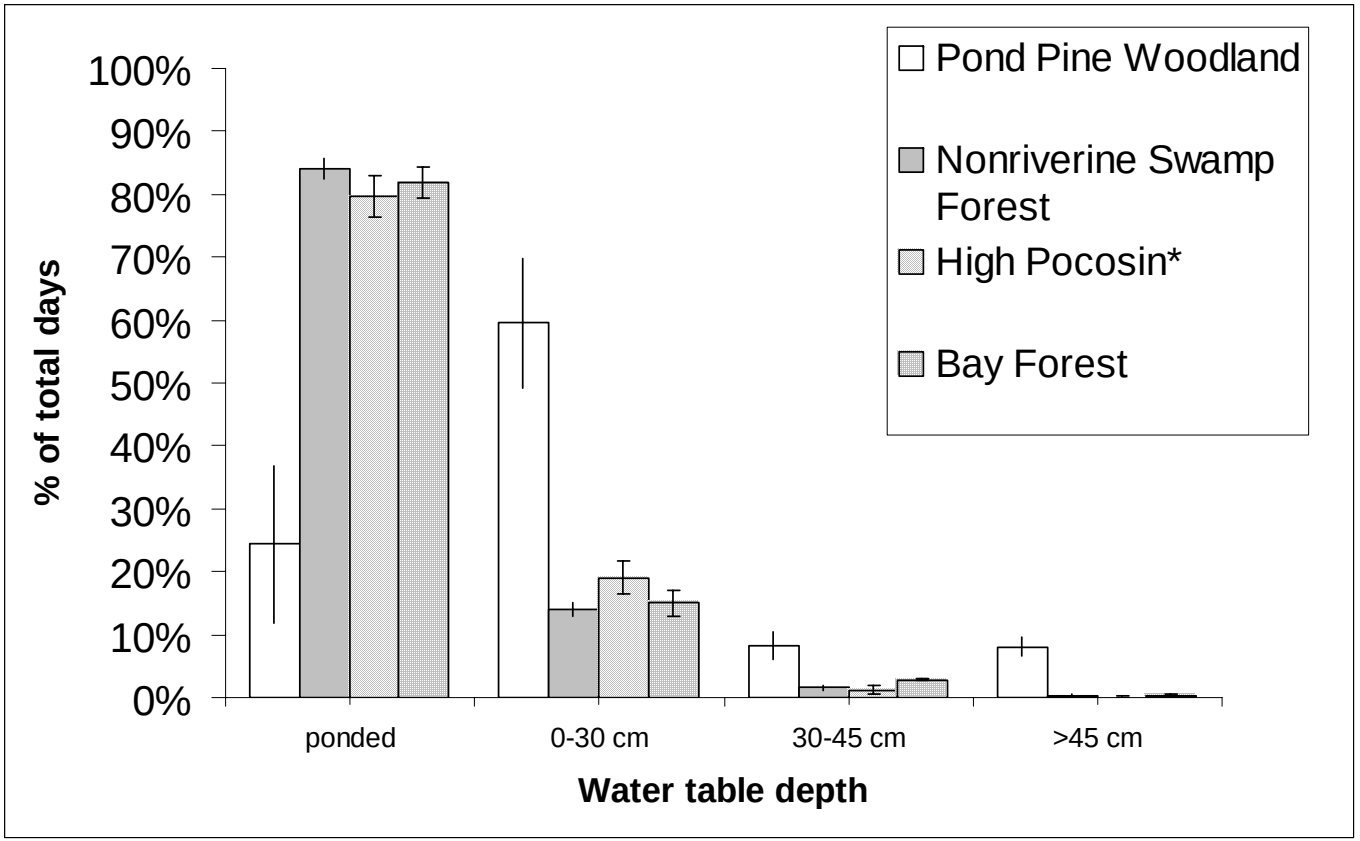

Figure 5.15. Percentage of time during the 40 yr simulation that the water table was at various depths for each plant community. Error bars indicate the standard error in the percentage of total days across all of the well locations in the same plant community.

* Charlie Long Millpond Bay well no. 3 not included in the average calculations for the high pocosin plant community.

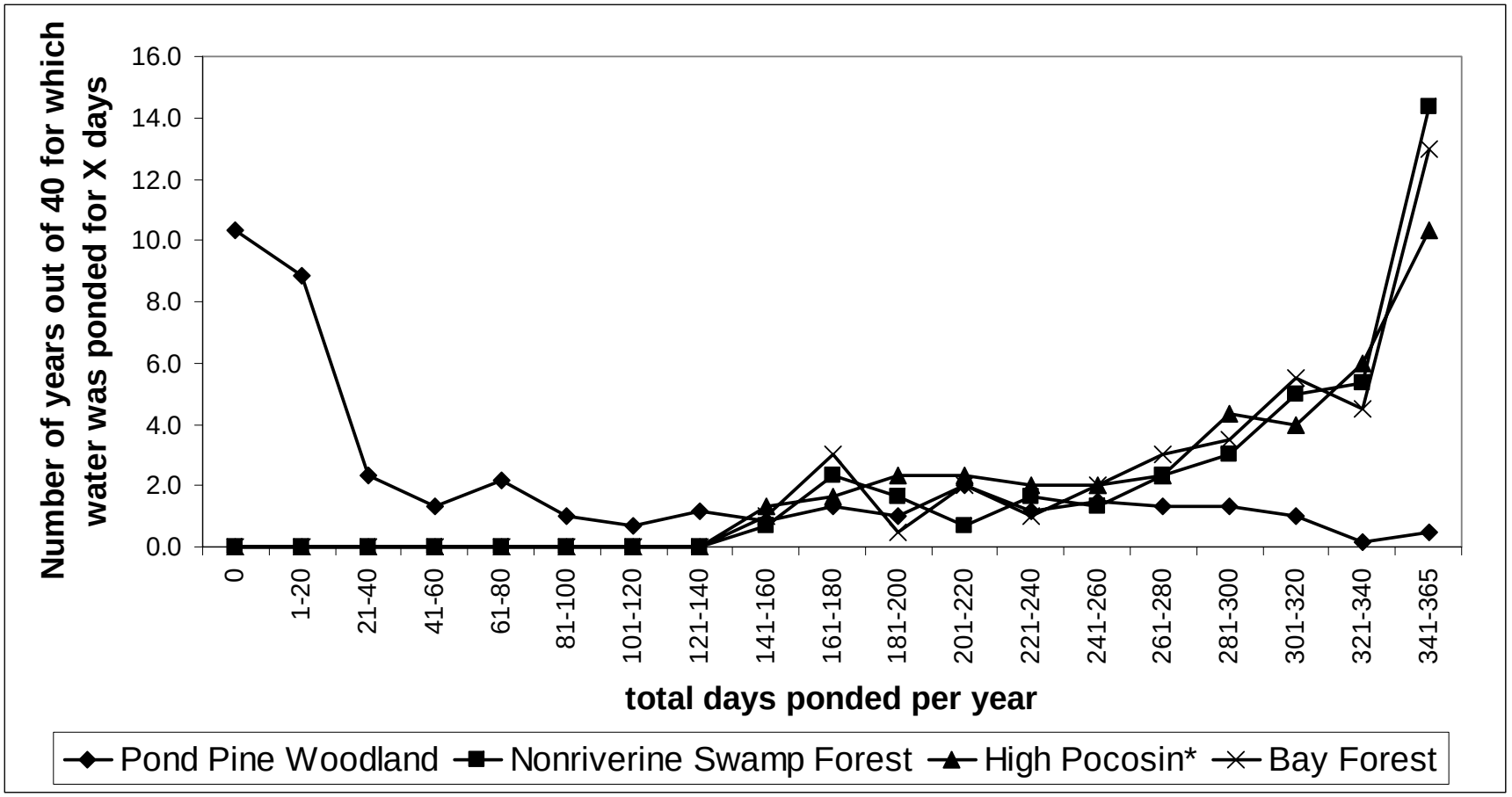

Figure 5.16. Frequency of various ranges of total days per year for which water was ponded on the surface for each plant community.

* Charlie Long Millpond Bay well no. 3 not included in the average calculations for the high pocosin plant community.

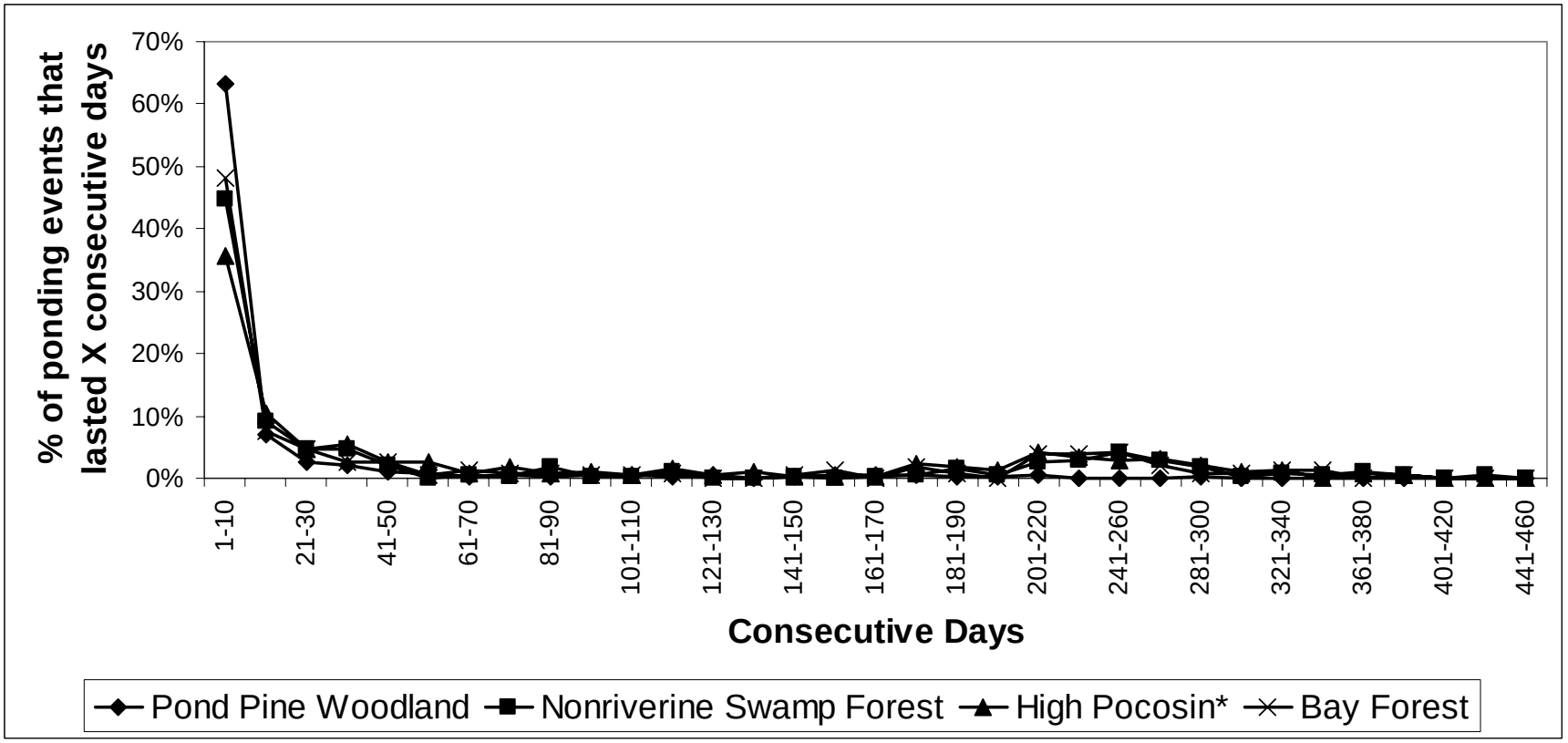

Figure 5.17. Percent of ponding events for which water was ponded on the surface for various ranges of consecutive days for each plant community.

* Charlie Long Millpond Bay well no. 3 not included in the average calculations for the high pocosin plant community.

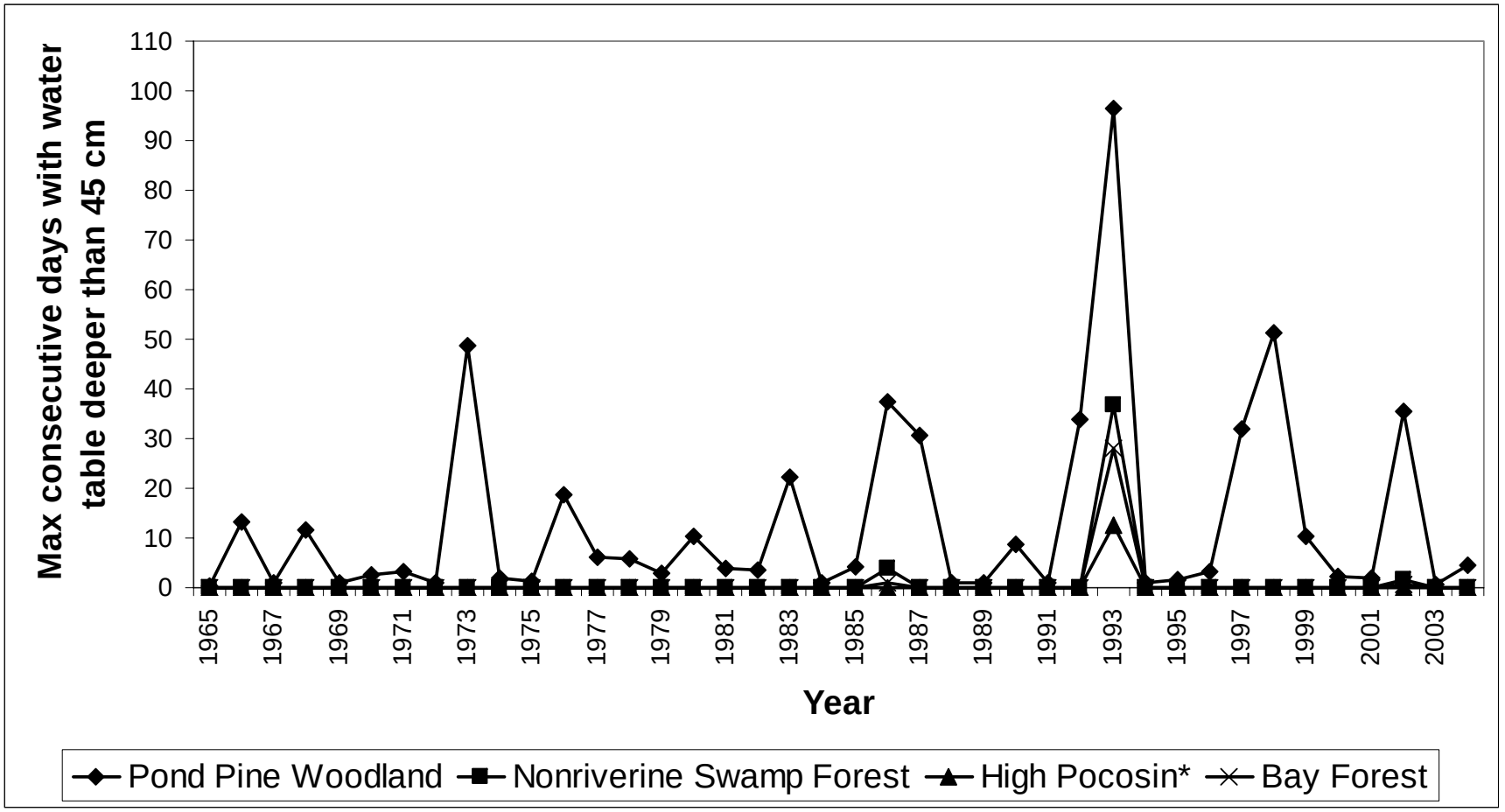

Figure 5.18. Maximum consecutive days for which the water table was deeper than 45 cm during each year of the 40 yr simulation.

* Charlie Long Millpond Bay well no. 3 not included in the average calculations for the high pocosin plant community.

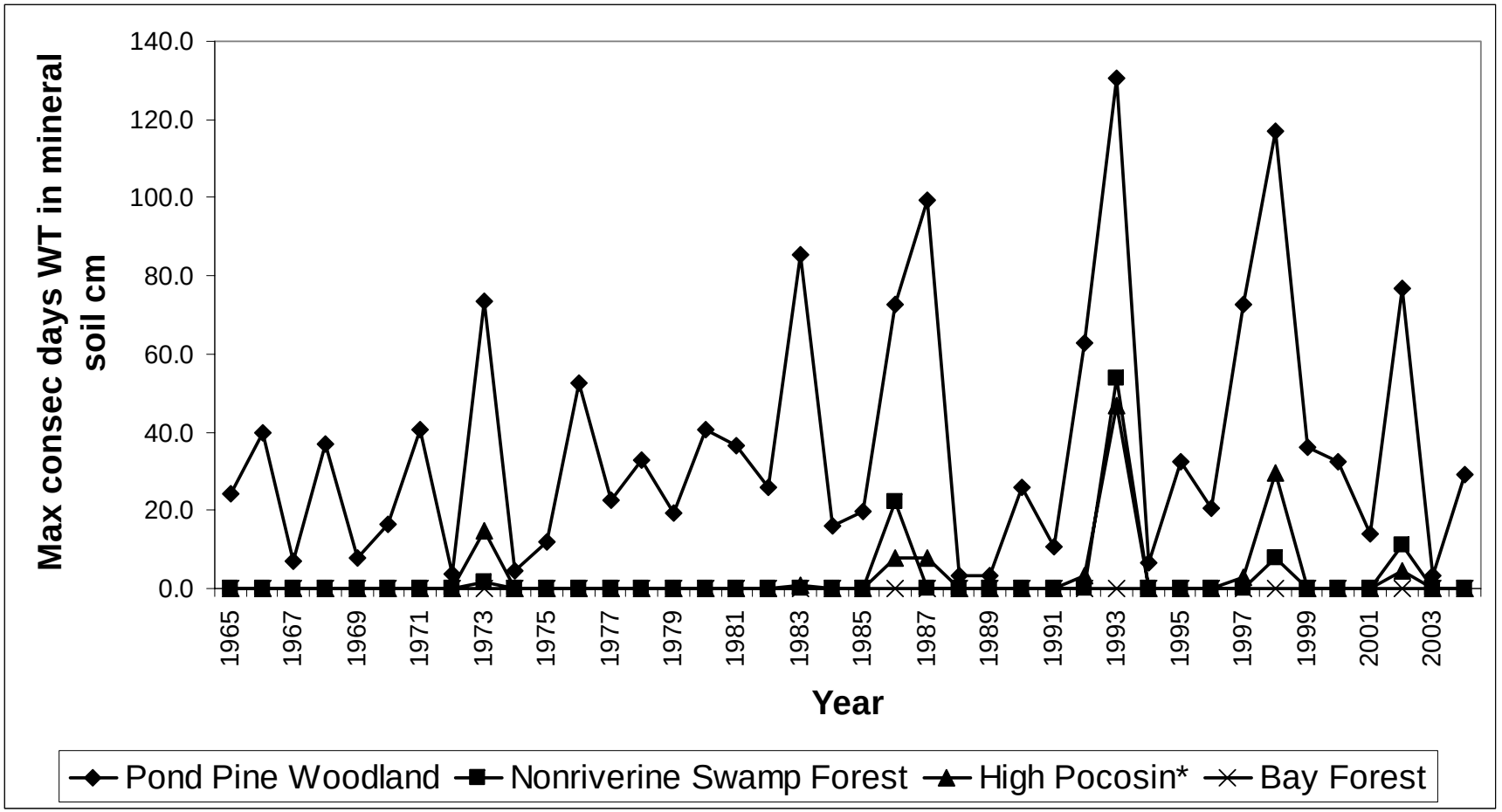

Figure 5.19. Maximum consecutive days for which the water table was in mineral soil during each year of the 40 yr simulation.

* Charlie Long Millpond Bay well no. 3 not included in the average calculations for the high pocosin plant community.

APPENDIX A

SOIL DATA

Table A.1. Raw soil data from laboratory analysis. CL = Charlie Long Millpond Bay, CW = Causeway Bay, TM = Tatum Millpond Bay. ND = Saturated hydraulic conductivity exceeded ability of laboratory apparatus to measure. Oi = fibric organic, Oe = hemic organic, Oa = sapric organic, MM = mucky mineral, M = mineral.

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)									
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
CL	2-3	1	20-28	Oi	0.31		39.54			0.41	0.43	0.45	0.47	0.50	0.57	0.64	0.80
CL	2-3	1	28-36	MM	0.72		0.28	0.24	0.26	0.48	0.50	0.53	0.55	0.58	0.63	0.67	0.70
CL	2-3	1	36-44	M	1.45		11.57			0.13	0.15	0.17	0.19	0.24	0.41	0.42	0.43
CL	2-3	1	44-52	M	1.54		12.89			0.09	0.11	0.13	0.15	0.19	0.37	0.37	0.38
CL	2-3	1	52-60	M	1.49		2.78			0.20	0.24	0.28	0.30	0.37	0.42	0.42	0.43
CL	2-3	1	60-68	M	1.65		1.04	0.03	0.08	0.18	0.21	0.25	0.27	0.31	0.35	0.35	0.36
CL	2-3	1	68-76	M	1.57		0.25			0.24	0.28	0.32	0.34	0.36	0.38	0.39	0.40
CL	2-3	1	76-84	M	1.55		0.29			0.25	0.29	0.35	0.36	0.39	0.41	0.42	0.42
CL	2-3	1	84-92	M	1.56		0.81			0.18	0.21	0.25	0.28	0.32	0.38	0.39	0.40
CL	5	2	0-8	Oi	0.11	1.65	ND			0.22	0.24	0.26	0.27	0.29	0.32	0.36	0.94
CL	5	2	8-16	Oi	0.22	1.85	3.43			0.43	0.46	0.49	0.51	0.56	0.62	0.67	0.88
CL	5	2	16-24	MM	0.44	2.13	1.41			0.42	0.46	0.50	0.52	0.58	0.65	0.70	0.79
CL	5	2	24-32	MM	0.63	2.36	0.29	0.40	0.49	0.42	0.45	0.49	0.51	0.56	0.62	0.67	0.73
CL	5	2	32-40	MM	0.95	2.43	0.03			0.42	0.45	0.48	0.49	0.52	0.55	0.58	0.61
CL	5	2	45-53	MM	0.65		5.47			0.47	0.48	0.49	0.50	0.52	0.56	0.62	0.72
CL	5	2	53-61	MM	1.33		1.34										
CL	5	2	61-69	M	1.50		3.56			0.11	0.13	0.15	0.17	0.20	0.35	0.36	0.36
CL	5	2	69-77	M	1.47		0.59	0.07	0.16	0.17	0.19	0.22	0.24	0.29	0.38	0.39	0.39
CL	5	2	77-85	M	0.96		0.42										
CL	5	2	85-93	M	1.31		0.47			0.31	0.34	0.38	0.40	0.43	0.46	0.47	0.48

Table A.1 (continued).

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)									
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
CL	6	3	0-12	Oi													
CL	6	3	12-21	Oe													
CL	6	3	21-29	Oe	0.15	1.39	ND	0.08	0.17	0.27	0.30	0.33	0.35	0.39	0.43	0.49	0.90
CL	6	3	29-37	Oe	0.34	1.92	3.49			0.38	0.43	0.48	0.51	0.56	0.62	0.66	0.83
CL	6	3	37-45	MM	0.41	2.15	0.65	0.19	0.27	0.38	0.44	0.49	0.51	0.56	0.60	0.64	0.81
CL	6	3	45-53	MM	0.63	2.33	0.03			0.38	0.44	0.48	0.50	0.53	0.58	0.62	0.73
CL	6	3	53-61	MM	0.83	2.34	0.23			0.41	0.44	0.47	0.48	0.51	0.54	0.56	0.65
CL	6	3	61-69	MM	0.81	2.32	0.02			0.43	0.46	0.48	0.49	0.52	0.55	0.57	0.65
CL	6	3	69-77	MM	0.94	2.42	0.03			0.40	0.44	0.47	0.48	0.51	0.54	0.55	0.61
CL	6	3	77-85	MM	0.95	2.36	0.06			0.36	0.43	0.46	0.47	0.50	0.52	0.54	0.60
CL	6	3	85-93	M	1.12	2.43	0.03	0.21	0.32	0.33	0.38	0.41	0.42	0.45	0.46	0.47	0.54
CL	6	3	93-101	M	1.35	2.46	0.02			0.33	0.36	0.38	0.39	0.41	0.41	0.42	0.45
CL	11-12	4	0-15	Oi													
CL	11-12	4	16-24	Oa	0.08	1.58	ND	0.30	0.52	0.20	0.21	0.22		0.24	0.28	0.31	0.95
CL	11-12	4	24-32	Oa	0.10	1.29	ND			0.25	0.27	0.30		0.37	0.41	0.46	0.92
CL	11-12	4	32-40	Oa	0.22	1.62	15.84			0.44	0.49	0.56		0.64	0.70	0.74	0.87
CL	11-12	4	40-48	MM	0.30	1.54	2.37	0.17	0.45	0.48	0.51	0.56		0.62	0.69	0.74	0.80
CL	11-12	4	48-56	MM	0.55	2.19	0.11			0.50	0.55	0.60		0.65	0.70	0.72	0.75
CL	11-12	4	56-62	MM	0.63	2.24	0.05			0.47	0.54	0.58		0.64	0.67	0.70	0.72
CL	11-12	4	62-70	MM	0.95	2.36	0.12			0.46	0.48	0.51		0.56	0.62	0.62	0.60
CL	11-12	4	70-78	MM	0.89	2.34	0.09			0.46	0.50	0.52		0.57	0.60	0.61	0.62
CL	11-12	4	78-86	MM	0.97	2.32	0.16			0.45	0.48	0.52		0.54	0.58	0.58	0.58

Table A.1 (continued).

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)								
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
CW	3	1	0-9	Oi													
CW	3	1	9-17	Oe	0.20		269.21	0.03	0.06	0.39	0.44	0.47	0.48	0.50	0.54	0.58	0.83
CW	3	1	17-25	Oe	0.57		67.68			0.48	0.49	0.50	0.52	0.54	0.60	0.62	0.75
CW	3	1	25-33	M1	1.32		6.65	0.01	0.05	0.27	0.31	0.36	0.37	0.39	0.42	0.44	0.47
CW	3	1	33-41	M1	1.50		17.48			0.27	0.31	0.36	0.38	0.40	0.41	0.42	0.43
CW	3	1	41-49	M1	1.50		0.85			0.26	0.29	0.34	0.36	0.39	0.40	0.41	0.42
CW	3	1	49-57	M1	1.56		1.17			0.24	0.27	0.32	0.35	0.40	0.41	0.41	0.42
CW	3	1	57-65	M1	1.59		3.37			0.19	0.21	0.23	0.25	0.30	0.38	0.38	0.39
CW	3	1	65-73	M1	1.61		13.85			0.08	0.09	0.10	0.11	0.15	0.33	0.33	0.33
CW	3	1	73-81	M1	1.70		0.80			0.16	0.17	0.19	0.21	0.25	0.33	0.33	0.34
CW	3	1	81-89	M2	1.68		0.03	0.07	0.15	0.22	0.24	0.26	0.27	0.28	0.32	0.33	0.34
CW	4-5	2	0-15	Oi													
CW	4-5	2	8-16	MM1	0.12	1.50	29.07	0.17	0.24	0.35	0.38	0.42	0.44	0.47	0.55	0.61	0.92
CW	4-5	2	16-24	MM1	0.24	1.77	1.74			0.42	0.46	0.51	0.53	0.57	0.64	0.70	0.86
CW	4-5	2	24-32	MM1	0.33	2.15	0.60			0.50	0.51	0.54	0.56	0.59	0.65	0.69	0.84
CW	4-5	2	32-40	MM1	0.52	2.23	1.08			0.44	0.49	0.56	0.59	0.64	0.70	0.74	0.77
CW	4-5	2	40-48	MM2	0.60	2.34	1.89	0.10	0.20	0.40	0.44	0.50	0.53	0.58	0.63	0.67	0.74
CW	4-5	2	54-62	MM2	0.26		32.21			0.51	0.56	0.60	0.62	0.66	0.73	0.78	0.87
CW	4-5	2	62-70	MM2	0.55		0.11			0.58	0.61	0.63	0.64	0.67	0.71	0.75	0.78
CW	4-5	2	70-78	M	0.85		0.11	0.09	0.16	0.50	0.52	0.55	0.56	0.59	0.62	0.63	0.65
CW	4-5	2	78-86	M	0.95		0.55			0.41	0.45	0.49	0.51	0.54	0.58	0.60	0.61
CW	4-5	2	86-94	M	1.33		1.61			0.24	0.27	0.30	0.31	0.37	0.47	0.48	0.49

Table A.1 (continued).

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)								
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
CW	6	3	0-16	Oi													
CW	6	3	16-27	Oa													
CW	6	3	27-35	MM	0.27	2.16	7.25	0.10	0.28	0.27	0.30	0.35		0.41	0.51	0.56	0.88
CW	6	3	35-43	MM	0.47	2.24	1.67			0.38	0.42	0.46		0.53	0.63	0.68	0.79
CW	6	3	43-51	MM	0.44	2.13	1.61			0.50	0.52	0.54		0.58	0.64	0.68	0.80
CW	6	3	51-59	MM	0.72	2.33	0.05			0.41	0.45	0.50		0.56	0.62	0.66	0.69
CW	6	3	59-67	MM	0.54	2.27	0.24			0.39	0.43	0.48		0.53	0.57	0.60	0.76
CW	15	4	0-13	Oi													
CW	15	4	13-21	Oi	0.10	1.63	ND			0.25	0.28	0.31	0.33	0.35	0.40	0.47	0.94
CW	15	4	21-29	Oe	0.11	1.55	ND	0.19	0.31	0.30	0.33	0.35	0.37	0.41	0.47	0.54	0.93
CW	15	4	29-37	Oe	0.12	1.50	ND			0.35	0.38	0.41	0.45	0.50	0.61	0.71	0.92
CW	15	4	37-45	Oe	0.15	1.62	12.76			0.50	0.54	0.58	0.62	0.67	0.74	0.80	0.91
CW	15	4	45-53	Oa	0.16	1.49		0.26	0.22	0.49	0.53	0.57	0.59	0.62	0.66	0.69	0.89
CW	15	4	53-61	Oa													
CW	15	4	61-69	Oa	0.18	1.48	8.49			0.56	0.60	0.64	0.68	0.73	0.81	0.85	0.88
CW	15	4	69-77	Oa	0.16	1.48	2.50			0.50	0.56	0.61	0.64	0.69	0.74	0.78	0.89
CW	15	4	77-85	Oa	0.16	1.47	0.29			0.51	0.57	0.61	0.64	0.69	0.74	0.78	0.89

Table A.1 (continued).

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)								
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
TM	1-2	1A	0-20	Oi													
TM	1-2	1A	20-35	Oe													
TM	1-2	1A	35-43	Oe	0.14		ND	0.04	0.02	0.29	0.30	0.32	0.33	0.36	0.42	0.47	0.80
TM	1-2	1A	43-51	MM	1.23		49.08	0.10	0.16	0.24	0.25	0.25	0.27	0.29	0.43	0.47	0.50
TM	1-2	1A	51-59	MM	1.66		26.63			0.06	0.07	0.09	0.10	0.12	0.26	0.31	0.32
TM	1-2	1A	59-67	M	1.42		0.58	0.04	0.06	0.19	0.22	0.26	0.28	0.32	0.40	0.42	0.43
TM	1-2	1A	67-75	M	1.50		0.18			0.20	0.24	0.29	0.31	0.37	0.41	0.41	0.43
TM	1-2	1A	75-83	M	1.47		5.59			0.26	0.28	0.30	0.32	0.34	0.37	0.39	0.41
TM	1-2	1A	83-91	M	1.09		36.78			0.22	0.23	0.25	0.26	0.28	0.35	0.41	0.46
TM	3	2	0-7	Oi													
TM	3	2	7-15	Oi	0.08	1.19	ND			0.28	0.30	0.33	0.33	0.38	0.44	0.48	0.94
TM	3	2	15-23	Oe	0.10	1.52	21.53	0.05	0.08	0.41	0.45	0.50	0.52	0.59	0.68	0.73	0.93
TM	3	2	23-31	Oe	0.13	1.54	6.71			0.44	0.46	0.55	0.57	0.63	0.70	0.76	0.92
TM	3	2	31-39	MM	0.40	2.17	0.80	0.07	0.07	0.39	0.43	0.53	0.55	0.61	0.67	0.70	0.82
TM	3	2	39-47	MM	0.55	2.27	2.96			0.42	0.45	0.53	0.56	0.60	0.66	0.69	0.76
TM	3	2	56-64	MM	0.81		2.97			0.31	0.34	0.39	0.41	0.46	0.57	0.62	0.75
TM	3	2	64-72	M	1.18		1.53	0.07	0.21	0.22	0.25	0.29	0.31	0.36	0.45	0.48	0.51
TM	3	2	72-80	M	1.20		0.74			0.32	0.33	0.34	0.36	0.38	0.43	0.47	0.49
TM	3	2	80-88	M	1.40		4.98			0.13	0.14	0.15	0.16	0.19	0.36	0.44	0.45

Table A.1 (continued).

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)								
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
TM	7	2A	0-23	Oi													
TM	7	2A	23-31	Oa	0.19	1.56	0.41	0.23	0.30	0.48	0.55	0.60	0.63	0.68	0.73	0.78	0.88
TM	7	2A	31-39	Oa	0.26	1.91	19.37			0.51	0.56	0.59	0.61	0.65	0.68	0.71	0.86
TM	7	2A	39-47	MM	0.35	2.13	0.39	0.14	0.25	0.56	0.61	0.65	0.67	0.71	0.75	0.78	0.83
TM	7	2A	47-55	MM	0.50	2.11	0.11			0.48	0.53	0.58	0.59	0.64	0.68	0.71	0.76
TM	7	2A	55-63	MM	0.61	2.32	0.29			0.58	0.60	0.61	0.62	0.64	0.67	0.69	0.74
TM	7	2A	63-71	MM	0.39	2.09	0.60			0.48	0.53	0.57	0.59	0.62	0.64	0.66	0.81
TM	8-9	3	0-34	Oi													
TM	8-9	3	34-42	Oe	0.17	1.61	6.94	0.14	0.19	0.46	0.50	0.54	0.56	0.61	0.67	0.71	0.90
TM	8-9	3	42-50	Oe	0.21	1.87	1.48			0.49	0.53	0.56	0.58	0.62	0.67	0.71	0.89
TM	8-9	3	50-58	Oa	0.28	1.46	1.47	0.23	0.47	0.49	0.54	0.56	0.57	0.62	0.67	0.70	0.81
TM	8-9	3	58-66	Oa	0.42	1.96	0.82			0.48	0.52	0.56	0.57	0.61	0.66	0.69	0.78
TM	8-9	3	66-74	Oa	0.43	1.93	0.43			0.50	0.54	0.58	0.59	0.64	0.68	0.71	0.78
TM	8-9	3	74-82	MM	0.59	2.01	0.09	0.38	0.48	0.48	0.52	0.56	0.58	0.62	0.65	0.67	0.71
TM	8-9	3	82-90	MM	0.59	2.14	0.06			0.50	0.53	0.56	0.57	0.61	0.64	0.65	0.73
TM	15	4	0-16	Oi													
TM	15	4	16-60	Oe													
TM	15	4	60-68	Oe	0.05	1.25	ND	0.14	0.16	0.18	0.19	0.23	0.24	0.26	0.29	0.33	0.96
TM	15	4	68-76	Oa	0.09	1.39	3.97	0.21	0.30	0.37	0.39	0.47	0.50	0.55	0.62	0.70	0.94
TM	15	4	76-84	Oa	0.08	1.36	2.19			0.34	0.39	0.48	0.51	0.56	0.63	0.70	0.94
TM	15	4	84-92	Oa	0.10	1.35	1.12			0.45	0.49	0.57	0.60	0.65	0.71	0.75	0.93
TM	15	4	92-100	Oa	0.11	1.43	0.36			0.51	0.54	0.63	0.66	0.71	0.75	0.79	0.93

Table A.1 (continued).

Bay	Plot	Well	Depth	Texture	Bulk Density	Particle Density	K_{sat}	Water Content at Pressure (cm)								
								15000	10000	400	200	100	80	45	20	10	0
			cm		g cm^{-3}	g cm^{-3}	cm hr^{-1}	--- cm cm^{-1} ---									
TM	17	5	0-9	Oi													
TM	17	5	9-57	Oe													
TM	17	5	57-65	Oe	0.13	1.65	17.30	0.20	0.38	0.29	0.32	0.37	0.40	0.44	0.51	0.71	0.92
TM	17	5	65-73	Oa	0.12	1.36	5.53	0.21	0.34	0.45	0.49	0.56	0.58	0.62	0.69	0.73	0.91
TM	17	5	73-81	Oa	0.11	1.26	0.61			0.53	0.57	0.65	0.68	0.72	0.78	0.83	0.91
TM	17	5	81-89	Oa	0.12		0.72			0.59	0.63	0.68	0.70	0.75	0.81	0.86	0.93
TM	17	5	89-97	Oa	0.12	1.37	0.27			0.55	0.57	0.63	0.66	0.70	0.76	0.81	0.91
TM	17	5	97-105	Oa	0.11	1.36	0.92			0.55	0.58	0.67	0.70	0.74	0.79	0.85	0.92
TM	19	6	0-8	Oi	0.12	1.41	18.42			0.39	0.42	0.51	0.54	0.59	0.65	0.77	0.92
TM	19	6	8-35	Oe1						0.37	0.40	0.48	0.51	0.55	0.62	0.71	0.92
TM	19	6	35-48	Oe2													
TM	19	6	48-56	Oe2	0.09	1.28	6.70	0.16	0.26	0.35	0.37	0.45	0.47	0.51	0.59	0.66	0.93
TM	19	6	56-64	Oe2	0.09	1.19	46.36			0.41	0.44	0.51	0.53	0.57	0.62	0.67	0.92
TM	19	6	64-72	Oe2	0.08	1.36	6.34			0.45	0.48	0.55	0.57	0.61	0.67	0.73	0.94
TM	19	6	72-80	Oe2	0.10	1.30	0.78			0.49	0.52	0.60	0.63	0.68	0.74	0.79	0.92
TM	19	6	80-88	Oa	0.14		0.03	0.23	0.42	0.59	0.61	0.65	0.67	0.72	0.79	0.85	0.91
TM	19	6	88-96	Oa	0.15		0.02			0.56	0.61	0.66	0.69	0.73	0.80	0.85	0.89
TM	19	6	96-104	Oa	0.15		0.07			0.57	0.59	0.59	0.59	0.61	0.66	0.70	0.73

Table A.2. Insitu saturated hydraulic conductivity measurements at each well location in the reference bays.

Bay	Plot	Well	Depth	Saturated Hydraulic Conductivity			
				Trial 1	Trial 2	Trial 3	Average
			cm	--- cm hr^{-1} ---			
CL	2-3	1	23-38	6.30	6.64		6.47
CL	2-3	1	53-68	2.84	3.34		3.09
CL	2-3	1	75-90	5.58	3.94		4.76
CL	5	2	25-35	12.61	15.70		14.16
CL	5	2	35-45	22.08	12.25		17.17
CL	5	2	65-75		13.43		13.43
CL	5	2	80-90	0.50	0.45		0.48
CL	6	3	17-32		9.78	5.71	7.75
CL	6	3	65-80	1.14			1.14
CL	6	3	90-105	0.88	1.20		1.04
CL	11-12	4	25-40	9.19		8.01	8.60
CL	11-12	4	65-80			0.20	0.20
CL	11-12	4	95-110	0.45	0.24	0.44	0.38
CW	3	1	65-80		4.50	10.31	7.41
CW	3	1	85-100	10.10	11.28	10.03	10.47
CW	4-5	2	9-19		277.47	336.67	307.07
CW	4-5	2	18-28	11.49	40.47	28.51	26.82
CW	4-5	2	28-38	10.86			10.86
CW	4-5	2	60-70	4.87			4.87
CW	4-5	2	90-100	4.43	6.74	8.41	6.52
CW	6	3	6-16	50.25		50.25	50.25
CW	6	3	27-37	6.25	7.90	9.63	7.93
CW	6	3	47-57	0.75	0.60		0.68
CW	6	3	68-78	2.26			2.26
CW	15	4	35-50	1.71	1.35	1.88	1.65
CW	15	4	85-100				
TM	1-2	1A	55-65	7.32		2.84	5.08
TM	1-2	1A	75-85		8.42	5.26	6.84

Table A.2 (continued).

Bay	Plot	Well	Depth	Saturated Hydraulic Conductivity			
				Trial 1	Trial 2	Trial 3	Average
			cm	--- cm hr^{-1} ---			
TM	3	2	15-25	17.33	19.81		18.57
TM	3	2	25-35	10.91		7.54	9.22
TM	3	2	60-70		5.54	6.55	6.05
TM	3	2	75-85	12.63	4.02	16.80	11.15
TM	7	2A	20-30	12.63		10.17	11.40
TM	7	2A	60-70	2.81	2.35	1.87	2.34
TM	7	2A	75-85				
TM	8-9	3	15-30	35.24		46.13	40.69
TM	8-9	3	45-60	11.01	10.69		10.85
TM	8-9	3	80-95		3.23	3.28	3.25
TM	15	4	5-15				
TM	15	4	58-68	5.32	1.52		3.42
TM	15	4	85-95	0.95	1.88	4.49	2.44
TM	17	5	20-30			58.41	58.41
TM	17	5	45-55	3.30		4.53	3.92
TM	17	5	80-90	0.31	1.02	0.17	0.50
TM	19	6	20-30		9.01	5.96	7.48
TM	19	6	60-70	0.51	0.58	0.49	0.53
TM	19	6	80-90	0.53		0.20	0.37

Table A.3. Soil data input for DRAINMOD models.

Bay	Well	Layer	Depth range	Root depth	Soil layer	Max root depth	Water Content at Pressure (cm)										K_{sat}
							15000	1000	400	200	100	80	45	20	10	0	
			cm	cm		cm	--- cm^3 cm^{-3} ---										cm hr^{-1}
CL	1	1	28	30	2	45		0.310[b]	0.414	0.429	0.453	0.468	0.497	0.565	0.643	0.799	39.54[c]
CL	1	2	36				0.236	0.256	0.482	0.501	0.531	0.546	0.576	0.630	0.669	0.704	6.47
CL	1	3	92				0.031	0.077	0.183	0.213	0.249	0.269	0.313	0.389	0.394	0.402	3.93
CL	2	1	16	30	2	45		0.245[b]	0.326	0.352	0.375	0.389	0.427	0.470	0.512	0.908	33.98[d]
CL	2	2	61				0.396	-	0.434	0.461	0.485	0.499	0.534	0.578	0.620	0.689	15.66
CL	2	3	93				0.065	0.161	0.193	0.220	0.252	0.270	0.307	0.398	0.403	0.411	6.95
CL	3	1	12					0.278[b]	0.370[a]	0.390[a]	0.414[a]	0.428[a]	0.462[a]	0.518[a]	0.578[a]	0.853[a]	36.76[a]
CL	3	2	37	30	2	45	0.08	0.173	0.377	0.436	0.487	0.508	0.560	0.608	0.650	0.818	7.75
CL	3	3	85				0.189	0.268	0.397	0.442	0.470	0.484	0.515	0.547	0.569	0.647	1.14
CL	3	4	101				0.206	0.32	0.330	0.369	0.396	0.406	0.427	0.438	0.444	0.496	1.04
CL	4	1	15	30	2	45		0.150[b]	0.200	0.211	0.222		0.244	0.278	0.307	0.946	36.76[a]
CL	4	2	40					0.261[b]	0.348	0.379	0.426		0.505	0.556	0.599	0.894	8.6
CL	4	3	94				0.169	0.453	0.467	0.507	0.550		0.596	0.637	0.654	0.678	0.25
CW	1	1	9					0.150[f]	0.200[e]	0.211[e]	0.222[e]		0.244[e]	0.278[e]	0.307[e]	0.946[e]	178.66[c]
CW	1	2	25	30	2	45	0.029	0.057	0.435	0.465	0.484	0.499	0.519	0.572	0.601	0.790	23.712[j]
CW	1	3	81				0.013	0.049	0.208	0.235	0.273	0.289	0.326	0.382	0.388	0.401	7.41
CW	1	4	89				0.074	0.149	0.220	0.244	0.258	0.268	0.282	0.321	0.326	0.340	10.47
CW	2	1	15					0.150[f]	0.200[e]	0.211[e]	0.222[e]		0.244[e]	0.278[e]	0.307[e]	0.946[e]	307.07
CW	2	2	40	30	2	45	0.172	0.242	0.43	0.46	0.50	0.53	0.57	0.63	0.69	0.85	18.84
CW	2	3	70				0.103	0.197	0.50	0.54	0.57	0.60	0.64	0.69	0.73	0.80	4.87
CW	2	4	94				0.092	0.163	0.39	0.41	0.44	0.46	0.50	0.56	0.57	0.59	6.52

Table A.3 (continued).

Bay	Well	Layer	Depth range	Root depth	Soil layer	Max root depth	Water Content at Pressure (cm)										K_{sat}
			cm	cm		cm	15000	1000	400	200	100	80	45	20	10	0	cm hr^{-1}
							--- cm^3 cm^{-3} ---										
CW	3	1	16	30	2	45		0.150[f]	0.200[e]	0.211[e]	0.222[e]		0.244[e]	0.278[e]	0.307[e]	0.946[e]	50.25
CW	3	2	27					0.201[f]	0.27[g]	0.30[g]	0.35[g]		0.41[g]	0.51[g]	0.56[g]	0.88[g]	7.93
CW	3	3	67				0.102	0.276	0.39	0.42	0.47		0.52	0.60	0.64	0.78	3.11
CW	4	1	21	30	2	45		0.189[f]	0.253	0.283	0.310	0.325	0.352	0.404	0.470	0.941	178.66[i]
CW	4	2	45				0.189	0.309	0.384	0.418	0.449	0.478	0.528	0.607	0.684	0.919	1.65
CW	4	3	85				0.256	-	0.515	0.564	0.608	0.638	0.683	0.737	0.776	0.888	3.11[h]
TM	1A	1	20	30	2	45		0.233[l]	0.335[k]	0.360[k]	0.420[k]	0.439[k]	0.483[k]	0.543[k]	0.625[k]	0.93[k]	23.55[n]
TM	1A	2	59				0.098	-	0.149	0.159	0.171	0.182	0.201	0.346	0.390	0.407	5.08
TM	1A	3	91				0.042	0.063	0.217	0.242	0.274	0.291	0.327	0.384	0.407	0.430	6.35
TM	2	1	15					0.191[l]	0.275	0.299	0.325	0.334	0.378	0.437	0.481	0.936	18.57
TM	2	2	31	30	2	45	0.052	0.083	0.424	0.458	0.523	0.548	0.610	0.690	0.742	0.924	9.22
TM	2	3	64				0.065	0.071	0.372	0.409	0.484	0.506	0.557	0.631	0.673	0.775	6.53
TM	2	4	88				0.073	0.207	0.223	0.242	0.261	0.278	0.309	0.412	0.465	0.482	8.81
TM	2A	1	23	30	2	45		0.288[l]	0.414[k]	0.429[k]	0.453[k]	0.468[k]	0.497[k]	0.565[k]	0.643[k]	0.80[k]	11.40
TM	2A	2	39				0.234	0.299	0.498	0.552	0.595	0.620	0.663	0.704	0.742	0.870	2.34
TM	2A	3	71				0.141	0.251	0.526	0.568	0.602	0.618	0.653	0.685	0.710	0.787	2.34
TM	3	1	34					0.288[l]	0.414[k]	0.429[k]	0.453[k]	0.468[k]	0.497[k]	0.565[k]	0.643[k]	0.80[k]	40.69
TM	3	2	50	30	2	45	0.135	0.19	0.475	0.511	0.551	0.568	0.616	0.674	0.711	0.892	14.45
TM	3	3	74				0.231	0.469	0.492	0.535	0.565	0.578	0.625	0.670	0.702	0.789	14.45
TM	3	4	90				0.384	0.476	0.490	0.528	0.561	0.575	0.618	0.645	0.663	0.716	3.25

Table A.3 (continued).

Bay	Well	Layer	Depth range	Root depth	Soil layer	Max root depth	Water Content at Pressure (cm)										
							15000	1000	400	200	100	80	45	20	10	0	K_{sat}
			cm	cm		cm	--- cm^3 cm^{-3} ---										cm hr^{-1}
TM	4	1	16	30	2	45		0.288[l]	0.414[k]	0.429[k]	0.453[k]	0.468[k]	0.497[k]	0.565[k]	0.643[k]	0.799[k]	23.55[n]
TM	4	2	68				0.138	0.156	0.179	0.190	0.225	0.240	0.261	0.290	0.329	0.956	3.42
TM	4	3	108				0.208	0.304	0.441	0.483	0.567	0.593	0.643	0.704	0.759	0.926	2.44
TM	5	1	9	30	2	45		0.288[l]	0.414[k]	0.429[k]	0.453[k]	0.468[k]	0.497[k]	0.565[k]	0.643[k]	0.799[k]	23.55[n]
TM	5	2	65				0.195	-	0.290	0.315	0.375	0.397	0.437	0.508	0.706	0.923	31.16
TM	5	3	105				0.213	0.338	0.535	0.565	0.637	0.664	0.707	0.766	0.819	0.916	0.50
TM	6	1	8					0.274[l]	0.395	0.421	0.514	0.543	0.588	0.649	0.769	0.918	23.55[n]
TM	6	2	35	30	2	45		0.258[l]	0.371[m]	0.396[m]	0.480[m]	0.506[m]	0.551[m]	0.618[m]	0.713[m]	0.924[m]	7.48
TM	6	3	80				0.156	0.263	0.425	0.454	0.528	0.550	0.593	0.654	0.710	0.930	0.53
TM	6	4	104				0.227	0.421	0.570	0.604	0.634	0.652	0.688	0.748	0.800	0.841	0.37

[a]Averaged between CL1 and CL2 surface horizons

[b]Estimated by calculating the average ratio of water content at 1000 cm to that at 400 cm for organic soils at CL bay

[c]Based on Ksat obtained in lab from core

[d]Obtained by taking the average ratio of core/piezometer Ksat from measured samples, and multiplying it by the core Ksat

[e]Based on CW4 surface horizon

[f]Estimated by calculating the average ratio of water content at 1000 cm to that at 400 cm for organic soils at CW bay

[g]Taken from next deepest sample (first in horizon 3) at CW3

[h]Same as horizon 3 for CW3

[i]Average Ksat for CW2 and CW3 horizons measured with piezometer method

[j]Obtained by calculating the average ratio of layer 2 to layer 3 (=3.2)

Table A.3 (continued).

[k]Average between TM2 and TM6 surface horizons
[l]Estimated by calculating the average ratio of water content at 1000 cm to that at 400 cm for organic soils at Tatum
[m]Estimated by averaging the surface horizon with the first sample collected from horizon 3
[n]Average Ksat for TM2, 2a, and 3 surface horizons measured with piezometer method

APPENDIX B

MODEL CALIBRATION DATA

Table B.1. Well serial numbers for reference bays.

Bay	Well	Serial Number				
		Original	4/10/03	10/1/03	11/3/04	12/13/04
Charlie	1	S158CBF	S158CBF	S158CBF	S158CBF	S158CBF
Long	2	S158AE2	S158AE2	S562B10	S562B10	S562B10
Millpond	3	S158D9E	S51BACE	S51BACE	S213E1E	S213E1E
Bay	4	S448A15	S448A15	S158AE2	S55ECD0	9BEC0C4
	1	S5175E0	S5175E0	S5175E0	S5175E0	S5175E0
Causeway	2	S213D61	S213D61	S213D61	S213D61	S213D61
Bay	3		S562EE4	S560CC7	S5632EA	S5632EA
	4	S213F47	S213F47	S213F47	S213F47	S213F47
	1A	S213E1E	S213E1E	S213E1E	9DE5512	9DE5512
	2	N/A	S56344E	S55ECD0	9DE7908	9DE7908
Tatum	2A	N/A	S561A92	S5632EA	9DE6E91	9DE6E91
Millpond	3	S448988	S561ABE	S561ABE	S561ABE	S561ABE
Bay	4	S213E08	S213E08	S213E08	S213E08	S213E08
	5	2213DB3	S561C2B	S561C2B	S561C2B	S561C2B
	6	N/A	S51BBEB	S51BBEB	S51BBEB	S51BBEB

N/A Well not installed until 4/10/03.

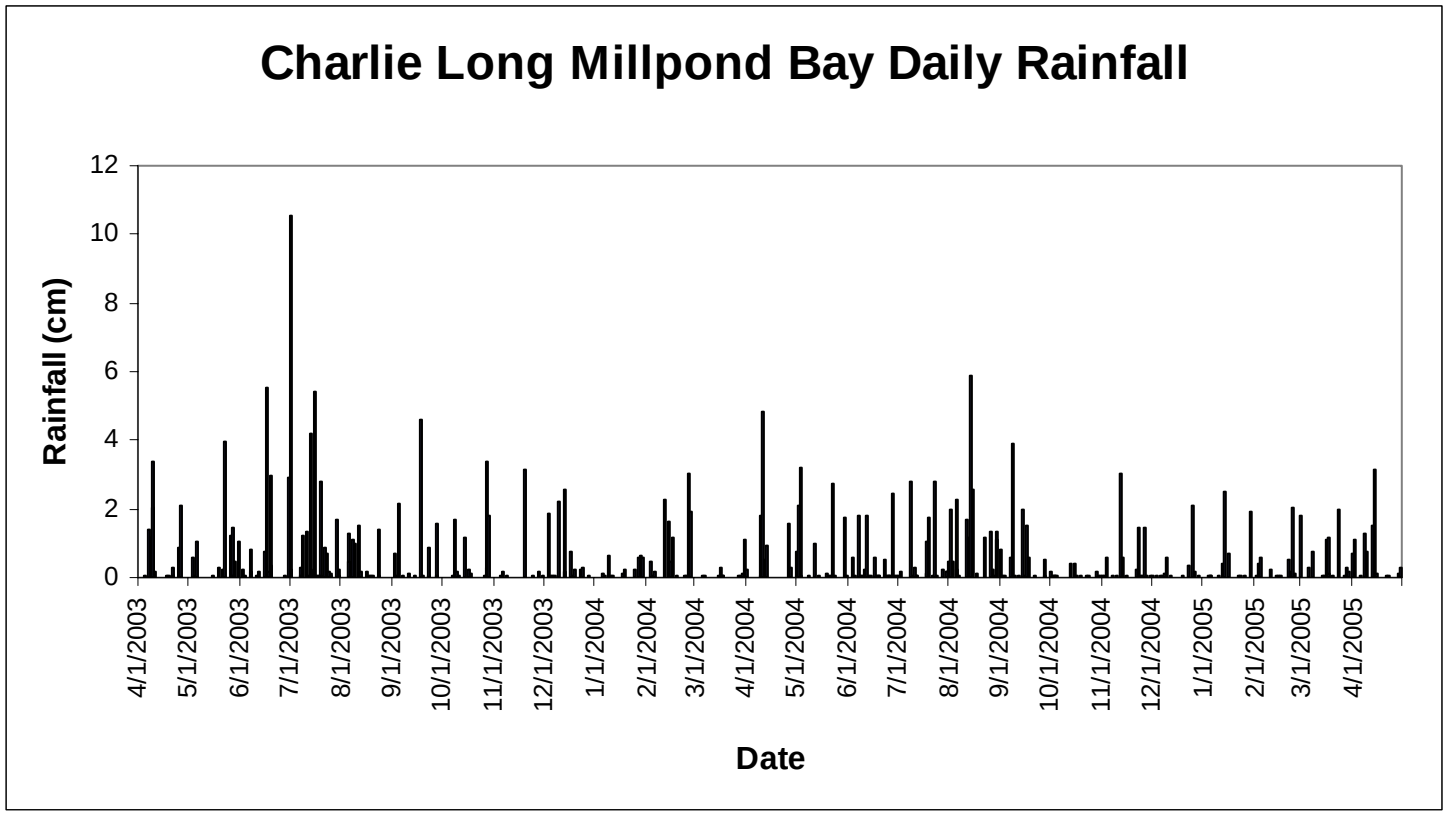

Figure B.1. Rainfall amounts at Charlie Long Millpond Bay during model calibration period.

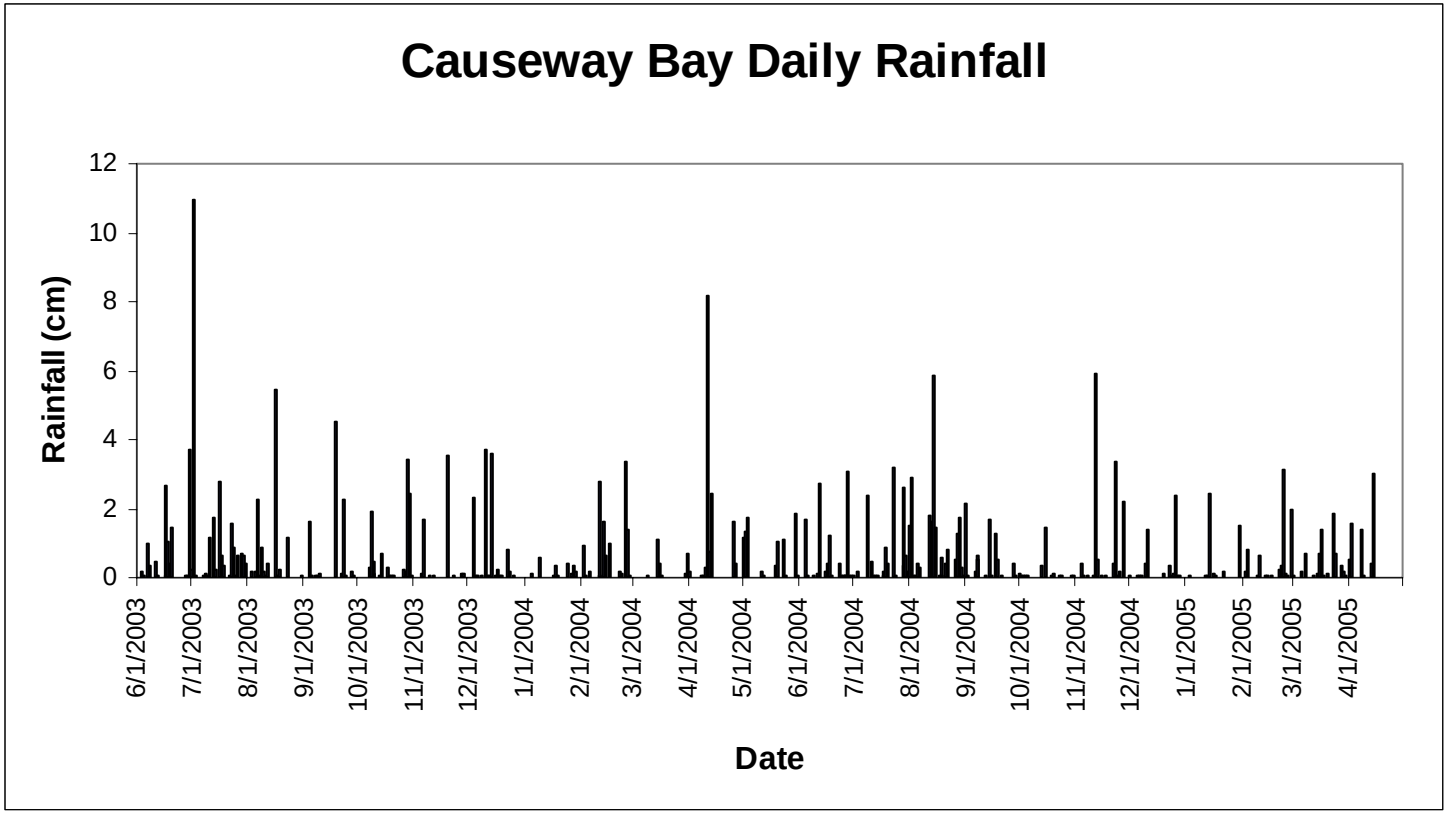

Figure B.2. Rainfall amounts at Causeway Bay during model calibration period.

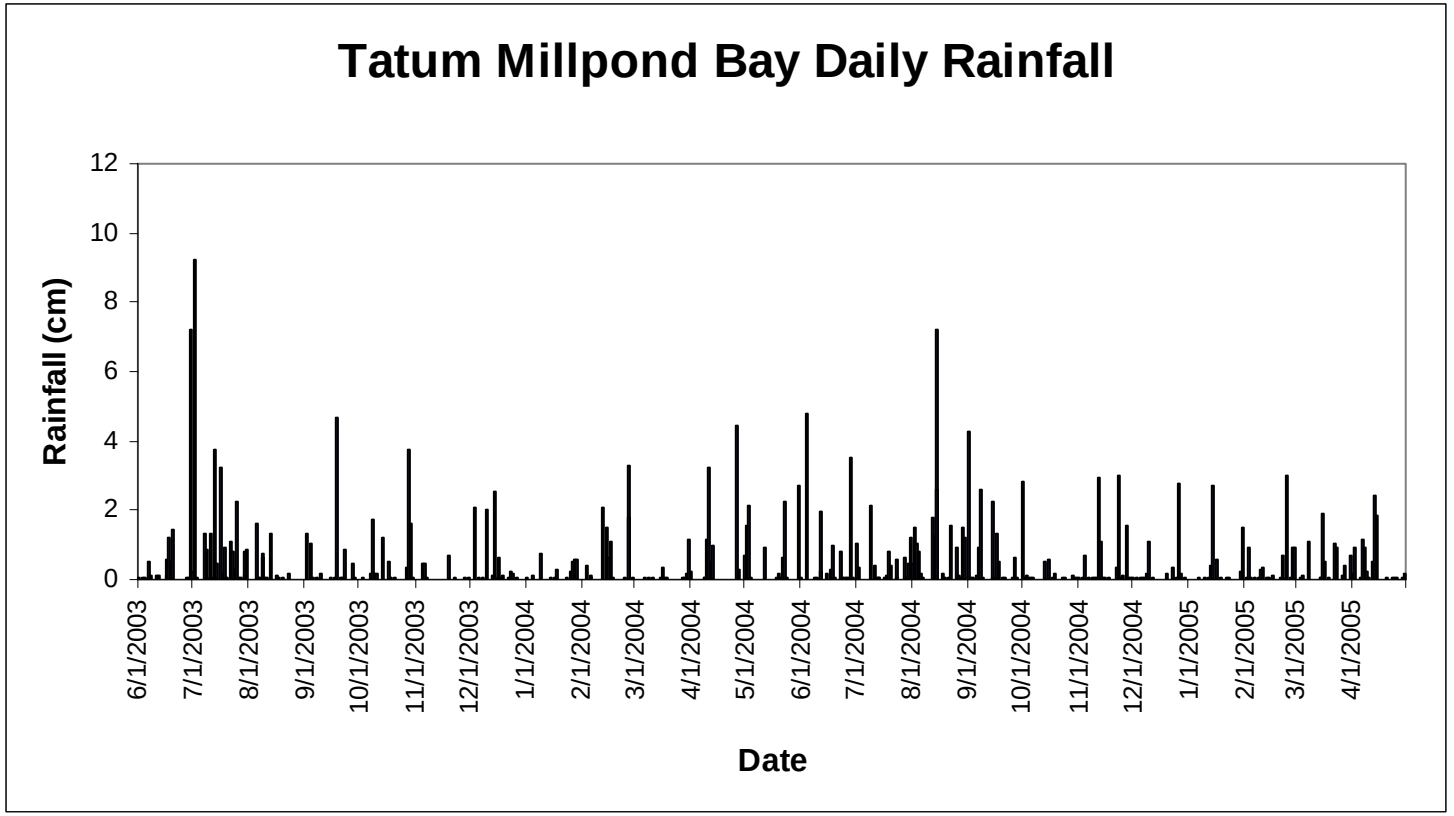

Figure B.3. Rainfall amounts at Tatum Millpond Bay during model calibration period.

APPENDIX C

MODEL SIMULATION RESULTS

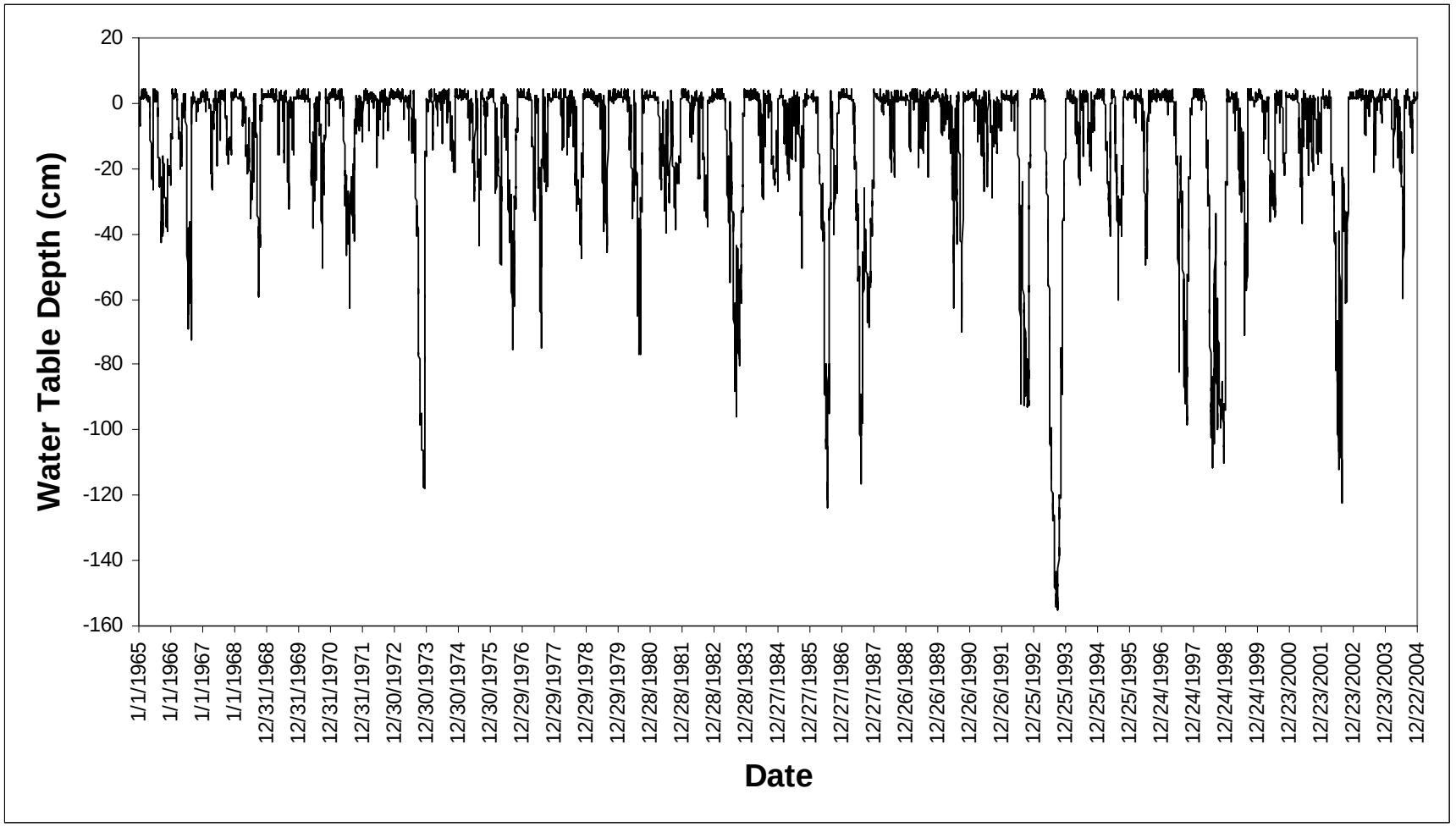

Figure C.1. Water table depths over the 40-yr DRAINMOD simulation for well no. 1 in Charlie Long Millpond Bay.

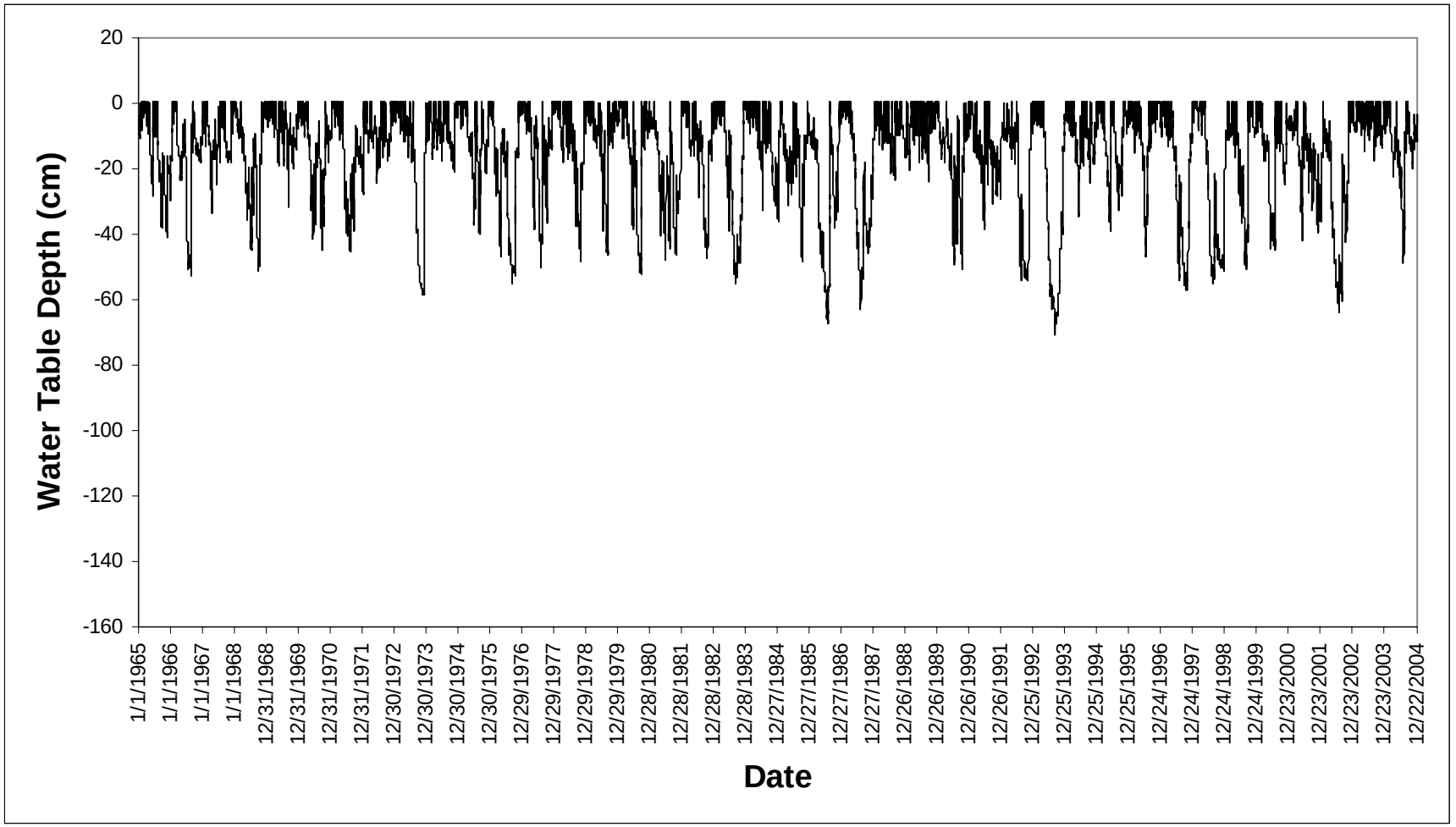

Figure C.2. Water table depths over the 40-yr DRAINMOD simulation for well no. 2 in Charlie Long Millpond Bay.

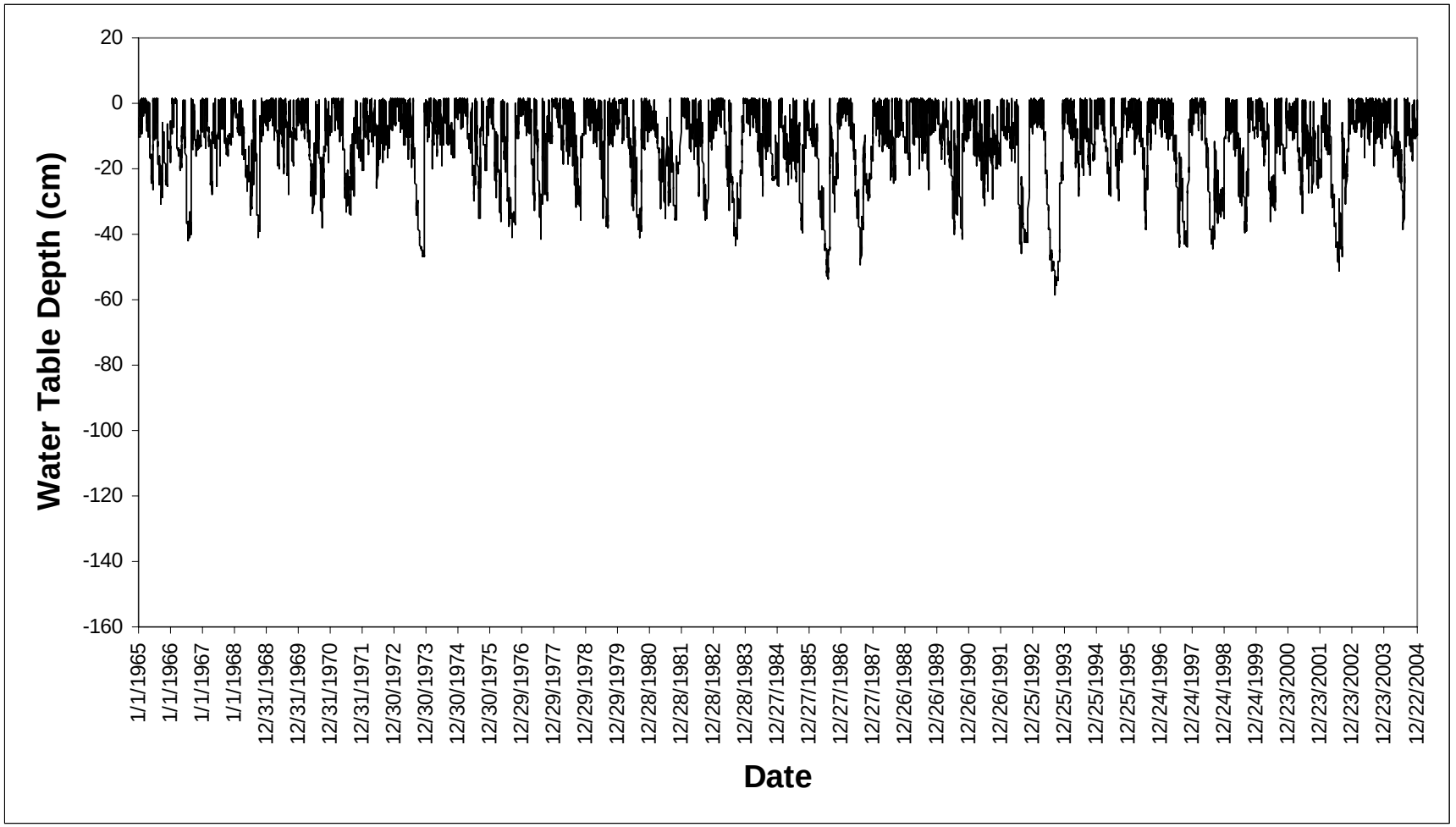

Figure C.3. Water table depths over the 40-yr DRAINMOD simulation for well no. 3 in Charlie Long Millpond Bay.

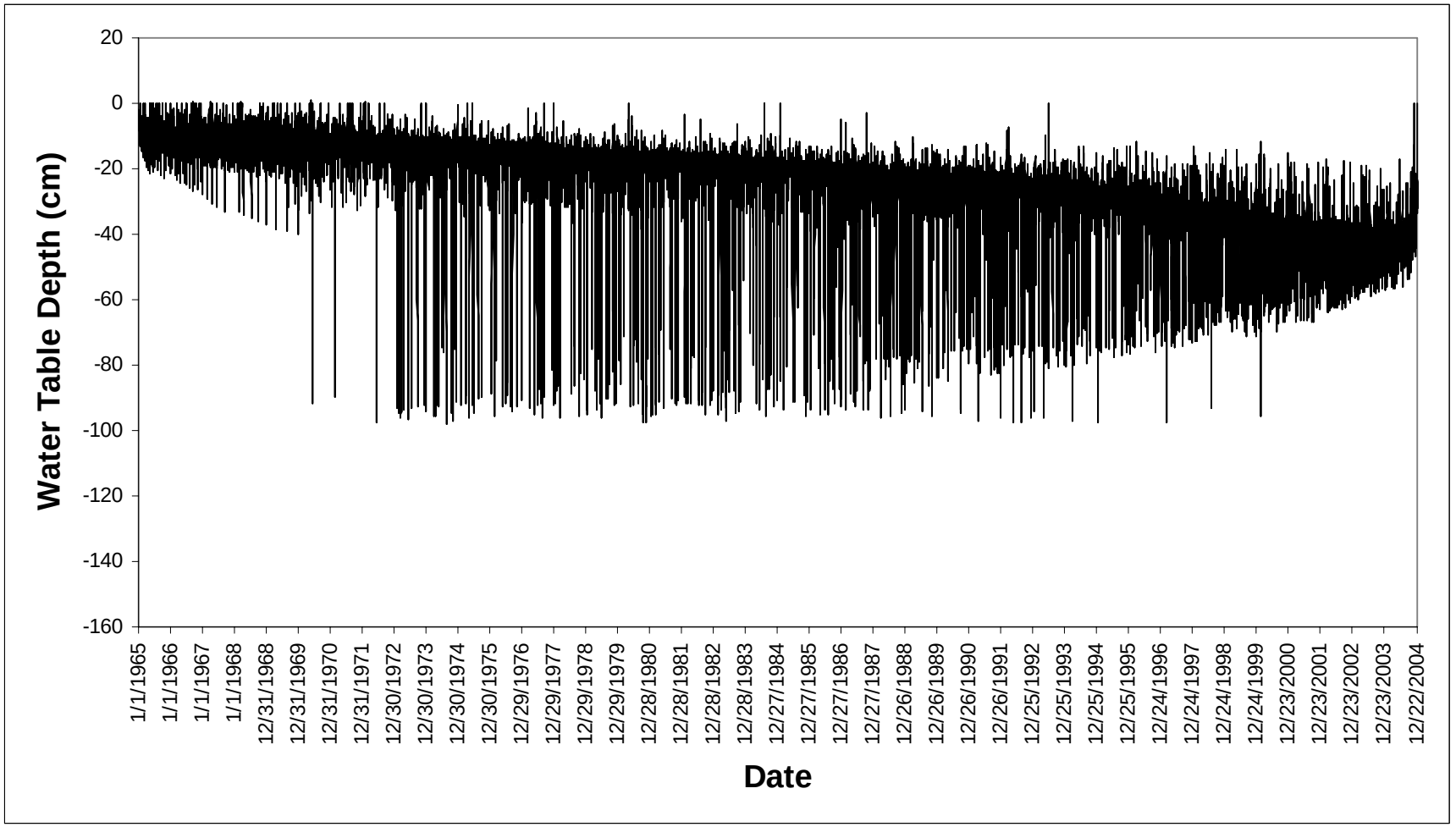

Figure C.4. Water table depths over the 40-yr DRAINMOD simulation for well no. 4 in Charlie Long Millpond Bay.

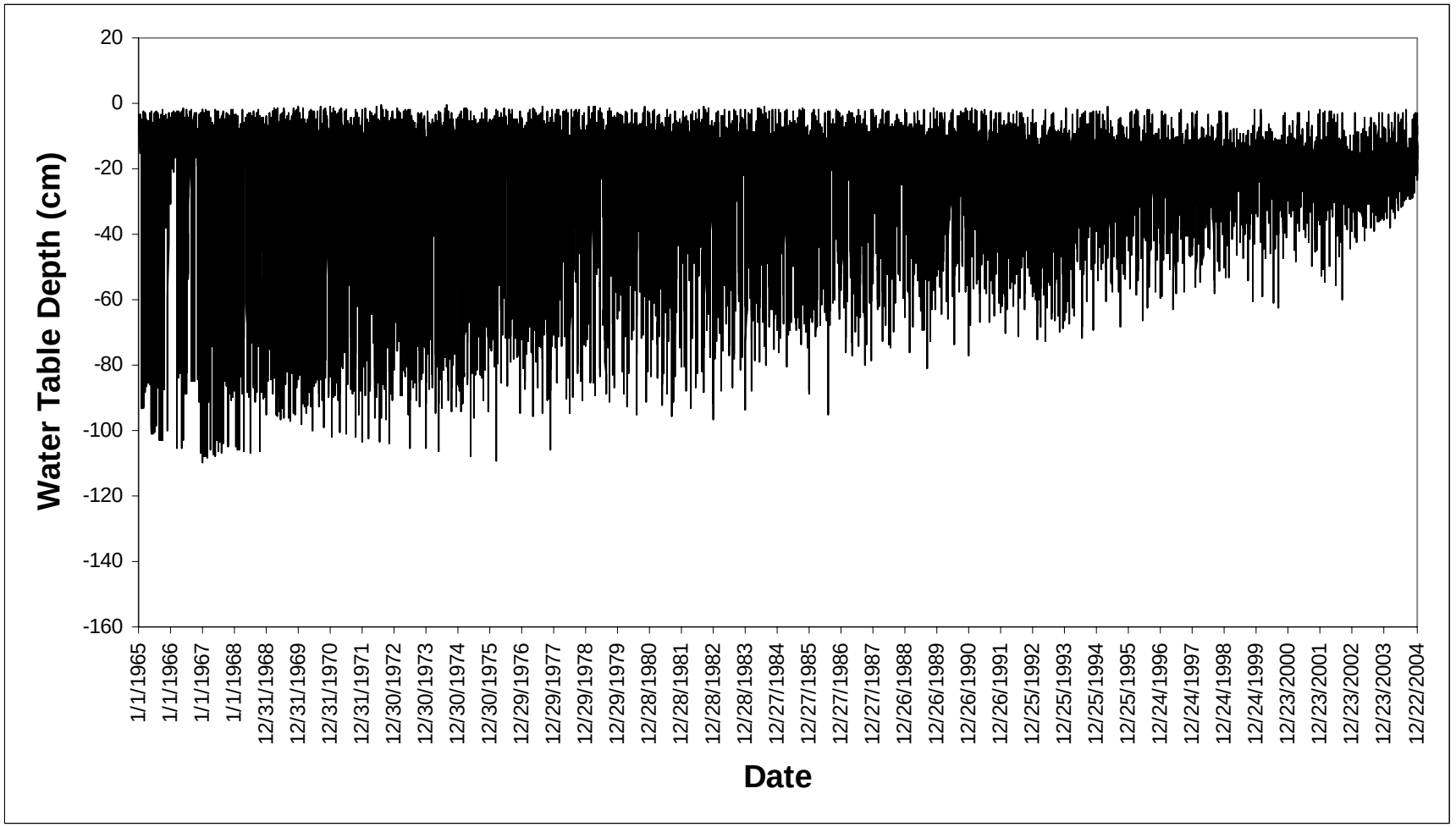

Figure C.5. Water table depths over the 40-yr DRAINMOD simulation for well no. 1 in Causeway Bay.

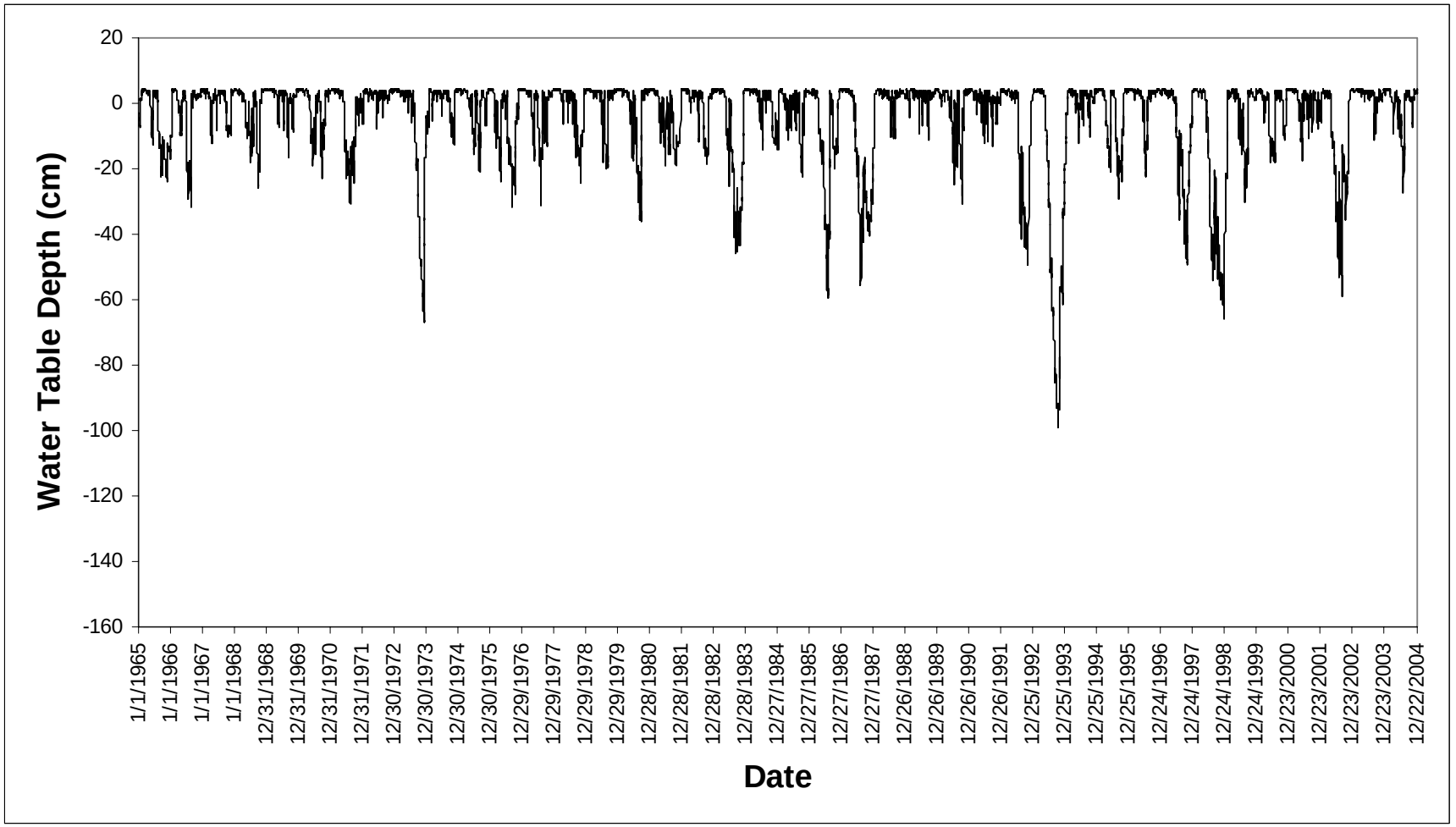

Figure C.6. Water table depths over the 40-yr DRAINMOD simulation for well no. 2 in Causeway Bay.

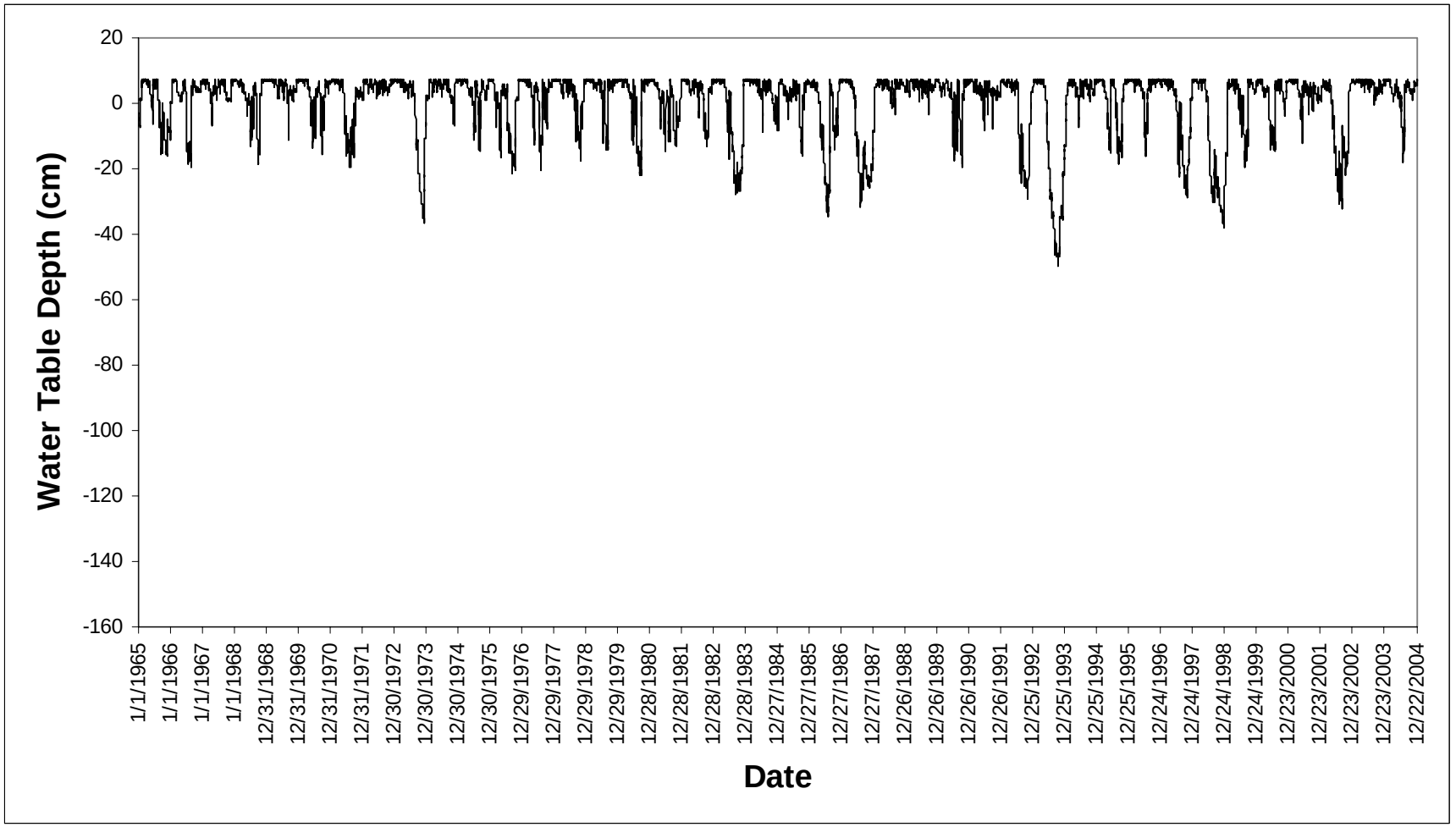

Figure C.7. Water table depths over the 40-yr DRAINMOD simulation for well no. 3 in Causeway Bay.

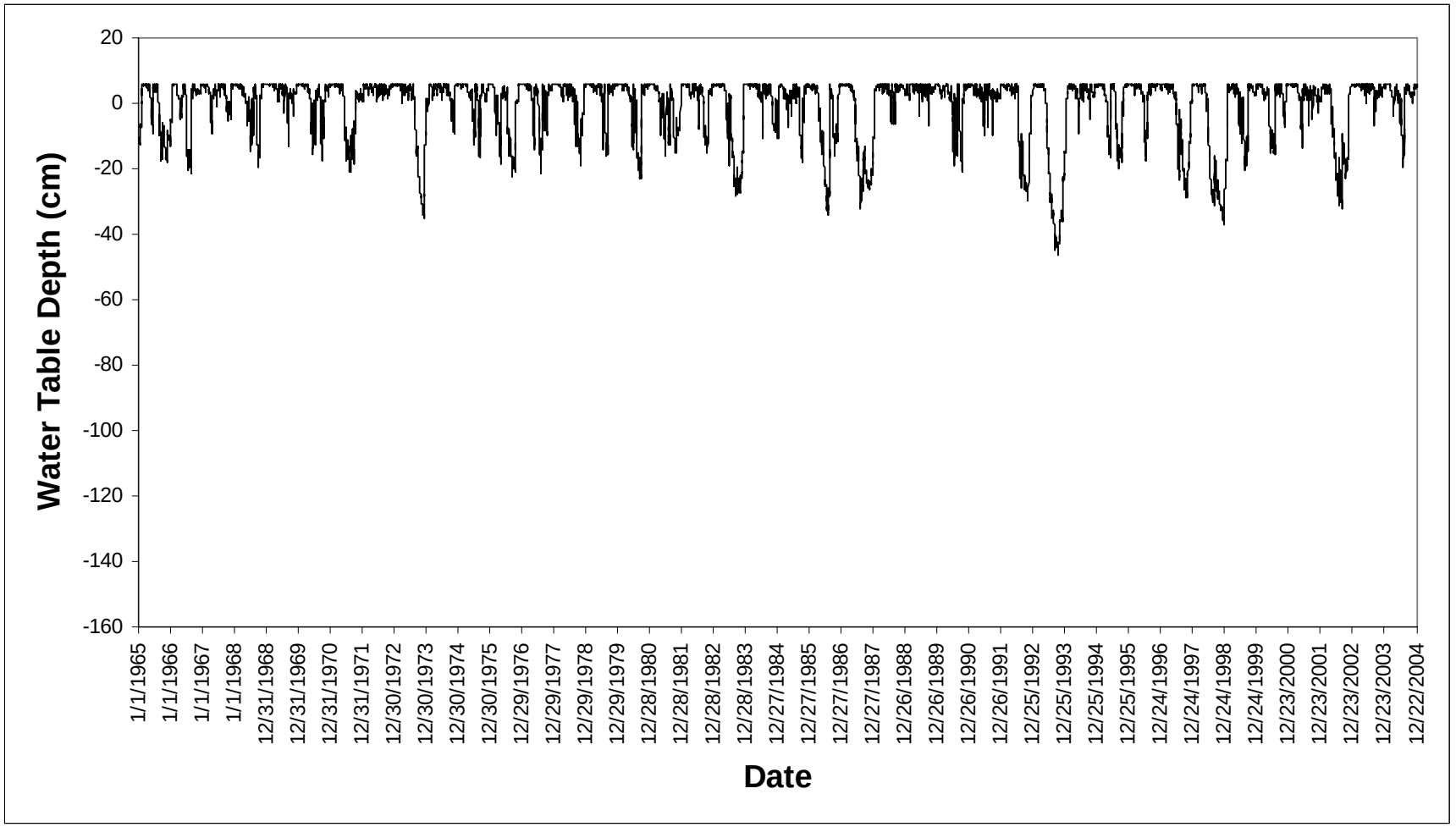

Figure C.8. Water table depths over the 40-yr DRAINMOD simulation for well no. 4 in Causeway Bay.

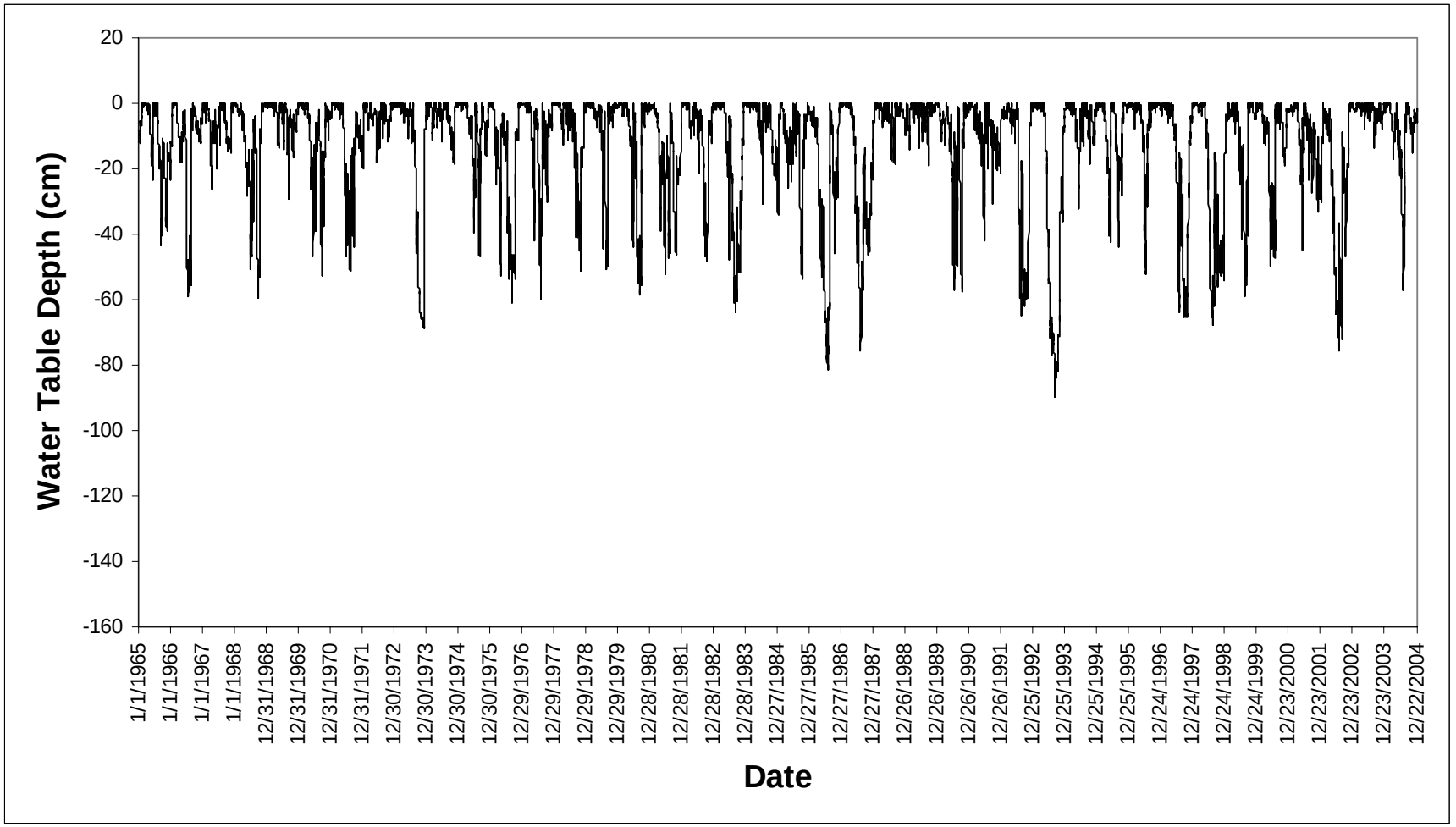

Figure C.9. Water table depths over the 40-yr DRAINMOD simulation for well no. 1A in Tatum Millpond Bay.

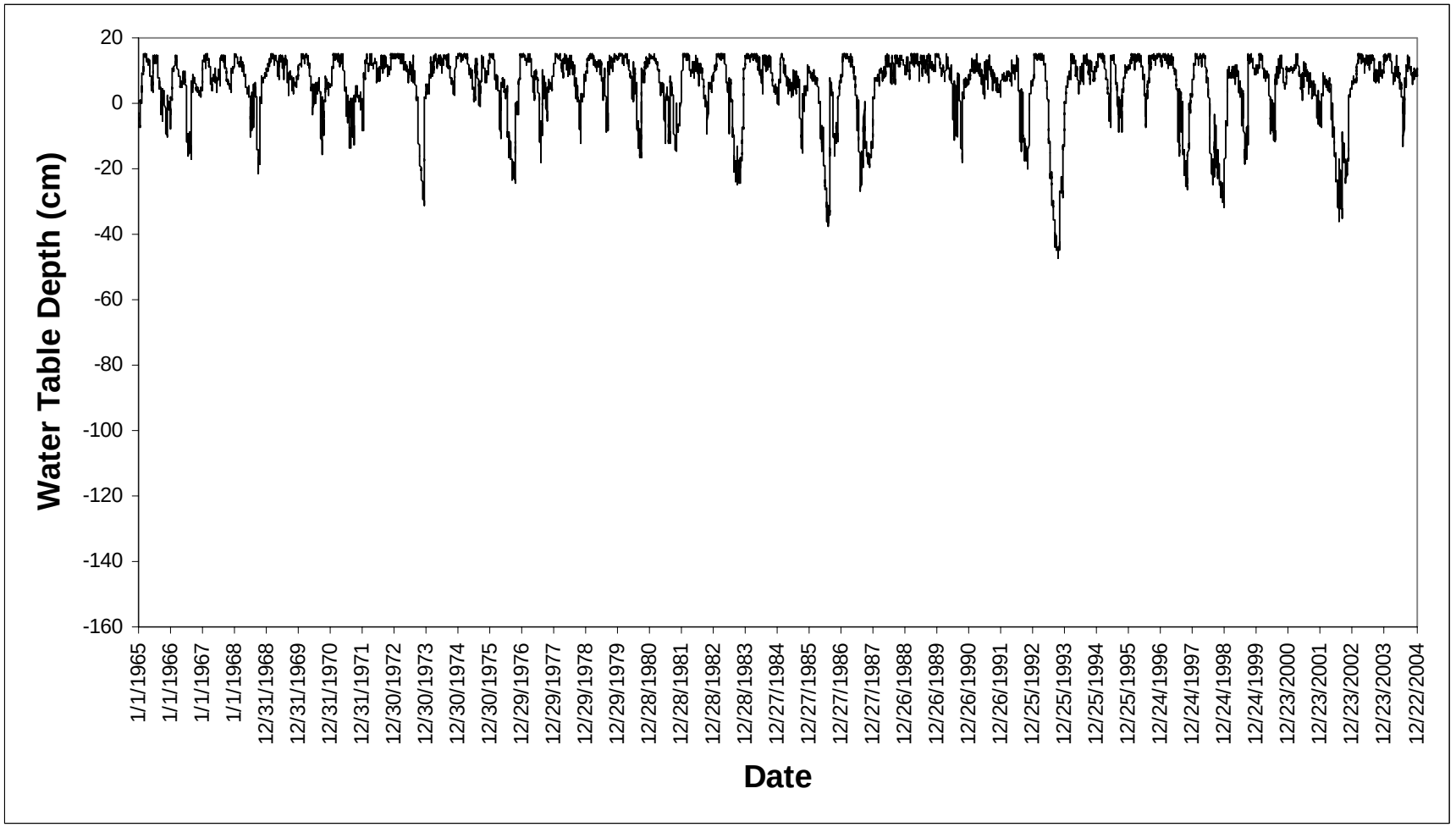

Figure C.10. Water table depths over the 40-yr DRAINMOD simulation for well no. 2 in Tatum Millpond Bay.

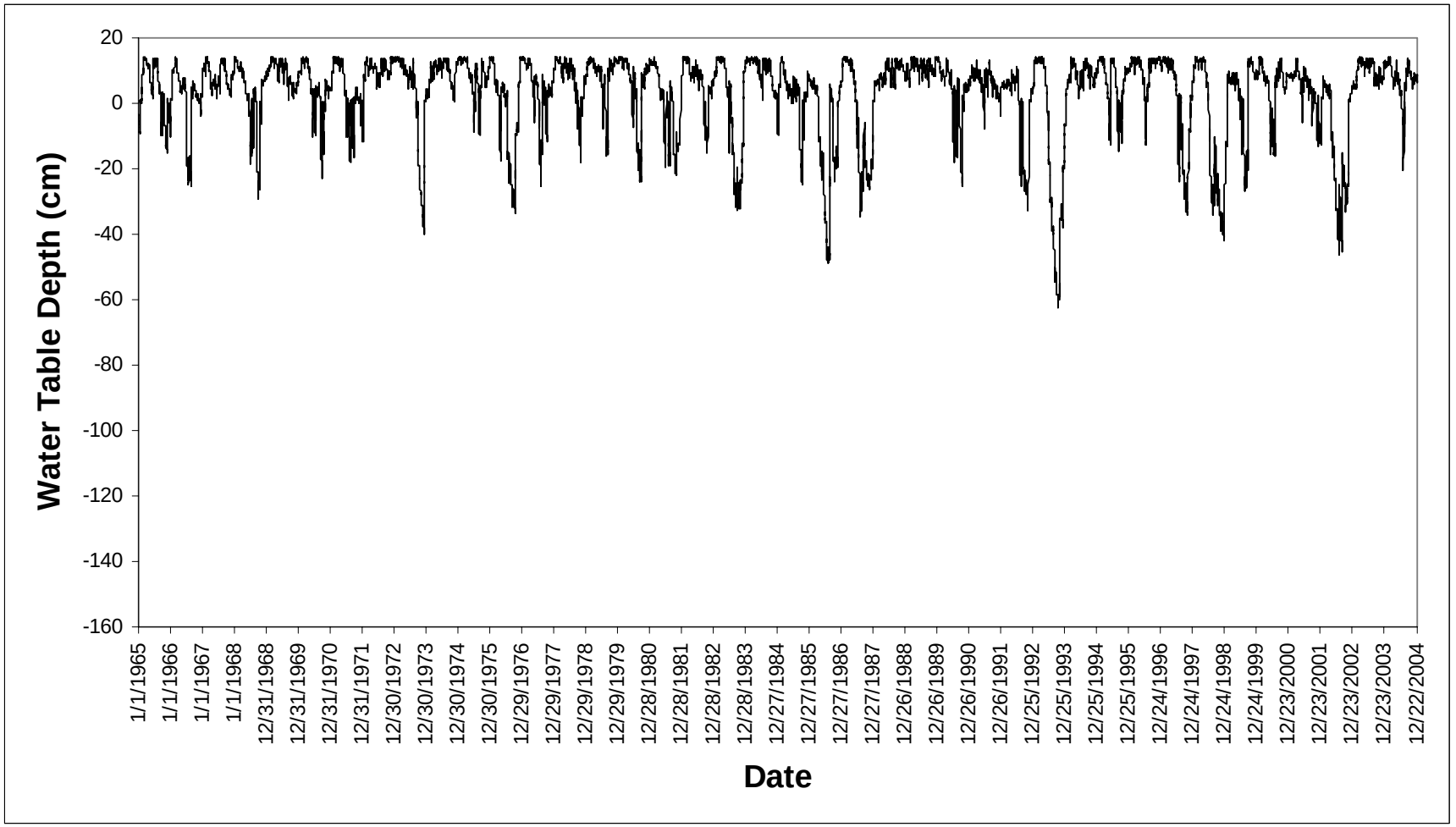

Figure C.11. Water table depths over the 40-yr DRAINMOD simulation for well no. 2A in Tatum Millpond Bay.

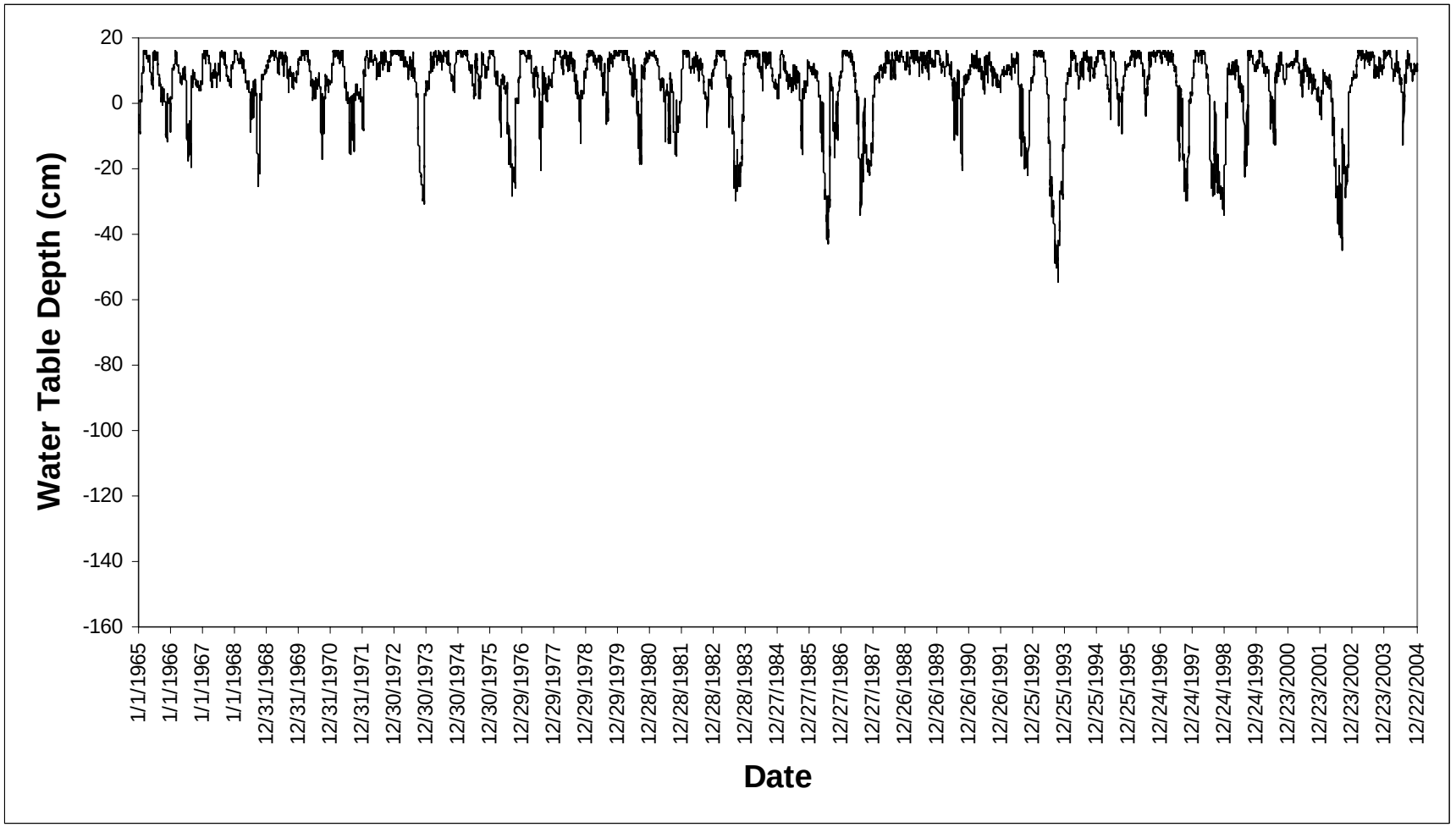

Figure C.12. Water table depths over the 40-yr DRAINMOD simulation for well no. 3 in Tatum Millpond Bay.

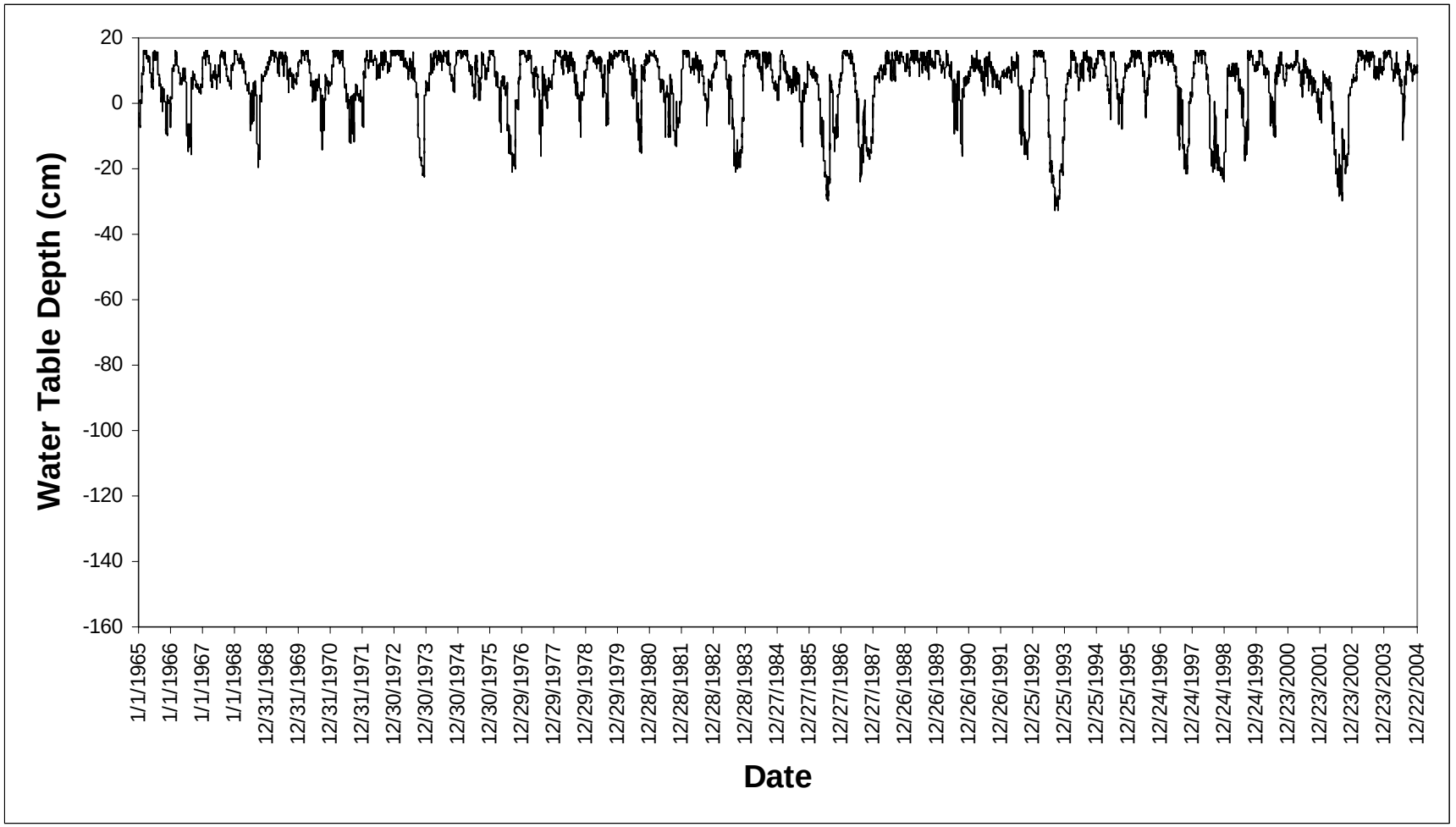

Figure C.13. Water table depths over the 40-yr DRAINMOD simulation for well no. 4 in Tatum Millpond Bay.

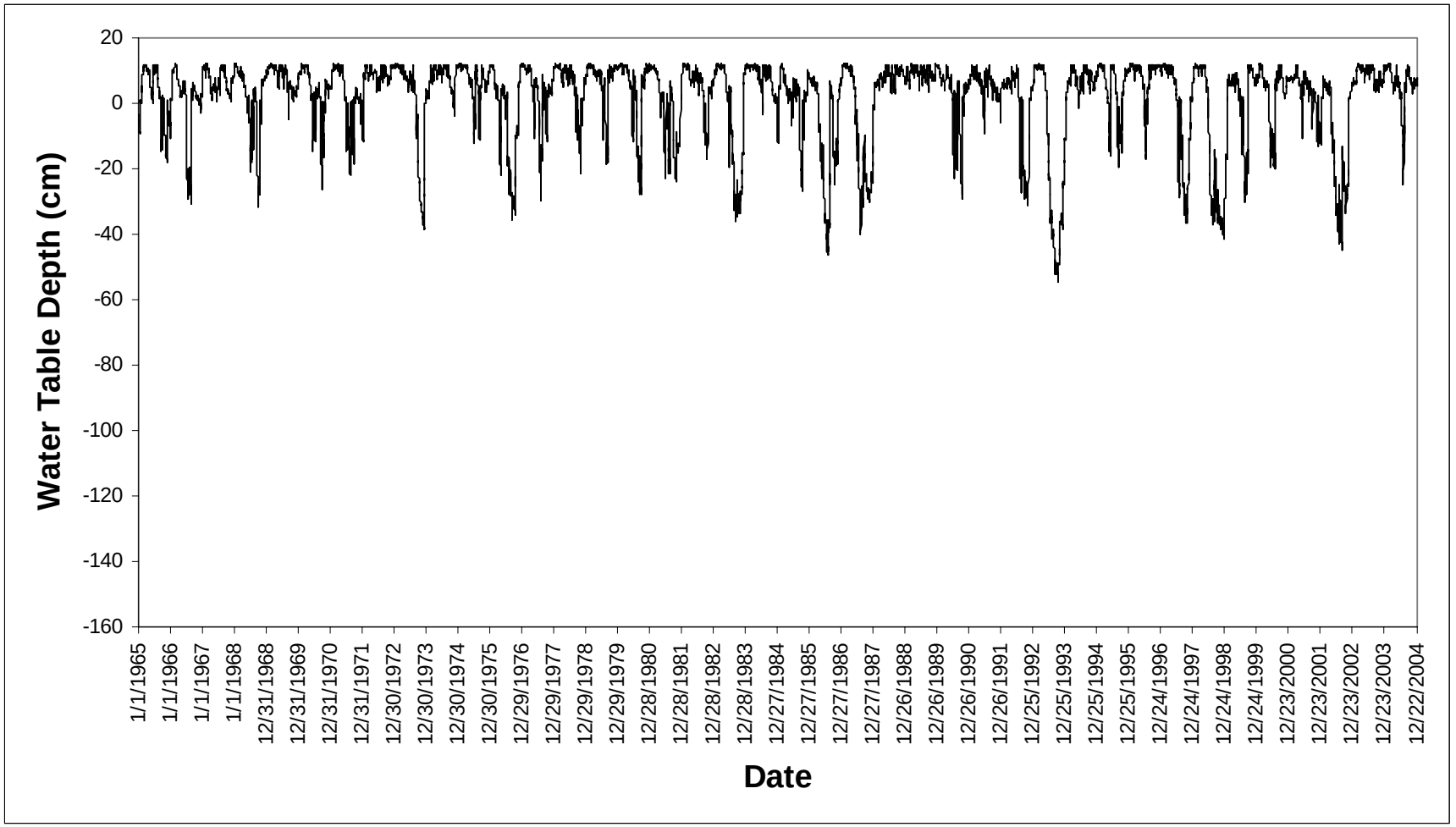

Figure C.14. Water table depths over the 40-yr DRAINMOD simulation for well no. 5 in Tatum Millpond Bay.

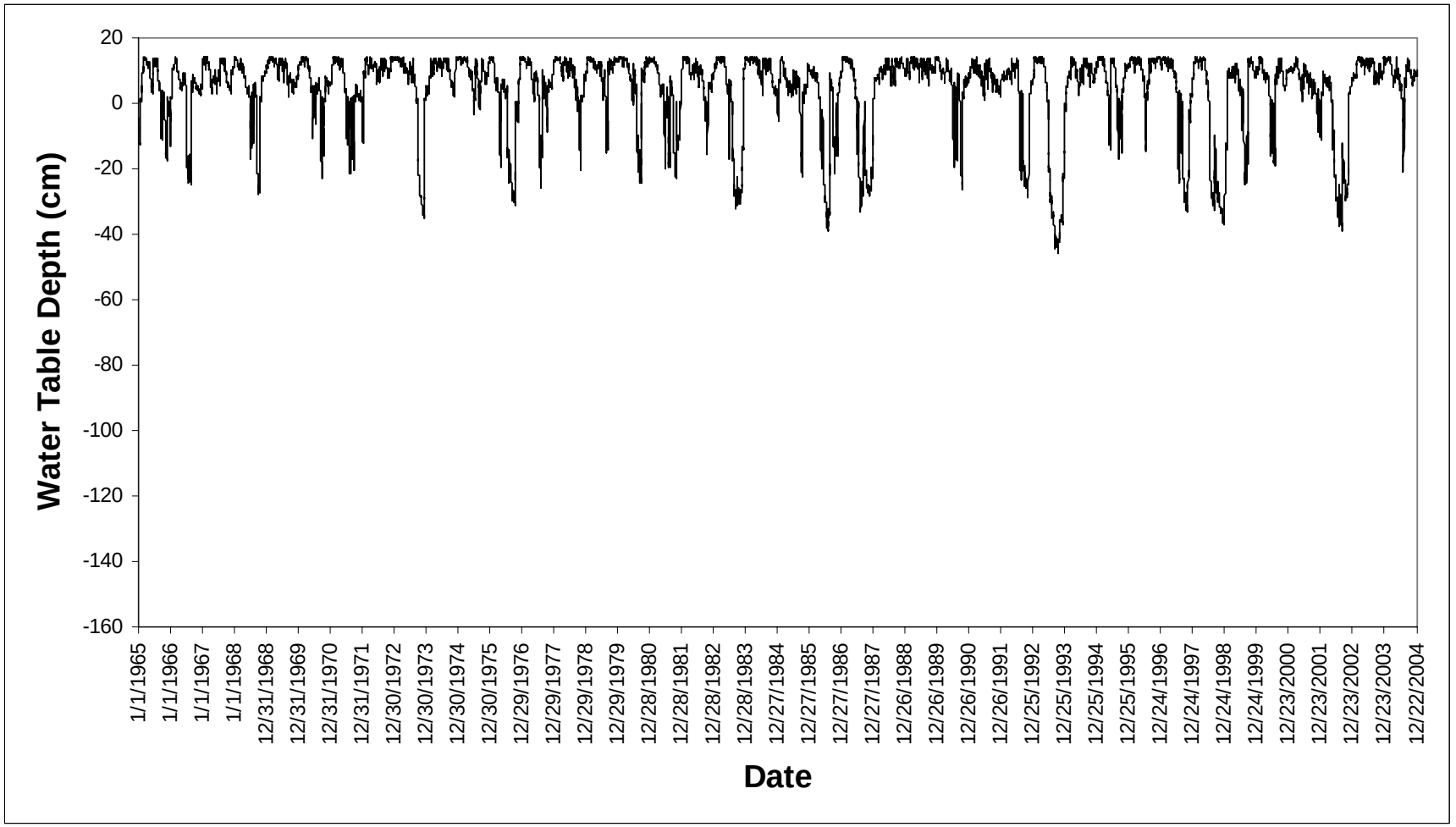

Figure C.15. Water table depths over the 40-yr DRAINMOD simulation for well no. 6 in Tatum Millpond Bay.

APPENDIX D

PLANT COMMUNITY HYDROLOGY PARAMETERS

Table D.1. Plant community hydrology parameters calculated from 40 yr simulated water table depths.

		Plant Community			
		Pond Pine Woodland N = 6	Nonriverine Swamp Forest N = 3	High Pocosin* N = 3	Bay Forest N = 2
Soil					
Depth of Organic	cm	23.2 ± 4.4[a]	48.0 ± 13.2	125.7 ± 49.4	180+
Water Balance Components					
Percent of total water input lost through ET	%	55.4 ± 2.9	64.3 ± 0.0	64.3 ± 0.0	64.3 ± 0.0
Percent of total water input lost as surface runoff	%	14.8 ± 4.6	16.6 ± 0.6	25.7 ± 4.6	18.4 ± 0.4
Percent of total water input lost as groundwater outflow	%	29.8 ± 6.5	18.9 ± 0.6	9.8 ± 4.5	17.2 ± 0.4
Percent of total water input from groundwater inflow	%	13.8 ± 4.5	0.0	0.0	0.0
Hydrograph Statistics					
40 year average water table depth	cm	-15.1 ± 3.2	5.2 ± 1.1	2.3 ± 2.4	3.2 ± 1.3
Standard deviation of 40 year daily water table depth	cm	17.7 ± 1.6	11.3 ± 0.7	9.6 ± 0.1	12.3 ± 0.3

Table D.1 (continued).

		Pond Pine Woodland	Nonriverine Swamp Forest	High Pocosin*	Bay Forest
Ponding					
Average ponding depth	cm	0.8 ± 0.5	9.5 ± 0.6	5.1 ± 2.0	8.3 ± 0.8
Percent of total days	%	24.4 ± 12.4	84.0 ± 1.8	79.7 ± 3.3	81.9 ± 2.5
Average total days per year	$d\ y^{-1}$	89.0 ± 45.4	307.0 ± 6.4	291.2 ± 12.1	299.0 ± 9.1
Average consecutive days of an occurrence	d	14.6 ± 8.7	123.5 ± 18.8	111.1 ± 20.6	104.4 ± 6.4
Percent of occurrences lasting less than 10 consecutive days	%	63.3 ± 17.0	44.7 ± 3.0	35.6 ± 1.0	48.1 ± 3.0
Percent of occurrences lasting 200-300 consecutive days	%	0.8 ± 0.8	14.4 ± 1.0	16.0 ± 0.3	15.0 ± 0.4
Water table below effective rooting zone (45 cm)					
Percent of total days	%	8.0 ± 1.5	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.2
Years out of 40 with an occurrence	y	26.5 ± 4.2	2.0 ± 0.6	0.7 ± 0.3	2.0 ± 1.0
Average total days per year	$d\ y^{-1}$	29.3 ± 5.6	1.2 ± 0.6	0.4 ± 0.3	0.9 ± 0.8
Average maximum consecutive days per year	$d\ y^{-1}$	13.0 ± 3.7	1.1 ± 0.5	0.3 ± 0.3	0.7 ± 0.7
Maximum consecutive days over 40 year simulation	$d\ y^{-1}$	96.3 ± 29.5	36.7 ± 17.1	12.7 ± 10.3	28.0 ± 26.0
Years out of 40 with occurrence lasting at least 10 consec. days	y	8.8 ± 3.3	1.3 ± 0.3	0.3 ± 0.3	0.5 ± 0.5
Years out of 40 with occurrence lasting at least 20 consec. days	y	6.5 ± 2.6	0.7 ± 0.3	0.3 ± 0.3	0.5 ± 0.5

Table D.1 (continued).

		Pond Pine Woodland	Nonriverine Swamp Forest	High Pocosin*	Bay Forest
Water table reaching mineral soil					
Percent of total days	%	20.0 ± 3.3	0.7 ± 0.4	0.9 ± 0.9	0.0
Years out of 40 with an occurrence	y	36.0 ± 1.4	3.3 ± 1.7	3.0 ± 3.0	0.0
Average total days per year	$d\ y^{-1}$	73.2 ± 17.7	2.6 ± 1.3	3.2 ± 3.2	0.0
Average maximum consecutive days per year	$d\ y^{-1}$	36.7 ± 11.6	2.4 ± 1.2	3.0 ± 3.0	0.0
Maximum consecutive days over 40 year simulation	$d\ y^{-1}$	130.5 ± 40.0	53.7 ± 26.8	46.7 ± 46.7	0.0
Years out of 40 with occurrence lasting at least 20 consec. days	y	17.3 ± 5.7	1.3 ± 0.7	0.7 ± 0.7	0.0
Years out of 40 with occurrence lasting at least 60 consec. days	y	8.2 ± 3.1	0.7 ± 0.3	0.7 ± 0.7	0.0

* Charlie Long Millpond Bay well no. 3 not included in average water table depth parameters for the high pocosin plant community.

[a] Standard error.