UNDERSTANDING THE HYDROLOGIC RESPONSE OF A COASTAL PLAIN WATERSHED TO FOREST MANAGEMENT AND CLIMATE CHANGE IN SOUTH CAROLINA, U.S.A.

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ABSTRACT

The hydrologic processes in wetland ecosystems are not well understood. There are also great concerns and uncertainties about the hydrologic response of wetlands to forest management and climate change. The objective of this study is to apply a hydrologic model to better understand the hydrologic processes of a low relief coastal forested watershed and its responses to potential land disturbance, and to test its sensitivity to potential climate variability and change. We applied MIKE SHE, a physically based and spatially distributed hydrologic model, at Watershed 80 within Santee Experimental Forest in the lower coastal plain of South Carolina, United States. With a user-friendly interface and GIS (Geographic Information Systems) linkage, the MIKE SHE model integrates surface water and groundwater, and it simulates the full hydrologic cycle including interception, evapotranspiration (ET), infiltration, overland flow, subsurface and channel flow (with MIKE 11), and unsaturated and saturated soil water movement. The model was validated by the water table and streamflow data collected at the site in 2003 and 2004. Overall, the model performed well in simulating the hydrologic dynamics of the study watershed. The model simulations indicate that runoff is mainly generated by the overland flow after the soil is saturated during wet periods. We applied the validated model to examine the responses of reduction of leaf area index (LAI), increase of air temperature by 2 °C, and decrease of precipitation by 10%. Generally, the modeling results suggest that forest removal will raise the water table, especially during the dry periods, due to decrease in ET. Increase of air temperature or decrease of precipitation will reduce groundwater recharge and result in lower water table and runoff.

KEYWORDS. Hydrologic modeling, Wetland hydrology, MIKE SHE, Forest management, Climate change

INTRODUCTION

Modeling is a common practice used in hydrology study. The natural systems are complicated and traditional experimental methods are too expensive to implement if not impossible. Mathematical model represented by a series of equations as simplified versions of real systems may give detailed hydrologic processes as much as a modeler desires. Once a model is developed, different scenarios can be simulated to evaluate the impacts of resources management practice or natural disturbance. Furthermore, a model, which is sufficient to conduct simulations, can be used to predict future scenarios by providing estimate inputs. Thus, the model serves as a tool for synthesizing data, providing interpretations, and identifying important knowledge gaps (Sun et al., 1998, Amatya el. 2001).

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Hydrologic modeling has become an essential tool in watershed management. The model can help us understand the physical, chemical and biological processes within a watershed and the interactions among them. Furthermore, successful application of the model will help us manage and protect the water resources and the water environment. The increasing demand for water resources also challenges our ability to understand and describe the underlying hydrologic processes. The impacts of forest management on the hydrology are not fully understood and the understanding of the hydrologic process is critical for watershed management. The growing concerns on climate change have also stimulated increased research into understanding the complex feedback between the atmosphere and the terrestrial hydrological cycle. (Graham and Butts, 2005). The hydrologic responses to climate change and forest management practices are complicated and the model is the necessary tool for such tasks.

Experiments in the southern US and elsewhere around the world showed that streamflow increased after forest harvesting in general (Sun et al., 2004; Andreassian, 2004). For example, clear-cut in the Appalachian mountains caused water yield to increase by 26-41 cm, or 28-65% of control during the first year after harvest (Douglass and Swank, 1972; Swank and Douglas, 1974; Swank et al., 2001). However, such magnitude was not found in the coastal plain region (Sun et al., 2004) presumably due to different hydrologic processes. Andreassian (2004) suggests that hydrological response to land management was controlled by climate, soil and vegetation development. Quantifying the influences of those factors requires a process-based approach. Similarly, understanding and quantifying the climate change effects are mostly done using computer simulation models at watershed and continental scales (McNulty et al., 1997; Sun et al., 2000; Amatya et al., this Volume).

The objective of this study is to apply a hydrologic model, MIKE SHE (DHI, 2004), to better understand the hydrologic processes of a low relief coastal forested watershed and its responses to potential land disturbance, and to test its sensitivity to potential climate variability and change. This study is a part of project investigating hydrologic processes across a physiographic gradient in the southeastern U.S.

METHODS

<u>Study Site</u>

The study site, a 160 ha forested watershed, is located at Santee Experimental Forest on the lower Atlantic Coastal Plain in eastern South Carolina, U.S. (Figure 1). The watershed consists of one first order stream as the main drainage pathway. The area has low topographic relief (< 4%) with surface elevation ranging from 3 - 10 m about mean sea level. This study site serves as the control watershed and has been relatively undisturbed for over eighty years, but it was damaged by Hurricane Hugo in 1989 (Harder, 2004).

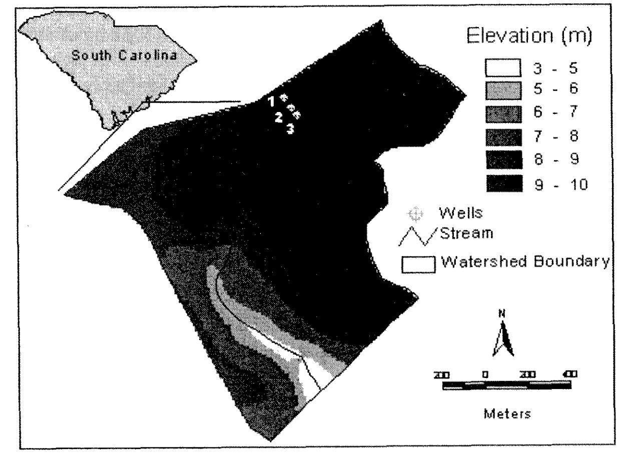

Figure 1. The study watershed (watershed 80) within the Santee Experimental Forest, SC, USA.

The vegetation coverage at this watershed is mainly composed of pine hardwood (39%), hardwood pine (28%) and mixed hardwoods (33%). Common tree types include loblolly pine (*Pinus taeda L.*), sweetgum (*Liquidambar styraciflua*), and a variety of oak species typical of the Atlantic Coastal Plain. Most of the tree stands are 14-15 years old. The study site consists of primarily sandy loam soils with clayey subsoils, and much of the soil is part of the Wahee-Lenoir-Duplin association (SCS, 1980). Soils are influenced by seasonally high water tables and argillic horizons at 1.5 meters below ground surface . The climate of the study site is classified as humid subtropical with long hot summers and short mild winters. Mean annual precipitation is about 1370 mm with July and August as the wettest months (28% of total) and April and November as the driest months (10% of total). Long-term (1951-2003) monthly averages are as low as 10°C in January and as high as 28°C in July. The long-term mean annual air temperature is 19.1°C. Approximately 23% of the WS80 is classified as wetlands (Harder, 2004).

<u>MIKE SHE Hydrologic Model</u>

The MIKE SHE model simulates the full hydrologic cycle characteristic of a forest ecosystem, including evapotranspiration (ET) and vertical soil water movement in the unsaturated zone to the groundwater. Detailed descriptions of the modeling procedures and mathematical formulation can be found in the MIKE SHE user's manual (DHI, 2004) and associated publications (Abbot et al., 1986; Refsgaard and Storm, 1995; Graham and Butts, 2005).

As the first generation of spatially distributed hydrologic model, the MIKE SHE model simulates the full hydrologic cycle of a watershed across space and time, including spatial distribution of groundwater table depth, soil moisture content, and ET. The model simulates both surface and groundwater flows and their interactions. The infiltration processes are modeled using the Richard's equation or a simple soil water balance equation. Saturated water flow in the subsurface is simulated by a 3-D groundwater flow model. The modeling package is user friendly with a window interface to Geographic Information Systems. We have tested this model at selected forested watersheds across a physiographic gradient in the southeastern U.S, and this study is a part of the project.

<u>MIKE SHE Model Setup</u>

Data required to run the MIKE SHE model included: 1) Watershed topography and landuse data - retention storage, Manning roughness number, and vegetation distribution (leaf area index (LAI) dynamics and rooting depth); 2) Soil data - soil depth, hydraulic properties (conductivity, porosity, field capacity and wilting point); 3) Meteorological data - precipitation and temperature; 4) Boundary conditions; 5) Stream network with the coupling of MIKE 11 model (DHI, 2004).

Watershed elevation data (Figure 1) were acquired from the GISDataDepot website (URL: http://data.geocomm.com/dem/) in 10 m DEM resolution. The elevation data were processed by ESRI ArcView 3.3 and organized as shape files, which were used directly as an input into the MIKE SHE model. Model grid cell size was set at 50 m, which was selected to allow for accurate representation of the watershed without placing excessive demands on model running time.

According to the vegetation coverage types, the160 ha watershed was considered as two landuse types, which was represented by a set of parameters in the MIKE SHE vegetation database. These included empirical constants for actual evapotranspiration (AET) and time series of LAI and rooting depth. LAI data were not available for this study site. It was assume that it had the same LAI as a one-year observed LAI data at a Florida wetland site based on the vegetation coverage type (Liu, 1996). LAI was assumed the same for each year during the study period (2003-2004). A rooting depth of 50 cm was used for vegetations across the entire watershed.

Daily rainfall and air temperature data were requested from the research station (Harder, 2004). The Hamon potential evapotranspiration (PET) method (Hamon, 1963; Lu et al., 2005) was used to calculate daily PET at this site with the calibrated coefficient as 1.2.

The soil characteristics were determined by Harder (2004) and retrieved from soil survey (SCS, 1980). In the MIKE SHE modeling system, the soil was defined as 3 m deep below the ground surface across the entire watershed. Three soil types were used at this watershed.

The watershed was assumed as a closed watershed, and there was no leakage through the watershed boundary. In other words, water only moved out of the watershed through evapotranspiration and the stream flow at the watershed outlet.

MIKE 11 was coupled with MIKE SHE to simulate stream flow at this watershed. A single stream was delineated from the DEM data. Cross-sectional area of the stream was estimated based on the field survey. Boundary conditions were set as zero inflow at the upstream open end and constant water level at the watershed outlet.

<u>Model calibration, validation and applications</u>

The purpose of the calibration is to obtain a set of model parameters, which provide a best agreement between field measurements and model simulations (Im et al., 2004). The process was conducted manually. Basically, a "trial and error" procedure, evaluated by statistical criteria, was used to examine the influence of various model parameters. After the calibration, all parameters obtained through the calibration process remained constant for model validation, which was performed to examine whether the model parameters derived from the calibration were generally valid. Daily streamflow and water table data from this watershed were used for the MIKE SHE model calibration and validation. The statistical parameters for evaluating the MIKE SHE model performance included mean error (ME), Pearson's Correlation Coefficient (R) and the Nash-Sutcliffe (1970) coefficient of efficiency (E).

After model calibration and validation were conducted, MIKE SHE was applied to simulate a base line and three hypothetical scenarios during the time of 2003 and 2004. These scenarios included: 1) Base line (BL); 2) Clear Cutting (CC); 3) Two degree (°C) temperature increase (TI); 4) Ten percent precipitation decrease (PD). The purposes of the applications were to examine how the model performances under "what-if" scenarios and test the model sensitivities. The BL scenario was based on the historically climatic data with the assumption that the site remained forested during 2003 - 2004. The CC scenario represented a simple forest management practice that was also based on the historically climatic data, but with the assumption that the entire site remain unvegetated during 2003 - 2004 with LAI reduced to 0.1 for the entire site (Gholz and Clark, 2002; Clark et al., 2004). The TI scenario represented the situation that daily temperature was increased 2 °C with no change in precipitation. The PD scenario simulated the case that daily precipitation decreased 10% whenever there was a rainfall event with no change in air temperature. The land cover remained the same as the base line for the two climate change scenarios.

RESULTS

<u>Model Calibration</u>

The MIKE SHE model was calibrated against the daily streamflow data (Harder, 2004) from the watershed in 2003. Compared to the long-term annual average precipitation at the study site, 2003 was a wet year that had a surplus of 300 mm of precipitation. Generally, the model could simulate the variations of the streamflow with R = 0.75, ME = 0.10 mm/day and E = 0.56 (Figure 2). However, the model did not catch all the peak flows, especially for one large storm event (Hurricane Isabelle) in the mid of September. The simulated peakflow rate (0.37 m^3/s) was much lower than the measurement (1.44 m^3/s). It was likely because the model took daily precipitation as input and could not represent the actual large rainfall intensities during this hurricane event.

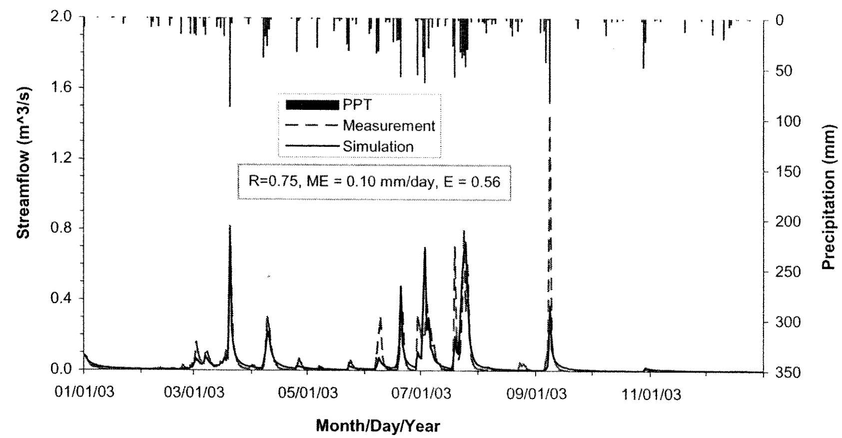

Figure 2. Calibration of MIKE SHE model with daily streamflow in 2003.

<u>Model validation</u>

The MIKE SHE model was validated with streamflow and water table depth (Figure 3 and Figure 4). Compared to the long-term annual average precipitation, 2004 was a dry year with a 409 mm rainfall deficit. There were only three stormflow events in the watershed, and there was no streamflow observed at all for entire five months (June, July, October, November, and December) in 2004. Generally, MIKE SHE simulated the streamflow dynamics under this extremely dry condition, but it over-predicted a peakflow rate in late August (Figure 3). This might be caused by the fact that MIKE 11 is a hydraulic model that simulates continuous water movement in the stream channel. In the modeling system, it did not allow drying river conditions and water continuously moved out of the watershed although it was in a very small volume during those five no-flow months. Thus, overall, the model over-predicted streamflow with ME = -0.31 mm/day and E = -3.61.

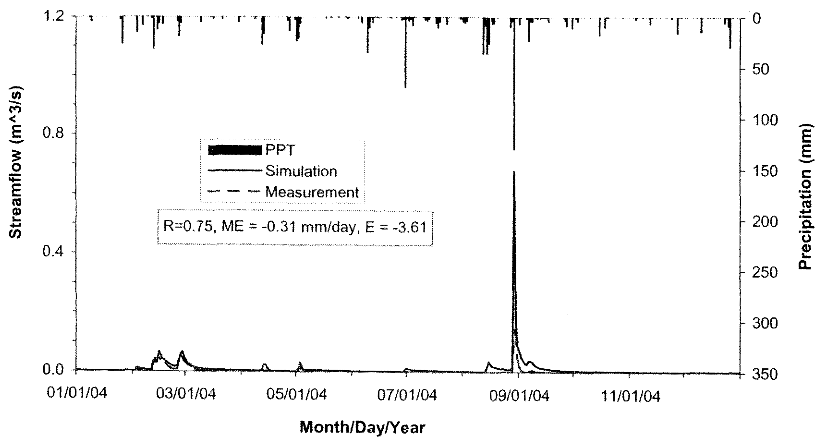

Figure 3. Validation of MIKE SHE model with daily streamflow in 2004.

A well transect, consisting of 3 wells (Figure 1) near the headwater area, was used for additional model validations. Well water table depths were measured by a bi-weekly schedule running from October 2003 through the end of 2004. By visual inspection, MIKE SHE generally simulated water table depth within the measurement range for Well 1 (Figure 4). However, it did not match as well at well 2 and well 3 (not shown) during dry periods.

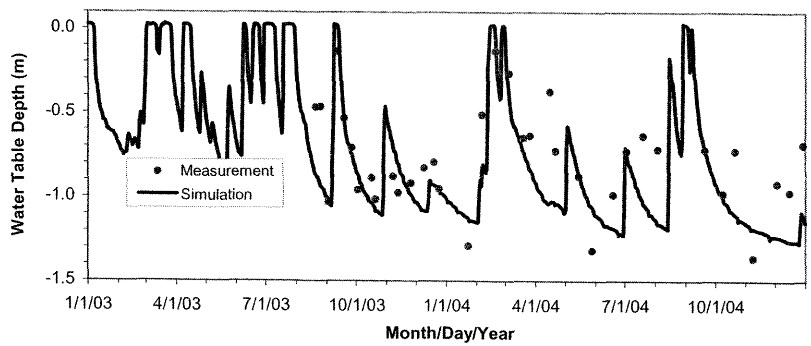

Figure 4. Validation of MIKE SHE model with water table depth at well 1.

Overland flow

According to the model simulation, overland flow made a big contribution to the annual total streamflow at the watershed. In 2003, a wet year, overland flow accounted for 42% of the total watershed streamflow. And in an extremely dry year 2004, overland flow composed of 20% of the total annual streamflow.

The model also indicated that runoff is mainly generated by the overland flow after the soil is saturated. During the big storm, overland flow was generated across the entire saturated watershed (Figure 5). Most of the overland flow depths were within 2 - 3 cm. Several modeling cells showed zero overland flow depth. It was because these cells directly interacted with the stream channel and overland water directly moved into the stream. Peak flows were well corresponding to overland flow. In contrast, during the small rainfall event or dry periods, no overland flow was generated and streamflow remained in the low levels.

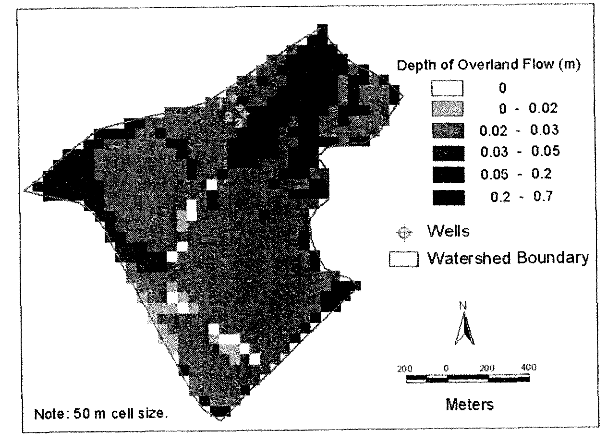

Figure 5. Spatial distribution of overland flow depth on 06-20-2003 across the study watershed.

Model applications

After the model calibration and validation were performed, MIKE SHE was applied to evaluate the effects of three hypothetical scenarios on ground water table and annual water yield during 2003 and 2004 (Figure 6 and Figure 7). The simulation results suggested that a clear-cut would raise the water table, especially during the dry periods, due to the decrease in ET. With increase of air temperature or decrease of precipitation, groundwater recharge would be reduced and thus result in a lower water table (Figure 6).

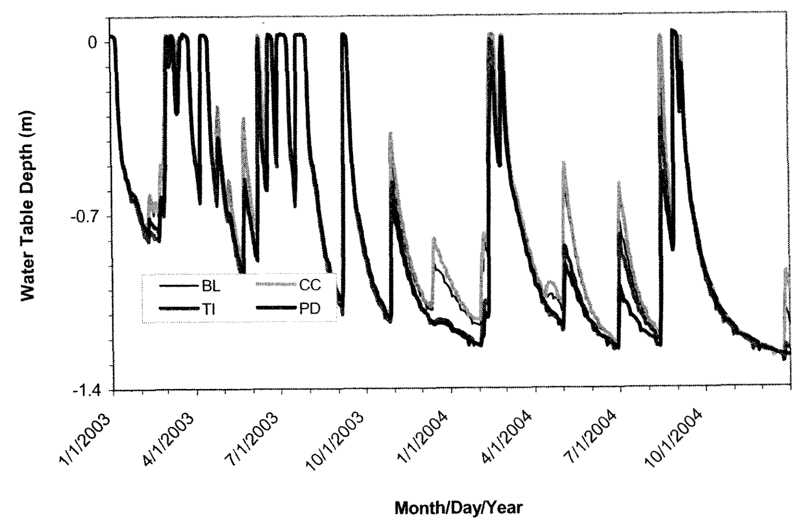

Figure 6. Impacts of clear-cut and climate change on ground water table at well 1.

The model results indicated that a clear-cut would slightly increase streamflow, while the climate change scenarios would result in significant decrease in streamflow (Figure 7). For both years, the magnitudes of water yield increase due to clear-cutting appeared much smaller than most literature suggested (Sun et al., 2004). The model results showed that ET remained similar to the base line amount after the watershed was harvested. It appeared that LAI change was not sufficient to represent the clear cutting scenario for the MIKE SHE model. Future studies are needed to examine how the model describes evapotranspiration processes under harvesting conditions. However, large water yield responses to both climate change scenarios were found. A 10% decrease of precipitation resulted in approximately 20-30% reduction of water yield. The impact of PD scenario is more significant than the TI scenario.

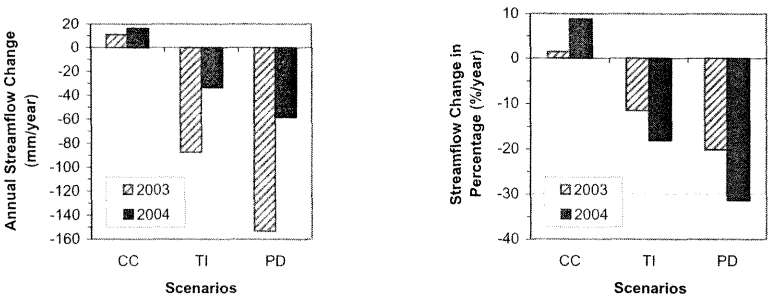

Figure 7. Impacts of clear-cutting and climate change on annual streamflow in total and percentage.

Conclusion

This study showed that MIKE SHE performed reasonably well at a coastal forested watershed in eastern South Carolina, USA. Generally, the model simulations could capture the dynamics of the streamflow and water table variations at the study site. The model results indicated that streamflow in the headwater streams was mainly generated by the saturation overland flow. The variable source area could be very large in this flat landscape. The climate change had great potential impacts on streamflow and water table at this study site.

However, it remains a challenge to simulate hydrologic processes at this low relief coastal watershed. The streamflow is highly variable at this watershed that contains an ephemeral stream. It seems that MIKE 11 could not simulate discontinuous streamflow conditions. Future studies are needed to examine how the model describes ET processes under the land use changes. These might be accomplished by calibrating ET parameters in order to accommodate the management practices.

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