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SENSITIVITY OF STREAM FLOW AND WATER TABLE DEPTH TO POTENTIAL CLIMATIC VARIABILITY IN A COASTAL FORESTED WATERSHED[1]

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ABSTRACT: A physically based distributed hydrological model, MIKE SHE, was used to evaluate the effects of altered temperature and precipitation regimes on the streamflow and water table in a forested watershed on the southeastern Atlantic coastal plain. The model calibration and validation against both streamflow and water table depth showed that the MIKE SHE was applicable for predicting the streamflow and water table dynamics for this watershed with an acceptable model efficiency ($E > 0.5$ for daily streamflow and >0.75 for monthly streamflow). The simulation results from changing temperature and precipitation scenarios indicate that climate change influences both streamflow and water table in the forested watershed. Compared to current climate conditions, the annual average streamflow increased or decreased by 2.4% with one percentage increase or decrease in precipitation; a quadratic polynomial relationship between changes in water table depth (cm) and precipitation (%) was found. The annual average water table depth and annual average streamflow linearly decreased with an increase in temperature within the range of temperature change scenarios (0-6°C). The simulation results from the potential climate change scenarios indicate that future climate change will substantially impact the hydrological regime of upland and wetland forests on the coastal plain with corresponding implications to altered ecosystem functions that are dependent on water.

(KEY TERMS: forest hydrology; water table; streamflow; MIKE SHE; climate change.)

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INTRODUCTION

Forested wetlands play a key role in the landscape controlling flooding and nonpoint source pollution (EPA, 2005), sequestering carbon (Trettin and Jurgensen, 2003), and providing wildlife habitat. These ecosystem functions are sensitive to changes in the hydrological regime (Carter, 1986; Conner *et al.*, 2002; Kozlowski, 2002; Haukos and Smith, 2006). For example, water-level rise in Louisiana has increased the mortality of flood intolerant plants (Conner *et al.*, 2002), while drought was shown to cause a reduction of hydrophilic plants in Carolina bays in South

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Carolina (Mulhouse *et al.*, 2005). With respect to hydrologic function of watersheds, runoff and water storage are highly affected by the proportion of wetlands within the watershed (Winter, 1988; Verry, 1997). Accordingly, an understanding of the likely changes in hydrological regimes that may be induced by climate change is needed to develop strategies to sustain wetland functions.

The hydrology of wetland-dominated watersheds, especially first-order watersheds on the Atlantic coastal plain, is heavily dependent on precipitation and evapotranspiration (ET) (Sun *et al.*, 2006). Therefore, climate change, including alterations in temperature and precipitation (IPCC, 2001; Wentz *et al.*, 2007; Zhang *et al.*, 2007), may be expected to significantly influence the hydrology of wetland-dominated watersheds (Sun *et al.*, 2006). Climate change is projected to affect water resources in the southern United States (U.S.) generally (Sun *et al.*, 2008), and alter wetland hydrology directly (Lu *et al.*, 2009). Many studies on the potential effects of climate change on coastal wetland ecosystems focus on losses due to sea-level rise caused by global warming (Nicholls, 2004). However, increased air temperatures in the mid-latitudes without changes in precipitation (IPCC, 2007) may be expected to increase ET thereby changing the water balance (Zhang *et al.*, 2007). The corresponding impacts on an altered coastal wetland hydrology as a result of climate change has been the subject of several recent studies (Nicholls *et al.*, 1999; Burkett and Kusler, 2000; Scavia *et al.*, 2002; Nicholls, 2004; Erwin, 2009).

Hydrologic models can be an effective tool for assessing the potential effects of climate change on wetland hydrology and the corresponding ecosystem functions (Freeman *et al.*, 1995; Mansell *et al.*, 2000; Amatya and Skaggs, 2001; Arnold *et al.*, 2001; Miller *et al.*, 2003; Christensen *et al.*, 2004; Dibike and Coulibaly, 2005; Sun *et al.*, 2006; Maurer, 2007; Martinez *et al.*, 2008; Lu *et al.*, 2009). However, most applications are with field scale models which may have difficulties describing hydrological processes in low topographic relief watersheds with complicated soil and vegetation distributions that are characteristic of the coastal plain (Amatya *et al.*, 2003; El-Sadek, 2007). The distributed hydrological model MIKE SHE (DHI, 2005) has been tested on multiple sites in the U.S. (Sahoo *et al.*, 2006; Lu *et al.*, 2009) and around the world (Graham and Butts, 2005; Mernild *et al.*, 2008; Vázquez *et al.*, 2008; Staes *et al.*, 2009), and been shown to be well suitable for simulating the hydrology of watersheds containing both uplands and wetlands. Accordingly, our objective was to overcome limitations of models that are not well suited to the low relief landscape of the coastal plain, and use MIKE SHE to quantify effects of potential climate change scenarios on streamflow and water table dynamics of a first-order wetland watershed thereby. MIKE SHE was calibrated and validated by using two measured hydrological parameters (streamflow and water table), and then used to simulate hydrology for 18 different climate change scenarios based on predicted temperature increases (IPCC, 2007) and precipitation changes (Wentz *et al.*, 2007; Zhang *et al.*, 2007). Our intent was to expand the consideration of scenarios to better assess the effects associated with wide variety of potential climatic conditions.

METHODS

Study Site

A gauged forested watershed that contains both uplands and wetlands, and is characteristic of the southeastern Atlantic coastal plain was used for this study. The watershed (WS-80) is located at 33.15°N, 79.8°W on the Santee Experimental Forest 55 km northwest of Charleston, South Carolina (Figure 1). This 160 ha first-order watershed drains into Huger Creek, a tributary of the East Branch of the Cooper River. The watershed boundary is bordered by roads which preclude surface flow across the divide. WS-80 is the reference watershed in a paired watershed system (Figure 1). The climate is subtropical, characterized by short, warm, and humid winters and long and hot summers (Sun *et al.*, 2000a); the annual average temperature is 18.7°C based on the 30-year average (1971-2000), and average annual precipitation is 1,350 mm (Amatya *et al.*, 2003). The elevation of WS-80 is between 4 and 10 m above mean sea level, the topography is planar, the slope is <4%, and approximately 23% of the watershed is classified as wetlands (Sun *et al.*, 2000a; Harder *et al.*, 2007). The predominant forest cover types are bottomland hardwoods in the wetland riparian zone and mixed pine-hardwoods elsewhere. The dominant trees are loblolly pine (*Pinus taeda* L.), sweetgum (*Liquidambar kstyraciflua*), and a variety of oak species (*Quercus* spp.) in both the uplands and bottomlands (Hook *et al.*, 1991; Harder *et al.*, 2007). The forest vegetation was heavily impacted by hurricane Hugo in 1989. Following the hurricane, the forest regenerated naturally yielding dense stands. The soils, developed in coastal plain sediments, are characterized by loam or sandy loam surface horizons overlaying a clayey subsoil. Average clay content is ≤30% in surface soil (upper 30 cm) and 40-60% in subsoil (>30 cm). The drainage classification ranges from moderately well

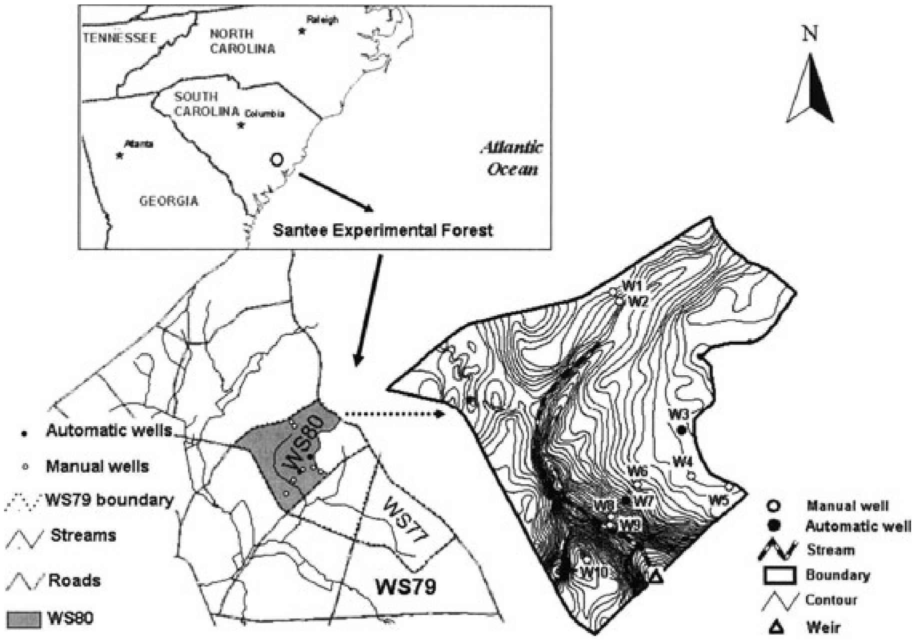

FIGURE 1. Watershed WS80 on Atlantic Coastal Plain, South Carolina. (W1-W10 are the identification number of wells.)

in the uplands to poorly drained in the riparian wetlands (SCS, 1980).

Field Measurements and Data Collection

Precipitation and air temperature were measured in WS-80 at hourly intervals. The data were processed to supply daily values. Additional meteorological data were collected at 30-min intervals at a weather station at the Santee Experimental Forest Headquarters about 3 km away from WS-80 for estimating potential evapotranspiration (PET); these data included precipitation, solar radiation and net radiation, wind speed, wind direction, temperature, vapor pressure, and relative humidity. The Penman-Monteith method was used to estimate hourly and daily PET (Monteith, 1965; Xu and Singh, 2005; Harder *et al.*, 2007).

Water table depth data were provided by two automatic recording wells and eight manual wells in WS-80. The automatic recording wells were installed in an upland area (2.3 m deep) and a riparian zone (57 cm depth before March of 2004 and 94 cm afterwards) to record water table elevation at 4 hour intervals (Figure 1) (2003-2007). The data were processed to obtain daily values which were further processed to obtain annual averages. The eight manual wells (≥2 m deep) were installed across the watershed (Figure 1) with biweekly observations taken during 2003-2004. Streamflow was measured based on stage-discharge relationships of a compound V-notch weir where stage was measured at 10 min intervals. Streamflow was calculated using a standard rating curve developed for the weir (Harder *et al.*, 2007), and integrated into daily, monthly, and annual values. To compare precipitation with streamflow, the streamflow was normalized from cubic meters per second (cms) to mm per day by dividing the watershed area. The measured annual streamflow and water table depth are presented in Table 1.

Leaf area index (LAI) was calculated from direct measures of leaf biomass (Lloyd and Olson, 1974; Bréda, 2003); supplemental measures of LAI were also taken periodically through one year using a

TABLE 1. The Measured Water Table, Streamflow and Rainfall in Watershed WS80.

		Streamflow (mm/day)				**Water Table Depth From Ground Surface* (m)**			
Year	**Rainfall (mm)**	***M***	***S***	**R^2**	***E***	***M***	***S***	**R^2**	***E***
2003	1,671	2.01	2.00	0.62	0.55	0.58	0.63	0.88	0.87
2004	962	0.28	0.37	0.63	0.56	0.88	0.98	0.79	0.76
2005	1,540	0.84	0.82	0.66	0.63	0.77	0.86	0.77	0.75
2006	1,255	0.38	0.52	0.83	0.81	1.02	1.09	0.66	0.65
2007	923	0.16	0.21	0.78	0.78	1.06	1.26	0.73	0.56

*The water table depth is the distance from ground surface to water table level where it is below the ground surface, and annual average water table depth from all wells. M is the measurement; S is the simulation; R^2 is the coefficient of determination; E is Nash-Sutcliffe model efficiency; the unit of streamflow is mm per day, normalized from cubic meters per second (cms).

LI-2000 leaf area meter. The physical soil properties were obtained from soil survey (SCS, 1980). Soil moisture retention was also measured in three typical profiles by Harder *et al.* (2007). Topography was obtained from a topographic survey of WS-80 at a scale of 1:200, which was used to produce 15 cm contours.

The MIKE SHE Model

MIKE SHE (DHI, 2005; Graham and Butts, 2005; Sahoo *et al.*, 2006) is a physically based distributed hydrological modeling system with the capability of simulating all of the major processes of the terrestrial hydrological cycle, including three-dimensional (3D) water movement in soil profiles, 2D water movement of overland flow and 1D water movement in rivers/streams, and ET. Detailed descriptions of the model and algorithms can be found in many publications, including Abbott *et al.* (1986a,b), DHI (2005), and Graham and Butts (2005), and examples of its recent applications to simulate watershed hydrology are provided by Graham and Butts (2005), Mernild *et al.* (2008), and Staes *et al.* (2009). For this study, the saturated flow was simulated using the 3-D Finite Difference method (DHI, 2005). The primary input for simulating saturated flow is soil hydraulic properties, including horizontal and vertical hydraulic conductivities, specific yield, and storage coefficient. The simulation of subsurface flow was included in this study, which requires a drainage depth (from the phreatic surface to the point where the flow of drainage water can be produced) and a drainage constant.

Unsaturated flow and ET were simulated using the Two-Layer Water Balance model designed for applications in the areas with a shallow groundwater table (Yan and Smith, 1994; DHI, 2005). The model divides the unsaturated zone into a root-zone where ET occurs, and a below-root-zone where ET does not occur (Yan and Smith, 1994). The input for simulating unsaturated flow and ET includes the vegetation characterized by LAI and plant rooting depth, and the physical soil properties including a constant infiltration capacity and the soil moisture contents at the wilting point, field capacity and saturation. Overland flow was simulated using 2D diffusive wave approximation. The input includes surface detention storage, initial water depth, and surface roughness (Manning *M* that is the inverse of Manning's *n*, and typically ranges from 10 to 100) (DHI, 2005). Channel/streamflows and channel surface water and upland groundwater interactions were modeled by coupling of MIKE SHE and MIKE 11 tracking stream water level using a fully dynamic wave version of Saint Venant equations (DHI, 2005).

Model Setup and Parameterization

In this study, MIKE SHE was coupled with the flow routing model MIKE 11, a one-dimensional river/channel water movement model, to simulate the full hydrological cycle of the watershed, including ET, infiltration, unsaturated flow, saturated flow, overland flow, and streamflow. The main input parameters for model setup include spatial data on topography, soils, land cover (i.e., LAI), drainage network, and temporal (daily) data on precipitation and PET.

As a distributed model, the 160 ha watershed (Figure 1) was divided into 675 (50 m × 50 m) cells. The parameters describing vegetation and physical soil properties were spatially distributed based on the occurrence within the watershed. Those parameters included horizontal and vertical hydraulic conductivity, specific yield, infiltration capacity, and the soil moisture contents at the wilting point, field capacity and saturation (Table 2). The drainage depth, surface detention storage, plant rooting depth, Manning M, initial water depth, ET surface depth, drainage time constant, and coefficient of canopy interception were initialized by default and empirical values (Table 2), and then they calibrated using observed streamflow and water table depth. As deep seepage only accounts for a small fraction of total precipitation on Atlantic

TABLE 2. Mainly Initial Parameters for MIKE SHE Simulation Model.

Parameter	**Value**
Plant rooting depth [mm]	500
Leaf area index (LAI) [m^2/m^2]	0.2-6.6 (2.8 on average)
Potential evapotranspiration (PET) [mm/day] (P-M)	0.0-7.5
Surface detention storage [mm]	50
Manning *M* [$m^{1/3}/s$]†	40†
Initial water depth [m]	0
Soil water content at saturated conditions (WCSC) [m^3/m^3]	0.4-0.496
Soil water content at field capacity (WCFC) [m^3/m^3]	0.3-0.458
Soil water content at wilting point (WCWP) [m^3/m^3]	0.2-0.38
Infiltration [$\times 10^{-6}$ m/s]	1-100
ET surface depth [m]	0.2
Horizontal hydraulic conductivity [$\times 10^{-6}$ m/s]	10-800
Vertical hydraulic conductivity [$\times 10^{-6}$ m/s]	1-80
Specific yield [m^3/m^3]	0.012-0.09
Drainage depth [m]	0.5
Drainage time constant [per second]	1e-07
C_{int} [mm]*	0.20

*C_{int} is the coefficient of canopy interception used in MIKE SHE (DHI, 2005); daily PET is based on Penman-Monteith (P-M) (Xu and Singh, 2005).

†Manning $M = (\text{Manning's } n)^{-1}$.

coastal watersheds (Heath, 1975; Riekerk *et al.*, 1979; Harder *et al.*, 2007), it was assumed to be negligible.

Simulation Time Steps

MIKE SHE has the flexibility of using variable simulation time steps for different hydrological modeling components and flow characteristics (DHI, 2005; Zhang *et al.*, 2008). However, the maximum allowed time step for every modeling component should be specified because MIKE SHE automatically adjusts its time steps within the maximum allowed time steps. In this study, the maximum allowed time steps were set to 2 hours for unsaturated flow, overland flow and ET, 4 hours for saturated flow, and 10 min for MIKE 11 (e.g., streamflow). The variable step rate (0-1) for reducing time step length was set to 0.05. The time steps for outputs were set to 4 hours for streamflow and 24 hours for water table; and the streamflow outputs were integrated into daily, monthly, and yearly values.

Model Calibration and Validation

Unlike most previous studies that used either streamflow or water table, we used both streamflow and water table observed for the model calibration (2003-2004) and validation (2005-2007). This is because distributed hydrological models should be evaluated by using more than one measurable parameter (i.e., multiple criteria), including distributed measurable parameters (Shrestha and Rode, 2008). Model calibration and validation using these two variables should allow for closer examination of the internal consistency of the model, and for evaluating whether some components of the model are biased due to the spatial and temporal variability of the water table (Ambroise *et al.*, 1995; El-Nasr *et al.*, 2001). Several quantitative methods were used to evaluate the model calibration and validation, including the model efficiency (E) (Nash and Sutcliffe, 1970), the coefficient of determination (R^2), and root mean squared error (RMSE). Model calibration was evaluated by minimizing RMSE and maximizing E of both daily streamflow and daily water table depth as objective functions. Model performance evaluation was performed based on the measure of E values suggested by Moriasi *et al.* (2007).

The climatic and hydrological data in 2003 and 2004 were used for model calibration; 2003 was extremely wet, with annual precipitation of 1,671 mm, which was 320 mm higher than the 30 year (1971-2000) average of 1,350 mm, and had an 84 mm storm event from Hurricane Isabelle. In contrast, 2004 was a dry year, with annual precipitation of 962 mm, and a high intensity precipitation event with over 130 mm of precipitation on August 29, 2004. The data from 2005 to 2007 were used for the model validation. These three years were drier than 2003. The precipitation in these three years was 130, 410, and 750 mm less than 2003, respectively; 2007 was an extremely dry year, with 430 mm less precipitation than the 30 year average. The large difference in precipitation within these years yielded significant year-to-year variations of streamflow and water table depth (Table 1). Accordingly, large climatological and hydrological changes within these years provided a good basis for model assessment. This also provided a basis to examine whether the calibrated model could perform equally as well when compared to another time period with a substantial difference in precipitation (Kirchner, 2006).

Model Applications

Eighteen climate change scenarios were developed to assess the responses of the watershed hydrology to altered climatic conditions in terms of the variations of daily and monthly streamflow and daily water table depth (Table 3). Current climate conditions

TABLE 3. Scenarios for Simulating Hydrologic Responses in Watershed WS80.*

Code	Description
CCC	Actual climate conditions
PIN1	Precipitation increased by 2% only
PIN2	Precipitation increased by 5% only
PIN3	Precipitation increased by 10% only
PIN4	Precipitation increased by 15% only
PIN5	Precipitation increased by 20% only
PDE1	Precipitation decreased by 5% only
PDE2	Precipitation decreased by 10% only
PDE3	Precipitation decreased by 15% only
TIN1	Temperature increased by 1°C only
TIN2	Temperature increased by 2°C only
TIN3	Temperature increased by 3°C only
TIN4	Temperature increased by 4°C only
TIN5	Temperature increased by 5°C only
TIN6	Temperature increased by 6°C only
PNT1	Combining temperature increase by 2°C with precipitation increase by 5%; PNT1 = TIN2 + PIN2
PNT2	Combining temperature increase by 2°C with precipitation increase by 10%; PNT2 = TIN2 + PIN3
PNT3	Combining temperature increase by 2°C with precipitation increase by 15%; PNT3 = TIN2 + PIN4
TVP	Combining temperature increased by 2°C with precipitation decreased by 10%; TVP = TIN2 + PDE2

*Precipitation increase for the scenarios PNT1, PNT2 and PNT3 was assumed based on the results reported by Wentz *et al.* (2007) and Zhang *et al.* (2007). Temperature increase was assumed based on Climate Change 2007 of IPCC (2007).

(scenario CCC) in a five-year time span (2003-2007) were used as the baseline for the comparison to the climate change scenarios. All scenarios were designed in the same time span. The five scenarios of precipitation increase (by 2, 5, 10, 15, and 20%) and three scenarios of precipitation decrease (by 5, 10, and 15%) assumed that the other climate conditions would not change in the watershed in the five-year simulation period. These eight scenarios of changes in precipitation were developed based on the precipitation increase in the last two decades as reported by Wentz *et al.* (2007) and on the precipitation decrease in tropical and subtropical areas as reported by Zhang *et al.* (2007). The scenarios for combining temperature increase (2°C) with precipitation increase (by 5% for PNT1, 10% for PNT2, and 15% for PNT3) were developed based on the precipitation increase at a rate of 6-7% per °C brought by global warming in the last 20 years as reported by Wentz *et al.* (2007). The six scenarios of temperature increase (by 1, 2, 3, 4, 5, and 6°C) were developed based on a warming of approximately 0.2°C per decade in the following two decades projected for a range of emission scenarios (Special Report on Emission Scenarios) (IPCC, 2000) and the temperature change ranged from 1 to 6°C in the 21st Century given by six emissions marker scenarios (IPCC, 2007). The Penman-Monteith PET was recalculated for the scenarios with changing temperature based on the assumption that global warming would elevate the air temperature in the future without changing other climate conditions in the watershed.

RESULTS AND DISCUSSION

Model Calibration

The initial model calibration showed that streamflow and water table were sensitive to drainage depth, the depth from the ground surface where the flow of drainage water can occur (calibrated range, 0.0-1.0 m). The E and RMSE indicated that water table depth (E: −4.93-0.45, RMSE: 0.19-0.61 m) was more sensitive to drainage depth than streamflow (E: 0.50-0.64, R: 3.2-3.8). This differential effect of drainage depth on the calibration of streamflow and water table depth was due to an assumption of a unified drainage depth across the watershed. Although WS-80 is considered planar, water table depth does vary over 1 m between upland and riparian areas, especially during dry periods. Therefore, a distributed drainage depth, based on the physical characteristics of the watershed [topography (slope) and the distance to the stream], is essential to accurately represent the spatial heterogeneity. The calibrated distributed drainage depth ranged from 5 to 95 cm, averaging 35 cm with an acceptable model efficiency ($E = 0.70$ for daily streamflow and 0.78 for daily water table depth).

Surface detention storage strongly influences water table depth and streamflow. Despite the planar nature of this watershed, surface detention storage was considered high due to the wetlands and heterogeneous surface micro-topography. The distributed detention storage function was employed in the model for WS-80 based on the distribution of wetlands and surface topography. The calibrated depressional depth ranged from 11 to 180 mm with an average of 36 mm, with an E of 0.70 for daily streamflow and 0.90 for daily water table depth. The average surface detention storage (36 mm) in this study is comparable to the depth of 4.0 cm used by Harder *et al.* (2006) in their hydrological simulation using DRAINMOD model on this site.

The calibrated plant rooting depth was 60 cm (calibration range: 30-90 cm, E: 0.42-0.64, RMSE: 0.21-3.5 mm for streamflow; E: 0.05-0.54, RMSE: 0.17-0.24 m for water table depth). The horizontal hydraulic conductivity was calibrated to 0.00001-0.0001 m/s (calibrated range from 0.000001 to 0.005), which is consistent with empirical values (Harder *et al.*, 2006), and related to the soil distribution within the watershed. Manning M was determined to 35 $m^{1/3}/s$ based on the calibration (range from 10 to 70). The calibration also showed that streamflow and water table depth were not sensitive to vertical hydraulic conductivity (0.0000005-0.005 m/s) or infiltration capacity (0.000001-0.001 m/s). Those results indicate that deep seepage is negligible in this watershed, which is consistent with previous studies and assumptions (Heath, 1975; Riekerk *et al.*, 1979; Harder *et al.*, 2007).

The time series comparison of measured daily streamflow and simulated flow from MIKE SHE for the calibration period is presented in Figure 2, and the corresponding statistical values are presented in Table 4a. During dry periods, streamflow was overpredicted, for example, see June 20, July 2 and 3, 2003, August 29, 2004 (Figure 2). The overprediction during these dry periods is mainly related to an artifact of MIKE SHE which does not allow stream to dry out (Lu *et al.*, 2006). The R^2 was 0.62, 0.63, and 0.64 for daily streamflow, and 0.97, 0.88, and 0.97 for monthly streamflow in 2003, 2004, and the calibration period (2003-2004), respectively (Table 4a). The E values were 0.55, 0.56, and 0.57 for daily streamflow, and 0.97, 0.82, and 0.97 for monthly streamflow in the same periods. Based on the suggestion that $E > 0.75$ for monthly flow represents a "very good" model performance (Moriasi *et al.*, 2007), the

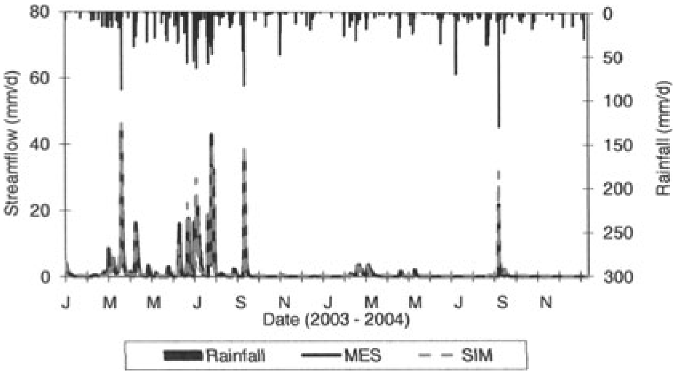

FIGURE 2. Time Series of Observed and Simulated Daily Streamflow in 2003-2004. (MES, measurement; SIM, simulation. Streamflow was normalized to mm per day per square meter.)

TABLE 4A. Measured and Simulated Streamflow for Calibration Period (2003-2004).*

Year	R^2	E	M	S	b
2003 daily	0.62	0.55	2.01	1.90	0.84
2003 monthly	0.97	0.97	61.2	57.7	0.97
2004 daily	0.63	0.56	0.22	0.30	0.80
2004 monthly	0.88	0.82	6.80	9.30	0.88
2003-2004 daily	0.64	0.57	1.12	1.10	0.84
2003-2004 monthly	0.97	0.97	34.0	33.5	0.97

*Daily streamflow is mm per day; monthly streamflow is mm per month; R^2 is the coefficient of determination; E is the model efficiency; M is the mean of measurements; S is the mean of the simulations; and b is the slope of the regression model.

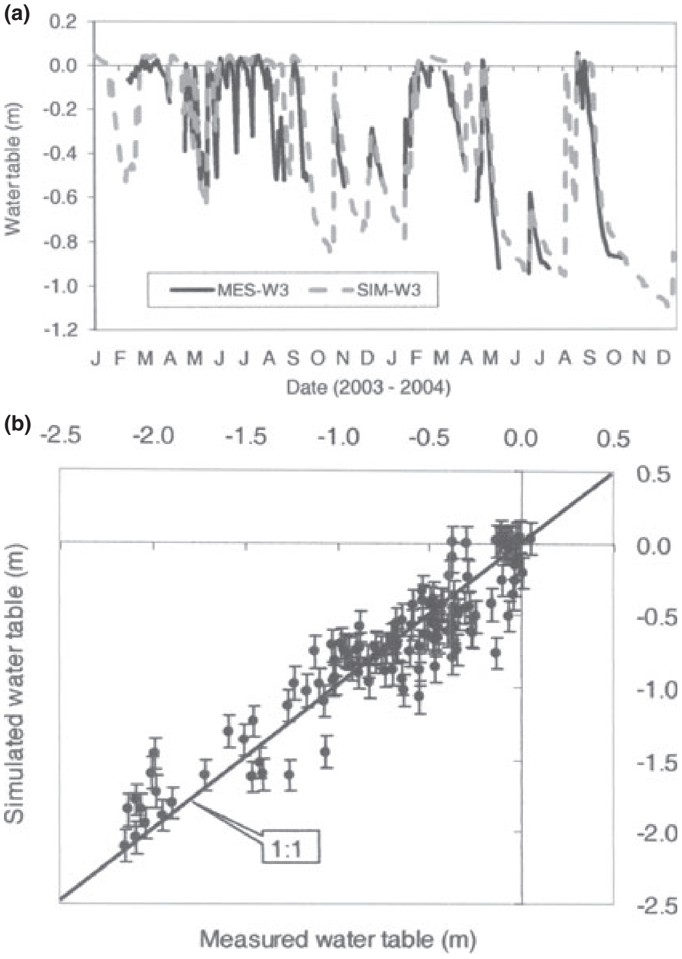

FIGURE 3. (a) Measured *vs.* Simulated Water Table at Well W3 in 2003-2004. (Note: This is a shallow well with WL40. Its maximum depth was 57 cm below ground surface before March 2004, and 94 cm afterwards. Any observed data of water table level close to the well bottom may be incorrect; missing data were due to the equipment failure for some time and water table level below the sensor.) (b) Measured *vs.* simulated water table depth synchronized with time for 10 wells in 2003-2004. (Bar is the mean absolute error between observation and simulation.)

calibration of MIKE SHE for WS-80 was highly successful. However, despite the overall high model efficiency, the simulated daily average streamflow for the dry year 2004 (0.37 mm/day) was higher than the measured flow (0.28 mm/day). The difference in daily average streamflow between observation and simulation was attributed to the overprediction during dry periods (Figure 2), especially on days when heavy precipitation followed a dry period, such as August 29, 2004. The stream draining WS-80 is intermittent, as a result of a shallow stream bed (<50 cm on average), and low water table levels during dry periods in the growing season. However, MIKE SHE maintained an extremely low flow during these dry periods to prevent the stream from drying out. In 2004, a dry year, the annual precipitation in this area was 390 mm less than the 30 year average of 1,350 and 710 mm less than that in 2003, and the stream on WS-80 ran dry for 216 days. The low flow maintained by MIKE SHE in the stream yielded a "wet stream bed" effect, which led to an overprediction of streamflow during extended dry periods.

The temporal water table dynamics in the watershed were well reflected by the simulation (Figure 3a), despite some differences (e.g., July and August 2003). A comparison of the observed *vs.* simulated water table depth for 10 wells distributed across the watershed showed that the simulation was in agreement with the measurements with an error of 8 cm between simulated average and observed average for the two-year calibration period (Figure 3b). A similar result was provided by the calculated R^2 (0.50-0.88) (Table 4b) for each of the 10 wells in the calibration period, and the E (0.82) and R^2 (0.84) and slope (b = 0.88) of the regression model between the measurement and simulation for all wells in the calibration period. These results demonstrate that MIKE SHE was effective at simulating water table dynamics in this watershed.

TABLE 4B. Measured and Simulated Water Table for All Wells in 2003-2004.*

Well	ELE (m)	Measured Mean	Measured SD	Simulated Mean	Simulated SD	R^2	Significance (p)
W1	9.2	−0.77	0.29	−0.82	0.37	0.50	<0.01
W2	8.2	−0.42	0.60	−0.57	0.40	0.59	<0.01
W3	9.1	−0.28	0.29	−0.33	0.39	0.78	<0.01
W4	8.8	−0.70	0.38	−0.81	0.37	0.55	<0.01
W5	9.6	−0.86	0.47	−0.87	0.35	0.66	<0.01
W6	8.7	−1.29	0.72	−1.45	0.42	0.66	<0.01
W7	8.1	−1.46	0.55	−1.49	0.40	0.74	<0.01
W8	5.6	−0.77	0.42	−0.94	0.39	0.78	<0.01
W9	5.5	−0.54	0.38	−0.66	0.38	0.78	<0.01
W10	8.6	−1.36	0.59	−1.23	0.64	0.88	<0.01

*R^2 is the coefficient of determination; unit of water table depth is meter and negative means water table level below ground surface; SD is the standard deviation; ELE is the elevation of the wells above mean sea level in meters; W1-W10 are the identification numbers of wells (Figure 1).

TABLE 5A. Measured and Simulated Streamflow for Validation Period (2005-2007).*

Year	R^2	E	M	S	b
2005 daily	0.66	0.63	0.84	0.82	0.81
2005 monthly	0.98	0.95	25.5	24.9	0.85
2006 daily	0.83	0.81	0.38	0.50	0.83
2006 monthly	0.97	0.88	11.5	15.3	1.03
2007 daily	0.78	0.78	0.16	0.21	0.73
2007 monthly	0.99	0.94	4.9	5.7	0.80
2005-2007 daily	0.70	0.69	0.46	0.48	0.78
2005-2007 monthly	0.93	0.88	13.9	18.3	0.96

*Daily streamflow is mm per day; monthly streamflow is mm per month; R^2 is the coefficient of determination; E is the model efficiency; M is the mean of measurements; S is the mean of the simulations; and b is the slope of the regression model.

Model Validation

A comparison of measured and simulated daily streamflow for the validation period (2005-2007) is presented in Figure 4a. The model captured the streamflow dynamics reasonably well during the validation period; however, an obvious overprediction occurred on June 2, 2005, after a normal dry period. Similar to calibration results, this overprediction is attributed to the model artifact which sustains a wet stream bed. The correspondence between measured and predicted streamflow (R^2 of 0.66-0.83 for daily streamflow in 2005-2007, and 0.97-0.99 for monthly streamflow) showed good agreement (Table 5a). Similarly, the E-statistic (0.63-0.81 for daily streamflow and 0.88-0.95 for monthly streamflow) showed that MIKE SHE was applicable for the prediction of both the daily and monthly streamflow dynamics in this watershed (Moriasi *et al.*, 2007). Similar to the calibration results, MIKE SHE was able to capture the water table dynamics effectively (Figure 4b and Table 5b), with the simulated water table being in good agreement with the observations (E: 0.65, and R^2: 0.71, n = 1988).

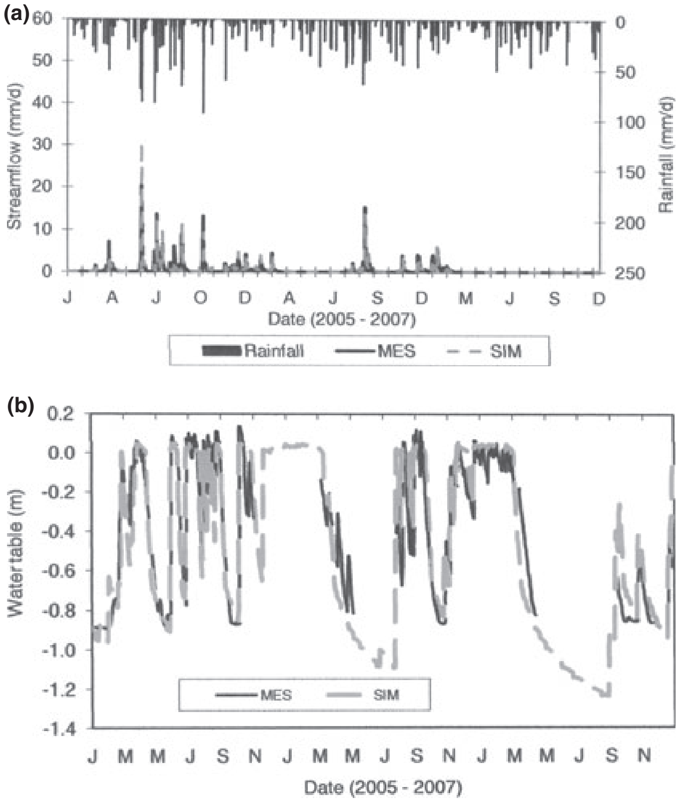

FIGURE 4. (a) Time Series of Daily Streamflows Observed and Simulated for Validation Period. (MES, measurement; SIM, simulation. Streamflow was normalized to mm per day per square meter.) (b) Measured and simulated water table at well W3 in 2005-2007. (MES, measurement; SIM, simulation.)

Model Applications

Streamflow Response to Climate Change. The effect of altered precipitation regimes (scenarios PIN1-PIN5 and PDE1-PDE3) on streamflow was large and linear (Figure 5a). These results are similar to other reports that have shown a high degree of correspondence between streamflow with natural fluctuation of precipitation (Karl and Riebsame, 1989) and simulated precipitation regimes to reflect altered climatic conditions (Poff *et al.*, 1996; Sun *et al.*, 2000b; Amatya *et al.*, 2006; Harder *et al.*, 2007; Qi *et al.*, 2009). These simulation results corresponded with the observed relationship between precipitation and streamflow in WS-80 between 1969 and 2007, which was a linear function (R^2 = 0.51,

TABLE 5B. Measured and Simulated Water Table for Automatic Wells in 2005-2007.*

	W3					W7				
	Measured		Simulated			Measured		Simulated		
Year	Mean	SD	Mean	SD	R^2	Mean	SD	Mean	SD	R^2
2005	−0.40	0.37	−0.48	0.47	0.89	−1.14	0.63	−1.13	0.51	0.66
2006	−0.50	0.33	−0.60	0.48	0.89	−1.45	0.73	−1.43	0.61	0.46
2007	−0.64	0.32	−0.76	0.43	0.85	−1.52	0.73	−1.66	0.52	0.54

*R^2 is the coefficient of determination. There was not measured water table data from 2005 to 2007 for the manual wells; SD is standard deviation.

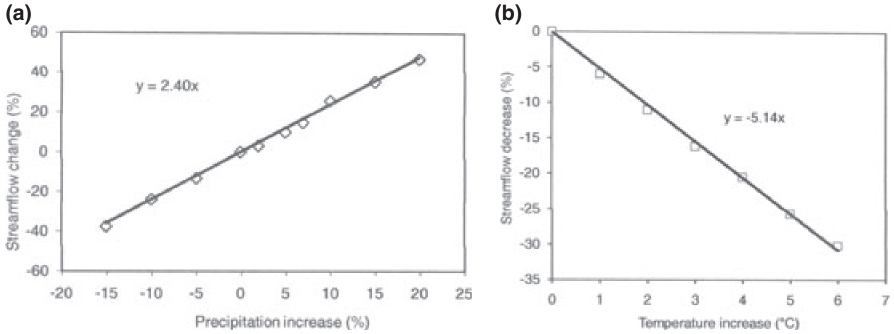

FIGURE 5. Effects of Changes in Precipitation (a) and Temperature (b) on Streamflow.

$p < 0.01$) producing a 2.3:1 proportional change (%) between streamflow and precipitation (Dai *et al.*, Unpublished). The simulated linear increase of 2.4% in streamflow corresponding with 1% increase in precipitation was comparable to the response in the Trend River basin in North Carolina where a 23% increase in streamflow corresponded to a 10% increase in precipitation (Qi *et al.*, 2009). Risbey and Entekhabi (1996) found a nonlinear relationship between precipitation and streamflow in the Sacramento Basin, California. These contrasting responses between streamflow and precipitation are likely affected by general climatic patterns and watershed conditions, such as land use, soils, and water storage (Rowe *et al.*, 1994; Sun *et al.*, 2000b).

Compared to current climate conditions (scenario CCC), the annual average streamflow decreased at a rate of approximately 5% per °C temperature increase, within a 0-6°C range (scenarios CCC and TIN1-TIN6) (Figure 5b). The monthly streamflow decreased by 1.0-11.6% per °C in the five-year period, and the decrease was not related to monthly precipitation ($R^2 = 0.06$, $n = 60$, $p > 0.05$). Using the PRMS model for the Trend River basin in North Carolina, Qi *et al.* (2009) predicted a slightly higher rate, with streamflow decreasing by 15% with a corresponding increase in temperature of 2.78°C. Eckhardt and Ulbrich (2003) reported a similar result in their hydrological modeling using Soil and Water Assessment Tool (SWAT) (Arnold *et al.,* 2001). The general decline in streamflow corresponding to increasing temperature is primarily in response to an increase in ET (Middelkoop *et al.*, 2001). In a pine plantation in eastern North Carolina, Sun *et al.* (2000b) reported an 8.7% increase in ET due to a 1.9°C temperature increase. That change in ET relative to temperature (1:4.6) is similar to the predicted change in streamflow on WS-80, which is also strongly affected by ET.

The results from the two-factor scenarios (PNT1, PNT2, and PNT3, which combined temperature increase by 2°C with precipitation increase by 5, 10, and 15%) showed that streamflow increased by 3.0, 12.5, and 28.7%, respectively. This result suggested that the increase in streamflow was likely to be larger, if global warming would increase precipitation at a rate higher than the 6-7% per °C reported by Wentz *et al.* (2007) and Lambert *et al.* (2008). If the temperature increased by 2°C and precipitation decreased by 10% (scenario TVP, see Table 3), the streamflow would decrease by 23.9% in wet years to as much as 38.5% in dry years. The decrease in streamflow given by scenario TVP in dry years was equal to the sum of the decreased streamflows resulted from scenario TIN2 (temperature increase by 2°C) and scenario PDE2 (precipitation decrease by 10%), but it was about 2% less than the sum in wet years. A 2% reduction in streamflow in wet years for scenario TVP was due to the ET demand during low precipitation periods, especially during the summer. Compared to current climate conditions (scenario CCC), streamflow response to increasing or decreasing precipitation intensity in this watershed was very significant ($R^2 = 0.997$, $p \ll 0.01$), and that reduced precipitation or drought would substantially decrease the streamflow.

Water Table Response to Climate Change. Water table depth on WS-80 was sensitive ($R^2 > 0.99$, $p < 0.01$) to the climate change scenarios (Figure 6a). The annual average water table level was higher for scenarios of increased precipitation (PIN1-PIN5) and lower when precipitation decreased (PDE1-PDE3) as compared to the current condition (CCC) yielding a quadratic polynomial function (Figure 6a). However, the magnitude of changes in water table depth within the watershed corresponded to the relative topographic position. The upland positions tended to exhibit larger changes in water table depth as compared to riparian or wetland areas. Similarly, Moorhead (2003) reported that the water table depth of nontidal wetlands in western North Carolina was substantially influenced by variations in precipitation, and drought reduced the average monthly water table depth by 26 cm in a mountain fen and 22 cm in the adjacent floodplain, demonstrating that precipitation is one of the key factors to regulate the water table level in nontidal wetlands.

Annual average water table depth decreased linearly with increasing temperature (scenarios TIN1-TIN6) (Figure 6b), exhibiting a reduction of 1.9 cm per °C temperature increase, within the simulated range of 0-6°C. The predicted water table depth changed by −0.6, +3.3, and +5.5 cm for scenarios PNT1, PNT2, and PNT3 (combination of increased temperature and precipitation), respectively, and decrease of 20.2% (17.4 cm) for the TVP scenario (combination of increased temperature and decreased precipitation). These results highlight the strong effect that ET has on water table dynamics in this landscape. The PNT1 scenario exhibited a decline despite the higher precipitation. The additional precipitation in PNT2 and PNT3 scenarios provided sufficiently more water to overcome the ET demand caused by the increased temperature. The TVP scenario reflects a large decrease in water table level due to the increased ET and decreased precipitation. Eckhardt and Ulbrich (2003) showed similar results that streamflow and water table depth were reduced by over 50% due to enhanced ET by increased temperature together with decreased precipitation. Jutras *et al.* (2006) also provided an example that ET was very important in regulating water table level in forested wetlands, and changes in water table depth were irrespective of soil types in their study watershed. Since most climate change scenarios predict an increased temperature regime, it is likely that the shallow water table characteristics of coastal forests will be affected (Lu *et al.*, 2009).

CONCLUSIONS

This is one of the few studies that have examined the spatial and temporal hydrological dynamics of a headwater watershed on the lower coastal plain using a distributed hydrological model (MIKE SHE). Based on five years of climatic data, the streamflow, and water table responses demonstrated that MIKE SHE was effective for simulating the streamflow and water table depth. However, the model overpredicted streamflow during dry periods, primarily due to an artifact in the model that would not allow for no-flow during prolonged dry conditions. The overprediction of streamflow during dry periods highlights the challenges in modeling intermittent streamflow of first-order watersheds. The multi-criteria calibration was important to obtaining decent simulation results from the physically based distributed, and highly parameterized hydrological model. Although the model calibration using a distributed water table may enlarge

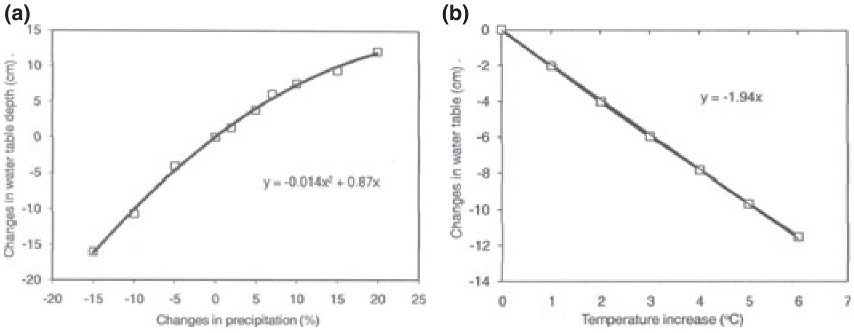

FIGURE 6. Effects of Changing Precipitation (a) and Temperature (b) on Water Table.

the bounds of the input uncertainties and increase the application cost, it is advantageous for optimizing input values and yielding results that allow assessments of hydrological change within the watershed.

The simulation of multiple temperature and precipitation scenarios shows that the hydrology of the forested coastal plain watershed is sensitive to climate change. The proportion of precipitation allocated to streamflow is projected to correspond to increases or decreases in precipitation. Similarly, the projected effect of climate change on water table depth is substantial. Changes in water table depth are significant with either an increase or decrease in precipitation and an increase in temperature. The impact of drought on the water table depth in the watershed is projected to be large.

The results from climate change scenarios indicate that the hydrological regime of forested watersheds on coastal plains is highly sensitive to changes in annual precipitation and temperature. Those hydrological effects are particularly critical to ecological functions of the upland and wetland forest ecosystems within the watershed. For example, watershed predicted reduction in water table depth under some scenarios would significantly shrink or end the existence of wetlands within the watershed. These results demonstrate that the spatially explicit, mechanistic hydrological model, MIKE SHE, is a useful tool for assessing eco-hydrological changes that may be associated with climate change for this type of coastal forested watersheds.

LITERATURE CITED

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell, and J. Rasmussen, 1986a. An Introduction to the European Hydrological System – Systeme Hydrologique Europeen, "SHE", 1: History and Philosophy of a Physically-Based, Distributed Modelling System. Journal of Hydrology 87:45-59.

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell, and J. Rasmussen, 1986b. An Introduction to the European Hydrological System – Systeme Hydrologique Europeen, "SHE", 2: Structure of a Physically-Based, Distributed Modelling System. Journal of Hydrology 87:61-77.

Amatya, D.M. and R.W. Skaggs, 2001. Hydrologic Modeling of a Drained Pine Plantation on Poorly Drained Soils. Forest Science 47:103-114.

Amatya, D.M., G. Sun, R.W. Skaggs, and J.E. Nettles, 2006. Hydrologic Effects of Global Climate Change on a Large Drained Pine Forest. *In*: Hydrology and Management of Forested Watersheds Proceedings of the International Conference 8-12 April 2006, Publication Number 701P0406. T. Williams and J. Nettles (Editors). ASABE, St. Joseph, Michigan, pp. 383-394.

Amatya, D.M., G. Sun, C.C. Trettin, and R.W. Skaggs. 2003. Long-Term Forest Hydrologic Monitoring in Coastal Carolinas. *In*: First Interagency Conference on Research in the Watersheds, October 27-30, 2003, Kenneth G. Renard, Stephen A. McElroy, William J. Gburek, H. Evan Canfield, and Russell L. Scott (Editors). U.S. Department of Agriculture, Agricultural Research Service, Washington, D.C., pp. 279-285.

Ambroise, B., J.L. Perrin, and D. Reutenauer, 1995. Multicriterion Validation of a Semidistributed Conceptual Model of the Water Cycle in Fecht Catchment. Water Resources Research 31:1467-1481.

Arnold, J., P. Allen, and D. Morgan, 2001. Hydrologic Model for Design and Constructed Wetlands. Wetlands 21:167-178.

Bréda, N.J.J., 2003. Ground-Based Measurements of Leaf Area Index: A Review of Methods, Instruments and Current Controversies. Journal of Experimental Botany 54:24032417.

Burkett, V. and J. Kusler, 2000. Climate Change: Potential Impacts and Interactions in Wetlands of the United States. Journal of the American Water Resources Association 36:313-320.

Carter, V., 1986. An Overview of the Hydrologic Concerns Related to Wetlands in the United States. Canadian Journal of Botany 64:364-374.

Christensen, N., A. Wood, N. Voisin, D. Lettenmaier, and R. Palmer, 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change 62:337-363.

Conner, W.H., I. Mihalia, and J. Wolfe, 2002. Tree Community Structure and Changes From 1978 to 1999 in Three Louisiana and Three South Carolina Forested Wetlands. Wetlands 22: 58-70.

Dai, Z., C. Trettin, C., H Li, D Amatya and G. Sun. Analyzing Climate Change Impact on Forest Hydrology of Santee Experimental Forest in the Last Half Century, unpublished data.

DHI, 2005. MIKE SHE Technical Reference. Version 2005. DHI Water and Environment, Danish Hydraulic Institute, Denmark.

Dibike, Y. and P. Coulibaly, 2005. Hydrologic Impact on Climate Change in the Saguenay Watershed: Comparison of Downscaling Methods and Hydrologic Models. Journal of Hydrology 307:145-163.

Eckhardt, K. and U. Ulbrich, 2003. Potential Impacts of Climate Change on Groundwater Recharge and Streamflow in a Central European Low Mountain Range. Journal of Hydrology 284: 244-252.

El-Nasr, A.A., J. Feyen, and J. Berlamont, 2001. Modeling a Mid-Size Chatchment Using a Physically Distributed Hydrologic Model. American Institute of Hydrology, Hydrological Science & Technology, Special Issue, 17:1-10.

El-Sadek, A., 2007. Upscaling Field Scale Hydrology and Water Quality Modeling to Catchment Scale. Water Resource Management 21:149-169.

EPA, 2005. National Management Measures to Control Nonpoint Source Pollution From Forestry. EPA 841-B-05-001, May 2005, EPA, Washington, D.C., pp. 103-121.

Erwin, K.L., 2009. Wetlands and Global Climate Change: The Role of Wetland Restoration in a Changing World. Wetlands Ecology and Management 17:71-84.

Freeman, C., R. Gresswell, M.A. Lock, C. Swanson, H. Guasch, F. Sabater, S. Sabater, J. Hudson, S. Hughes, and B. Reynolds, 1995. Climate Change: Man's Indirect Influence on Wetland Microbial Activity and the Biofilms of a Wetland Stream. *In*: Man's Influence on Freshwater Ecosystems and Water Use, Proceedings of Boulder Symposium, July 1995, Publ. no 230, G. Petts (Editor). IAHS, Boulder, Colorado, pp. 199-206.

Graham, D.N. and M.B. Butts, 2005. Flexible Integrated Watershed Modeling With MIKE SHE. *In*: Watershed Models, V.P. Singh and D.K. Frevert (Editors). CRC Press, Boca Raton, Florida, pp. 245-272.

Harder, S.V., D.M. Amatya, T.J. Callahan, and C.C. Trettin, 2006. Modeling the Monthly Water Balance of a First Order Coastal Forested Watershed. Hydrology and Management of Forested Wetlands Proceedings of the International Conference 8-12

April 2006, New Bern, North Carolina, Publication Date 8 April 2006, Publication Number 701P0406, ASABE, St. Joseph, Michigan, pp. 218-230.

Harder, S.V., D.M. Amayta, T.J. Callahan, C.C. Trettin, and J. Hakkila, 2007. Hydrology and Water Budget for a Forested Atlantic Coastal Plain Watershed, South Carolina. Journal of the American Water Resources Association 43:563-575.

Haukos, D.A. and L.M. Smith, 2006. Effects of Soil Water on Seed Production and Photosynthesis of Pink Smartweed (*Polygonum Pensylvanicum L.*) in Playa Wetlands. Wetlands 26:265-270.

Heath, R.C., 1975. Hydrology of the Albemarle-Pamlico Region of North Carolina. USGS Water Resources Investigation 9-75, Raleigh, North Carolina, 98 pp.

Hook, D.D., M.A. Buford, and T.M. Williams, 1991. Impact of Hurricane Hugo on the South Carolina Coastal Plain Forest. Journal of Coastal Research (Special Issue) 8:291-300.

IPCC, 2001. Climate Change 2001: The Scientific Basis. *In*: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors). Cambridge University Press, Cambridge, United Kingdom, pp. 6-7.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Paris.

Jutras, S., A.P. Plamondon, H. Hökkä, and J. Bégin, 2006. Water Table Changes Following Precommercial Thinning on Post-Harvest Drained Wetlands. Forest Ecology and Management 235:252-259.

Karl, T. and W. Riebsame, 1989. The Impact of Decadal Fluctuations in Mean Precipitation and Temperature on Runoff: A Sensitivity Study Over the United States. Climatic Change 15:423-447.

Kirchner, J.W., 2006. Getting the Right Answers for the Right Reasons: Linking Measurements, Analysis, and Models to Advance the Science of Hydrology. Water Resources Research 42:W03S04.

Kozlowski, T.T., 2002. Physiological-Ecological Impacts of Flooding on Riparian Forest Ecosystems. Wetlands 22:550-561.

Lambert, F.H., A.R. Stine, N.Y. Krakauer, and J.C.H. Chiang, 2008. How Much Will Precipitation Increase With Global Warming? EOS 89, No. 21, 20 May 2008, p. 193.

Lloyd, F.T. and D.F. Olson, 1974. The Precision and Repeatability of a Leaf Biomass Sampling Technique for Mixed Hardwood Stands. Journal of Applied Ecology 11:1035-1042.

Lu, J., G. Sun, D.M. Amatya, S.V. Harder, and S.G. McNulty, 2006. Understanding the Hydrological Response of a Coastal Plain Watershed to Forest Management and Climate Change in South Carolina, USA. Hydrology and Management of Forested Wetlands Proceedings of the International Conference 8-12 April 2006. New Bern, North Carolina. Publication Date 8 April 2006 701P0406, pp. 231-239.

Lu, J., G. Sun, S.G. McNulty, and N. Comerford, 2009. Sensitivity of Pine Flatwoods Hydrology to Climate Change and Forest Management in Florida, USA. Wetlands 29:826-836.

Mansell, R., S. Bloom, and G. Sun, 2000. A Model for Wetland Hydrology: Description and Validation. Soil Science 165: 384-397.

Martinez, C., K. Campbell, M. Annable, and G. Kiker, 2008. An Object-Oriented Hydrologic Model for Humid, Shallow Water-Table Environments. Journal of Hydrology 351:368-381.

Maurer, E., 2007. Uncertainty in Hydrologic Impacts of Climate Change in the Sierra Nevada, California, Under Two Emissions Scenarios. Climatic Change 82:309-325.

Mernild, S., B. Hasholt, and G. Liston, 2008. Climatic Control on River Streamflow Simulations, Zackenberg River Drainage Basin, Northeast Greenland. Hydrological Processes 22:1932-1948.

Middelkoop, H., K. Daamen, D. Gellens, W. Grabs, J.C.J. Kwadijk, H. Lang, B.W.A.H. Parmet, B. Schädler, J. Schulla, and K. Wilke, 2001. Impact of Climate Change on Hydrological Regimes and Water Resources Management in the Rhine Basin. Climatic Change 49:105-128.

Miller, N., K. Bashford, and E. Strem, 2003. Potential Impact of Climate Change on California Hydrology. Journal of the American Water Resources Association 39:771-784.

Monteith, J.L., 1965. Evaporation and Environment. *In:* Proceedings of the 19th Symposium of the Society for Experimental Biology, G.E. Fogg (Editor). Cambridge University Press, New York, pp. 205-234.

Moorhead, K.K., 2003. Effect of Drought on the Water-Table Dynamics of a Southern Appalachian Mountain Floodplain and Associated Fen. Wetlands 23:792-799.

Moriasi, D.N., J.G. Arnold, M.W.V. Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith, 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. ASABE 50:885-899.

Mulhouse, J.M., D.D. Steven, R.F. Lide, and R.R. Sharitz, 2005. Effects of Dominant Species on Vegetation Change in Carolina Bay Wetlands Following a Multi-Year Drought. Journal of the Torrey Botanical Society 132:411-420.

Nash, J.E. and J.V. Sutcliffe, 1970. River Flow Forecasting Through Conceptual Models- Part I: A Discussion of Principles. Journal of Hydrology 10:282-290.

Nicholls, R.J., 2004. Coastal Flooding and Wetland Loss in the 21st Century: Changes Under the SRES Climate and Socio-Economic Scenarios. Global Environmental Change 14:69-86.

Nicholls, R.J., F.M.J. Hoozemans, and M. Marchand, 1999. Increasing Flood Risk and Wetland Losses Due to Global Sea-Level Rise: Regional and Global Analyses. Global Environmental Change 9:s69-s87.

Poff, N.L., S. Tokar, and P. Johnson, 1996. Stream Hydrological and Ecological Responses to Climate Change Assessed With an Artificial Neural Network. Limnology and Oceanography 41:857-863.

Qi, S., G. Sun, Y. Wang, S.G. McNulty, and J.A. Moor Myers, 2009. Streamflow Response to Climate and Land Use Changes in a Coastal Watershed in North Carolina. ASABE 52(3):1-11.

Riekerk, H., S.A. Jones, L.A. Morris, and D.A. Pratt, 1979. Hydrology and Water Quality of Three Small Lower Coastal Plain Forested Watersheds. *In*: Proceedings of the Soil and Crop Science Society of Florida, E.S. Horner (Editor). Soil and Crop Science Society of Florida, Gainesville, Florida, Vol. 38, pp. 105-111.

Risbey, J.S. and D. Entekhabi, 1996. Observed Sacramento Basin Streamflow Response to Precipitation and Temperature Changes and Its Relevance to Climate Impact Studies. Journal of Hydrology 184:209-223.

Rowe, C.M., K.C. Kuivinen, and F. Flores-Mendoza, 1994. Sensitivity of Streamflow to Climate Change: A Case Study for Nebraska. Great Plains Research 4:27-49.

Sahoo, G.B., C. Ray, and E.H. Carlo, 2006. Calibration and Validation of a Physically Distributed Hydrological Model, MIKE SHE, to Predict Streamflow at High Frequency in a Flashy Mountainous Hawaii Stream. Journal of Hydrology 327:94-109.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayan, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger, and J.G. Titus, 2002. Climate Change Impacts on U.S. Coastal and Marine Ecosystems. Estuaries 25:149-164.

SCS (Soil Conservation Service), 1980. Soil Survey of Berkeley County. United States Department of Agriculture, South Carolina, 99 pp.

Shrestha, R.R. and M. Rode, 2008. Multi-Objective Calibration and Fuzzy Preference Selection of a Distributed Hydrological Model. Environmental Modeling and Software 23:1384-1395.

Staes, J., M. Rubarenzya, P. Meire, and P. Willems, 2009. Modelling Hydrological Effects of Wetland Restoration: A Differentiated View. Water Science and Technology 59:433-441.

Sun, G., D.M. Amatya, S.G. McNulty, R.W. Skaggs, and J.H. Hughes, 2000b. Climate Change Impacts on the Hydrology and Productivity of a Pine Plantation. Journal of the American Water Resources Association 36:367-374.

Sun, G., T.J. Callahan, J.E. Pyzoha, and C.C. Trettin, 2006. Modeling the Climatic and Geomorphologic Controls on the Hydrology of a Carolina Bay Wetland in South Carolina, USA. Wetlands 26:567-580.

Sun, G., J. Lu, D. Gartner, M Miwa, and C.C. Trettin, 2000a. Water Bugets of Two Forested Watersheds in South Carolina. *In*: Proceedings of the Spring Special Conference, R.W. Higgins (Editor). American Water Resources Association, Miami, Florida, pp. 199-202.

Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen, 2008. Impacts of Multiple Stresses on Water Demand and Supply Across the Southeastern United States. Journal of the American Water Resources Association 44:1441-1457.

Trettin, C.C. and M.F. Jurgensen, 2003. Carbon Cycling in Wetland Forest Soils. *In*: Carbon Sequestration in US Forests, J. Kimble, R. Birdsie, and R. Lal (Editors). CRC Press LLC, Boca Raton, Florida, pp. 311-331.

Vázquez, R., P. Willems, and J. Feyen, 2008. Improving the Predictions of a MIKE SHE Catchment-Scale Application by Using a Multi-Criteria Approach. Hydrological Processes 22:2159-2179.

Verry, E.S., 1997. Hydrological Processes of Natural Northern Forested Wetlands. *In*: Northern Forested Wetlands – Ecology and Management, C.C. Trettin, M.F. Jurgensen, D.F. Grigal, M.R. Gale, and J.K. Jeglum (Editors). CRC-Lewis Pub, Boca Raton, Florida, pp. 163-188.

Wentz, F.J., L. Ricciardulli, K. Hilburn, and C. Mears, 2007. How Much More Rain Will Global Warming Bring? Science 317:233-235.

Winter, T.C., 1988. A Conceptual Framework for Assessing Cumulative Impacts on the Hydrology of Nontidal Wetlands. Environmental Management 12:605-620.

Xu, C. and V.P. Singh, 2005. Evaluation of Three Complementary Relationship Evapotranspiration Models by Water Balance Approach to Estimate Actual Regional Evapotranspiration in Different Climatic Regions. Journal of Hydrology 308:105-121.

Yan, J.J. and K.R. Smith, 1994. Simulation of Integrated Surface Water and Ground Water Systems – Model Formulation. Water Resources Bulletin 30:1-12.

Zhang, X, F.W. Zwiers, G.C. Hegerl, F. Hugo Lambert, N.P. Gillett, S. Solomon, P.A. Stott, and T. Nozawa, 2007. Detection of Human Influence on Twentieth-Century Precipitation Trends. Nature 448:461-465.

Zhang, Z., S. Wang, G. Sun, S.G. McNulty, H. Zhang, J. Li, M. Zhang, E. Klaghofer, and P. Strauss, 2008. Evaluation of the MIKE SHE Model for Application in the Loess Plateau, China. Journal of the American Water Resources Association 44:1108-1120.