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MODELING THE CLIMATIC AND SUBSURFACE STRATIGRAPHY CONTROLS ON THE HYDROLOGY OF A CAROLINA BAY WETLAND IN SOUTH CAROLINA, USA

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Abstract: Restoring depressional wetlands or geographically isolated wetlands such as cypress swamps and Carolina bays on the Atlantic Coastal Plains requires a clear understanding of the hydrologic processes and water balances. The objectives of this paper are to (1) test a distributed forest hydrology model, FLATWOODS, for a Carolina bay wetland system using seven years of water-table data and (2) to use the model to understand how the landscape position and the site stratigraphy affect ground-water flow direction. The research site is located in Bamberg County, South Carolina on the Middle Coastal Plain of the southeastern U.S. (32.88° N, 81.12° W). Model calibration (1998) and validation (1997, 1999–2003) data span a wet period and a long drought period, which allowed us to test the model for a wide range of weather conditions. The major water input to the wetland is rainfall, and output from the wetland is dominated by evapotranspiration. However, the Carolina bay is a flow-through wetland, receiving ground water from the adjacent upland, but recharging the ground-water to lower topographic areas, especially during wet periods in winter months. Hypothetical simulations suggest that ground-water flow direction is controlled by the gradient of the underlying hydrologic restricting layer beneath the wetland-upland continuum, not solely by the topographic gradient of the land surface. Ground-water flow may change directions during transition periods of wetland hydroperiod that is controlled by the balance of precipitation and evapotranspiration, and such changes depend on the underlying soil stratigraphy of the wetland-upland continuum.

Key Words: wetland hydrology, ground water, Carolina bays, modeling, geomorphology

INTRODUCTION

Depressional wetlands, or geographically isolated wetlands, such as cypress (*Taxodium ascendens* Brongn.) swamps and Carolina bays, are common land features in the Atlantic Coastal Plain of the southeastern U.S. (Tiner et al. 2002). They vary in size from less than a hectare to more than several hundred hectares. Depressional wetlands may be undisturbed for a long period of time, but their surrounding 'uplands' are often managed for timber or agricultural production due to drier soil conditions. These wetlands occur on flat topography between river divides and have no apparent surface-water connections with rivers or lakes. However, in locations where the water-table is close to ground surface, depressional wetlands can become temporarily connected to other water bodies through overland sheet flow (Winter and LaBaugh 2003). Shallow ground-water flow also links the surface-water in the wetland to its surrounding upland, especially when the entire landscape is wet, such as in the winter months (Sun et al. 2000).

Although isolated wetlands, like many other types of wetlands, play important roles in providing wildlife habitats (Sharitz 2003), ground-water recharge, water quality improvement, and carbon sequestration (Li et al. 2003), they are under enormous stress from both land development and climate change and variability (U.S. Global Change Program 2000). Understanding their hydrologic processes is one of the keys to wetland restoration and management (De Steven and Toner 2004). Wetland hydrology of depressional wetlands, as controlled by water levels within the wetland and surrounding uplands, is complex because of the dynamic nature of ground-water and surface-water interactions (Sun et al. 2000; Bliss and Comerford, 2002). The hydrogeomorphic (HGM) wetland classification scheme (flat, depressional, riverine, etc.) stresses the important topographic and geologic control on wetland hydrology at a landscape scale (Brinson 1993). Lide et al. (1995) found that ground-water-surface-water interactions were variable depending on both climate and local soil layering and geology, but few studies have explicitly explored the causes of the interactions. In a hydrologic study on cypress swamps in north-central Florida, USA, Sun et al. (2000) suggested that lateral ground-water-surface-water interactions were common, but the largest fluxes were during the wet-dry transition periods, whereas the hydraulic gradients were reduced during both dry and wet periods. They concluded that the interactions between ground water and surface-water in wetlands were not well connected to the deeper aquifers, and thus, vertical exchange of ground water was not common.

While field investigations provide many insights into the complex interactions among climate, surface-water, ground-water, and surface and subsurface soils, they are often time-consuming and expensive. It is often difficult to determine if the wetland hydrology observed during the monitoring period is actually typical for the region. Computer simulation models can be helpful in determining the detailed processes and fluxes of water flows over both space and time by less expensive means and at scales that are not feasible with field experiments. Furthermore, a well validated model can be used to answer 'what if' management questions (Skaggs et al. 1991). For depressional wetlands, water-table levels are essentially controlled by two types of fluxes, one in the vertical direction (precipitation and evapotranspiration) and another in the lateral direction (shallow ground-water flows). Thus, this requires a multi-dimensional model to describe fully the hydrology of depressional wetlands (Mansell et al. 2000). A comprehensive model that captures the full hydrologic cycle also acts as an integration tool to link all variables and hydrologic fluxes measured at a research site and is useful to identify gaps in monitoring.

Several hydrologic models are available for modeling the water budgets of wetland ecosystems in the southern U.S. The most widely used is the lumped DRAINMOD model (Skaggs et al. 1991) that was designed for and is most applicable to drained flat landscapes with parallel ditches. The model can simulate the spatial distribution of water-table dynamics of each 'drained field' but is limited in describing explicitly the hydrologic interactions of surface water and ground water in a wetland-upland system. The WETLANDs model (Mansell et al. 2000) describes the hydrology of a wetland-upland system by the combination of 2-D Richard's equation and the water balance in wetland. This model has the capability to include the heterogeneity of both geology/soils and land cover. Other lumped wetland hydrology models, such as SWAT (Arnold et al. 2001) and Soil Water Balance Model (Walton et al. 1996 cited in Arnold et al. 2001), cannot simulate the lateral interactions of surface-water and ground-water interactions at the interface between a wetland and its upland.

The overall goal of this study was to use a computer model as an alternative tool to understand the hydrologic processes in Carolina bays. Specially, the objectives of this paper were (1) to test and validate a distributed forest hydrology model, FLATWOODS, for a Carolina bay wetland system using seven years of water-table data and (2) to apply the validated model to predict the effects of climate and subsurface soil layering or stratigraphy on lateral ground-water flow directions (i.e., ground-water and surface-water interactions).

METHODS

The FLATWOODS Model

The FLATWOODS forest hydrology model was originally developed for the flatwoods ecosystems, a mosaic of cypress swamps and slash pine uplands of Florida, U.S.A, a region dominated by poorly-drained soils, low topographic relief, and high precipitation and evapotranspiration rates (Sun et al. 1998a, b). The advantages of using this model in other locations of

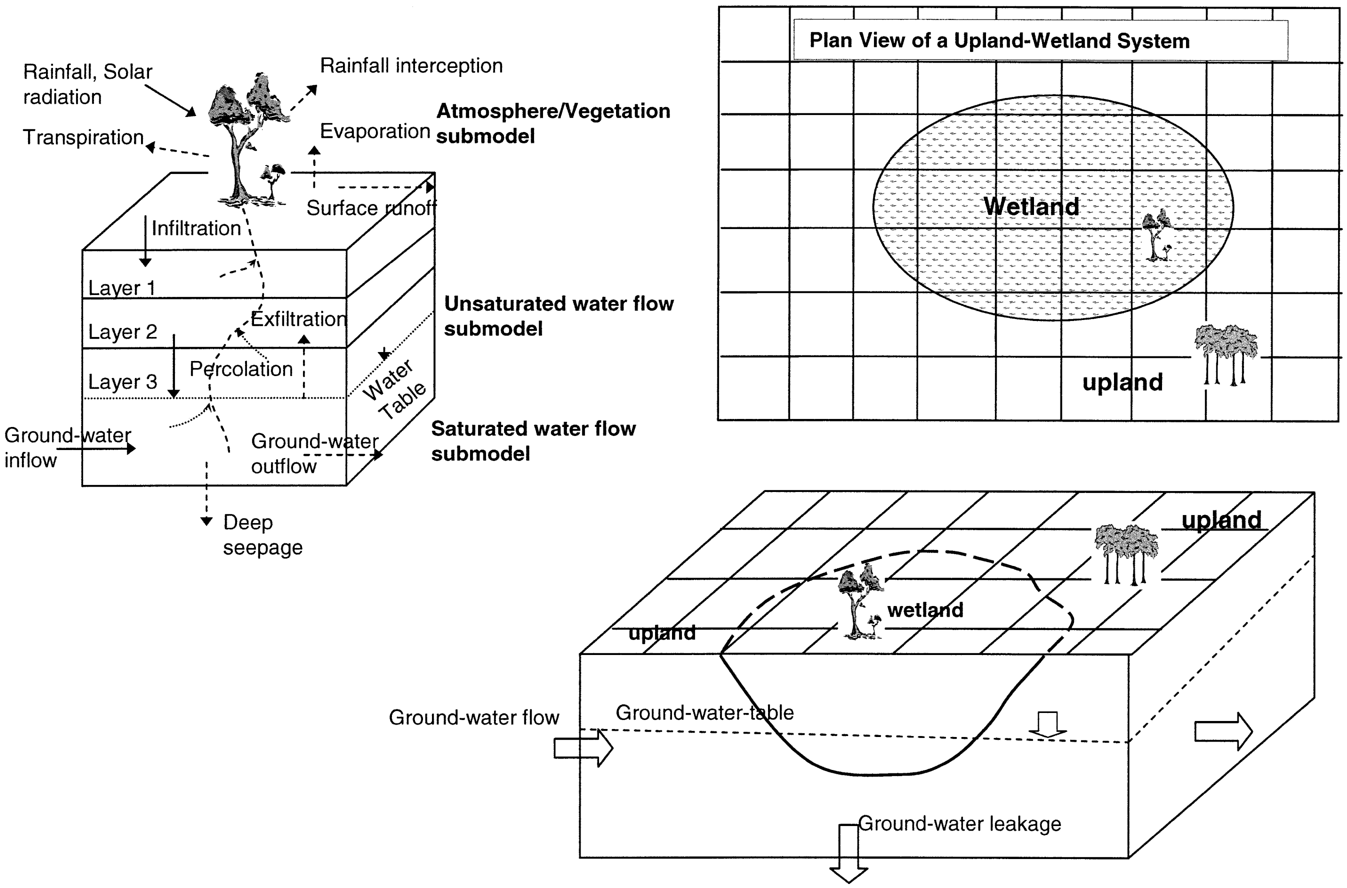

Figure 1. Sketch of the FLATWOODS model structure and hydrologic components.

the Southeastern U.S. are 1) it has been validated for humid, warm, poorly drained forested conditions, and 2) it is a distributed model that simulates the complete hydrologic cycle of both a wetland and its surroundings, including evapotranspiration, vertical soil-water flow (infiltration and soil moisture redistribution), and lateral ground-water flow in a shallow unconfined aquifer. Most importantly, the model can explicitly simulate the hydrologic interactions between a wetland and upland through the lateral ground-water-flow component. The FLATWOODS model includes three major submodels, or modules, to simulate the spatial distribution of ground-water-table and hydrologic fluxes. At a gridded 'cell' level, the evapotranspiration module simulates daily water loss due to forest canopy interception, plant transpiration, and soil/water evaporation as a function of potential evapotranspiration, rooting depth, and plant growth stage. Daily potential evapotranspiration rate is calculated by Hamon's method (Hamon 1963) as a function of air temperature and day light hours (Fedder and Lash 1978). The unsaturated water-flow module uses a simple water-budget algorithm to estimate recharge to the shallow ground-water system beneath the unsaturated soil zone. Recharge was calculated as the surplus of daily net precipitation data (atmosphere precipitation—canopy interception) above soil-water field capacity. Infiltrated water first fills up the available storage of the unsaturated zone before recharging the surficial aquifer. The ground-water-flow module is the core of the modeling system. This module tracks the water- table hydraulic head of each gridded cell using a 2-D (x and y) ground-water-flow algorithm that simulates the water-table fluctuations as a function of evapotranspiration loss from the aquifer, water loss due to surface outflow, recharge to shallow aquifers, and water loss/gain from surrounding neighbor cells. Surface outflow occurs only when the ground-water table reaches the ground surface. Surface water is allowed to move out of the model boundary in one time step (one day). The model structure is presented in Figure 1 to illustrate the modeling components and interactions of water fluxes in a wetland-upland landscape. Details of model algorithms, model validation, and application in pine flatwoods are found in Sun et al. (1998a, b). Key model input and output variables and calibrated soil parameters are listed in Table 1.

Table 1. Major model inputs and outputs of the FLATWOODS hydrologic model.

Model Overview		Variables and Parameters
Input requirements	Climate	Measured daily precipitation, average air temperature for estimating potential evapotranspiration calculated using Hamon's method (Hamon 1963; Federer and Lash 1978)
	Vegetation	Deciduous in the wetlands and uplands; leaf areas vary with time with canopy interception rates reported by Helvey and Patric (1965). Leaf out date starts April 1 to full April 30, and leaf drop starts November 1 and ends November 30 according to field observation.
	Soils	Hydrologic restricting layer depth 4.0 and 3.0 m below ground for upland and wetland respectively; hydraulic conductivity: 3.7 m/day for upland; 0.37 m/day for wetland. Specific Yield: 0.05; porosity 0.35; plant wilting point 0.15 for both wetland and upland (parameter calibrated from initial values provided in the report by USDA SCS (1966).
Ouputs	Daily canopy interception, transpiration, soil evaporation, soil moisture content (%), ground-water-table depth.	

Study Site and Field Data Acquisition for Model Testing

The research site is in Bamberg County, South Carolina on the Middle Coastal Plain of the Southeastern U.S. (32.88° N, 81.12° W). Long-term (1951–2004) annual average air temperature and total precipitation in the region are 17.9 °C and 1210 mm, respectively (Southeast Regional Climate Center 2005). The precipitation patterns can be greatly influenced by tropical storms between the months of July and October when daily extremes are most likely to occur (Southeast Regional Climate Center 2005). A standard weather station at the study site recorded precipitation with a tipping bucket raingage and air temperature with a temperature probe (Campbell Scientific, Inc., Logan, UT). When on-site weather data were missing due to equipment failure, data collected at the Bamberg County weather station about 25 km from the study site were used.

Three Carolina bay ecosystems have been extensively monitored since 1997 by Pyzoha (2003). This modeling study focused only on Chapel Bay, one of the three intensively monitored Carolina Bay wetlands. We briefly describe methods employed in deriving various model parameters. Selected ground-water-table datasets are presented for justifying model setups for boundary conditions and evaluating model performance in calibration, validation, and application. Detailed field installation and data summary are reported by Pyzoha (2003).

The Chapel Bay wetland studied herein has an area of about 8 ha covered mostly by deciduous bottomland hardwood plants including water oak (*Quercus nigra* L.), willow oak (Q. *phello*s L.), black cherry (*Prunus serotina* Ehrh), swamp tupelo (*Nyssa biflora* Walt.), sweet gum (*Liquidambar styraciflua* L.), loblolly pine (*Pinus taeda* L.) and some pond cypress (*Taxodium ascendens*) in the interior. During the field data collection period of 1997–2003, the land-use types surrounding the Carolina bay were composed of crop lands, intensively-managed, short rotation hardwood plantations of sycamore (*Acer pseudoplatanus* L.) and cottonwood (*Populus deltoides* Bartr. ex Marsh.) and natural pine stands. The soil in the wetland is typified by poorly drained sandy loams, while wetland-upland margins and the uplands are dominated by better drained loamy sand or deep sandy soils (USDA SCS 1966).

Small changes of surface elevation will alter surface-water flow directions in this relatively flat landscape. Although a Digital Elevation Model (DEM) with a 30-m resolution is available, the surface elevations of the wetland and its surrounding area were resurveyed to a precision of 1.5 mm at 30-m measurement distance and geo-referenced into a 100-m by 100-m grid system for model setup and validation (Trimble Spectra Precision Laser Level, Trimble Navigation, Ltd., Sunnyvale, CA) (Figure 2). The highest elevation is in the northwest corner and the lowest in the south edge of the wetland. A highway (Highway 301) intersects with wetland at the southeast corner. Field inspection found several storm drains that connect the roadside ditches on both sides of the highway. Although the wetland has a berm at the dissected side of the wetland, field evidence suggested that surface water could flow over the barrier when the wetland is full.

The general stratigrahy of the wetland and surrounding upland area was determined from logs to approximately 10 m during well and piezometer installation. Water-table wells were constructed from PVC or stainless steel piping screened the entire length and installed to a depth up to 2.5 m. Piezometers were constructed with PVC pipes with a diameter of 3.8–5.1

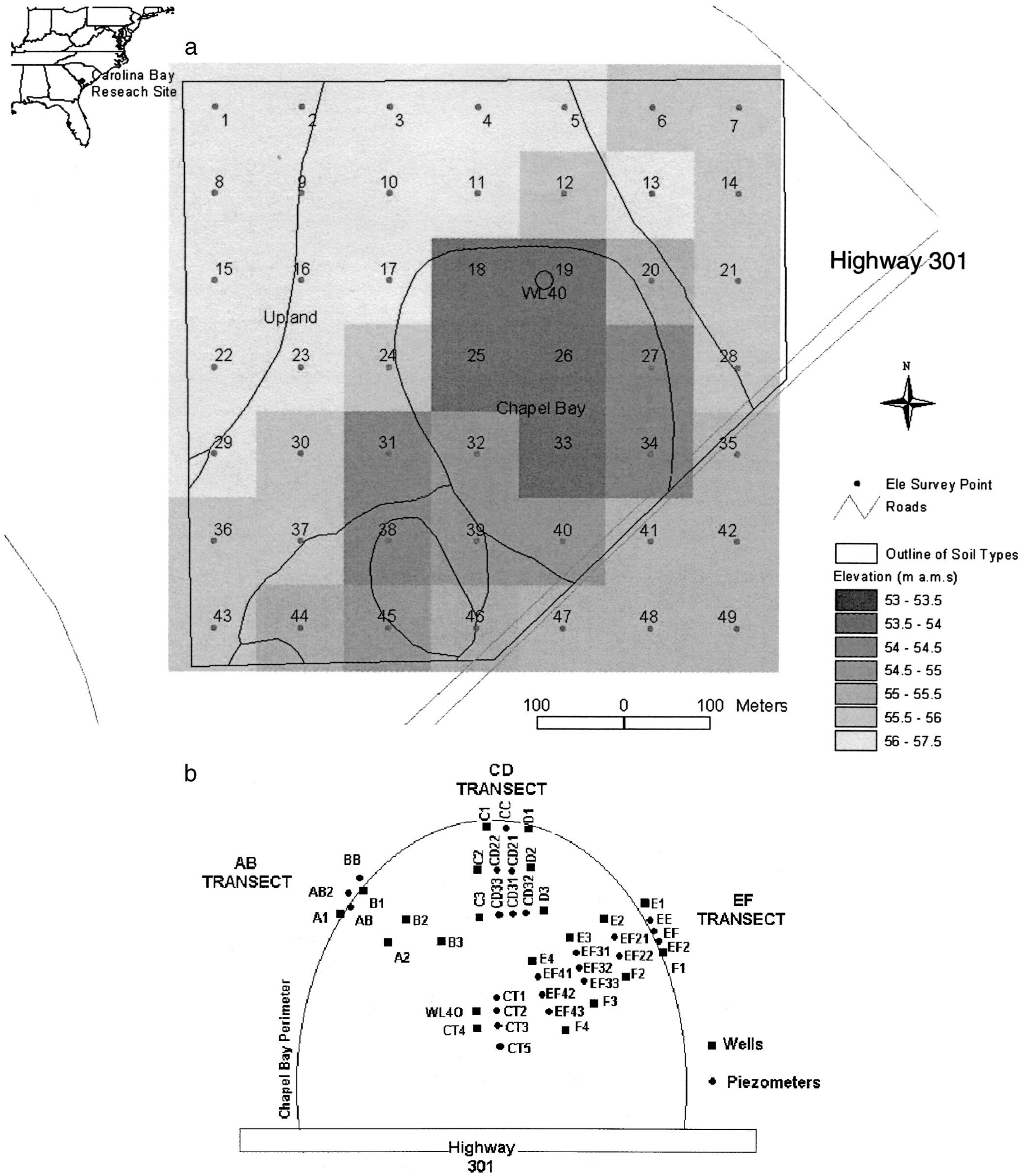

Figure 2. Model grid (100 m by 100 m) setup and surface elevation (a), and sketch of instrumentation (not to scale) (b), at the Chapel Bay research site.

cm with a porous ceramic cup sealed at the bottom and were installed to a depth up to 3.5 m and 9 m deep in the wetland and upland, respectively. In Chapel Bay and surrounding area, 21 wells and 24 piezometers were employed during different periods of the seven-year field study. Selected well or piezometer data were used in this study to justify model setups and validation. Complete data description was found in Pyzoha (2003).

Saturated hydraulic conductivity was determined by slug and bail tests (Bouwer and Rice 1976). Hydraulic conductivity values were measured in the range of 1.2–5.4 m/day for upland sediments with the well screen at about 4.5 m below the ground surface. Slug tests were not successful in wetlands, but the sediments in wetlands were suspected to have lower hydraulic conductivity values because of their greater clay contents. Hydraulic conductivity of wetland soils with sandy loams and sandy clay loams have a range of 0.5–1.5 m/day (USDA SCS 1966). A clay layer about 1–1.5 m below ground and up to 1 m thick was observed in Chapel Bay during well installation. In contrast, two clay layers were found (from 2.75 to 4.75 m and from 4.5 m to 7.5 m depth), with the former layer rather thin (0.2–0.5 m). It appears that uplands have a thicker surficial aquifer with higher hydraulic conductivity, while the wetland portion of the landscape has an aquitard closer to the ground surface and is poorly drained. The surficial aquifer in the area that most likely affects the hydroperiod of the wetland is the top 5 m soil layers.

In addition to the 45 manual water-table wells and piezometers around Chapel Bay as described above, a digital recording well (WL40) was installed to a depth about 0.5 m to record water-table level continuously during the entire study period (1997–2003). This shallow well was located in the lowest area of the wetland (i.e., having standing water more often) and had the longest recording history. Hydraulic head data measured by three piezometers and the WL40 well were used in this study to provide evidence that the 0–5 m aquifer was unconfined.

The year 1998 was marked by an extremely wet spring but a dry summer and autumn. Therefore, this year was selected for model calibration to test the model under a wide range of water-table conditions, and the rest of the water-table data from 1997 and 1999–2003 were used for model validation (Figure 2). Starting from 1999 through fall 2002, the research site experienced severe-extreme draught conditions, with a 330-mm deficit in annual precipitation.

The entire modeling system was divided into 49 1-ha cells. Lateral model boundary conditions were initially determined by the road networks as a first approximation of the flow regime. For example, several cells of the lower southeast corner of the simulation grid system were assumed to have no flows because of intersection with the highway (Highway 301). The vertical flow boundary was determined from the stratigraphy data and comparison of hydraulic head in the paired shallow wells and piezometers. Piezometers were installed deeper than the shallow wells. We selected three representative piezometers and one shallow well (WL40) to determine the bottom flow boundary and whether the ground-water system is artesian, confined, or unconfined. Initial conditions of the model on water-table depth were approximated using the measured hydraulic head data from the wetland and upland wells.

Model performance was first evaluated by graphically comparing simulated daily water-table level at particular modeling cells in the wetland (Cell 18, 19, 26) and upland (Cell 17, 12) (Figure 2a) and measured values at shallow wells located in those cells in 1998. Initially, a no-flow boundary condition was set for all the modeling boundaries because no apparent overland outflow was recorded or observed by the field study. After the model was properly calibrated, the model was validated by comparing measured water level at well WL40 and simulated for cell 19 during 1997–2003. The same set of soil and vegetation parameters was used during model calibration and validation periods.

RESULTS

Field Evidence of an Unconfined Aquifer System and General Ground-Water Flow Directions

Hydraulic heads measured at one transect (EF) by piezometers at the upland (EE, 4.6 m below ground surface), wetland-upland margin (EF22, 2.5 m below ground surface), and the wetland center (2.5 m deep for the piezometer CT3 and 0.5 m for well WL40) provided important information of ground-water flow directions in the lateral and vertical directions (Figure 3). First, it appears that the observed clay layer at a depth of 1.5 m in the wetland did not result in an artesian effect since the hydraulic heads measured by the wetland piezometer (CT3) at a depth of 2.5 m were similar to those of the shallow wells of WL40, especially during wet periods. Small differences were noticed during dry-wet transition periods (e.g., middle 2002). Thus, for modeling purposes, it is reasonable to approximate the entire bay ground-water system as an unconfined aquifer with a hydrologic restricting layer at about 2 m in the wetland and about 4 m in the upland. Secondly, ground-water recharge from the surrounding upland to the wetlands was mostly pronounced during the wet periods in the winter months

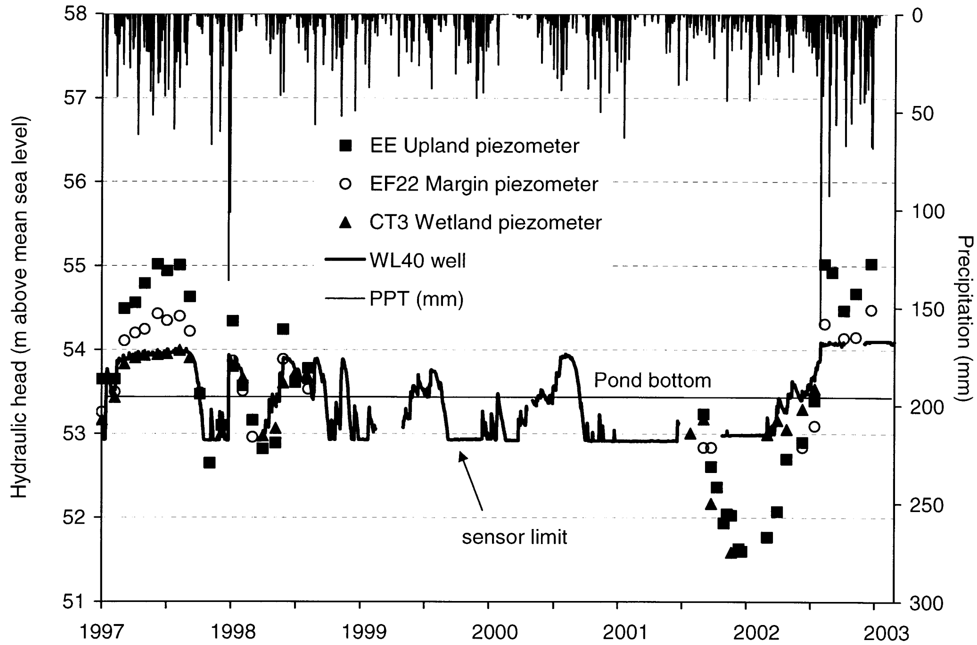

Figure 3. Measured water-table elevation (i.e., total hydraulic head) data at the upland, wetland-upland margin, and in the wetland indicates that the Chapel Bay is an unconfined aquifer system.

of 1998 and spring and summer of 2003. A maximum of about 1 m hydraulic head difference was measured between the upland piezometer (EE) and the piezometer (CT3) and well (WL40) located in the wetland. The difference of surface elevation between the two points was about 2.4 m, and they were about 100 m apart.

Model Calibration and Validation

We found that the model greatly over-estimated the water-table elevations for all the wells when a no-flow boundary condition was used (Figure 4a). A close examination of the water-table data recorded by the automatic water-table wells found that the wetland water-level rose very slowly when the water-level elevation reached about 54 m above mean seal level (msl). This phenomenon suggested that significant shallow ground-water outflow and/or fast surface flow from the wetland might have occurred, and thus, the no-flow boundary assumption was not appropriate. A field inspection confirmed our suspicion that surface outflow might have occurred at the south corner of the wetland during extreme wet conditions. The storm-water drain beneath Highway 301 might have exerted influence on the wetland flow regime. Consequently, a constant-head flow boundary condition was imposed allowing ground-water flow out of the boundary cells when the water-table reached 54 m msl. This change greatly improved model performance (Figure 4b). Soil specific yield was also adjusted to achieve overall best fit to the measured data. When surface-water was present in the wetland, specific yield was raised to a maximum of 1.0. The adjusted correlation coefficient for averaged measurements and model predictions for the three wetland wells was $R^2 = 0.78$ with the regression equation (Simulated Hydraulic Head in m = 0.704 * Measured Hydraulic Head + 15.8, n=274). For upland cells, the model captured the wet-dry cycle of ground-water-table ($R^2 = 0.72$ for the upland cell 17), yet the model over-estimated the water-table levels, especially for upland cell 12 (Figure 4b). The regression equation for cell 17 calibration was determined as Simulated Hydraulic Head in m = 1.389 * Measured Hydraulic Head −21.35, n=9).

In general, the model captured the water-table fluctuations reasonably well during the seven-year validation period (Figure 5). The model simulated the full wet-dry cycles of the wetland water level and also matched the maximum values. However, the model overestimated water levels during the transition periods from a wet to a dry condition, such as the Fall 1998 and Summer 2001, when the system presumably had a large water loss through evapotranspiration. Simulation errors were most pronounced when the water-table levels were in the low range, about 0.5 m below the ground surface (elevation 53.5 m) (Figure 5 and Figure 6), and the discrepancy between modeled and measured values was the smallest when the wetland becomes flooded (elevation >53.5 m). Thus, we believe that soil parameters (specific yield) and the evapotranspiration submodels are critical to simulate

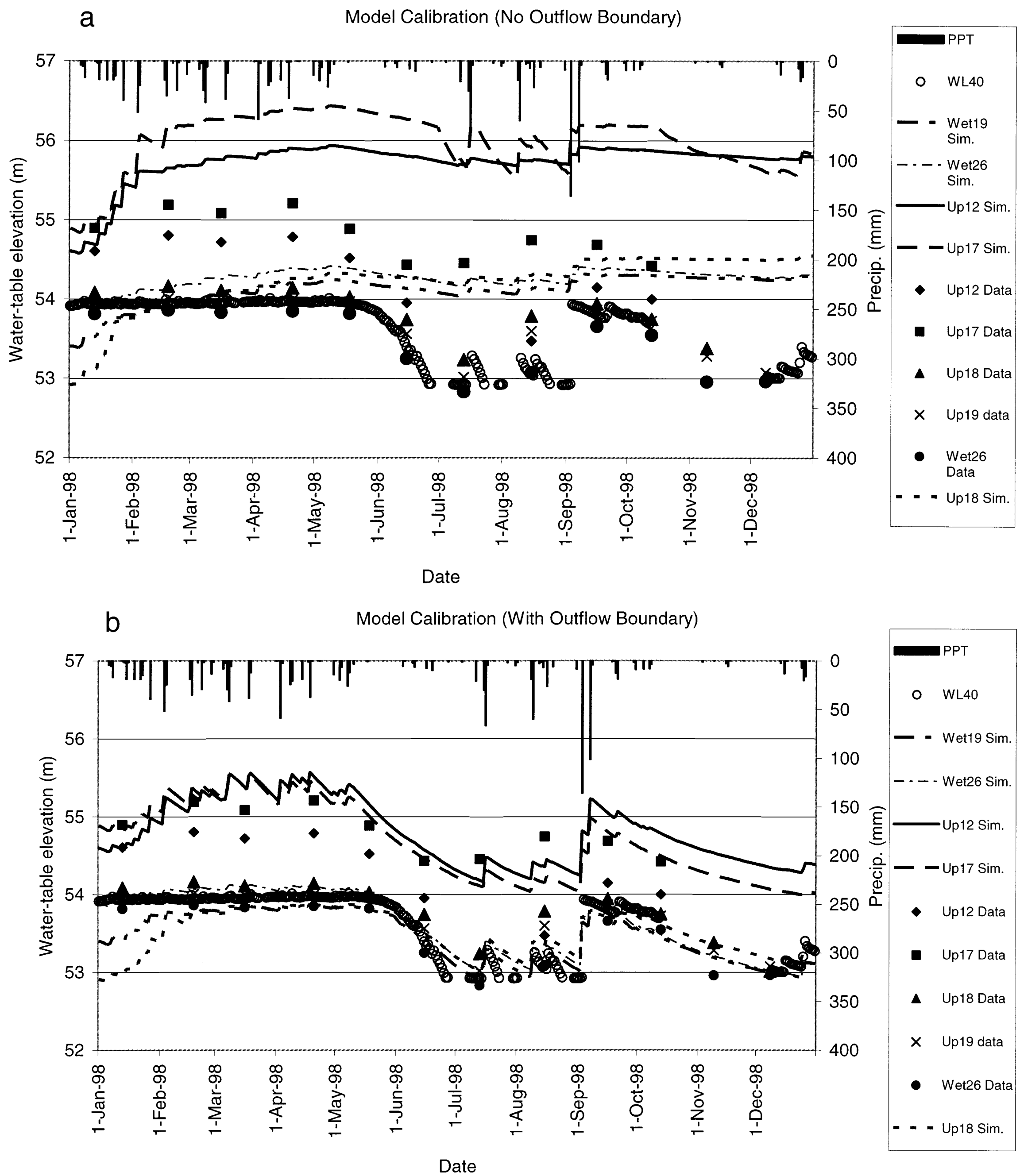

Figure 4. Model calibration using a) a no flow boundary and b) a fixed-head (54 m a.s.l.) boundary condition suggests that Chapel Bay is not hydrologically isolated from the surrounding upland and that lateral ground-water- surface-water interactions are common.

the dynamics of wetland hydroperiod accurately. On the other hand, the accuracy of precipitation data is equally important to model validation. In fact, this modeling study used climate data recorded at local county weather station when on-site data were missing for part of year 2000. Thus, model results may be suspect for late 2000 and early 2001 (Figure 5) due to precipitation data problems.

The annual water budgets show that precipitation and evapotranspiration are the two major fluxes in the overall water budgets (Figure 7). During wet years (1997 and 1998) when annual precipitation was above the 30-year average (1230 mm), net flows (surface- and ground-water flow) might be a significant flux in the wetland water balance. During the drought years (2000–2002), evapotranspiration was nearly balanced with precipitation at an annual scale, although periodic surface water was present during those years (Figure

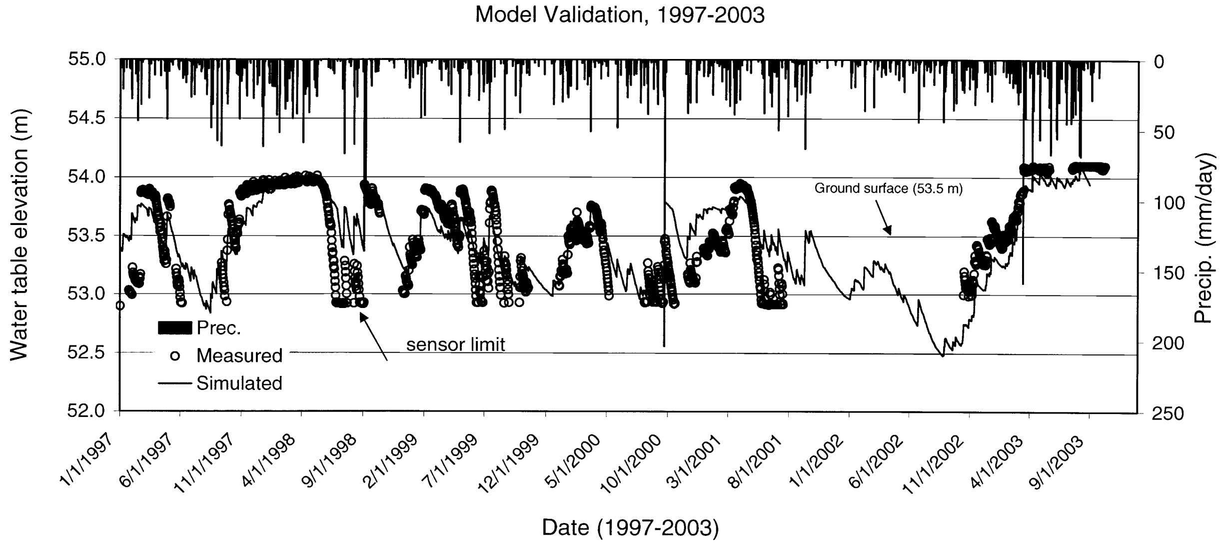

Figure 5. A seven-year model validation suggests that the wetland hydroperiod is mostly controlled by climate variability and that it can recover from extended drought rather quickly.

6). The modeling results reported here did not separate net surface flow and net ground-water (i.e. water exchange through wetland boundaries). The majority of the net flow in Figure 6 was surface outflow since there was no overland flow input and ground-water input and output probably balanced.

Model Applications

Once the model was reasonably validated, it was applied to test one hypothesis that has important implications to constructed wetlands. This study tested the hypothesis that lateral ground-water flow direction at the upland-wetland boundary is determined by the subsurface gradient of the hydrologic restricting layer, rather than solely by the ground topographic gradient. Therefore, two additional scenarios (Case 2 and Case 3) were hypothetically constructed to evaluate two possible subsurface soil layering scenarios as variations of the reference natural condition (Case 1) (Figure 8). For Case 1, the wetland is in the depression area and the subsurface clay layer follows a similar, but subdued gradient as the topography. Case 2 represents a scenario where a flat hydrologic restricting layer (elevation of 51.0 m) occurs beneath the surficial aquifer, while Case 3 represents a scenario in which the subsurface gradient is the opposite of the land topographic gradient, with a slope set as about 0.13%. The three scenarios have the same land topography. The ground-water flow directions were determined by comparing the total hydraulic head (i.e., water-level elevations) at the three selected points: upland, upland-wetland margin, and wetland (Figure 8). The 12-year climate data series was constructed by repeating the 1997–2002 climate file twice to represent an extended wet-dry climatic cycle.

For Case 1, simulated water-table elevations suggest that ground-water flow is in the upland-margin-wetland direction, which is similar to the topographic gradient, throughout the 12 synthetic climate years (Figure 9a). The upland-wetland water-table gradients are larger during wet periods (winter months) than those during dry periods (summer and autumn months). The wetland receives ground-water discharge from the surrounding uplands, and it is a water ‘sink.’

Compared to Case 1, water-flow directions change greatly in Case 2 (Figure 9b). Notably, the hydraulic gradients between upland and the margin are much smaller throughout the simulation period. The initial upland-wetland hydraulic gradient is caused by the initial water-table conditions. The water-table gradient between the upland and the wetland diminishes toward the end of a dry cycle but reappears during the wet winter period and following several storm events. During the following dry period, there is a small ground-water gradient in the wetland-upland system. A thicker unsaturated zone is developed in the upland than the wetland due to the fact that the upland ground surface is relatively higher than that of wetland for Case1.

The water-table gradient from the upland to the wetland for the Case 3 scenario is similar to Case 2 in the first climatic cycle (Figure 9c), but some differences between the two cases are obvious during the wetting phase of the climatic cycle. Except for the extreme wet period, the simulated water level in the depressional wetland is constantly higher than at the margin and upland, creating a small reversal of hydraulic gradient against the topography. During the wet period, the wa-

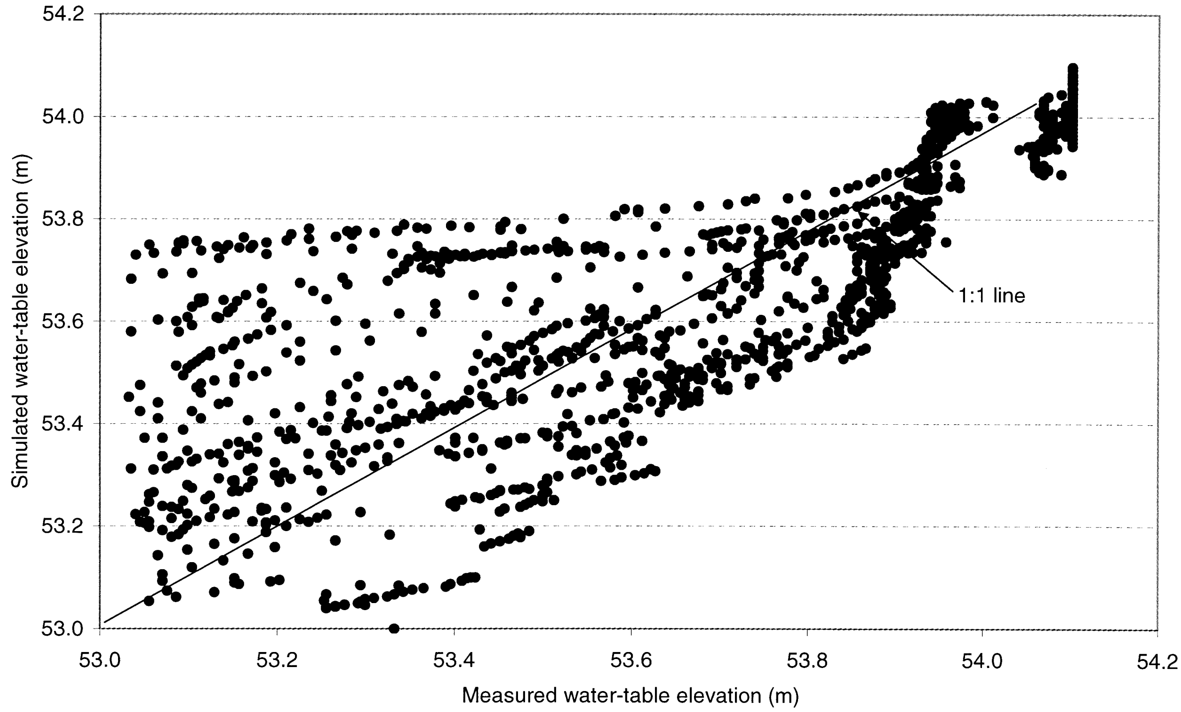

Figure 6. Comparison of simulated and measured water-table elevation (i.e., total hydraulic head) at Chapel Bay during the entire study period showing significant correlation but overestimation mostly during dry periods.

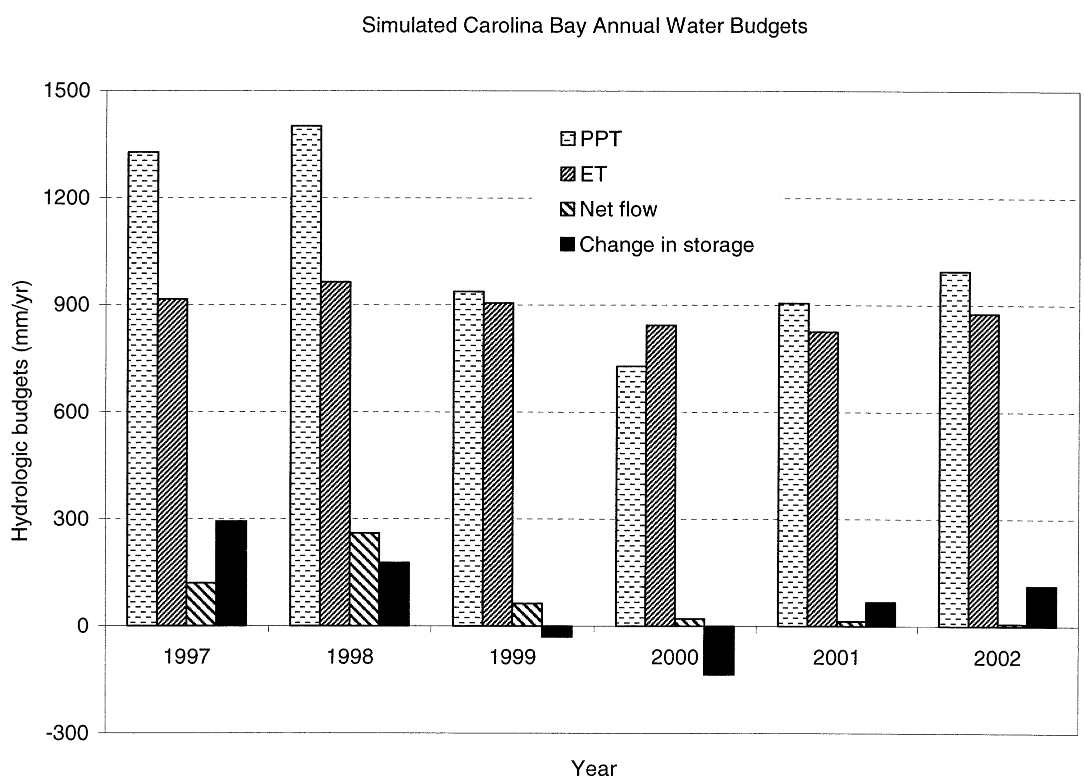

Figure 7. Simulated annual water budgets of the Chapel bay during 1997–2002 showing the water balance dominated by precipitation and evapotranspiration and ground-water flow most pronounced during wet years.

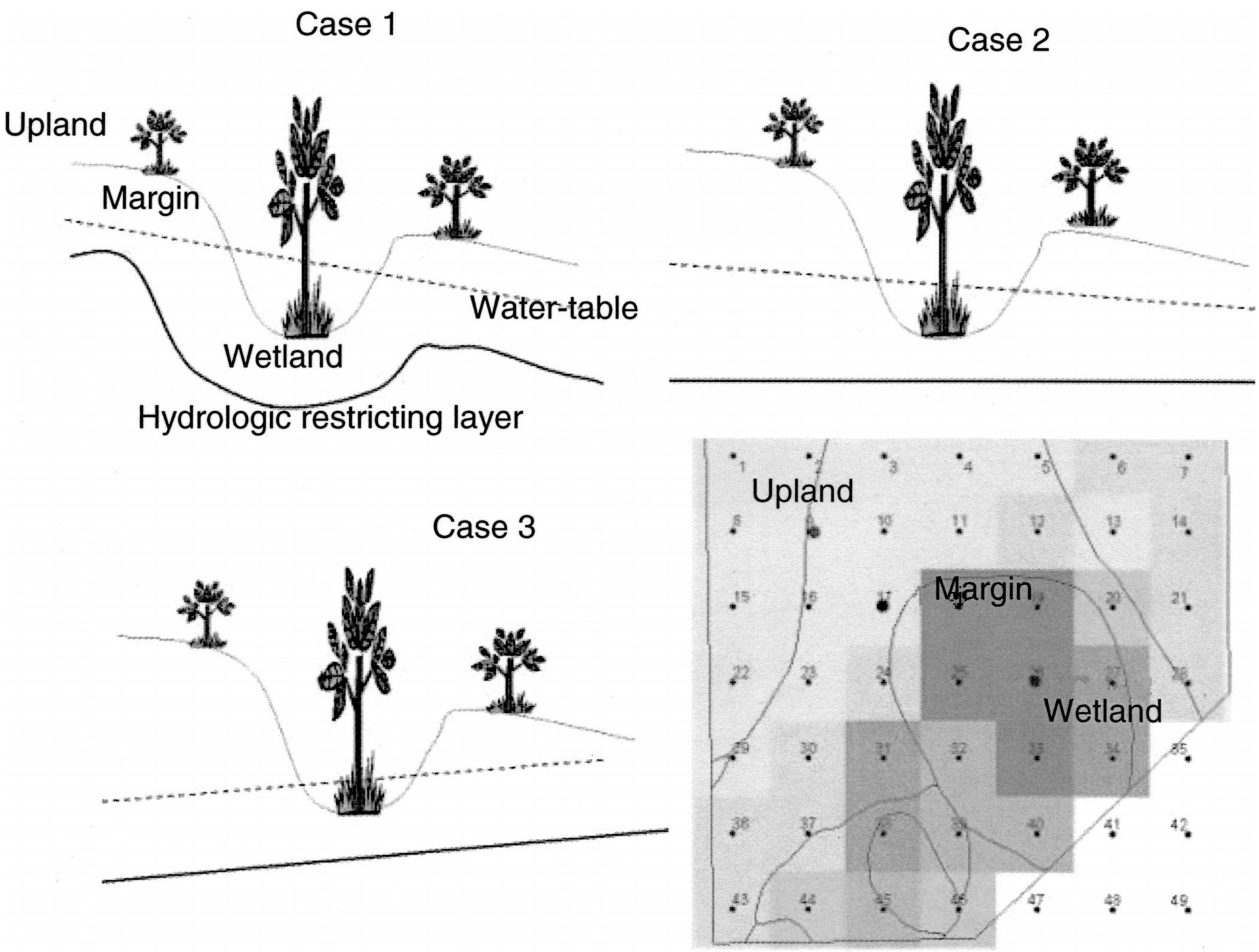

Figure 8. Sketch of three hypothetical scenarios for subsurface layering: Case 1: Subsurface restricting layer parallels the ground topography, Case 2: Flat subsurface restricting layer at a 51 m elevation, and Case 3: reversed subsurface restricting layer to topographic gradient.

ter-table gradient at the wetland-upland interface for Case 3 has the same direction with a smaller magnitude than that for Case 2.

DISCUSSION

Constructing complete water budgets even for small isolated wetlands (<10 ha) remains challenging due to several factors. First, the wetland watershed surface and subsurface boundaries are difficult to determine; secondly, the dynamic feature of wetland hydrology requires long-term commitment to field monitoring, and thus, the study is often expensive and maintaining field equipment becomes challenging. Computer simulation models offer an alternative means to examine the climatic and physical control on wetland hydrology.

The integrated forest hydrologic model FLATWOODS was modified and applied to a depressional forested wetland, Carolina Bay. Model calibration and validation results suggest that the model can capture the spatial and temporal dynamics of shallow groundwater-table in a heterogeneous landscape, and it is necessary to use a 2-D hydrologic model to describe the surface-water and ground-water interactions in this type of wetland. Simulation accuracy may be improved when more detailed soil, geological, and topographic information exist, and when locally measured precipitation data are incorporated into the model inputs.

This modeling study demonstrated that models were a powerful tool in identifying monitoring gaps and field data problems. For example, our simulation results suggested that the Carolina bay examined by this study was not hydrologically 'isolated' during wet periods, and large volumes of surface water and/or ground-water were discharged through surface flow and/or lateral ground-water flow. Even though we only

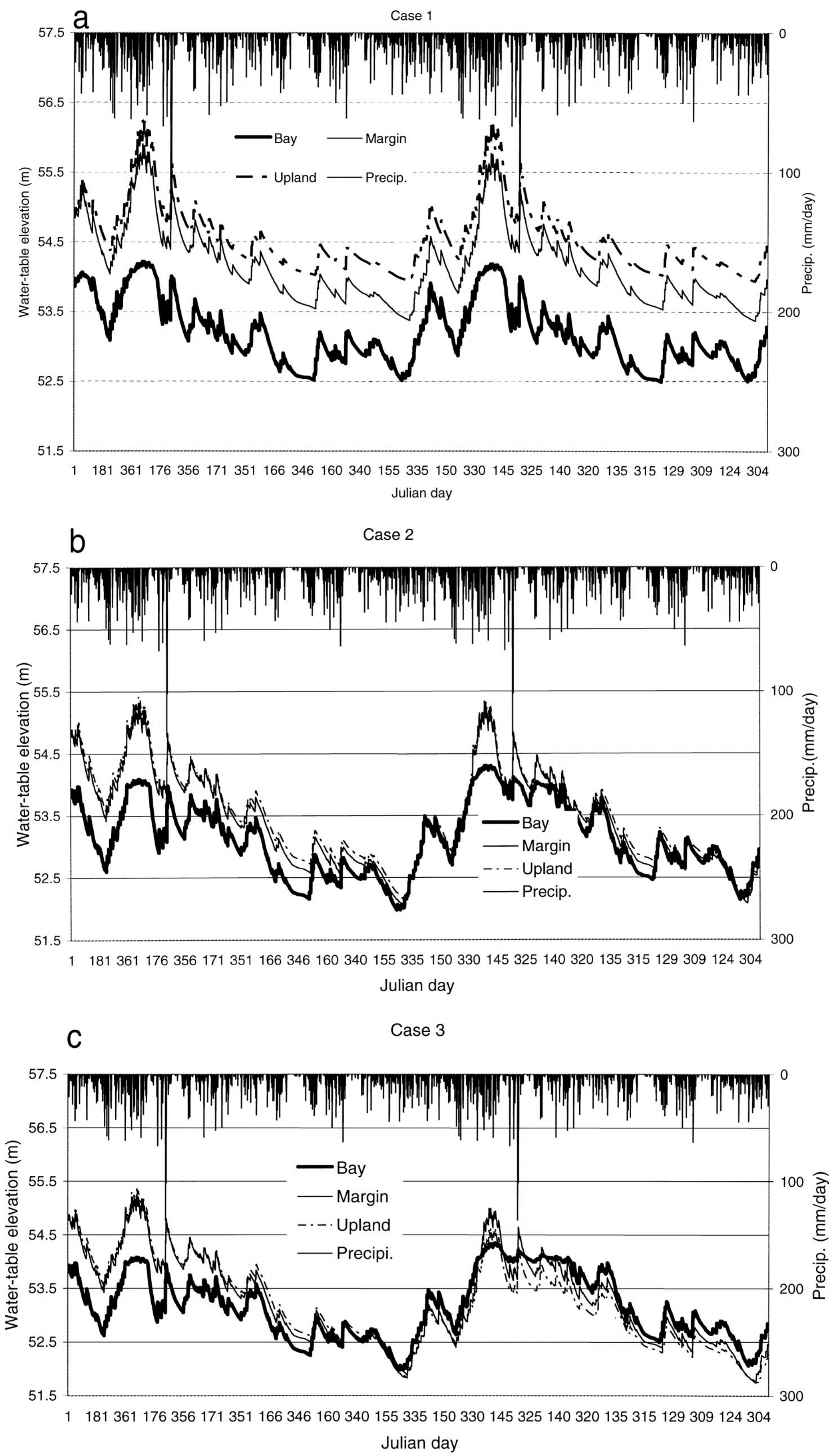

Figure 9. Comparison of water-table elevations (i.e., total hydraulic head) across the upland-wetland gradient for a) Case 1: Subsurface restricting layers parallel ground topography, b) Subsurface restricting layers are flat at 51 m elevation, and c) Case 3: reversed subsurface restricting layer to topographic gradient.

examined one particular bay system, we suggest that the common assumption that Carolina bays have no-flow boundaries around their perimeters may not be accurate.

The results also suggest that wetland position on the landscape is one important factor in determining the hydrologic interactions between surface water in the wetland and the local ground-water system. The Carolina bay examined in this study appears to be a flow-through wetland, receiving ground-water discharge on one side and recharging ground water on other side of the bay. One reason for this was the buildup of landscape-level hydraulic pressure from the northwest to the south, primarily due to topographic gradient and underlining subsurface clay layers. This flow pattern was further enhanced by the constructed drainage system consisting of storm water drains and roadside ditches. Crownover et al. (1995) examined ten small depressional cypress swamps embedded in pine flatwoods in north-central Florida. They found that most of the wetlands were of the flow-through variety and that purely ground-water discharging, depressional wetlands existed but were not common. The topographic gradient at this site in South Carolina is greater than the pine flatwoods of northern Florida; thus, we expect that the flow-through type feature is probably more common for Carolina bays due to the larger landscape-level hydraulic pressure control.

Model application confirmed our hypothesis that the ground-water flow directions in a depressional wetland-upland system on a flat landscape are mostly determined by the underlying subsurface hydrologic restricting layer. Land topography is important for estimating water flow directions for high water-table (wet) periods, but it can be misleading when subsurface soil information is not available. Field data are needed to verify the two hypothetical scenarios that have a flat or a reversal sloping hydrologic restricting layer to the general land topography. The simulation results have important implications for restoring or constructing depression wetlands. For example, a flat restricting layer in the upland and wetland will likely allow wetlands to discharge surface water to the surrounding upland during dry periods but collect lateral upland ground-water seepage during wet periods. In contrast, a natural isolated wetland generally has a sloping ground surface and subsurface layer, locally and at the landscape scale, resulting in a flow-through ground-water flow pattern.

CONCLUSIONS

The hydrology of southern forested wetlands such as forested Carolina bays is extremely dynamic and is affected by the balance between precipitation and evapotranspiration. Any deviation of normal precipitation will have an impact on Carolina bay hydroperiod patterns. However, ground water can be an important component of the water budgets of Carolina bays, especially during wet periods when ground water discharges into the wetland from surrounding upland. Carolina bays receive ground water from surrounding uplands during and following rainfall events and can then recharge the ground-water system during dry periods. However, the generalized patterns depend on the geomorphologic setting of individual wetlands. The subsurface restricting layer of the upland-wetland continuum may also play an important role in ground-water flow directions and, thus, the hydrologic functions of Carolina bays.

Our simulation study and associated field data show that Carolina bays are sinks for runoff and ground-water discharge and collect water, especially when the depressions are empty mostly during the spring and summer months. This hydrologic function may be critical to the Coastal Plain, especially following large events such as tropical storms in the late summer and early autumn months. To understand fully the complex controls of climate, geomorphology, and subsurface geology on Carolina bay hydrology, landscape or watershed-scale studies are needed in the future.

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