MODELING THE HYDROLOGIC PROCESSES OF A DEPRESSIONAL FORESTED WETLAND IN SOUTH CAROLINA, U.S.A.

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ABSTRACT

Depressional forested wetlands or geographically isolated wetlands such as cypress swamps and Carolina bays are common land features in the Atlantic Coastal Plain of the southeastern US. Those wetlands play important roles in providing wildlife habitats, water quality improvement, and carbon sequestration. Great stresses have been imposed on those important ecosystems due to rapid human population growth and climate change in the region. The objectives of this research were to (1) test a distributed forest hydrology model, FLATWOODS, for a Carolina bay wetland system using seven years of water table data and (2) apply the validated model to understand how wetland position (geomorphology) and geology affect lateral groundwater flow directions. The research site is a 6-ha depressional wetland known as a Carolina bay and is located in Eamberg County, South Carolina on the Lower Coastal Plain of the southeastern US (32.88 N, 81.12 W). Model calibration (1998) and validation (1997, 1999-2003) data span a wet and a long drought period allowing testing of the model for a wide range of weather conditions. While the major input to the wetland is atmospheric rainfall and output from the wetland is through evapotranspiration, modeling results suggest that the Carolina bay is a flow-through wetland, receiving discharged groundwater from one part of the upland area, but losing water as groundwater recharge to the other side, especially during wet periods in winter months. The simulation study also suggests that groundwater flow direction is controlled by the gradient of the underlying hydrologic restricting layer beneath the wetland-upland continuum, not by the topographic gradient of land surface. Groundwater flow appeared to change flow direction during the transition period during the wet-dry cycle. The changes depend on the geomorphoiogy and underlying geology of the wetland-upland continuum.

1. INTRODUCTION

Forested depressional wetlands or geographically isolated wetlands such as cypress swamps and Carolina bays are common land features in the Atlantic Coastal Plain of the southeastern US (Tiner et al., 2002). These types of wetlands occur on flat topography between river divides and have no apparent surface water connections with rivers or lakes. However, when the groundwater table intersects the land surface, isolated wetlands are connected through overland sheet flow (Winter and

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LaBaugh, 2003). Shallow groundwater flow also links the surface water in the wetland and its surrounding upland, especially when the entire landscape is wet usually in the winter months (Sun et al., 2000). Those isolated wetlands vary in size from less than a hectare to over several hundred hectares. The 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 their relatively drier soil conditions.

Although isolated wetlands, like many other types of wetlands, play important roles in providing wildlife habitats (Sharitz, 2003), groundwater recharge, flood attenuation, water quality improvement, and carbon sequestration (Li et al., 2003), they are under enormous stress from both land development and climate change. However, the effects of land management on the hydrology of these wetlands are poorly understood. The hydrology of depressional wetlands as controlled by the water levels within the wetland and its surrounding uplands is complex because of the dynamic nature of groundwater and surface water interactions (Miwa et al, 2003; Winter et al., 2002). The hydrologic interactions are found to be variable depending on both climate and local soil layering and geology (Lide et al,, 1995), besides the upland management practices.

While empirical field investigations can provide insight to these complex interactions, they can be rather time consuming and expensive. It is often hard to determine if a monitored wetland does actually have a hydrology typical of 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 physically based model can be used to answer 'what if management questions. For depressional wetlands, the water table levels are essentially controlled by two fluxes, one vertically (precipitation and evapotranspiration (ET)) and another laterally (shallow groundwater flows). Such wetlands require a multi-dimensional model to fully describe the hydrology of depressional wetlands. A comprehensive model that describes the full hydrologic cycle also can link all variables and hydrologic fluxes measured at a research site and can identify monitoring gaps.

The objectives of this paper are to (I) validate the distributed forest hydrology model, FLATWOODS, for a Carolina bay wetland system using six years of water table data and (2) use the validated model to understand how wetland positions (geomorphology) and geology on the general landscape affect lateral groundwater flow directions (i.e. groundwater and surface water interactions).

2. METHODS

2.1 The FLATWOODS Model

Several hydrologic models have been used for developing the water budgets of wetland ecosystems in the southern U.S. The most widely used model is the lumped DRAINMOD model (Skaggs, 1978) that was developed for predicting hydrologic effects of land management practices on poorly drained flat landscapes with parallel ditches. The model simulates the drainage outflows and water table dynamics of each 'drained field', but is limited in describing explicitly the hydrologic interactions of surface water and groundwater in a wetland-upland system. The model was used to simulate the hydrology of "pocosin" wetlands (Skaggs et al., 1991) and to evaluate the wetland hydrology of poorly drained soils as affected by rainfall, ET, and drainage (Skaggs et al., 1994). The WETLANDs model (Manse11 et al. 2000) describes the hydrology of a wetland-upland system by the combination of the 2-D Richard's equation and the water balance in wetland. This model has limitation to include the heterogeneity of both geology/soils and landcovers. 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), do not simulate the lateral interactions of surface water and groundwater interactions at the interface between a wetland and its upland.

The FLATWOODS forest hydrology model was originally developed for the flatwoods ecosystems, a mosaic of cypress swamps and slash pine uplands, in Florida, southeastern U.S., region dominated by poorly drained soils, low topographic relief, and high precipitation and evapotransiration (Sun et al. 1998a). The FLATWOODS model includes three major submodels to simulate the spatial distribution of groundwater table and hydrologic fluxes. At a gridded 'cell' level, the evaportansiration module simulate daily water loss due to forest canopy interception, plant transpiration, and soil/water evaporation as a function of potential evapotranspiration, rooting depth (60 cm for trees), and plant growth stage (leaf development). The unsaturated water flow module tracts daily net precipitation (atmospheric precipitation – canopy interception) and calculates the amount of water that recharges to the surficial aquifer as a function of soil water field capacity. The groundwater flow module is the core of the entire modeling system. This module tracts water table heads of all the gridded 'cells' using a 2-D (x and y) groundwater flow model that simulates the water table fluctuations as a function of evapotransiration loss from the aquifer, recharge to the aquifer, water loss due to surface outflow, and water loss/gain from surrounding neighbor cells. Surface outflow is allowed to 'tip off" the model boundary. In summery, the advantages of the model include: (1) it has been validated for the humid, warm, poorly drained forested conditions, (2) it is a distributed model that simulates the fully hydrologic cycles of both wetland and its surroundings including evapotranspiration, vertical unsaturated soil water flow (infiltration and soil moisture redistribution), and lateral groundwater flow in the water table aquifer. Most importantly, the model explicitly simulates the hydrological interactions between wetland and upland through the lateral groundwater flow component. Model structure is presented in Figure 1. Details of model algorithms, model validation and application are found in Sun et al. (1998a, 1998b).

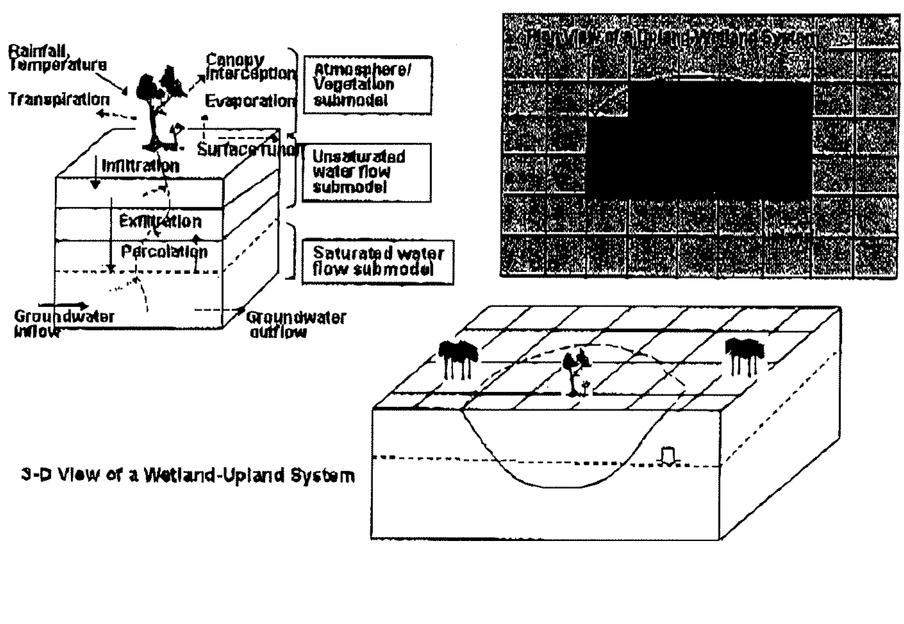

Figure 1. Sketch of the FLATWOODS model structure.

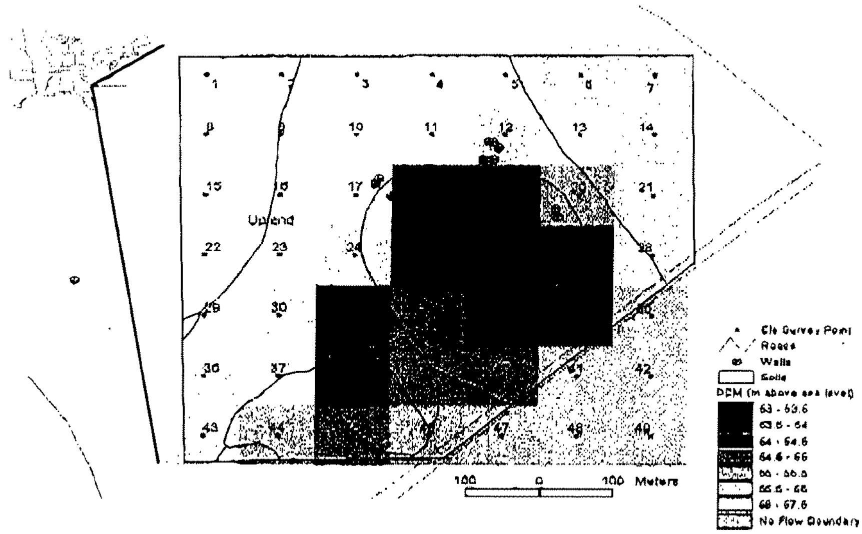

Figure 2 Instrumentation and model grid setup at the Chapel bay site

2.2 Research Site and Data Acquisition

The research site is located in Bamberg County, South Carolina on the lower coastal plain of the southeastern US (32.88 N, 8 1.12 W). Details of site description and instrumentation can be found in Miwa et al (2003) and Pyzoha (2003). This paper provides brief information of the site with a focus on the geology of the Chapel bay wetland only. The region receives an average of 1230 mm precipitation mostly falling during the early spring and summer months. The precipitation patterns can be modified by hurricanes mostly in late summer and fall. Average annual air temperature is about 17^{o} C. The Chapel bay wetland studied herein has an area of about 6 hectares covered by bottomland hardwoods in the interior, and the landuses in the surrounding area were composed of crop lands, intensively managed hardwoods (sycamore and cottonwood), and natural pine stands during the data collection period of 1997-2003.

The surficial aquifer that most likely affects the hydroperiod of the wetland and has the highest transmisivity lies approximately 6 m below the ground surface. This 6-m geological layer was further classified into five horizons (A, E, B, SC, S) according to their saturated hydraulic conductivity (K,) values. The A and E horizon layers (0. l-l .7 m thick) are composed mainly of sand in the upland areas (K_s> 6 m/day), and ranges from sandy loams to loamy sands within the wetlands with K_s in the range 0.5-1.5 m/day. The horizon B about 1 m in thickness located beneath the E horizon is composed of sandy clay loams in the upland areas (K_s values 3.0-6.0 m/day), and sandy clay loam and sandy clay within the wetlands (K_s in the range 0.5-1.5 m/day), Below the B horizon is a clay-sand ‘sandwiched’ layer (SC, S) that serves as aquitard to shallow groundwater. Well logs down to 10 m below the ground surface suggest that two clay layers about 2-3 m thick exist in the SC-S layer in the wetland and upland areas.

Land topography plays an important role in regulating water flow in this relatively flat landscape. Although a Digital Elevation Model (DEM) with a 30 m resolution is available, the elevations of the wetland and its surrounding area were resurveyed and geo-referenced into a 100 m by 100 m grid system for model setup and validation (Figure 2). The entire modeling system was divided into 49 cells. Model boundaries were initially set as the roads. For example, several cells of the SE corner of the grid system were assumed to have no flow as they were across a highway from the wetland (Figure 2).

About 46 water table wells and piezometers were installed in a transect form to monitor water table levels (Figure 2). The well located in the deepest area of the wetland (Cell 19 in Figure 2) was equipped witb a WL-40 water table recorder (Global Water, Inc., Gold River, CA USA) and has the longest recording history. The area experienced an extremely wet spring in 1998 (2/98 - 6/98) but both a dry summer and fall season were selected for model calibration, and the rest of the water table data from years 1997 and 1999-2003 were used for model validation (Figure 2). A drought occurred in the southeastern US occurred during 2000-2002. Precipitation and air temperature data were collected continuously with an automated tipping bucket raingage and a temperature probe on site. Data gaps were filled with county weather station data.

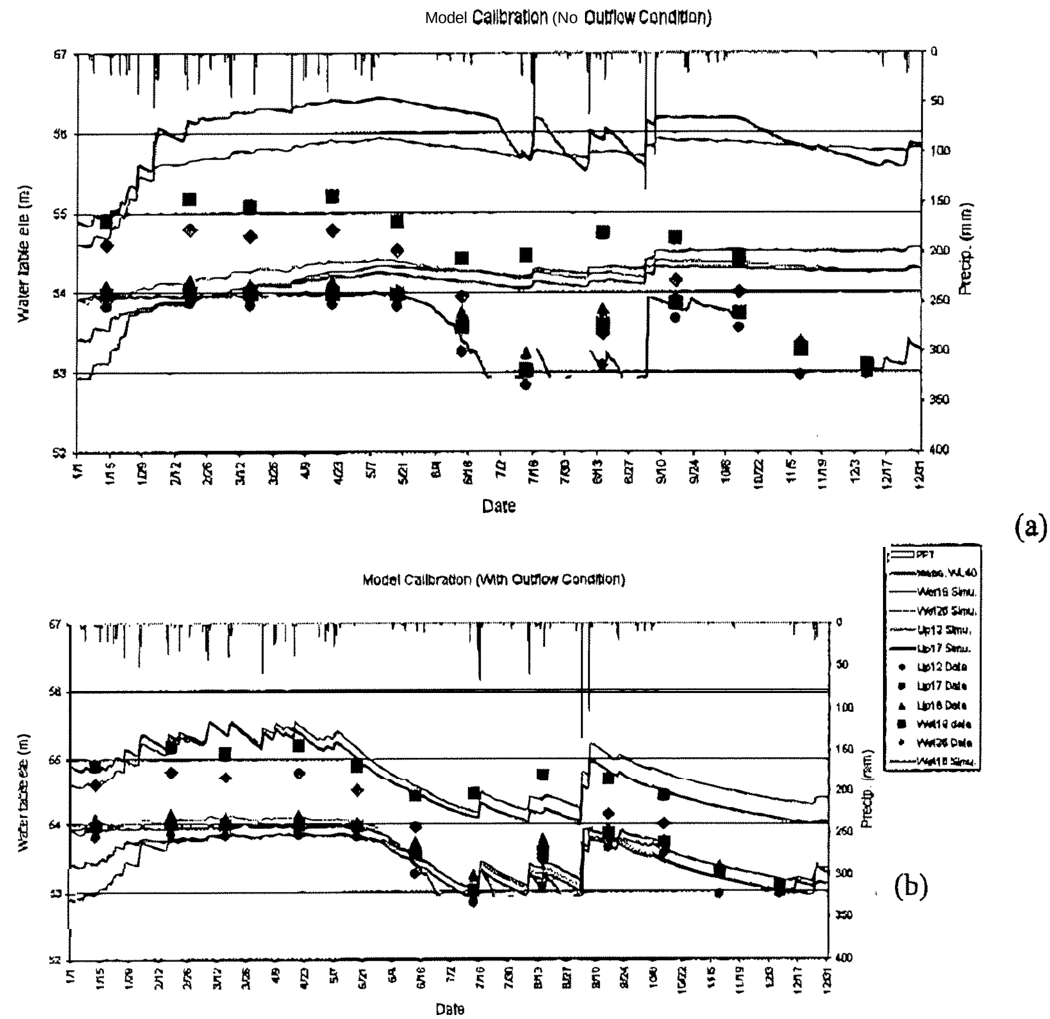

Figure 3 Model calibration using: a) a no flow boundary (top) and b) fixed-head boundary conditions.

3. RESULTS

3.1. Model Calibration and Validation

Model performance was evaluated by graphically comparing simulated daily water table levels at particular modeling cells for wetland (Cell 18, 19, 26) and upland (Cell 17, 12) with field measurements in the bay during 1998 (Figure 2). Initially, a no-flow boundary condition was set for all the modeling boundaries because field experience suggested there was no apparent overland flow occurred in the modeling area. However, we found the model greatly over-estimated the water table elevations for the wells (Figure 3a). A close examination of the water table data recorded by the WL40 water table wells found that the wetland water level would rise very slowly when the water level elevation reached an elevation of 54 m above sea level (asl). This suggests that shallow groundwater outflow from the wetland may have occurred and the no-flow boundary assumption may not be appropriate. Consequently, a 'fixed head' flow boundary condition was imposed asusming that groundwater was flowing out of the boundary cells when the water table rose above 54 m asl. This change greatly improved model performance (Figure 3b). The model parameter for soil specific yield was also adjusted to achieve overall best fit to the measured data. The correlation coefficient between averaged measurements and model predictions for the three wetland wells was $R2 = 0.75$ (slope =1.0, SE=0.17m). For upland cells, the model could capture the wet-dry cycle of upland wells, but the model overestimated the water table levels, especially for upland cell 12.

Model validation was conducted using daily wetland water table data recorded at the deepest spot of Chapel bay (Cell 19). After the model was calibrated using data from 1998, the model was run again using the same set of soil and vegetation parameters but a new set of climate data from all years (1997-2003) (Figure 4). It appears that the model simulated the water table fluctuations reasonably well. The model approximated the full wet-dry cycles of wetland water level and the extremes. However, overestimation of water elevations occurred during the wet-dry transition periods, e.g., Fall 1998 and Summer 2001, when the system had large water loss through forest evapotranspiration. Model validation suggested that soil parameters (specific yield) and the evapotranspiration submodels in FLATWOODS are critical to accurately simulate the dynamics of a wetland's hydroperiod. Equally important for model validation is the climatic input variable, precipitation. In this study, climate data from both on-site measurements and local county weather station data were used when on-site data were in questions for the year 2000.

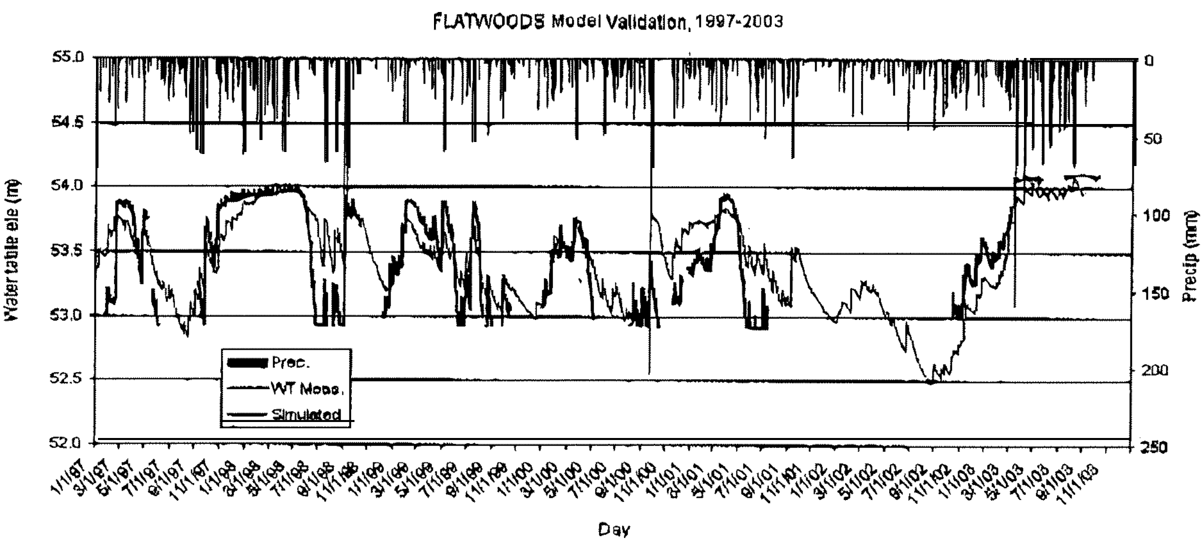

Figure 4. Seven-year model validation using a fixed-head boundary condition. Wetland ground surface is at about 53.5 m.

3.1 Model Application

Once the model was validated, it was applied to test hypotheses and answer 'what-if scenario questions that may not have been easily achieved in the field. This study tested one central hypothesis that the lateral groundwater flow direction at the upland-wetland continuum is determined by the subsurface topographic gradient not by the land surface topographic gradient. Therefore, two additional scenarios (Case 2 and Case 3), besides the existing one (Case 1), were constructed to represent two possible subsurface soil layering (Figure 5). Case 2 represents a situation where a fiat hydrologic restricting layer underlines the surficial aquifer while Case 3 represents a geological scenario that subsurface gradient is the opposite of the land topographic gradient. The groundwater flow direction for these scenarios can be determined by comparing the water level elevations at the three selected points: upland, upland-wetland margin, and wetland (Figure 5). The 12-year climate data series was constructed by repeating the 1997-2002 climate file.

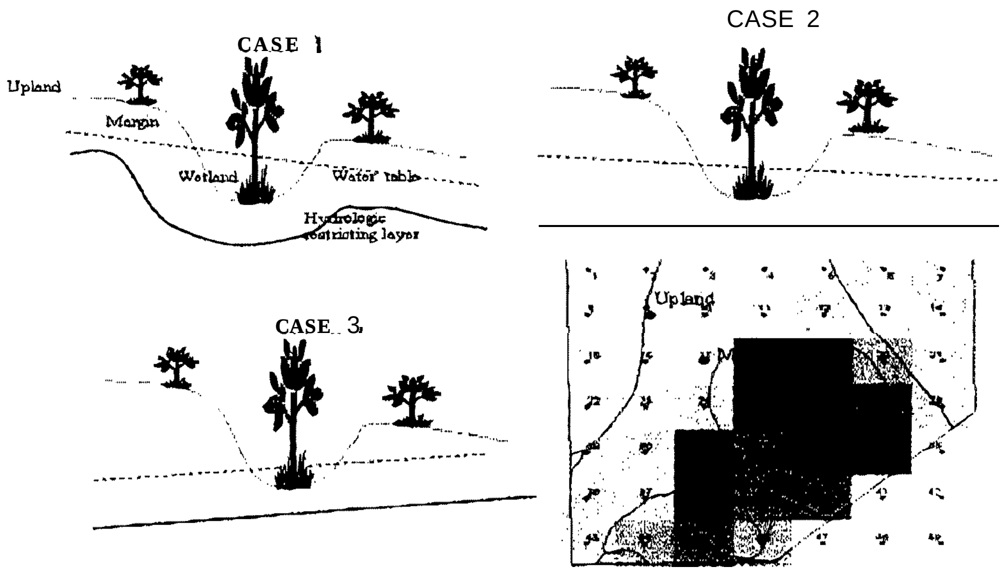

Figure 5. Three hypothetical scenarios for the subsurface layering: Case I : Subsurface restricting layer parallels the ground topography, Case 2: Flat subsurface restricting layer at a 5 1 m elevation, and Case 3: reversed subsurface restricting layer.

For case 1, simulated water table elevations suggest that groundwater flow moves in upland-margin-wetland direction, similar to the topographic gradient throughout the 12 synthetic climate years (Figure 6a). The upland-wetland water cable gradients are larger during wet periods (winter months) than those during dry periods (Summer and Fall months), It appears that the wetland is in a discharge area receiving groundwater from the surrounding upland, especially during high water table periods.

Compared to Case 1, simulated water flow directions changed greatly in Case 2 (Figure 6b). Notably, there are little gradients between upland and the margin. 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 at the end of the dry cycle, but reappears during the wet winter period and several storm events afterwards, Again, during the following dry period, there is small groundwater 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 the flat bottom restrictive layer.

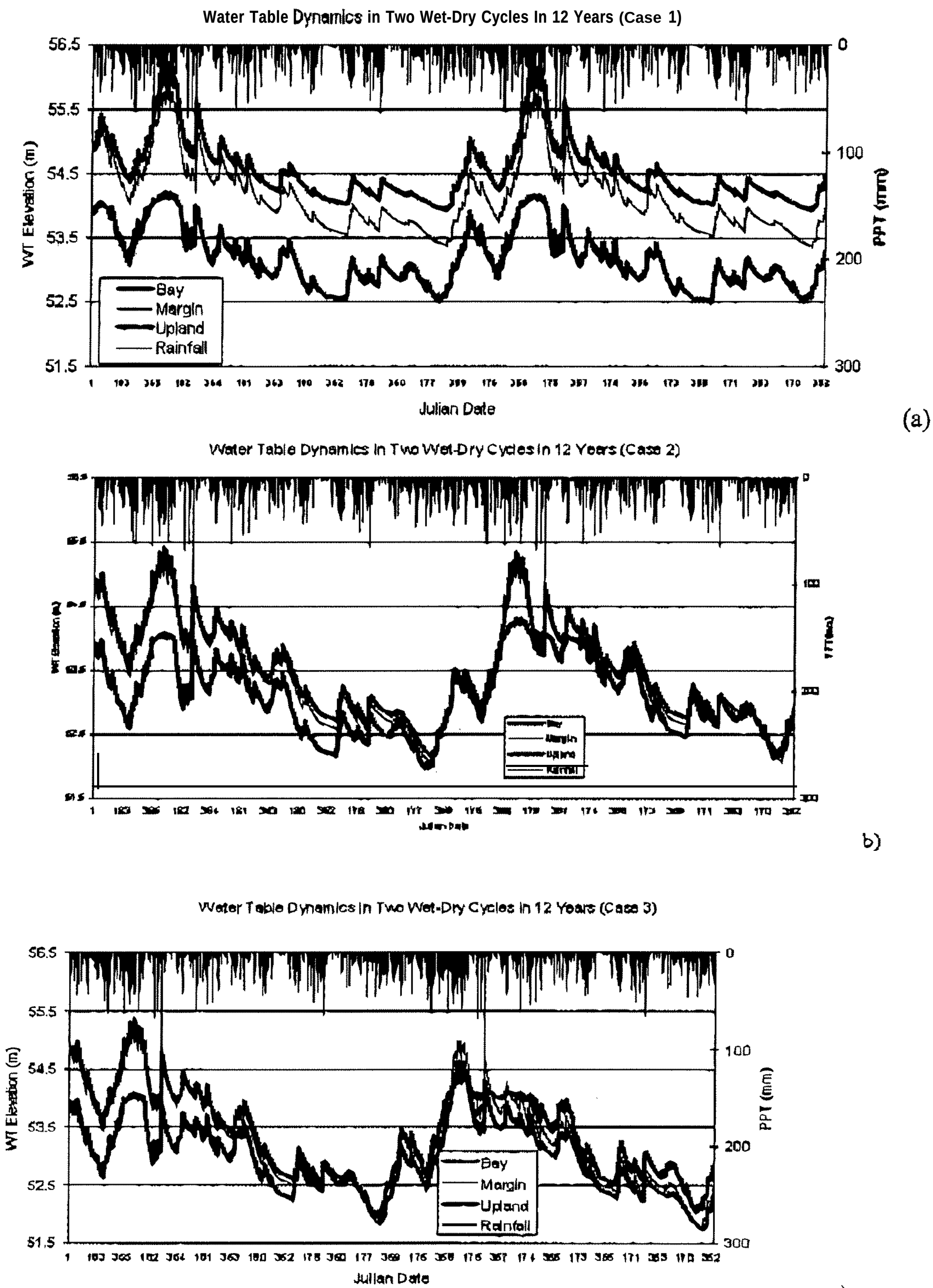

Figure 6. Comparison of water table elevations across the upland-wetland gradient for a) Case 1: Subsurface restricting layers parallel ground topography, b) Subsurface restricting layers are flat at 51 m elevation, and c) Case 3: reversed subsurface restricting layer.

The simulated water table gradient for the Case 3 scenario is similar to Case 2 in the first climatic cycle (Figure 6c). The differences occur during the hydrologic recovery phase. The wetland water level is constantly higher than those at the margin and upland although the differences among the three are small. Unlike Case 2, the wet period does not cause large water table gradient at the wetland-upland interface. In fact, the small hydraulic gradient changes over time with majority of the time gradient pointing towards the upland. Only during the wet period water tends to move from upland to wetland.

5. DISCUSSION AND CONCLUSIONS

The integrated forest hydrological model FLATWOODS was modified and applied co a depressional isolated forested wetland system. Model calibration and validation results suggest the model can capture the spatial and temporal dynamics of shallow groundwater table in a heterogeneous landscape. This modeling study proved to be useful to identify monitoring gaps and detecting data monitoring problems such as precipitation records. We found that water table monitoring must be continuous and should record the water table fluctuations during storm events in order to capture the transient features of hydrologic interactions between upland and wetland.

Periodic monitoring on a weekly or monthly schedule may not be effective to detect the highly dynamic interactions. Model application study confirmed our hypothesis that the groundwater flow directions in a wetland-upland system are mostly determined by the underlying subsurface hydrologic restricting layer. Land topography is important for estimating water flow directions for high water table (wet) period, but it can be misleading when subsurface geology 'information is not available. This study further suggests that wetland position on the general landscape is one important factor in determining the hydrologic interactions between surface water in wetiand and its surrounding upland.

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REFERENCES

Arnold, J.G., P.M. Allen, and D.S. Morgan, (2001). "Hydrologic Model for Design and Constructed Wetlands". Wetlands. Vol. 21, No. 2.

Li, C., J. Cui, G. Sun, and C. Trettin. (2003). "Modeling Impacts of Management on Carbon Sequestration and Trace Gas Emissions in Forested Wetland Ecosystems, Environmental Management". (In Press).

Lide, R.H., V.G. Meentememeyer, J.E. Pinder, III, L.K. Beatty. (1995). "Hydrology of A Carolina Bay Located on the Upper coastal Plain Western South Caroina". Wetlands, Vol 15, No. 1.

Mansell, R.S., S.A. Bloom, and G. Sun. (2000). "A Model for Wetland Hydrology: Description and Validation", Soil Science. Vol 165, No, 5.

Miwa, M., C.C. Trettin, S.E. O'Ney, and M.H. Eisenbies. 2004. Hydrologic processes in the vicinity of a Carolina bay, Wetlands. (In press)

Pyzoha, J.E. 2003. "The Role of Surface Water and Groundwater Interactions within Carolina Bay Wetlands". M.S. Thesis. College of Charleston. 121 p.

Sun, G., Riekerk, H., Comerford, N.B. (1998a). "Modeling the Hydrologic Impacts of Forest Harvesting on Florida Flatwoods. Journal of the American Water Resources Association. Vol.

34, No. 4. pp. 843-854.

Sun, C., H. Riekerk, N.B. Comerford. (1998b). "Modeling the hydrologic impacts of forest harvesting on flatwoods". Journal of American Water Resources Association.Vol. 34:843-854.

Sun, G., H. Riekerk, L.V. Komak. (2000). 'Groundwater Table Rise after Forest Harvesting on Cypress-pine Flatwoods in Florida". Wetlands. Vol 20, No. 1.

Sharitz, R. (2003). "Carolina Bay Wetlands, Unique Habitats of the Southeastern United States". Wetlands. Vol. 23, No. 3.

Skaggs, R.W. 1978. A Water Management Model for Shalow Water Table Soils. Report No. 134, Water Res. Res, Inst. Of the Univ. of North Carolina, NC State Univ., Raleigh, NC.

Skaggs, R.W., J.W. Gilliam, and R.O. Evans. 1991. A Computer Simulation Study of Pocosin Hydrology. Wetlands, Vol. 11, Special issue, pp:399-416.

Skaggs, R.W., D.M. Amatya, R.O. Evans, and J.E. Parsons. 1994. Characterization and Evaluation of Proposed Hydrologic Criteria for Wetlands. Journal of Soil and Water Conservation, Vol. 49(5):354-363.

Tiner, R.W., H. C. Bergquist, G. P. DeAlessio, and M. J. Starr. 2002. "Geographically Isolated Wetlands: A Preliminary Assessment of Their Characteristics and Status in Selected Areas of the United States". U.S. Department of the Interior, Fish and Wildlife Service.

Winter, T.C, J.W. Harvey, O.L. Franke, and W.M. Alley. 2002. "Ground Water and Surface Water: A Single Resource". U.S. Geological Survey, Circular 1139, 79 p.

Winter, T.C. and J. W. LaBaugh. (2003). "Hydrologic Considerations in Defining Isolated Wetlands". Vol. 23, No3.