USING THE HYDROLOGIC MODEL MIKE SHE TO ASSESS DISTURBANCE IMPACTS ON WATERSHED PROCESSES AND RESPONSES ACROSS THE SOUTHEASTERN U.S.

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Abstract-- A clear understanding of the basic hydrologic processes is needed to restore and manage watersheds across the diverse physiologic gradients in the Southeastern U.S. We evaluated a physically based, spatially distributed watershed hydrologic model called MIKE SHE/MIKE 11 to evaluate disturbance impacts on water use and yield across the region. Long-term forest hydrologic data from a southern Appalachian Mountain and a lower coastal plain watershed in South Carolina were used as model inputs. The model captured the temporal and spatial dynamics of shallow groundwater table movement and streamflow. Results suggest climate change and tree removal would have pronounced hydrologic effects; especially during dry periods. We also found that the data parameterization for even small scale distributed watershed-scale modeling remains challenging where spatial subsurface characteristics are often not known. The global change implications on hydrologic processes and response to in the two landscapes are discussed.

INTRODUCTION

Over half the land mass of the Southeastern U.S. is forested. The region has high biodiversity, and favorable climate for plant and animal growth, and human habitation. However, forest ecosystem services are threatened by global changes that include population growth, urban sprawl, climate change, and other natural and human stressors (Wear and Greis, 2004). These current and future biotic and abiotic changes will have long-term impacts on watershed ecosystems through their direct effects on the water cycle within the region (McNulty and others 1998). Although forested watersheds provide the best water, potential water quantity and water quality degradation from intensive forest management practices, landuse changes, wildfires and other disturbances is of regional concern (Swank and others 2001). Watershed management and restoration practices, such as Best Management Practices (BMPs) require an accurate understanding of the basic controlling factors of hydrologic processes at a watershed-scale across the diverse physiologic gradients in the Southeastern U.S. (Sun and others 2004)

The southeastern U.S. has a long history of forest hydrologic research (Jackson and others 2004; Amayta and others 2005). Over the past 50 years, numerous watershed manipulation experiments were conducted in strategic locations representing the three major physiographic regions across the southeast (i.e., coastal plain, piedmont, and mountain). The paired watershed experiments developed by those studies provided much of our current knowledge about the hydrologic processes and how watershed responds to disturbances and alternative land management practices. Past studies suggest that forest harvesting an increase in water yield and elevates groundwater tables due to the reduction of total ecosystem evapotranspiration. The increase in stream run-off has also been associated with elevated nutrient and sediment loading to streams (Swank and others 2001; Sun and others, 2001). Water quality effects diminish with vegetation regrowth and forest canopy cover restoration. The time required for canopy restoration to pre-disturbance levels is relative short compared to other part of the nation, and varies from a few years to several decades (Sun and others 2004). Synthesis studies in the southeast region (Sun and others 2002; Sun and others 2005) and worldwide literature (Andreassian 2004; Sun and others 2006) suggest that climate, soil, and topographic class (e.g., wetlands vs. uplands) control the hydrologic processes and responses to disturbance or land management. For example, shallow groundwater tables dictate the slow moving streamflow processes in forested watersheds on the flat coastal plains (Riekerk, 1989; Amayta and Skaggs, 2001) while hillslope processes and gravity (both saturated and unsaturated subsurface flows) control the water flow in steep mountain watersheds (Hewlett and Hibbert, 1967). Over 70% of precipitation returns to the atmosphere as evapotranspiration in the coastal watersheds due to high temperature, but upland watersheds in the piedmont and Mountains have a lower proportion of the total precipitation returned to the atmosphere as ET (i.e., 30-70% of precipitation) due to lower temperature and higher precipitation (Lu and others 2003; Lu and others 2005). A larger fraction of the precipitation is therefore removed from the watershed as higher stream flow peaks and volumes in piedmont and mountain regions.

Hydrologic modeling has become an essential and powerful tool in watershed studies (Graham and Butts, 2005), and perhaps the only way to extrapolate hydrologic experimental finding from small watersheds to large basins and the region. Process-based, spatially distributed models are best suited for understanding how different types of watersheds respond to disturbance.

Traditional small watershed experiment used a 'black box' approach that focuses on the effects of land management on streamflow measured at the watershed outlets. Modern forest hydrologic studies focus on the processes and interactions between the hydrologic cycle and other biological processes under a changing environment at multiple temporal and spatial scales. Computer simulation models are useful in this technology transition in hydrological research.

It is important tot understand how climate and topography influence hydrologic responses to disturbance at the regional scale across the southeast U.S. for regional water supply and forest management and policy purposes. Empirical studies in the past century have provided valuable location-based data to develop mathematical models to 'scale up' hydrologic findings to the region and examine how forested watersheds respond to global change. McNulty and others (1996) and Liang and others (2002) examined potential climate change impacts on regional forest water yield using the monthly time step, stand level forest ecosystem models, PnET-II and PnET-3SL, respectively. Both models linked forest growth, productivity, and water use (ET). Both models proved useful in modeling regional ET from forests. Sun and others (2005) applied a simpler annual-scale ET model and examined the potential water yield changes due to deforestation across the region. Those types of region-orientated modeling studies show a strong spatial variability in predicted forest water use and yield due to variations of climate, topography, and forest types across the region.

In this paper, we hypothesized that different regions would have different hydrologic responses to forest management practices and climate change due to differences in topographic, climatic, and vegetation conditions. Models that are developed on physical principles should be applicable to physiographic regions. Thus, the objectives of this study were: 1) to test the process-based, groundwater-surface integrated watershed hydrologic model, MIKE SHE, to accurately predict ground water movement at multiple sites with long-term forest hydrologic monitoring data across the southeastern U.S., and 2) to apply the validated model to examine hydrologic responses to forest harvesting and climate changes across a physiographic gradient across the region.

METHODS

Study Sites

MIKE SHE model evaluation and application was conducted at two research sites representing the coastal plain and the Appalachian Mountain physiographic regions - in the southeastern U.S. (Figure 1). These are two intensively studied small experimental forested watersheds with varying land cover and soil types (Table 1). One watershed is located on the mountainous upland of North Carolina and the other is located on the lower coastal plain in South Carolina. Streamflow, baseflow and peakflow rates, and spatial distributions of groundwater table were the major hydrologic variables used in the evaluation of model performance. Detailed results for two additional model testing sites are found in a dissertation by Lu (2006).

Table 1. Characteristics of two watersheds used for model evaluation in the Southeastern U.S.

Site	Landscape characteristics	Area (ha)	Average Precipitation (mm/year)	Soil	Vegetation Coverage	Data for calibration and validation
Santee Watershed 80	Coastal plain, SC	160	1370	Sandy loam	Mixed hardwood and pine	2003 model calibration; 2004 model validation (streamflow and water table)
Coweeta Watershed 2	Appalachian Mountains, NC	12	1772	Loamy soil	Mixed hardwood	1987-1988 model calibration; 1985-86; 1989-1990 model validation (streamflow)

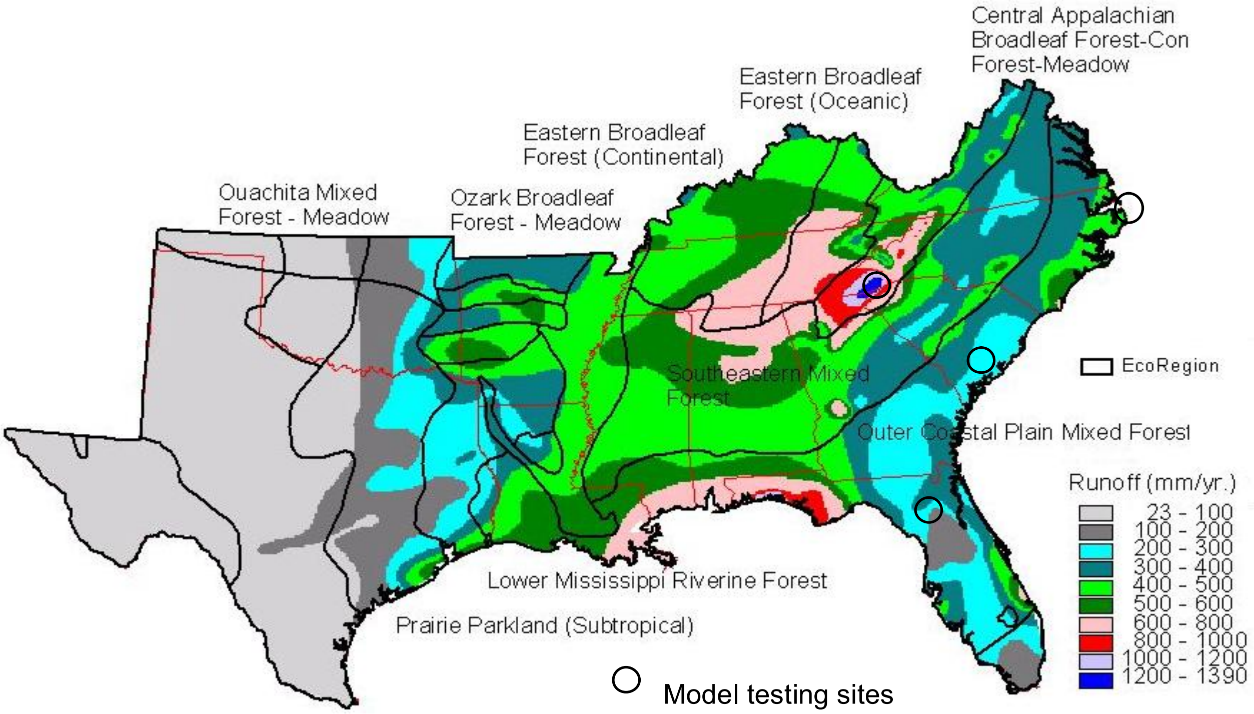

Figure 1 - Provinces of the Bailey ecoregion, annual runoff, and locations of model testing sites in the southeastern U.S.

The Santee Watershed 80 is located in the Santee Experimental Forest, part of the Francis Marion National Forest, on the lower Atlantic Coastal Plain, eastern South Carolina (33.15°N, 79.80°W) (Figure 2). As the control watershed for a paired watershed study, it was installed in the mid-1960s by the USDA Forest Service for studying forest management on water quality and quantity in the coastal plain geographic region (Amatya and others 2005; Harder, 2004). The watershed has a low topographic relief (< 4%) with surface elevation ranging from 3 - 10 m above mean sea level and consists of an ephemeral stream as the main drainage pathway.

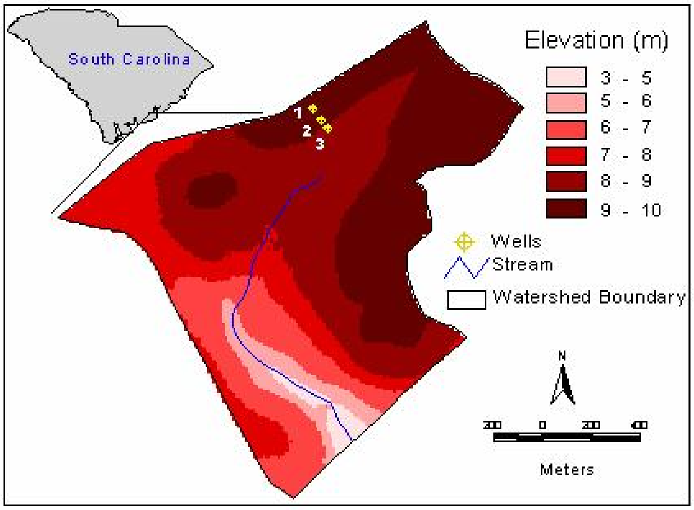

Figure 2 - Santee Watershed 80 topography and instrumentation.

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. July and August are the wettest months (receiving 28% of total annual precipitation) and April and November are the driest months (receiving 10% of total annual precipitation). January is the coldest month with a maximum average low air temperature of 10 ºC, and July is the hottest month with a maximum average high air temperature of 28 ºC. The mean annual air temperature is 19.1 ºC. Approximately 23% of the watershed is classified as wetlands (Sun and others 2000). The forest coverage is mainly composed of pine-hardwood (39%), hardwood pine (28%) and mixed hardwoods (33%). Dominated tree species include loblolly pine (*Pinus taeda L.*), sweetgum (*Liquidambar styraciflua*), and a variety of oak species typical of the Atlantic Coastal Plain. Most of the trees are 17 years old, and regeneration after damage caused by Hurricane Hugo in 1989. The study site consists primarily of sandy loam soils with clay subsoils. Much of the soil is part of the Wahee-Lenoir- Duplin association (SCS, 1980) that are somewhat poorly drained to poorly drained (SCS, 1980). Soils are influenced by seasonally high water tables and argillic horizons 1.5 meters below ground surface.

Coweeta Watershed 2

Coweeta's 12 ha, Watershed 2 was selected for model evaluation and application of the southern Appalachian Mountain upland conditions. This watershed is located at the USDA Forest Service Coweeta Hydrologic Laboratory, a Long Term Ecological Research (LTER) Center site in western North Carolina (35°03′N, 83°25′W) (Figure 3). The Coweeta Hydrologic Laboratory was established for forest hydrologic research in 1934 and has been a National Science Foundation (NSF) LTER site since 1980 (Swank and Crossley 1988). Large amount of classic forest hydrologic research has been conducted in this facility (Hibbert 1967; Swank and Douglas, 1974; Swift and Swank 1975; Swank and others 1988; Vose and Swank 1992).

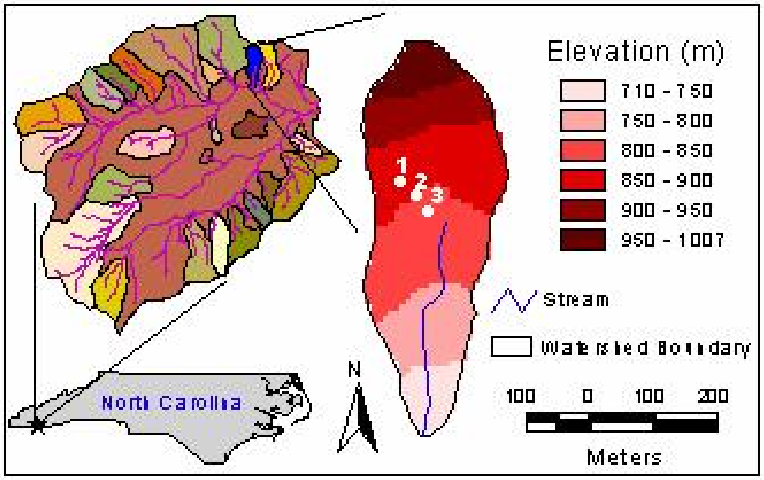

Figure 3 - Location of the study watershed (Watershed 2) at Coweeta Hydrologic Laboratory in southern Appalachian Mountains, western NC.

The climate in Coweeta is classified as marine, humid temperate with a water surplus in all seasons. Watershed 2 is one of Coweeta's control watersheds, and has not been disturbed since it was clear-cut in 1927. The average of 1772 mm of precipitation is evenly distributed through out the year. The mean annual streamflow is around 854 mm, which is 48% of precipitation. Long-term average monthly air temperature is as low as 3.3 °C in January and is as high as 21.6 °C in July (Swank and Crossley 1988). The watershed has an average slope of 23^{o} with a maximum of 49^{o}, The elevation ranges from 710 m at the watershed outlet to 1007 m at the ridge top. The south-southeast facing watershed is covered by mixed hardwoods with scattered Pitch Pine (*Pinus rigida*) on the ridge top. Tree species mainly include eastern hemlock (*Tsuga canadensis*), tulip (*Liriodendron tulipifiera*), sweet birch (*Betulalenta*), white oak (*Quercus alba*), and red oak (*Quercus rubra*) with great rhododendron (*Rhododendron maximum*), flame azalea (*Rhododendron calendulaceum*), laurel (*kalmia latifolia*), and blueberry (*Vaccinuim pallidum*) as the understory. The soil series are Chandler and Fannin (Swank and Crossley, 1988; Rosenfeld, 2003). The soil physical parameters are derived from Vose and Swank (1992). Although Watershed 2 is a much smaller 12-ha watershed, it has a first order perennial stream flowing year round.

The MIKE SHE/MIKE 11 Model

Numerous watershed-scale hydrologic models are available in the literature. The choice of models should be based on the objectives of use. Literature review suggests that the MIKE SHE/MIKE 11 modeling package (DHI, 2004) (Figure 4) has several advantages for achieving our objectives: 1) it is a distributed model and most of the algorithms in describing the full water cycles are physically based, 2) it simulates explicitly groundwater-surface water interactions, so it is ideal for wetland dominated systems as well as storage-based systems commonly found in humid regions, 3) it has been commercialized and a GIS user interface was built in the system that can directly use spatial GIS databases for model inputs. Also, the model has a strong visualization facility that makes interpretation of modeling outputs much easier.

MIKE SHE is a first generation of spatially distributed, physically based, hydrologic model (Abbott et. al., 1986a, 1986b). MIKE SHE simulates the terrestrial water cycle including evapotranspiration (ET), overland flow, unsaturated soil moisture and groundwater movement (Figure 3). Evapotranspiration is modeled as a function of potential ET, leaf area index, and soil moisture content using the Kristensen and Jesen (1975) method. The unsaturated soil water infiltration and redistribution processes are modeled using Richard's equation or a simple wetland soil water balance equation. Saturated water flow (groundwater) is simulated by a 3-D groundwater flow model similar to the MODFLOW model (McDonald and Harbaugh, 1988). Channel flows and channel surface water and upland groundwater interactions are handled by the MIKE 11 model and coupling of MIKE SHE and MIKE 11. MIKE 11 is a one-dimensional model that tracks channel water levels using a fully dynamic wave version of the Saint Venant equations. The coupling of MIKE SHE and MIKE 11 is especially important for simulating the dynamics of variable source areas in both wetland and upland watersheds. 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 and others 1986a, 1986b; Graham and Butts 2005).

Identical graphical and statistical methods were used to evaluate models performance for the two watersheds. The statistical measures included mean estimation error (ME), Correlation Coefficient (R) and the Nash-Sutcliffe (1970) coefficient of efficiency (E). The model was first calibrated with data from 2003 for the Santee and for data from for each site for 2003 with data from 1988 to 1989 for the Coweeta watershed. The models were validated with 2004 data from Santee and with from 1985-1987 and 1990 for Coweeta (Table 1).

Model Application Scenarios

After model calibration and validation were conducted, the MIKE SHE model was applied to four scenarios for both watersheds. These scenarios included: 1) Base line (BL); 2) Clear Cutting (CC); 3) a average annual temperature increase of 2 °C (TI); and 4) a average annual precipitation decrease (PD) of 10%. The purpose of the scenarios were to examine watershed hydrologic response land management and climate change.

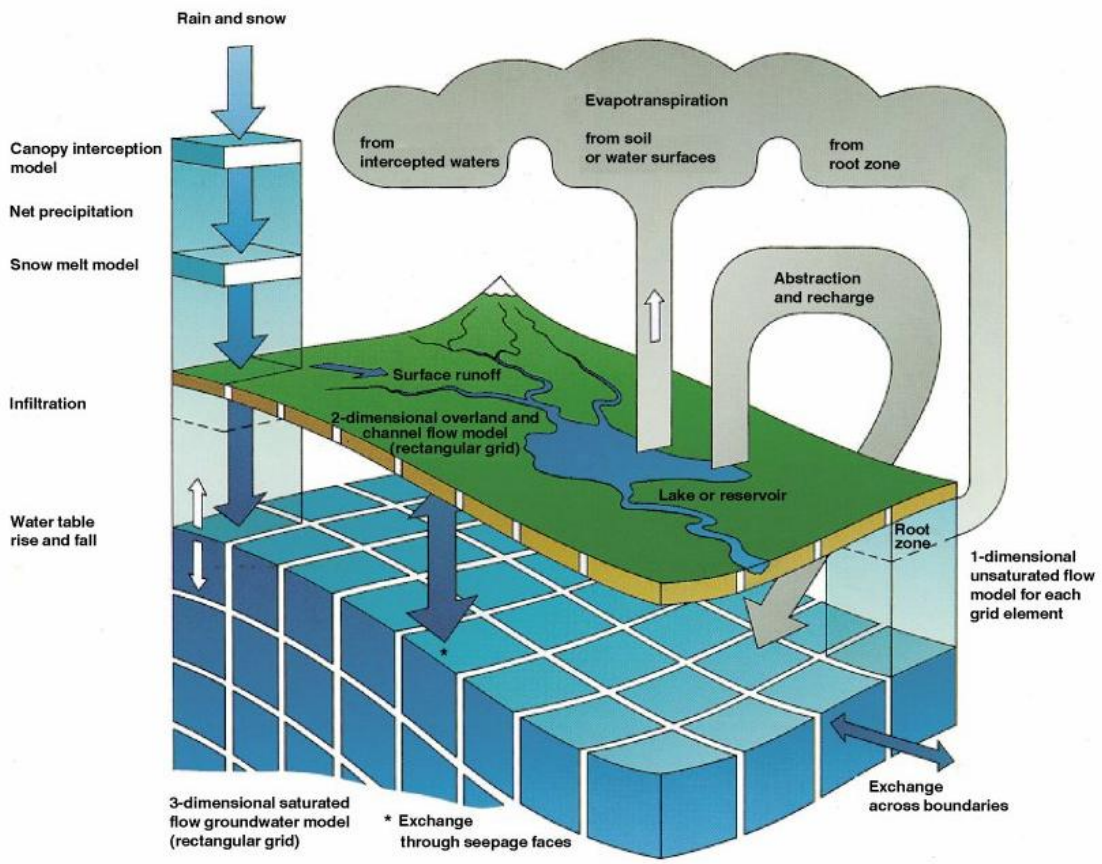

Figure 4 – MIKE SHE Model structure and hydrologic components(DHI, 2004)

RESULTS
Model Calibration and Validation

Santee Watershed 80
The MIKE SHE model was calibrated against the daily streamflow data from 2003. Compared to the long-term annual average precipitation at the study site, 2003 was a wet year with a 300 mm surplus in precipitation (Harder, 2004).Model parameters were finalized after calibrations resulted in the best match between simulated and measured daily streamflow as gauged by the established model performance criteria.

Generally, the model could simulate the daily variations of streamflow with R = 0.75, ME = 0.10 mm day^{-1} and E = 0.56 during the calibration (Figure 5). However, the model did not catch all the peak flows, especially for one large mid-September storm event (i.e., Hurricane Isabelle). The simulated peakflow rate of 0.37 m^3 sec^{-1} was much lower than the measurement peakflow rate of 1.44 m^3 sec^{-1} for that storm event.

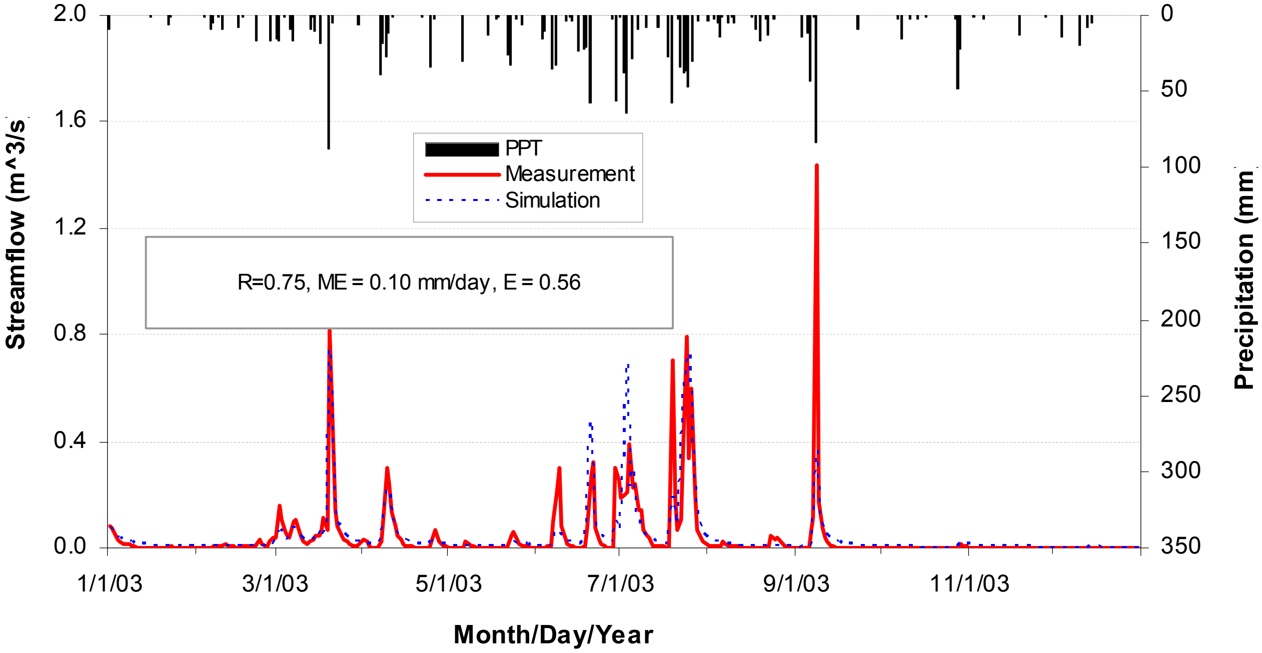

Figure 5 – MIKE SHE model calibration with daily streamflow in 2003 at Santee Watershed 80.

The MIKE SHE model was validated with daily streamflow data in 2004 and water table depth measured from the end of 2003 though 2004. 2004 was a dry year with 409 mm less rainfall than the long-term annual average. There were only three stormflow events in the entire year, and there was no streamflow observed during June, July, October, November, and December (Figure 6). Overall, MIKE SHE simulated the streamflow dynamics with a R = 0.75 under these extremely dry conditions, but it over-predicted a peakflow rate in late August. Overall, the model over-predicted streamflow with ME = -0.31 mm day^{-1} and E = -3.61. Simulated water table depths compared reasonably with Well #1 (Figure 3, and Figure 7) but failed to match measured stream flow depths in two other wells located on the watershed. (not shown).

Coweeta Watershed 2
The MIKE SHE model was calibrated with the daily streamflow data in 1988 and 1989. Compared to the long-term annual average precipitation of 1770 mm, 1988 was a dry year (i.e., 1267 mm), and 1989 was a wet year (i.e.,2341 mm). Generally, the model performed reasonably well with R = 0.88, ME = -0.04 mm/day and E = 0.74 (Figure 8). On the annual basis, the model over predicted streamflow in 1988 by only 31 mm, and almost exactly predicted measured 1989 streamflow of 1019 mm.

At the daily basis, the biggest differences in streamflow were found in January of 1988 and during the summer of 1989. The approximately 7 mm day^{-1} over estimate of streamflow in the early 1988 may have been partially caused by poor estimates of initial conditions. The base line simulation run from 1985 to 1990 showed that the difference in predicted and measured streamflow was reduced to 5 mm day^{-1} for that particular date. The largest discrepancy in the summer of 1989 may have been due to the relatively shallow soil depth used in this modeling study. We used the same soil parameters to a depth of 3 m since there was no data available for soil properties below the 1.8 m depth. The soil properties were distributed uniformly across the entire watershed. In reality, the soil depth is likely to be highly variable across the watershed (Yeakley 1993; Miner 1968).

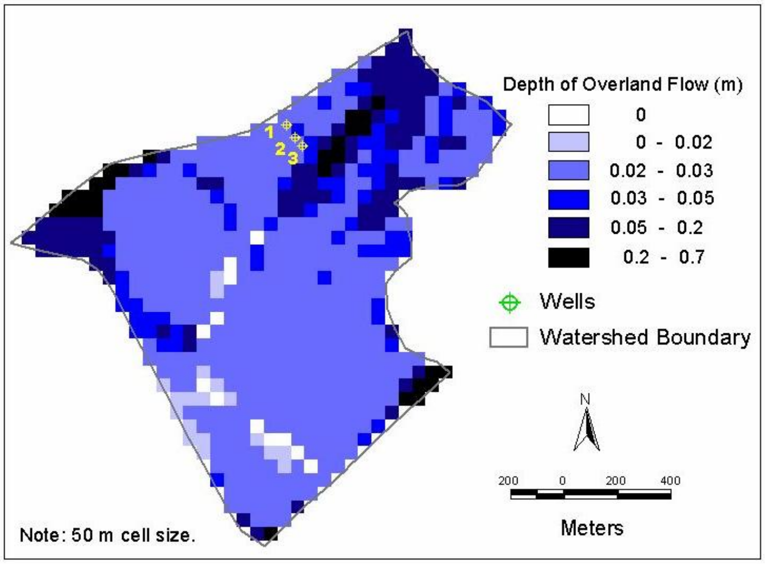

Figure 6 – Simulated spatial distribution of overland flow depth on 06-20-2003 at Santee watershed. Spatial rsoulution is 50 m.

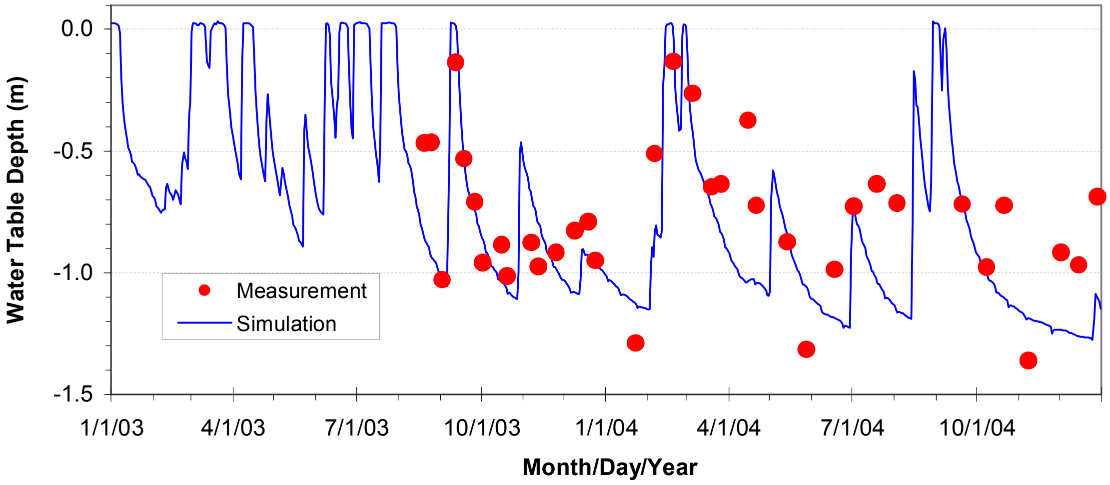

Figure 7 - Validation of MIKE SHE model with water table depth at Well 1 during October 2003 - December 2004 at Santee Watershed 80.

The MIKE SHE model was validated with the daily streamflow data recorded in 1985-1987 and 1990 (Figure 9). Compared to the long-term average precipitation at the watershed, 1985-1987 were extreme dry years and 1990 was a wet year. The model generally could match the streamflow dynamics with R = 0.85, ME = 0.04 mm day^{-1} and E = 0.72. Simulated streamflow values were close to measured except for the big storms in February and March of 1990 when the model overestimated daily daily streamflow values up to 10 mm day^{-1}. On an annual basis, the model had a tendency to over-predict streamflow in a dry year and under-predict streamflow it in a wet year.

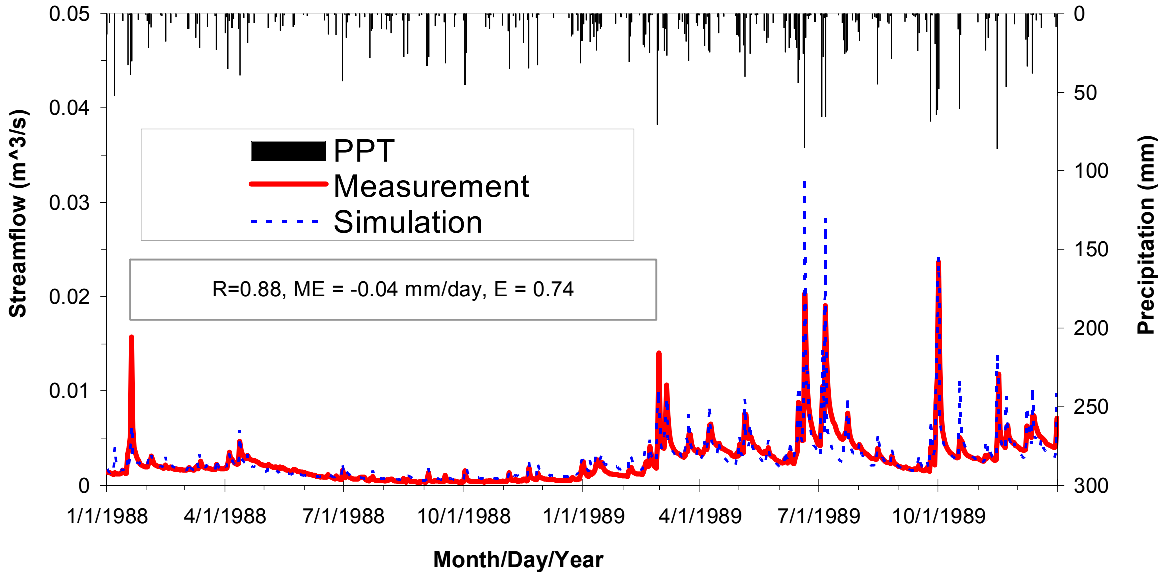

Figure 8. MIKE SHE model calibration with daily streamflow in 2003 at Coweeta Watershed 2.

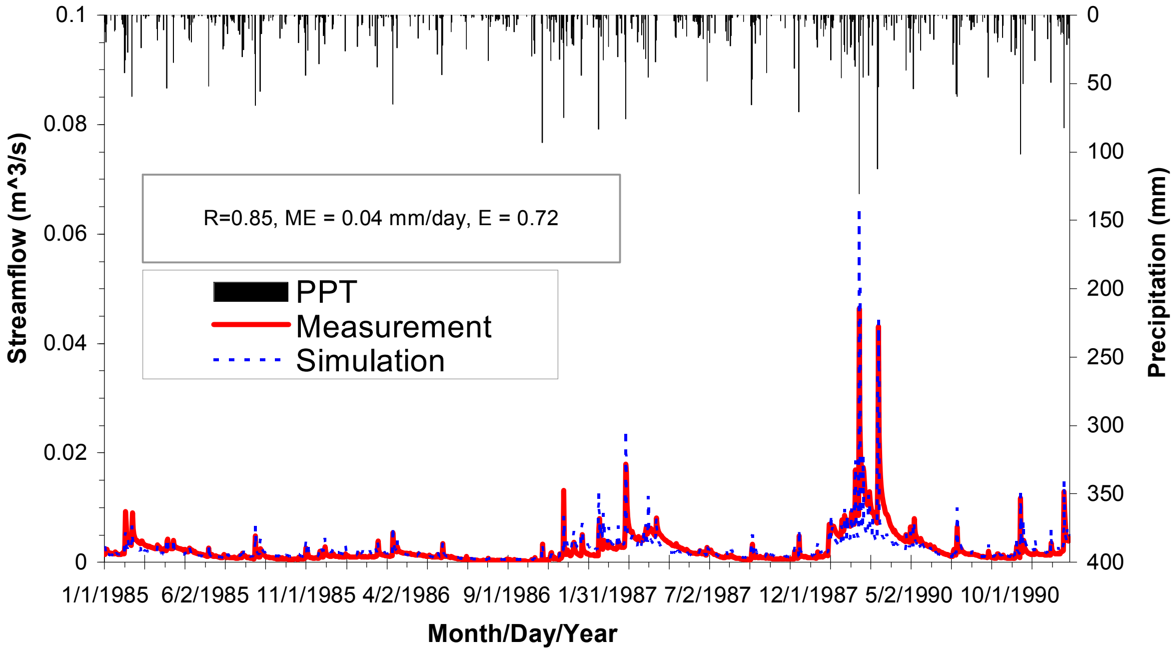

Figure 9. Model validation with daily streamflow during 1985-1987 and 1990.

Model Applications

We evaluated the potential effects of three hypothetical scenarios on the ground water table and annual water yield during 2003 and 2004 at the Santee Watershed 80, and from 1985-1990 for Coweeta Watershed 2 using the validated model from both watersheds (Figure10). Our simulation results suggested that clear-cut would decrease ET, elevate the groundwater table level, and increase water yield. The effect is especially pronounced during dry periods when the ET differences between the baseline (BL) and disturbed scenarios were largest. Harvesting reduces leaf area and will result in a decrease in potential ET. Plant transpiration capacity and total ecosystem ET will decrease, and therefore soil water recharge for streamflow generation will increase. Increase in temperature by 2°C caused increase in PET, while decrease 10% precipitation caused direct soil water recharge. Both climate change scenarios will result in lower water table level.

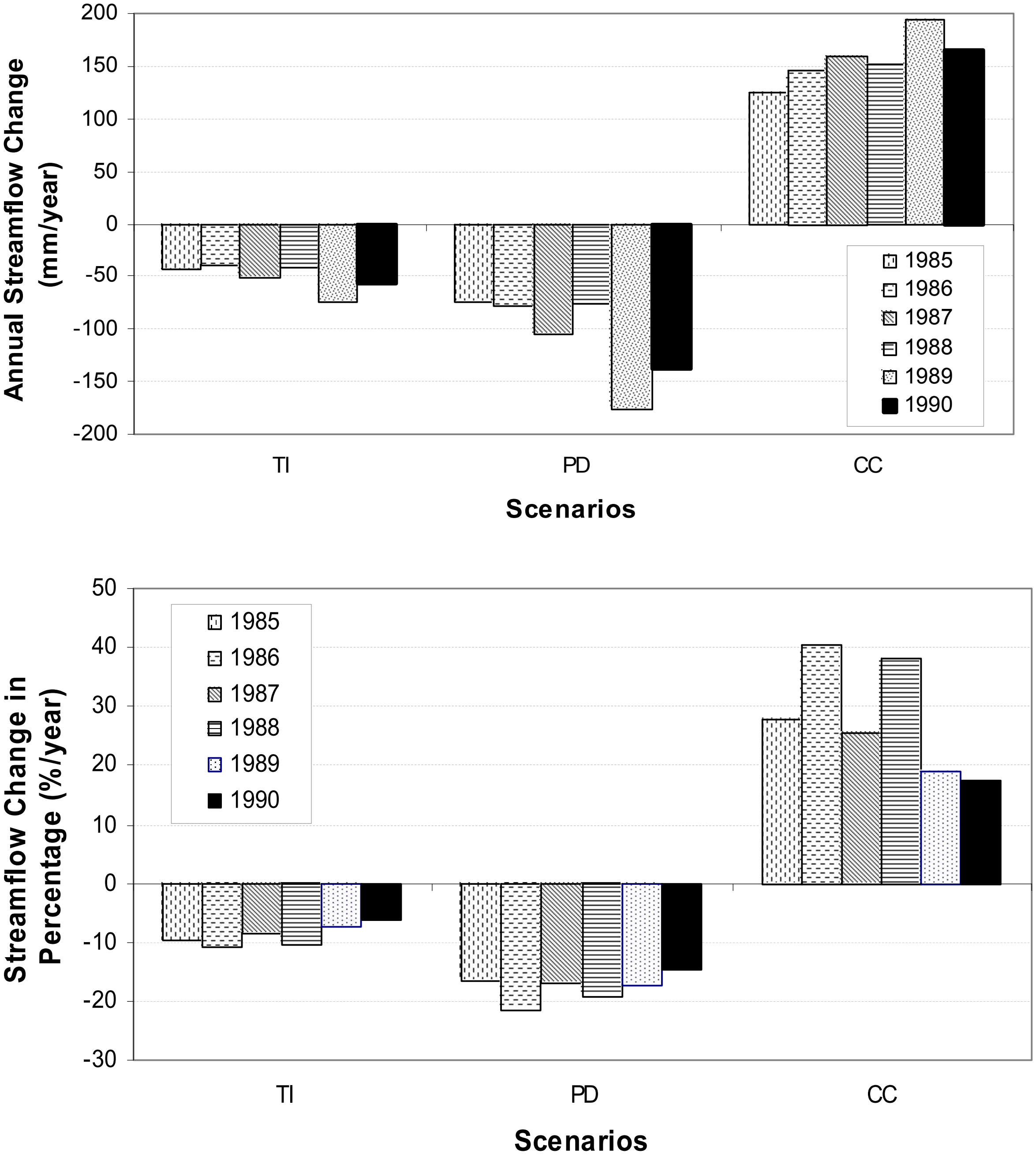

Figure 10. Simulated effects of clearcutting (CC), increase of air temperature by 2°C (TI), decrease of precipitation by 10% on streamflow as expressed by: a) change in absolute annual streamflow amount, b) change in percentage of annual streamflow at the Coweeta Watershed 2. For the CC case, a 30% reduction of potential ET was assumed (Grace and Skaggs, 2006; Sun, G. Unpublished data).

DISCUSSION

Computer simulation models are a powerful tool for data syntheses, understanding the hydrologic processes, and for predicting potential future conditions. Watershed-scale experiments are expensive to conduct, and a modeling approach can be cost-effective, especially for answering large-scale hydrologic questions. The MIKE SHE model was evaluated with hydrologic data from two small headwater watersheds on two separate contrasting landscapes in the humid southeastern U.S. In general, the model performed reasonably well for simulating daily streamflow measured at the watershed outlet, and for estimating the spatial distribution patterns of the shallow groundwater table depth. However, parameterizing the physically based, distributed watershed-scale model was a challenging task, even for small watershed with a size in the tens of ha. For example, data on the spatial distribution of soil water storage, the depth until bed rock, or on restricting soil layers is rarely available. Thus, model calibration is still needed produce reasonable model results. Climate and landuse change will have a major impact on ET. Thus process-based ET algorithms are needed in the MIKE SHE model. Validating distributed hydrologic models requires detailed measurements of internal processes, such as streamflow at subwatersheds, spatial distribution of water table over the landscape, soil moisture distribution, and hillslope processes. Most of those measurements are rarely available in one watershed.

Streamflow in the flat coastal watershed (Santee Watershed 80) is controlled by the dynamic shallow groundwater table that reflects the water balances of rainfall and ET. Saturation-overland flow contributes the majority of the total flow in the first order, ephemeral stream. In contrast, saturation overland flow is not common in the steep mountain watershed (Coweeta Watershed 2). The MIKE SHE model could simulate the variable source areas that contribute directly to stormflows during large rainfall events. It appears that the Santee Watershed 80 had higher variability of storage capacity as characterized by large peakflows and discontinuous flow patterns when compared to the upland watershed. The flushness of the wetland watershed reflects large extent of overland flow during large storm events. The upland watershed suggested to have higher water ‘turnover’ rates (low residence time) because of the frequent rainfall events and steeper hillslopes. The frequent rainfall and lower ET in the upland watershed result in continuous streamflow in this mountain watershed. Accurately simulating the narrow saturated variable source areas in the upland watershed remains elusive because the model data is restricted to the coarse10 m digital elevation model spatial resolution.

CONCLUSIONS

This study concluded that the hydrologic response to disturbance in the two watersheds varies with climate. Soil moisture is normally unrestricting for plant growth on both the upland and wetland watersheds in the humid southeast region. Hydrologic responses are most pronounced during dry years when surface soil evaporation is minor, but forest transpiration is usually not severely reduced even during dry years.

Findings from this study have important implications to forest management practices at the regional scale. Best Management Practices (BMPs) for protecting water quality from harvesting or wildfires should consider a much larger extent than just the riparian zones as the practices do for the hilly piedmont and mountain regions because watershed-wide overland flows in the lowland watersheds are the sources of surface waters in the coastal region. In contrast, overland flow is rare and saturated subsurface flows are the sources of streamflow for the upland watersheds. Thus, forest roads that are often cut into bed rocks will likely alter water flowpaths, resulting in increase in sediment and peakflow rates. Best management practices should include on the entire hillslope for the protection of riparian zones.

Findings from this study also have implications to water yield under the projected global climate change. If global warming results in an increase in air temperature and drought, the role of forests in affecting streamflow, especially baseflow (lowflows) will increase. On another extreme climate change scenario, when rainfall intensity increases, the role of forest cover in soil protection will be most important.

The role of soil depth on hydrologic response to disturbances has been well examined in the literature. Also, mechanistically understanding watershed responses to forest management and climate change need focus on the changes in forest evapotranspiration processes. Improvements to the ET algorithms in MIKE SHE model are needed for its application in global change studies.

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