ABSTRACT

Lu, Jianbiao. Modeling Hydrologic Responses to Forest Management and Climate Change in Contrasting Watersheds in the Southeastern United States. (Under the direction of Dr. Ge Sun and Dr. James D. Gregory.)

Hydrologic pathways and processes vary greatly from the coastal plain to the mountainous upland across the southeastern United States due to large physiographic and climatic gradients. The coastal plain is generally a groundwater dominated system with a shallow water table, while the mountainous upland is hillslope controlled system. It was hypothesized that these two different regions have different hydrologic responses to forest management and climate change due to different conditions: topography, climate, soil, and vegetation. The hydrologic impacts of climate change and forest management practices are complex and nonlinear, and a model is an advanced tool for addressing such tasks. The objectives of this study were: 1) to evaluate the applicability of a physically-based, distributed hydrologic modeling system - MIKE SHE/MIKE 11 - in the southeastern United States; and 2) to use the MIKE SHE/MIKE 11 modeling system to examine the hydrologic processes and responses to forest management practices and climate change on the coastal plain and the mountainous upland in the southeastern United States.

Four experimental watersheds, three wetlands on the coastal plain and one Appalachian mountainous upland, were selected. The model was first evaluated to determine if it could sufficiently describe the hydrological processes in these diverse watersheds in two contrasting regions. Next, the model was applied to simulate the hydrologic impacts of forest

management and climate change at the four study sites, four simulation scenarios per site. These included the base line, clearcut, 2 °C temperature increase, and 10% precipitation decrease scenarios. Water table level and streamflow amount were two responses used to evaluate the forest management and climate change impacts.

This study indicated that forest management and climate change would have potential impacts on the wetland water table, especially during dry periods. The absolute magnitudes of streamflow reduction were larger in a wet year than in a dry year for the two watersheds under both climate change scenarios (2 °C temperature increase and 10% precipitation decrease). In terms of streamflow reduction percentages, the results seemed to suggest that climate change would have larger impacts on the coastal plain than the mountainous upland. However, more field data and research are needed to further test this hypothesis.

This study showed that MIKE SHE over-predicted soil evaporation from harvested lands. Thus, the model may have underestimated the streamflow impacts under the clearcut scenario. A process-based evapotranspiration model is needed to fully describe soil evaporation processes under forest harvest conditions.

Modeling Hydrologic Responses to Forest Management and Climate Change at Contrasting Watersheds in the Southeastern United States

By

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BIOGRAPHY

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Chapter 1

Introduction

1.1 Background

Climate, topography, and underlying geology are the major factors controlling regional hydrologic patterns, soil development, and forest structure and function (Sun et al., 2004). To evaluate the impacts of forest management practices and climate change on hydrology, these factors must be considered. Most southeastern United States (U.S.) forests are located in the climate system described as humid, with warm to hot summers and cool winters (Muller and Grymes III, 1998). However, topography and elevation in the southeastern U.S. alter this pattern greatly and result in a variety of hydrologic conditions (Daniels et al., 1973). By comparing the watershed hydrology of two coastal forested wetlands and a mountainous upland watershed in the southeastern U.S., Sun et al. (2002) showed that climate was the most important factor in determining watershed water balances, and that topography affected stream flow patterns, stormflow peaks and volume, and is the key to wetland development in the southeastern U.S. Considering the physiographic variability across North Carolina, Calvo-Alvarado and Gregory (1997) developed different sets of regionalized regression equations to predict mean annual runoff and suspended sediment yield for the coastal plains, piedmont and mountains. An investigation of long-term annual evapotranspiration (ET) from 36 forested watersheds across the southeastern U.S. showed that ET had a general pattern of decrease from south to north and from the coast to the mountains (Figure 1-1) (Lu et al., 2003). Regional runoff for the southeastern U.S. also suggested a strong runoff gradient across this region (Figure 1-2) (Sun et al., 2004).

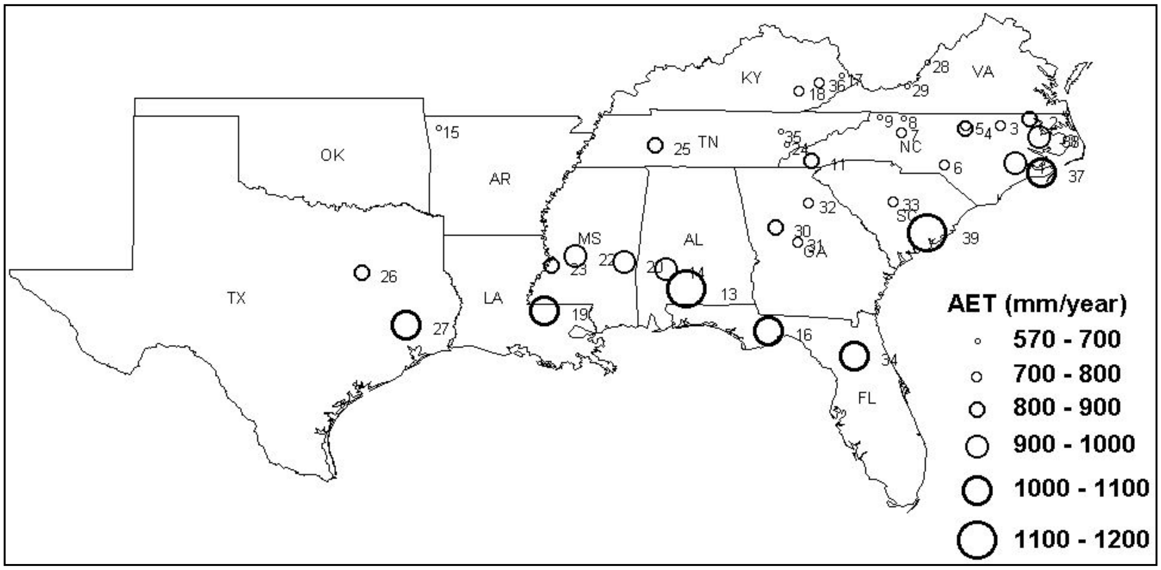

Figure 1-1. Actual evapotranspiration estimated by the water balance from 36 forested watersheds across the southeastern U.S. (numbers represent watershed IDs; from Lu et al., 2003).

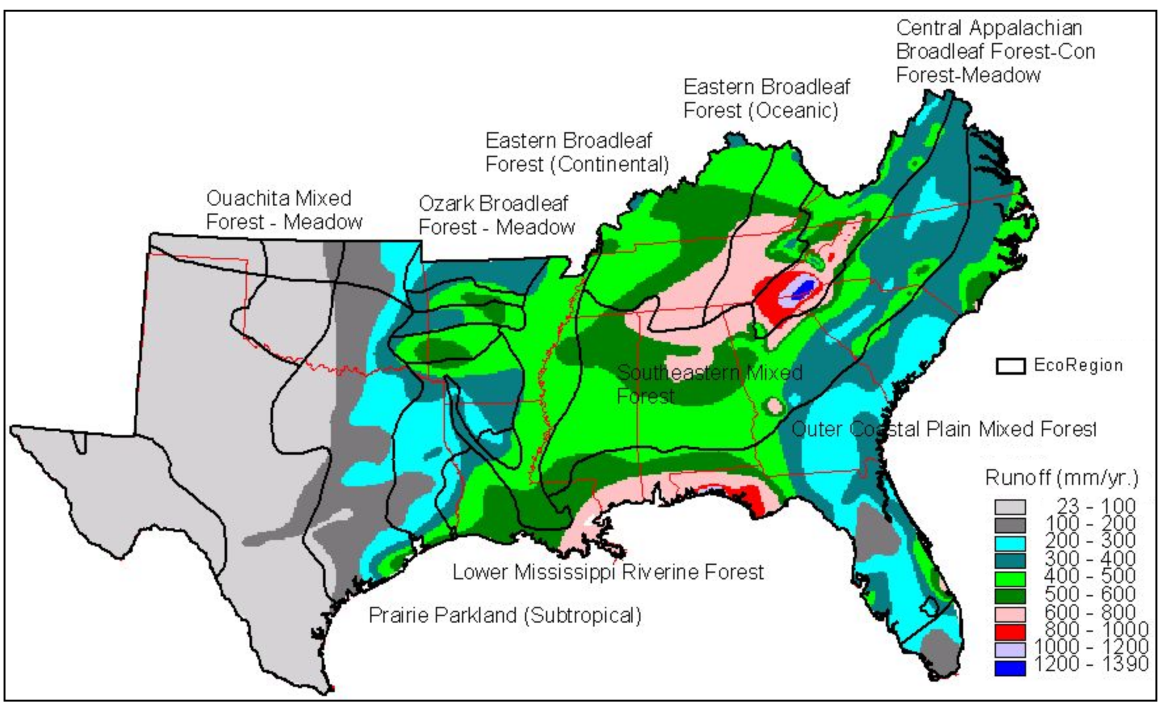

Figure 1-2. Provinces of Bailey ecoregions and annual runoff of the southeastern U.S. (from Sun et al., 2004).

There are great concerns about how fire, forest management, and climate change will affect water quantity and quality in the southeastern U.S. Researchers have strived to address these issues, but effects of fire on forest ecosystems vary greatly and depend on the quality and quantity of fuels, soil properties, topography, climate, weather, and fire frequency and intensity (Richter et al., 1982). Experiments in the southern U.S. and elsewhere around the world have shown that streamflow generally increased after forest harvesting (Sun et al., 2004; Andreassian, 2004; Bosch and Hewlett, 1982). For example, forest clear cutting in the Appalachian mountains caused water yield to increase by 26 mm to 41 cm, or 28% to 65% of base line 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. Water table rise after harvesting is also common in the coastal plain (Sun et al., 2000a), with associated hydrologic and water quality changes. Projected climate change across the region may have even larger and wider impacts (McNulty et al., 1997). Andreassian (2004) suggested that hydrologic responses to land management were controlled by climate, soil, and vegetation development. Quantifying the influences of these factors requires a process-based approach. Similarly, understanding and quantifying climate change effects are mostly conducted via computer simulation modeling at watershed to continental scales (McNulty et al., 1997; Sun et al., 2000a).

Hydrology is an important factor in biogeochemical cycling modeling. An effort is underway to link hydrology to the DNDC (DeNitrification-DeComposition) model (Li et al., 1992), which is a soil biogeochemistry model used for predicting soil organic matter decomposition and soil nitrogen turnover. DNDC requires water table depth, an important factor for biogeochemical processes, as an input to feed the model. However, water table depth may not be available in most cases, especially spatially distributed water table depth across a watershed. The current hydrologic sub-model of DNDC is not a physically based or distributed design. Thus, the application of the DNDC model is limited by its weakness in hydrologic simulations. By linking to a sound hydrologic model that provides good estimates of water table depths, DNDC can substantially broaden its applicability and improve its simulation results. However, evaluation of such a hydrologic model is needed before this linkage can be made.

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

Hydrologic modeling has become an essential tool in watershed management. While paired watershed experiments serve as a "black box" approach to achieve the experimental data and results, modeling can serve as a process-based approach. A model can help us understand the physical, chemical and biological processes within a watershed and the interactions among them. Furthermore, successful application of a model can help us to manage and protect 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 (e.g., prescribed burning, thinning, etc.) on watershed hydrology are not fully understood, and the understanding of the hydrologic process is critical to watershed management. Growing concerns about climate change have also stimulated increased research on understanding the complex feedback between the atmosphere and the terrestrial hydrological cycle (Graham and Butts, 2005). Hydrologic responses to climate change and forest management practices are complex, and a model is the necessary tool for such studies.

1.2 Literature review on existing forest hydrologic models

Several models have been developed and applied to simulate the hydrologic impacts of forest management and climate change. These include lumped models and distributed models. Lumped models provide uniform output for a whole watershed or study area. Their advantages are fewer data input requirements and high computational efficiency. However, they are often oversimplified and include few flow pathway processes. Distributed models, on the other hand, not only provide output for a whole watershed, but also provide information for any location within a watershed or study area. However, they require extensive data input and demand considerable computational resources.

1.2.1 PROSPER

As a lumped parameter model, PROSPER was developed to predict water stress for an upland forest stand by implementing atmosphere-soil-plant water flow processes (Goldstein et al., 1974). In this model, ET, a major component that depletes soil water, is calculated by a combined energy balance-aerodynamic method. An approximate numerical solution was used to solve soil water movement between soil layers, which is modeled by Darcy's law (Darcy, 1856) and mass balance. Daily precipitation, air temperature, relative humidity, solar radiation, and wind speed are the major climate data requirements for PROSPER. Other input parameters are mean values for albedo, vegetation leaf area, typical resistance values for water movement through soils, plants, and atmosphere, soil hydraulic conductivity, and root distribution. Daily ET and soil water potential at different soil layers are major outputs from PROSPER. The model has been used to investigate hydrologic responses to forest conversion (Swift and Swank, 1975) and climate change (Vose and Maass, 1999).

1.2.2 PnET-II

The PnET-II model is a monthly-time-step, lumped-parameter, stand-level model that was designed to simulate carbon and water dynamics of mature forests (Aber et al., 1995). It simplifies complex physiological and eco-physiological processes such as photosynthesis, transpiration, respiration, allocation, decomposition, and phenology by describing key biological and hydrologic processes. In addition, simple input parameters were employed for large regional application, rather than only intensively studied research sites. PnET-II has been validated and modified for southern upland forest ecosystems (Aber et al., 1995; Liang et al., 2002) and southern pines (McNulty et al., 1996; Sun et al., 2000a). It has also been used to evaluate the potential impacts of climate change on forest hydrology at a regional scale (McNulty et al., 1996).

1.2.3 FLATWOODS

FLATWOODS is a physically-based, distributed, and watershed scale surface-groundwater model (Sun et al., 1998a). It was developed and tested specifically for the purpose of examining the hydrologic impacts of forest harvesting in a heterogeneous cypress-pine flatwoods landscape (Sun et al., 1998b). The model simulates the full daily hydrologic cycle of each uniform segment (or cell) of a watershed and links each cell with shallow groundwater flow. A simplified Darcy's equation (Darcy, 1856) was applied to calculate the vertical unsaturated water flow. The standard groundwater flow equation with Dupuit assumptions was used to model the 2-D lateral groundwater flow. ET consists of canopy interception, soil and surface water evaporation, and tree transpiration. The temperature-based Hamon's potential ET (PET) method (Hamon, 1963; Lu et al., 2005) was used to calculate PET. Interception is modeled as a function of leaf area index (LAI), precipitation, and PET. Soil and surface evaporation are simulated as a function of LAI and groundwater level. Transpiration accounts for the rest of PET, but it is limited by soil moisture status. Total outflow that is affected by average groundwater table and saturated areas is computed by using an empirical power function derived from experimental data. Total daily flow and distributed groundwater levels are major outputs from this model. FLATWOODS has been recently applied to simulate the hydrology of Carolina bays in the coastal plain of South Carolina (Sun et al., 2006a).

1.2.4 ANSWERS

ANSWERS-2000 (Bouraoui, 1994; Byne, 2000) is a long-term, continuous simulation, distributed parameter, physically-based, watershed scale, upland planning model developed for evaluating the effectiveness of agricultural and urban BMPs in reducing sediment and nutrient delivery to streams in surface runoff and leaching of nitrogen through the root zone. It was designed for application in watersheds where data for model calibration are not available. Beasley and Huggins (1982) developed the original ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) model in the late 1970s. Originally, the model was conceived as a distributed-parameter hydrologic model only (Huggins and Monke, 1966), but sediment (Beasely et al., 1980) and nutrient (Storm et al., 1988; Dillaha et al., 1988) components were added to make it more appropriate for non-point source pollution concerns. This event-based model has been validated successfully on five upland watersheds in the upper coastal plain in Mississippi (Thomas and Beasley, 1986b). However, unsatisfactory results were reported when the model was tested on two steep mountain watersheds at Coweeta in North Carolina, where soils and topography are believed to be unique, and baseflow rates are relatively higher than those of the piedmont watersheds.

1.2.5 DHVSM

DHSVM (Distributed Hydrology Soil Vegetation Model; Table 1-1; Beckers and Alila 2004; Wigmosta et al., 1999; Wigmosta et al., 1994) is a physically-based, distributed hydrologic model that explicitly represents the effects of topography and vegetation on water flux through the landscape. DHSVM is typically applied at high spatial resolutions, on the order of 100 m for watershed sizes up to 104 km^2. The model is usually applied at sub-daily timescales for multi-year periods. DHSVM has been applied predominantly to mountainous watersheds in the Pacific northwest region of the U.S. It has been applied in a number of studies that focused on prediction of streamflow, ET, and other surface energy and moisture flux. It has also been utilized to study the interactions between climate and hydrology and the potential impacts of climate change on water resources. The model has been proven as an important tool for assessing the impacts of forest management practices on watershed processes. HSVM is a research model and as such is continuously under development. There are only very limited efforts have been made to develop a user-friendly interface for this model (DHSVM web site, 2002).

1.2.6 RHESSys

RHESSys (Regional Hydro Ecological Simulation System; Table 1-1; RHESSys web site, 2005; Band et al., 2001; Band et al., 1993) is a GIS-based, hydro-ecological modeling framework designed to simulate carbon, water, and nutrient fluxes at a daily time step over multi-year time periods. It combines a set of physically based process models and a methodology for partitioning and parameterizing the landscape. RHESSys models the spatial distribution and spatial-temporal interactions between different processes at a watershed scale. Its original process models have been adapted from several pre-existing models, including the MTN-Clim model (Running et al., 1987), the BIOME-BGC model (Running and Coughlan, 1988; Running and Hunt, 1993), the TOPMODEL model (Beven and Kirkby, 1979), and the DHSVM model (Wigmosta et al., 1994). Specific algorithms within these original models have been modified to reflect various developments in the associated literature or to fit within the RHESSys modeling framework.

1.2.7 MIKE SHE

MIKE SHE (Table 1-1; Graham and Butts, 2005; DHI, 2004a; Refsgaard and Storm, 1995) is commercial hydrologic software developed by DHI (Danish Hydraulics Institute). It is a dynamic, distributed, physically based and user-friendly hydrologic modeling system capable of simulating all major hydrological processes occurring in the land phase of the hydrological cycle. The model can be used for the analysis, planning, and management of a wide range of water resource and environmental problems related to surface water and groundwater. MIKE SHE is a further development based on Système Hydrologique Européen (SHE), which was developed and became operational in 1982. SHE was sponsored and developed by a European consortium of three organizations: the Institute of Hydrology (UK), the French consulting firm SOGREAH, and DHI (Abbott et. al., 1986a, 1986b). Subsequently, DHI continues to improve the model and commercialize it. MIKE SHE has been widely used around the world (Begey et al.,1999; Cargnelutti et al., 1999; Styczen et al., 1999; Xevi et al., 1997; Yang et al., 2000). In the U.S., it has been applied for Everglade restoration in south Florida (Yan et al., 1998; Yan et al., 1999), and wetland restoration in the San Francisco Bay area, California (Leonardson et al., 2003). It has also been used by consulting firms to solve groundwater seepage and contamination concerns (Prucha et al., 2003).

1.3 Model comparisons

In a recent study, Tague et al. (2004) compared the hydrologic simulations between RHESSys and a modified version of MIKE SHE (Andersen et al., 2001). The models were applied to a 34 km^2 mountainous watershed near Santa Barbara in California, which is a typical semiarid chaparral dominated Mediterranean Type Ecosystem (MTE). Monthly and annual streamflow and soil moisture patterns were compared for the two models. This study demonstrated the tradeoff between using additional parameters and storage terms and limiting the need for extensive calibration. The additional parameters in MIKE SHE allowed this model to more accurately capture observed streamflow behaviors, although this accuracy might not necessarily reflect a better representation of internal hydrologic processes. The additional complexity in the vertical soil discretization in MIKE SHE did not appear to improve model predictions of monthly streamflow patterns. Thus, the computational cost due to multiple soil layers indicates that the simpler approach in RHESSys may be preferred. However, under conditions of higher temporal resolutions or overland flow dominated areas, the ability to explicitly model infiltration dynamics in MIKE SHE might be required. This study also suggested that modification of RHESSys to include a deeper basin scale groundwater reservoir might be warranted. In particular, three distributed models were reviewed intensively and comparisons among them were summarized (Table 1-1).

Table 1-1. Comparisons among three distributed models - MIKE SHE, RHESSys and DHSVM.

Comparisons	MIKE SHE	RHESSys	DHSVM
Model essential	An integrated hydrologic modeling system, simulating the complete hydrologic cycle. Has linkage with other models/options. Uniform grids applied.	A hydro-ecological modeling framework, simulating carbon, water, and nutrient flux. No linkage to other models. Often uses irregular patch sizes and shapes.	A stand-alone hydrology-vegetation model, applying uniform grids in the entire modeling domain.
ET simulation	Kristensen-Jensen model and Two-Layer UZ/ET model	1. evaporation - Penman method 2. transpiration - Penman-Monteith method	Penman-Monteith method
Overland flow simulation	2-D Saint Venant equation	Explicit routing method used in DHSVM	Based on Dupuit-Forchheimer assumptions, explicit routing method

Table 1-1. Comparisons among three distributed models - MIKE SHE, RHESSys and DHSVM (Continued).

Comparisons	MIKE SHE	RHESSys	DHSVM
Unsaturated zone flow simulation	One-dimensional simulation: 1. Richards equation 2. Simplified gravity flow 3. Simple two-layer water balance	One-dimensional simulation. Phillip equation simulates infiltration. Drainage from unsaturated zone is limited by field capacity.	One-dimensional simulation. Green-Ampt for infiltration and Darcy's law with simplified gravity flow.
Saturated zone flow simulation	General 3-D groundwater flow equation as in MODFLOW	Explicit routing approach used in DHSVM	Based on D-F assumptions, explicit routing method
Channel flow simulation	Saint Venant equation for 1-D river simulation by coupling with MIKE 11.	No explicit channel flow simulation. Simple accounting as all subsurface/overland water is assumed to exit the basin on the same day it is generated.	No explicit channel flow simulation. Simple accounting as all subsurface/overland water is assumed to exit the basin the on same day it is generated.
Input requirements	Most intensive	Moderately intensive	Least intensive
Output utility	Stable, robust, friendly, and helpful	Limited	Very few
Advantages for southeast applications	Good interface, more flexibility and many options are available. Water movement is physically based and solved implicitly. Can be applied for large basins or confined groundwater simulations.	Free, simpler, computational efficiency, already linked to the carbon and nutrient cycling. Can be applied for mountainous watersheds.	Free, simple, computational efficiency. New function/routine can be added. Have been intensively applied for mountainous watersheds.
Disadvantages for southeast applications	Have to pay. Intensive input requirement. ET was empirically developed from agricultural field. Cannot modify the source code.	Intimidating interface. Not for large basins. There isn't much snow accumulation and melting in the southeaster U.S. It might not applicable in the coastal plain that is relatively flat.	Not user friendly interface. Not for large basins. There isn't much snow accumulation and melting in the southeaster U.S. It might not applicable in the coastal plain.

With the improvement of modeling techniques, physically-based, spatially distributed modeling systems have particular advantages for the study of hydrologic impacts of forest management and climate change. ANSWERS-2000 was developed for agricultural conditions, and it is not readily applicable for forested watersheds. The forest version of ANSWERS (Thomas and Beasley, 1986a, 1986b) is an event-based model and its functionalities are quite limited. DHSVM has been applied predominantly to mountainous watersheds in the Pacific northwest U.S., while in the southeast the great attention to the snow accumulation and melting are not necessary. Both DHVSM and RHESSys are difficult to apply, because they lack a user-friendly interface. RHESSys is not fully distributed. In landscapes with large regions of relatively flat terrain where flow routing is more diffuse and significantly dependent upon micro (or sub-scale) topography, the assumptions used in the DHSVM explicit routing model are no longer valid. This might limit the performance of RHESSys and DHSVM in the coastal plain, although both models have great potential in the mountains. FLATWOODS uses similar theories as those in the water movement module of MIKE SHE. However, MIKE SHE is more robust and user-friendly. Furthermore, MIKE SHE is an advanced hydrologic modeling tool that integrates surface and ground water simulations. MIKE SHE also has the advantage of GIS linkage; it is tightly integrated with ESRI's ArcView GIS file formats, and ArcView can be used for both pre-processing of input data and post-processing of output data. Thus, it is easy to manipulate and manage the distributed data using MIKE SHE. As a physically based model, MIKE SHE simulates the full hydrologic cycle characteristics of a forest ecosystem, including ET and vertical soil water movement in the unsaturated zone to the groundwater.

It could be applied to both lowlands and uplands. Thus, MIKE SHE was selected for this study.

1.4 Objectives and hypotheses

The purpose of this study is to investigate hydrologic responses to forest management and climate change in two different geographic regions, the coastal plain and the mountainous uplands of the southeastern U.S. MIKE SHE (coupled with MIKE 11) was used as a tool to carry out this task. With a distributed hydrologic model, we can investigate the total watershed response and that of an area of interest or particular location within the watershed. Thus, the objectives of this study are:

1. Evaluate the applicability of the MIKE SHE/MIKE 11 modeling system in the southeastern U.S.

2. Apply the MIKE SHE/MIKE 11 modeling system to test the hydrologic responses in different geographic regions (the coastal plain and the mountainous uplands) under the impacts of forest management practices and climate change in the southeastern U.S.

The general hypothesis for this study is that different regions have different hydrologic responses to forest management practices and climate change due to their topography, climate, soil, and vegetation conditions. If this is true, different forest management strategies should be applied in different regions. It is also hypothesized that effects of forest management practices and climate change vary between different seasons (wet vs. dry) in a year.

1.5 Dissertation structure and organization

The writing of this dissertation was organized into seven chapters. Chapter 1 serves as an introduction. Chapter 2 outlines methods. Chapters 3 through Chapter 6 describe model evaluation and application for four watersheds. Each watershed is an independent chapter with similar organization and structure. Chapter 7 includes discussion and study conclusions.

Chapter 2

Methods

As described in the last chapter, current existing forest hydrologic models were reviewed and the MIKE SHE model was selected as the most appropriate model for the regional modeling comparison study. Four study sites (Figure 2-1), which have long-term forest hydrology data and represent both wetland and upland conditions, were selected from the two regions in the southeastern U.S. MIKE SHE/MIKE 11 was evaluated and applied at each site and modeling results were analyzed. The following flow diagram (Figure 2-2) summarizes the general research procedures taken in this study. The underlining assumption was that MIKE SHE should be applicable to any watershed conditions because it is physically based.

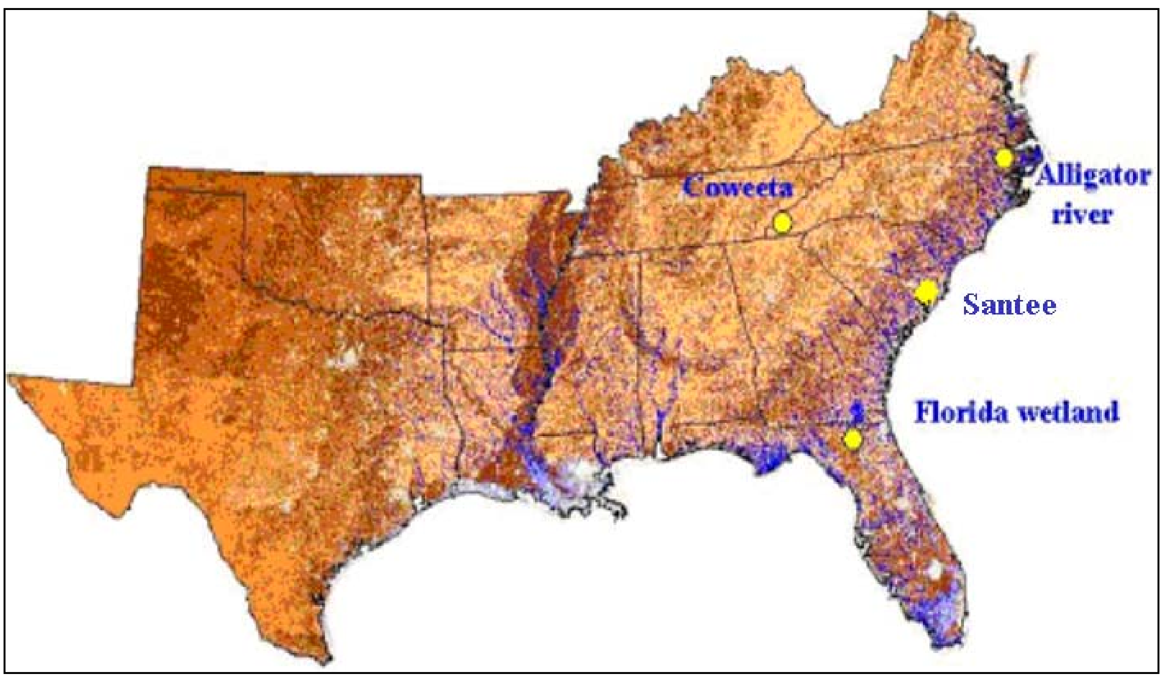

Figure 2-1. Locations of the four study sites in the southeastern U.S.

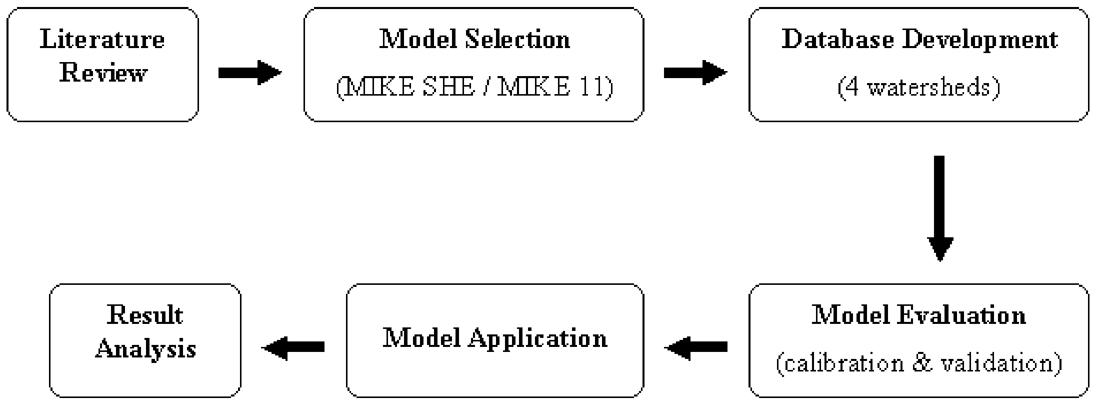

Figure 2-2. Procedures of the study.

2.1 MIKE SHE descriptions

As the first generation of spatially distributed hydrologic model, MIKE SHE is a comprehensive deterministic, distributed and physically based hydrologic modeling system (Abbott et. al., 1986a, 1986b). The modeling package is user friendly with a window interface to Geographic Information Systems. MIKE SHE can be applied to a wide range of water resources and environmental problems for the simulations of surface and ground water movement, the interactions between the surface water and ground water systems, and the associated point and non-point water quality problems

MIKE 11 (DHI, 2004b) is a one-dimensional modeling tool for streamflow and water level simulations using a fully dynamic wave version of the Saint Venant equations. Both simple and complex river and channel systems can be simulated, as can flows over a variety of structures. The coupling of MIKE SHE and MIKE 11 enhances the representation of the wetland and watershed hydrology, and is expected to improve the accuracy of simulation results.

The modular structure was implemented in MIKE SHE. This feature allows users to apply only those modules that are necessary for their projects. The water movement module serves as the MIKE SHE core and is the fundamental module. MIKE SHE water movement module simulates the hydrological components including ET, overland flow, channel flow, unsaturated soil water movement and groundwater movement (Figure 2-3 and Figure 2-4). The major processes of the MIKE SHE model were briefly presented in the following sections. Detailed descriptions of the modeling procedures and mathematical formulation can be found in the MIKE SHE user's manual (DHI, 2004a) and associated publications (Abbot et al., 1986a, 1986b; Refsgaard and Storm, 1995; Graham and Butts, 2005).

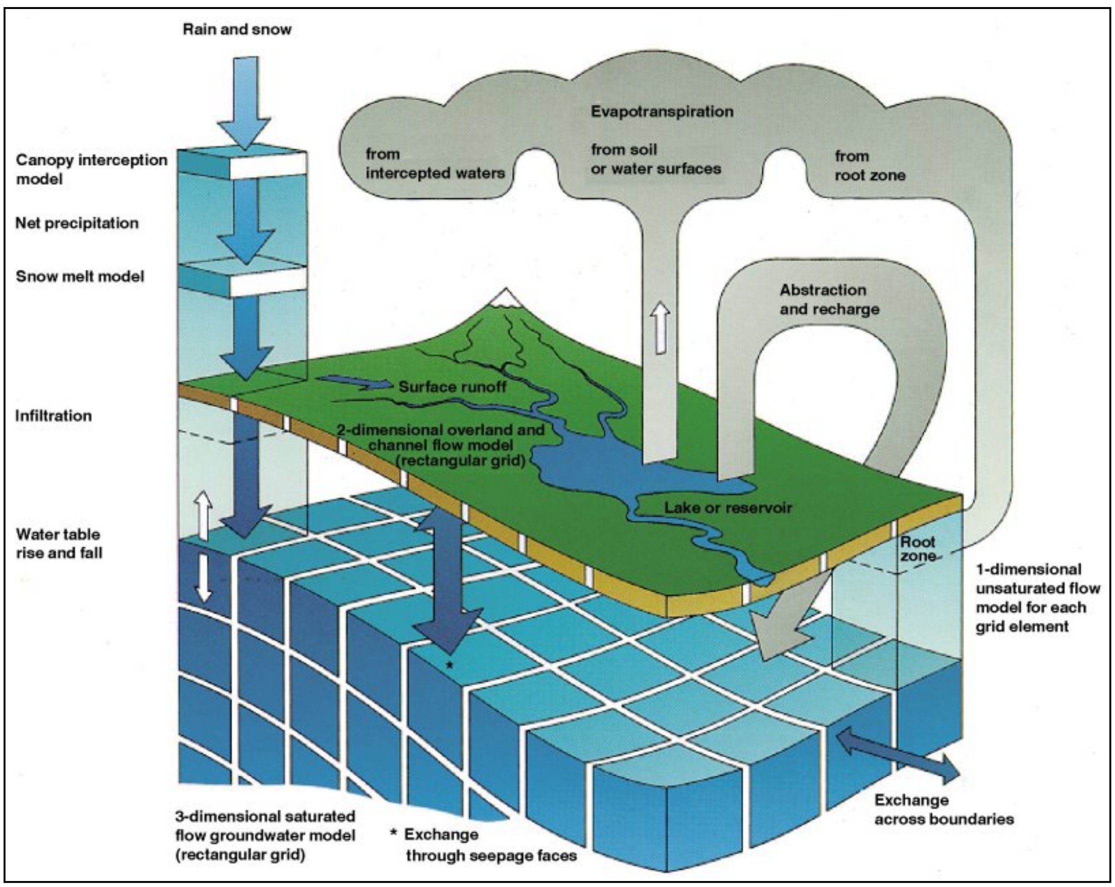

Figure 2-3. The MIKE SHE model structure (from DHI).

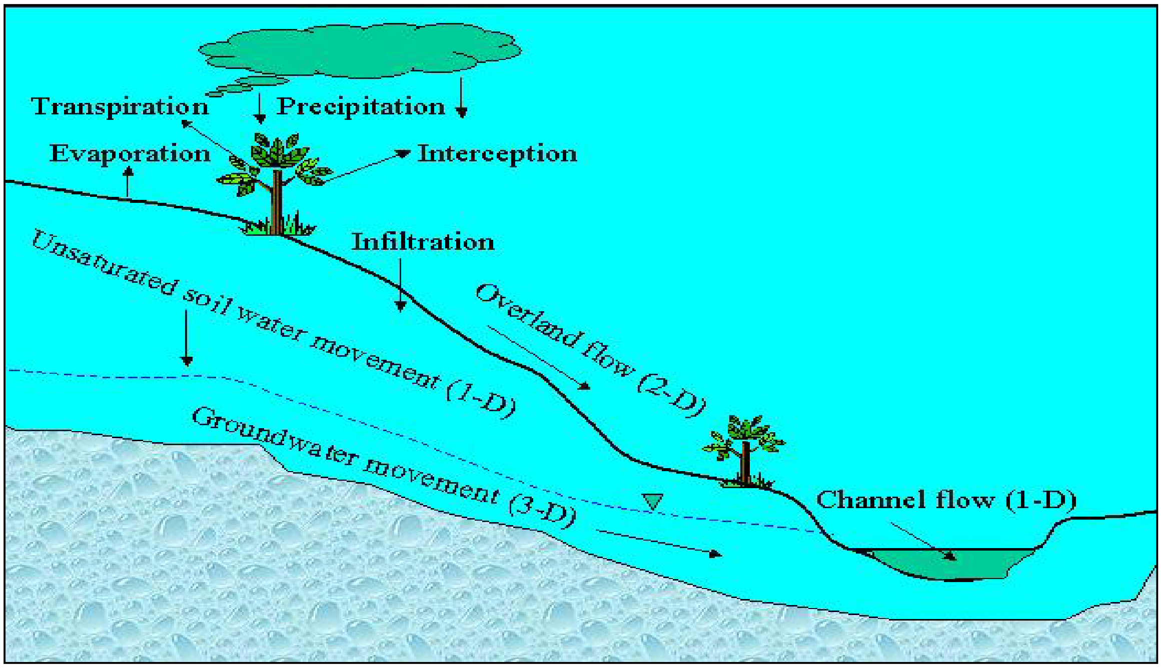

Figure 2-4. Hydrologic processes simulated in the MIKE SHE model.

2.1.1 Evapotranspiration (ET)

ET includes canopy interception, evaporation from ponded water, soil evaporation and plant transpiration from the unsaturated and saturated zones. ET is calculated by Kristensen-Jensen model (Kristensen and Jensen, 1975) or Two-Layer Water Balance model (Yan and Smith, 1994). Kristensen-Jensen model generally assumes that temperature is over 0 °C and there is no snow occurs. In Kristensen-Jensen model, ET is calculated as the function of leaf area index (LAI), soil moisture content, root distribution and potential evapotranspiration (PET). As an alternative to the Kristensen-Jensen model, the simplified Two-Layer Water Balance model is used with the main purpose of providing an estimate of the actual ET (AET) and the amount of water that recharges the saturated zone. It is primarily applicable for areas with shallow water table such as wetlands. The model is less suitable for areas with deeper and drier unsaturated zones because it does not consider the flow dynamics in the unsaturated zone.

PET is required as an input to both models to calculate AET. Hamon PET method (Hamon, 1963; Lu et al., 2005) was used to calculate daily PET for each site in this study.

The Hamon PET is estimated as:

$$PET = K_{pet} \times 0.1651 \times L_d \times RHOSAT \quad (1)$$

Where PET is daily PET in mm; K_{pet} is calibration coefficient; L_d is daytime length (which is time from sunrise to sunset in multiples of 12 hours); RHOSAT is saturated vapor density in g/m^3 at the daily mean air temperature (TEMP).

$$RHOSAT = 216.7 \times ESAT / (TEMP + 273.3) \quad (2)$$

$$ESAT = 6.108 \times EXP(17.26939 \times TEMP / (TEMP + 237.3)) \quad (3)$$

Where TEMP is daily mean air temperature in °C; ESAT is saturated vapor pressure in mb at the given TEMP.

2.1.1.1 Kristensen and Jensen method

The Kristensen-Jensen model is based on empirically derived equations from work conducted by Kristensen and Jesen (1975) in Copenhagen, Denmark. The empirical equations in the model are developed based on agricultural field measurements. The required inuput includes time series of PET, leaf area index (LAI) and the root depth, as well as values for several empirical parameters (C_{int}, C1, C2, C3, A_{root}) that control the distribution of ET within the system. The Kristensen-Jensen method is used with the Richards equation and gravity flow methods for modeling the unsaturated water movement (Graham and Butts, 2005).

First, net rainfall is calculated by subtracting the amount of canopy interception from the gross precipitation. Net rainfall is added to the ground surface where it either infiltrates or ponds. Evapotranspiration is first removed from canopy interception, followed by ponded water at the PET rate. If PET is not yet satisfied for the current time step, then the left over enery is used to remove water from the root zone via transpiration. The actual soil moisture content, soil field capacity and wilting point in each vertical layer are used to control the amount of transpiration. The vertical distribution of transpiration is controlled by the root density and a root shape factor (A_{root}) to distribute ET within each layer of the root zone.

2.1.1.1.1 Evaporation from the canopy

First, the canopy interception is modelled as an interception storage (I_{max}), which must be filled before stem flow occurs.

$$I_{max} = C_{int} \times LAI \tag{4}$$

Where C_{int} is an interception coefficient, which defines the interception storage capacity of the vegetation.

The evaporation from the canopy storage is equal to PET if sufficient water has been intercepted on the leaves, that is

$$E_{canopy} = \text{minimum}\ (I_{max}, PET \times \Delta t) \tag{5}$$

Where E_{canopy} is the canopy evaporation, and Δt is the time step length for the simulation.

2.1.1.1.2 Plant transpiration

The transpiration from the vegetation, E_{plant}, is controlled by LAI, the soil moisture content in the root zone and the root density as:

$$E_{plant} = f_1(\mathrm{LAI}) \times f_2(\theta) \times \mathrm{RDF} \times \mathrm{PET} \tag{6}$$

Where $f_1(\mathrm{LAI})$, $f_2(\theta)$ and RDF are functions of LAI, soil moisture content in the root zone and root distribution, respectively.

$$f_1(\mathrm{LAI}) = \mathrm{C2} + \mathrm{C1} \times \mathrm{LAI} \tag{7}$$

Where C1 and C2 are empirical parameters. C1 is plant dependent. C2 influences the distribution between soil evaporation and transpiration. For higher values of C2, a larger percentage of the AET will be soil evaporation.

$$f_2(\theta) = 1 - \left(\frac{\theta_F - \theta}{\theta_F - \theta_w} \right)^{\frac{\mathrm{C3}}{\mathrm{PET}}} \tag{8}$$

Where θ_F and θ_w are the volumetric moisture content at field capacity and wilting point, θ is the actual volumetric moisture content, and C3 is an empirical parameter, which may depend on soil type and root density.

RDF is controlled by root depth and root shape factor - A_{root}, which describes the root mass distribution in the root zone and determines how the water extraction is distributed along the soil depth. Usually, the transpiration tends to become smaller for higher values of A_{root}.

2.1.1.1.3 Soil evaporation

Soil evaporation, E_{soil}, occurs from the upper part of the unsaturated zone and is limited to about 10 cm below ground surface in the MIKE SHE model. As described in equation (9), it consists of a basic amount of evaporation and the additional evaporation from excess soil water as the soil saturation reaches field capacity.

$$E_{soil} = PET \times f_3(\theta) + [\ PET - E_{plant} - PET \times f_3(\theta)\ ] \times f_4(\theta) \times [\ 1 - f_1(LAI)\ ] \qquad (9)$$

Where $f_3(\theta)$ and $f_4(\theta)$ are empirical functions determined by soil moisture parameters and empirical parameters C2.

In the absence of vegetation (LAI = 0), $f_1(LAI)$ and E_{plant} can go to zero. Thus, equation (9) can be simplified as

$$\frac{E_{soil}}{PET} = f_3(\theta) + f_4(\theta) - f_3(\theta) \times f_4(\theta) \qquad (10)$$

This shows that soil evaporation is solely controlled by soil moisture content and the empirical parameters C2 under a given PET. When the soil moisture content is above or at the field capacity, soil water will be removed by the left PET energy.

2.1.1.2 Two-Layer Water Balance method

The Two-Layer Water Balance ET mothod is used when the Two-Layer Water Balance model is used for modeling water flow in the unsaturated zone. It divides the unsaturated zone into a root zone, from which ET can be extracted, and a zone below the root zone where ET does not occur. Canopy interception and transpiration are modeled by the same methods as those in the Kristensen-Jensen method. And similar to the

Kristensen- Jensen mothod, ET is extracted first from canopy interception, then ponded water and lastly via transpiration from the root zone, based on an average water content in the root zone. If no ET occurs, the average water content in the root zone decreases linearly with the water table depth. However, ET reduces the water content in the root zone and creates unsaturated zone storage. The minimum water content in the root zone is the wilting point, but this can only occur when the water table is below the root zone.

2.1.2 Unsaturated flow

The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as soil moisture is replenished by rainfall and removed by ET and recharge to the groundwater table. Unsaturated flow is assumed to be primarily vertical, since gravity dominates infiltration. Therefore, unsaturated flow in MIKE SHE is calculated only vertically in one-dimension, which is sufficient for most applications. However, this may limit the validity of the flow description in some situations such as on very steep hill slopes with contrasting soil properties in the soil profile. Three options are available for calculating vertical flow in the unsaturated zone. These are: 1) One-dimension Richards equation (Richards, 1931); 2) A simplified gravity flow procedure; and 3) A simple Two-Layer Water Balance method for shallow water tables (Yan and Smith, 1994). Richards equation and the simple Two-Layer Water Balance methods were used in this study.

Method 1:

By combining mass balance and Darcy's law, one dimensional Richards equation can be expressed as:

$$C\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial \psi}{\partial z}\right) + \frac{\partial K}{\partial z} - S \tag{11}$$

Where,

$C = \dfrac{\partial \theta}{\partial \psi}$	is soil water capacity (m^{-1})
θ	is soil moisture content
$\psi(z, t)$	is pressure head (m)
t	is time (s)
z	is vertical space coordinate (m)
$K(\theta, z)$	is hydraulic conductivity (m/s)
S(z, t)	is source/sink term (e.g. root transpiration extraction and soil evaporation as sinks; Rainfall as a source) (s^{-1})

Method 2:

The gravity flow option ignores the pressure head and the vertical driving force is due entirely to gravity. Thus, equation (11) is simplified as:

$$C\frac{\partial \psi}{\partial t} = \frac{\partial K}{\partial z} - S \tag{12}$$

Method 3:

The Two-Layer Water Balance option divides the unsaturated zone into a root zone and a zone below the root zone. These tow layers represent average conditions in the unsaturated zone. Unsaturated zone storage is determined by average and maximum water contents at the unsaturated zone. Infiltration discharges immediately to the saturated zone whenever the unsaturated zone storage is zero. This occurs when the water content is equal to the maximum water content. The method simply calculates the amount of water that recharges the saturated zone, while accounting for unsaturated zone storage.

2.1.3 Overland flow

Overland flow is calculated by the diffusive wave approximation of Saint-Venant equations (Saint-Venant, 1871) of continuity and conservation of momentum at two dimensions. Finite difference method was used to solve the differential equations. Precipitation becomes surface runoff when net rainfall rate exceeds the infiltration capacity of the soil, or when groundwater flows onto the surface (e.g. in wetlands). Ponded water is routed downhill as surface runoff toward the river system. The flowpath and quantity is determined by the topography and flow resistance, as well as losses due to evaporation and infiltration along the path it takes.

Local depressions in the topography are conceptually modeled as detention storage, which restricts overland flow and allows water to more easily evaporate or infiltrate. Usually, overland flow is solved using the same time step as the unsaturated flow and ET. Ponded water is transferred to and from the other hydrologic components at the beginning of every overland flow time step.

2.1.4 Channel flow

Channel flow is simulated by the coupling of MIKE SHE and MIKE 11, which is the DHI's river hydraulic model. The representation of the river in the MIKE SHE model is approximated to run along the boundaries of MIKE SHE's modeling grids for overland and saturated flow exchange with MIKE 11 river network, depending on the hydraulic head gradient. Because the exchange occurs on the edges between grid cells, the more refined the MIKE SHE grid is, the more accurately the spatial distribution of the exchange will be represented. The fully dynamic Saint Venant equations are used to simulate one-dimensional river flows and water levels. Through this component the water exchange between surface water and aquifer is simulated. The entire river system is always simulated in the MIKE 11 hydraulic model. However, MIKE SHE will only exchange water with a sub-set of the MIKE 11 river model that intersects the MIKE SHE overland flow/groundwater grid. The calculated exchange flows are fed to MIKE 11 as lateral flow to or from the corresponding calculation points.

2.1.5 Saturated flow

Three-dimensional ground water flow is simulated by MIKE SHE using the general three-dimensional groundwater flow equation (Eq. 13) which is solved by the implicit finite difference method. The saturated flow simulation in MIKE SHE is very similar to that in MODFLOW (McDonald and Harbaugh, 1988) and the outputs from these two models are comparable (DHI, 2001).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial h}{\partial t} \qquad (13)$$

Where K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivity along the x, y and z axes of the model, which are assumed to be parallel to the principle axes of hydraulic conductivity tensor; h is the hydraulic head; Q represents the source/sink terms; S_s is the specific storage coefficient for confined aquifers and specific yield for unconfined aquifers; and t is time.

In the MIKE SHE model, discharge to or recharge from the river system occurs from all computational cells located along the river links. The surface and ground water interactions account for dynamic variations in river water levels. This feature is often lacking in the traditional ground water models (e.g. MODFLOW) (DHI, 2004a).

2.2 Study watersheds

MIKE SHE model evaluation and application were conducted at four sites representing two physiographic regions - the coast and the mountain - in the southeastern U.S. (Figure 2-1). These are four intensively studied small experimental forested watersheds with varying land cover and soil types, and areas ranging from 12-ha to 160-ha that have long-term hydrologic data. One watershed is located on the mountainous upland, North Carolina and the other three are located on the lower coastal plain in North Carolina, South Carolina and Florida, respectively. Streamflow, baseflow and peakflow rates, and spatial distributions of groundwater table were the major hydrologic variables used in the evaluation of model performances. More information about each site will be given in the next four chapters. Similar organization and structure were employed for each site as an independent chapter. The last chapter serves as a summary of this study.

Table 2-1. Basic information of the four study watersheds.

Site Name	Area (ha)	Location	Average Precipitation (mm/year)	Soil	Vegetation Coverage
Florida wetland site	42	Coastal plain, FL	1330	Sandy soil	Cypress and slash pine
Alligator River site	18	Coastal plain, NC	1523	Organic soil	Pond pine and loblolly bay
Santee Watershed 80	160	Coastal plain, SC	1370	Sandy loam	Mixed hardwood and pine
Coweeta Watershed 2	12	The Appalachian Mountains, NC	1772	Loamy soil	Mixed hardwood

2.3 Model evaluation methods

In this study, graphical inspections as a qualitative method and the statistical criteria as a quantitative method were used to evaluate the MIKE SHE model performances at the four study watersheds. The statistical parameters included mean error (ME), Pearson's Correlation Coefficient (R) and the Nash-Sutcliffe (1970) coefficient of efficiency (E). After each model run, these values were calculated to evaluate model performances. ME (Eq. 14) is commonly used to determine the average systematic error among the simulated and the observed values. Positive values of ME indicate model underpredictions, while negative values correspond to overpredictions. E (Eq. 15) varies from minus infinity to 1.0, with higher values indicating better agreement. E is, however, over sensitive to peak values because of larger random errors associated with higher values (Vazquez et al., 2004). R (Eq. 16) is a measure of the strength of the association between observed and predicted values. It may take any values between -1 and 1.

$$ME = \frac{\sum_{i=1}^{n}(O_i - P_i)}{n} \tag{14}$$

Where O_i is the i-th observed value, P_i is the i-th simulated value, and n is the number of observations.

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{15}$$

Where $\overline{O}$ is the average of observed values.

$$R = \frac{\sum_{i=1}^{n}\left[\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \cdot \sqrt{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}} \tag{16}$$

where $\overline{P}$ is the average of simulated values.

2.4 Model calibration, validation and applications

Similar procedures were used to calibrate and validate the MIKE SHE model at the four study watersheds. Four application scenarios were simulated at each watershed afterwards.

2.4.1 Model calibration and validation

The purpose of the calibration is to obtain a set of model parameters, which provide 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 graphical inspections and 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. Water table and stream flow data were used for the MIKE SHE model calibration and validation at four study watersheds (Table 2-2).

Table 2-2. Data used for model calibration and validation at four study watersheds.

Site Name	Model Calibration	Model Validation
Florida wetland site	Water table	Water table
Alligator River site	Water table	Water table
Santee Watershed 80	Streamflow and water table	Streamflow and water table
Coweeta Watershed 2	Streamflow	Streamflow

2.4.2 Model application scenarios

After model calibration and validation, the MIKE SHE model was applied to simulate four scenarios. These scenarios included: 1) Base line (BL); 2) Clear Cutting (CC); 3) Two degree (°C) temperature increase (TI); and 4) Ten percent precipitation decrease (PD). The purposes of the applications were to examine the model performances under "what-if" scenarios and test the model sensitivities.

BL scenario was based on the historically climatic data with the assumption that the watershed remained all forested throughout the study period. CC scenario represented a simple forest management practice that was also based on the historically climatic data but with the assumption that the entire watershed was clear-cut. Apparently, the most significant effect of the harvesting on model parameters was the reduction of leaf area index (LAI). Soil structure of the site might have been altered due to compaction by the mechanical operations (NCASI, 2004). However, the change was difficult to quantify and was ignored in this study (Sun et al., 1998b). The last two scenarios represented two simple climate change cases. A temperature increase of 2 °C scenario represented the situation that every daily temperature was increased 2 °C with land cover remained the same as base line. The 10% precipitation decrease scenario represented a case that daily precipitation decreased 10% when there was a rainfall event, while the land cover remained the same as the base line.

Chapter 3

MIKE SHE Evaluation and Application at a Cypress-Pine Flatwoods Watershed in North Central Florida

3.1 Objectives

The objective of this study is to apply a physically-based, distributed hydrologic model, MIKE SHE, to better understand the hydrologic processes in this typical flatwoods landscape and its responses to potential land disturbance, and to test its sensitivity to potential climate variability and change.

3.2 Methods

3.2.1 Site description

The study site was in Gator National Forest, which was located about 33 km northeast of Gainesville, Alachua County in north central Florida (Figure 3-1). A long-term intensive wetland hydrology study was conducted in the 1990s (Crownover et al., 1995; Sun et al., 2000b; Bliss and Comerford, 2002). As an important ecological plant community in the southeastern Coastal Plain, the flatwoods consists of a mixture of wetlands and uplands (Figure 3-2). The flatwoods covers approximately 50% of the Florida land area, or approximately three million hectares (Bliss and Comferford, 2002). The cypress swamps are depression wetlands providing many important ecological functions including groundwater recharge, water purification, wildlife habitat and biomass production.

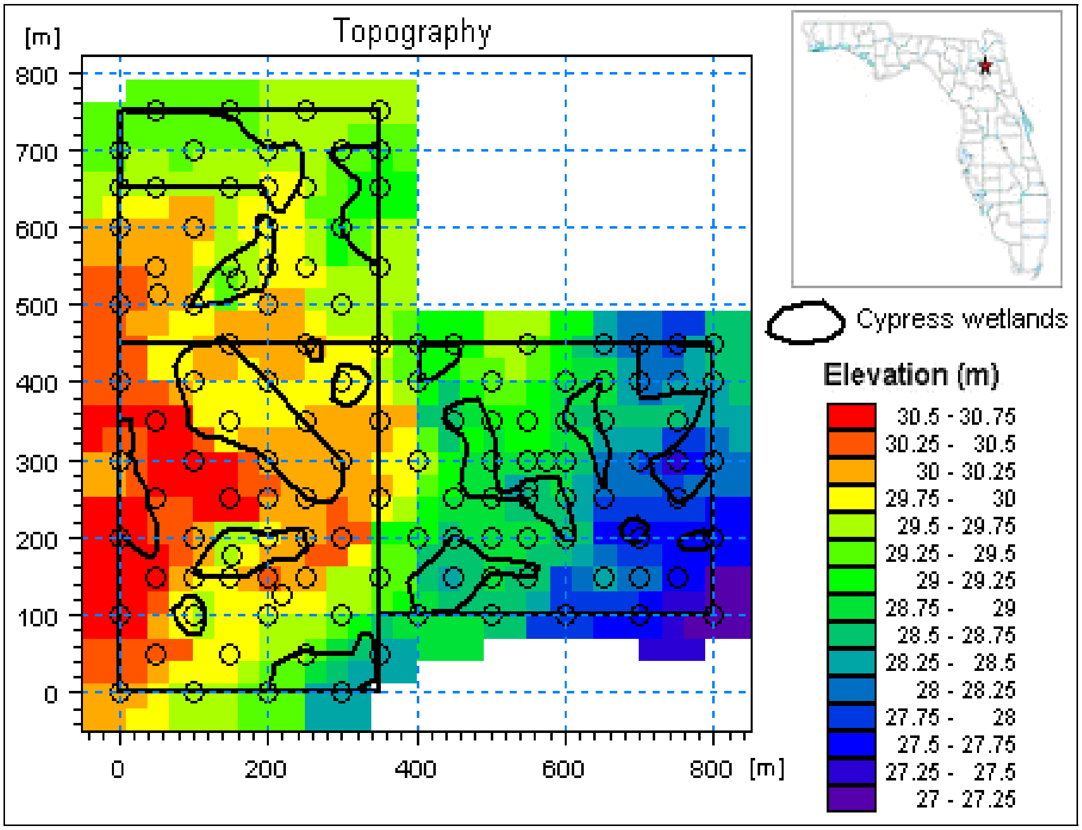

Figure 3-1. Topography of the Florida wetland site.

Geology at this site was dominated by Plio-Pleistocene terrace deposits and the Hawthorne Formation with ground slopes ranging from 0% to 1.6% (Figure 3-1). The shallow ground water was separated from the underlying artesian secondary aquifer by impermeable blue-green clays (> 4 m thick), which was underneath the top organic and sandy soil layers (2-3 m thick).

The cypress swamps accounted for about 35% percent of the study area with wetland sizes ranging from a few square meters to more than 5-ha (Figure 3-1). Pond cypress (*Taxodium ascendens* Brongn.) dominated the vegetation in the wetland, along with slash pine (*Pinus elliottii* Engelm) and swamp tupelo (*Nyssa sylvatica var. biflora* Sarg.). The remaining upland was dominated by a 29-year old mature slash pine plantation in 19920with saw palmetto (*Serenoa repens* Small) and gallberry (*Ilex glabra* Gray) shrubs as the understory (Sun et al., 2000b).

Figure 3-2. Aerial view of the Florida wetland site.

The average annual air temperature was 21 °C, with a mean monthly low of 14 °C in January and high of 27 °C in July. Average annual rainfall was about 1330 mm, with two distinct dry periods within a year. The first dry period was from April to June, and the second one was from October to December (Figure 3-3 and Figure 3-4). The soil type was predominantly Pomona fine sand (a Spodosol; Utic Haplaquods; sandy siliceous, themic) (Sun, 1995; Mansell et al., 2000).

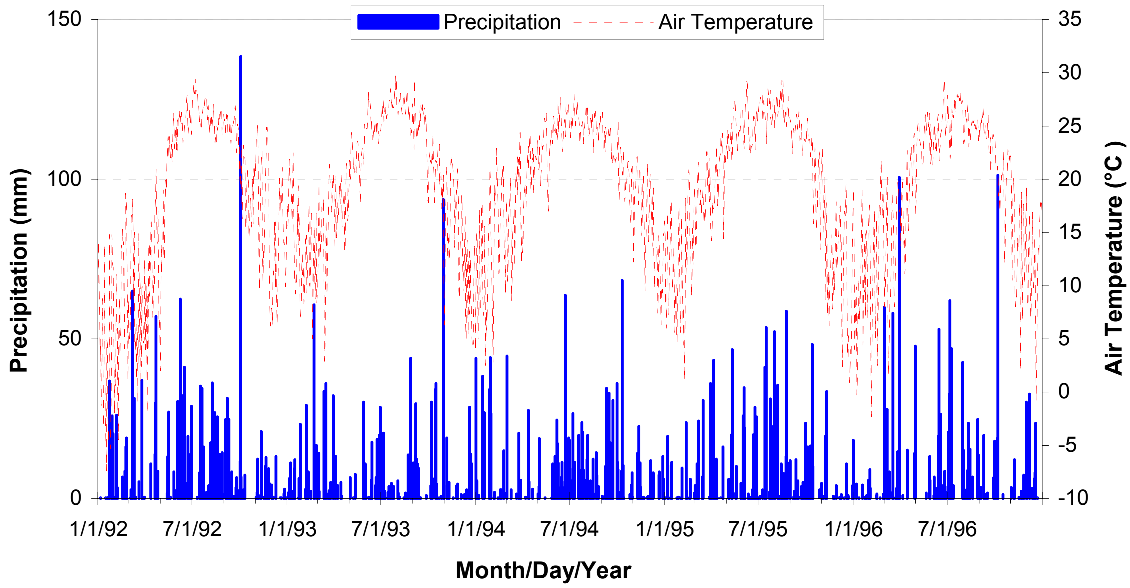

Figure 3-3. Daily precipitation and air temperature during the study periods (1992-1996) at the Florida wetland site.

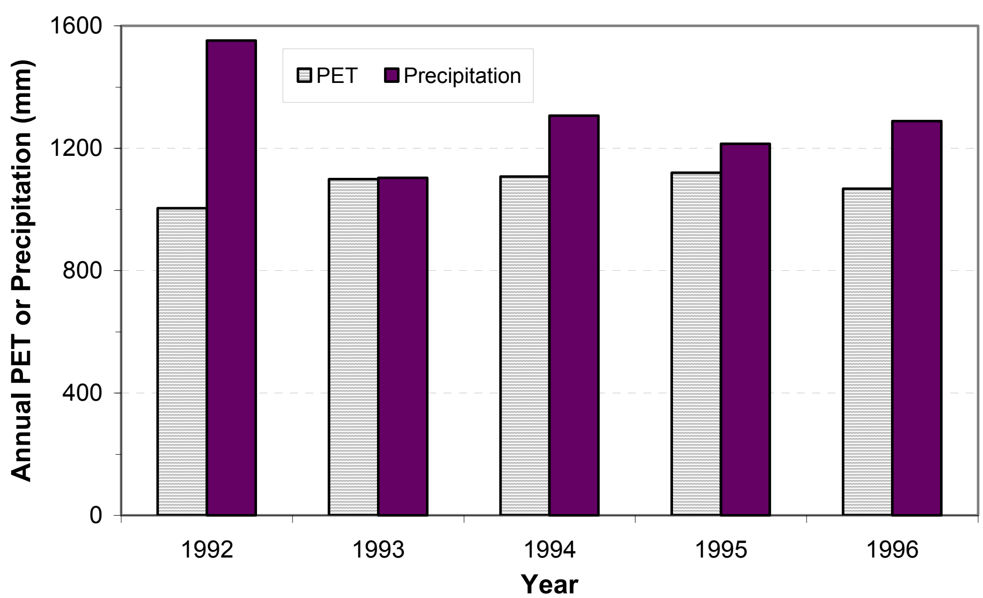

Figure 3-4. Annual PET and precipitation during the study periods (1992-1996) at the Florida wetland site.

3.2.2 Data collection

Beginning in January 1990, the study area was surveyed to establish a 50 m × 50 m grid system. An arbitrary datum with the elevation of 30.480 m above mean sea level was set at the reference coordinate (0, 0). The actual elevation of the study site was about 47 m above mean sea level (Sun et al., 2000b). Each grid point was marked and labeled with a steel post, and its elevation relative to the datum was measured in the field.

Shallow water table wells were installed at approximately every second grid point. Thus, 122 manual wells and six automatic wells were available at this site (Figure 3-1). The 5-cm diameter, 1.5-m long polyvinyl chloride (PVC) water table wells were installed in the holes drilled with a 5-cm hand auger. The bottom 1 m of the PVC pipes had well screening attached to a well point, and the remaining 0.5 m was a PVC riser with a well cap to cover the aboveground opening. Well depths varied from 1 m to 1.4 m, depending on the depth of the argillic horizon and water table conditions at the time of well installation (Crownover et al., 1995). A more detailed description of the site establishment, well installations and earlier data reports can be found in Crownover et al., (1995), Sun et al. (2000b), and Bliss and Comerford (2002).

Water table depths of the 122 manual wells were measured on a bi-weekly schedule from 1992 to 1995 (Crownover et al., 1995; Sun et al., 1998b). Water table depths of the six automatic wells were recorded daily from 1992 to 1996 (Sun et al., 2000b). Detailed description of well water table measurements and recordings were given in Crownover et al. (1995) and Sun (1995).

3.2.3 Model setup and parameterization

Data required to set up MIKE SHE model for this site included: 1) Topography and landuse data – surface flow retention storage, Manning roughness number, and vegetation distribution (leaf area index (LAI) dynamics and rooting depth); 2) Soil data - soil depth, soil moisture and hydrologic properties (soil moisture release characteristics); 3) Meteorological data - precipitation and air temperature; 4) Boundary conditions; and 5) Initial conditions (spatial water table depth and overland flow depth).

The elevation and land use data were processed by the ESRI ArcView 3.3 software and were organized as shape files, which were used directly as an input into the MIKE SHE model. Model grid cell size for the site was set as 30 m. This spatial resolution was selected to allow for an accurate representation of the site without placing excessive demands on model running time.

The landuse of the study site was classified as wetlands and uplands. For each landuse type, a different set of parameters was used. These included empirical constants for actual evapotranspiration (ET) calculations – C_{int}, C1, C2, C3 and A_{root} (see MIKE SHE descriptions in chapter 2), and time series for LAI and root depth that were given for the vegetations in each land use type. Observed LAI in 1992 (Figure 3-4) was available for this study site (Liu, 1996) and was used for all the other years. A rooting depth of 45 cm was used for both land covers across the site (Mansell et al., 2000).

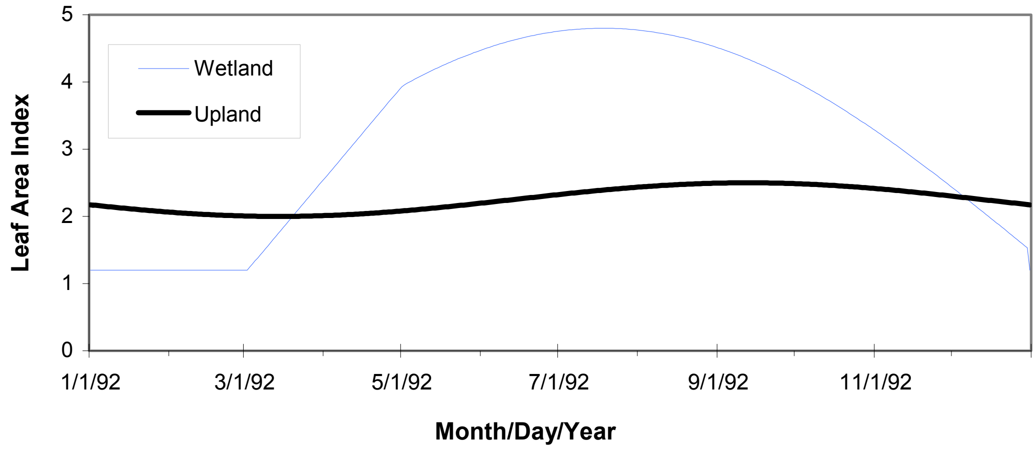

Figure 3-5. Forest Leaf Area Index (LAI) dynamics used by the MIKE SHE model at Florida wetland site (Liu, 1996).

Daily rainfall was recorded at the research site. Daily average air temperature was requested from weather station at the Gainsville Airport, located 8 km from the study site (Mansell et al., 2000). Hamon PET method (Hamon, 1963; Lu et al., 2005) was used to calculate daily potential evapotranspiration at this site with the calibrated coefficient (K_{pet}) as 1.0.

Soil data were mainly referred to soil characterization data from two model pits of the Florida state soil survey (Carlisle et al., 1978; Carlisle et al., 1981; Crownover et al., 1995). The surveyed soils were within 10 km of the study site and had similar soil morphology as the Spodosols at the study site (Crownover et al., 1995). One pit was assigned for wetland soils and the other pit was for upland soils. In the MIKE SHE modeling system, the soil depth to the confining layer was uniformly defined as 3 m below the ground surface across the study site. Van Genuchten method (van Genuchten et al., 1991) was used to implement soil moisture release and hydraulic conductivities.

Table 3-1. Soil and hydraulic properties for the MIKE SHE model at Florida wetland site.

Land use	Soil Depth (m)	Saturated Moisture Content (cm^3/cm^3)	Residual Moisture Content (cm^3/cm^3)	Ks (m/s)	α	n
Wetland	0 – 1	0.399	0.16	8.1×10^{-5}	0.068	1.32
	1 – 3	0.35	0.14	7.4×10^{-6}	0.138	1.592
Upland	0 – 1	0.388	0.16	5.6×10^{-5}	0.068	1.32
	1 – 3	0.34	0.14	3.1×10^{-5}	0.138	1.592

Lateral groundwater flow boundary conditions were set up using the water table elevation along the physical boundaries of the study site (Figure 3-1). First, the site boundaries were divided into 13 sections. At each section, the water table elevation was set as the average measured water elevation of the manual wells along the section. To derive daily water table values from bi-weekly measurements for each section, average water table elevations of manual wells were correlated to those of automatic wells, which were on a daily time step. The correlation coefficients were in a range of 0.61 - 0.93 with an average of 0.80.

Initial hydraulic heads, the starting water table elevations, were first approximated by the interpolation of the measured water table elevations on 11-19-1993 with 0 m depth of surface water. Then, the "hot start" feature of the MIKE SHE model was used to initiate the model simulations. The "hot start" option allows users to save a simulation that can be used as the start of a new simulation. This is similar to a "spin-up" feature in the RHESSys model (Band et al., 1993). A hot start file, containing initial data for a new simulation, is particularly useful for simulations requiring a long warm up period or for generating initial conditions for scenario analysis (DHI, 2004a).

First, the model was run using above set up for 1992-1993. Then, the new simulation, using site conditions on 06-15-1993 as the “hot start”, was rerun. The hydrologic status on that particular date was used as the initial conditions for the new simulation. The selection of this “hot start” date was based on the fact that spring 1992 was relatively dry, according to the measured well water table. The same initial condition or “hot start” was used for all the rest of simulations for this study.

3.2.4 Model calibration, validation and applications

As explained in the last chapter, water table data were used for the MIKE SHE model calibration and validation. Water table data were available from various locations at this site.

The study site was divided into three blocks - NW block, SW block and SE block (Figure 3-6). SW block was not disturbed during 1992-1996, but cypress wetlands in NW block were harvested and both wetlands and uplands in SE block were harvested by clear-cutting methods (Table 3-2). Within each block, a representative cypress wetland-upland system was selected, and automatic wells were installed to record daily water table depth (Sun et al., 2000b). Thus, three wetland-upland well pairs with automatic recording water table data were used for MIKE SHE model calibration and validation (Figure 3-6). Among the six automatic recording wells, the three wells that were located in wetlands had data starting on January 23, 1992. However, the other three upland wells did not have data until May 01, 1993. All six automatic wells had data till the end of December 1996. Thus, additional three upland manual wells (Figure 3-6) were chosen for model calibration and validation. The three manual wells had bi-weekly data during the period of February 02, 1992 to June 22, 1995.

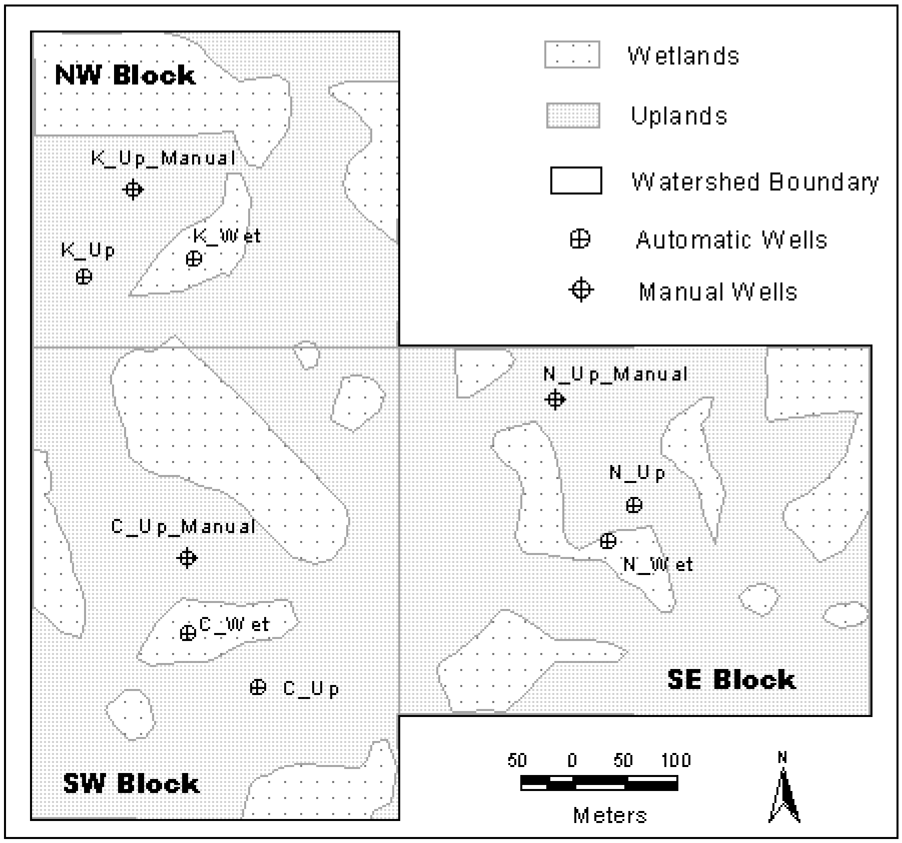

Figure 3-6. Wells used in MIKE SHE calibration and validation at the Florida wetland site.

Table 3-2. Land cover conditions at the Florida wetland site during 1992-1996.

Block	Wetlands	Uplands
NW block	Clearcut (April - May, 1994)	Undisturbed
SW block	Undisturbed	Undisturbed
SE block	Clearcut (April - May, 1994)	Clearcut (April - May, 1994)

The model was calibrated against water table data for a wet year (1992) and a dry year (1993) to cover a wide range of water table fluctuation conditions. Compared to the long-term annual average precipitation at the site (precipitation = 1330 mm in a normal year), the wet year had a surplus of 170 mm of precipitation while the dry year had the deficit of 230 mm (Sun et al., 1998a). The rest of the water table data (1994-1996) that represented a year with dry spring (1994) and two normal years (1995-1996) in terms of total annual precipitation were used for model validation (Figure 3-3 and Figure 3-4).

After model calibration and validation, the MIKE SHE model was applied to simulate four scenarios, which were described in the last chapter. It was assumed that LAI was reduced to 0.4 and 0.1 for harvested wetlands and uplands under the clear-cut conditions (Gholz and Clark, 2002; Clark et al., 2004).

3.3 Results and discussions

3.3.1 Model calibration

Water table data from multiple wells were used to calibrate the MIKE SHE model during 1992 - 1993. Table 3-3 listed the calibrated parameters, their ranges and final values at the Florida wetland site. These calibrated parameters remained the same during the validation periods (1994-1996).

Table 3-3. Calibrated parameter values of MIKE SHE at the Florida wetland site.

Parameters	Parameter Values			
	Initial	Minimum	Maximum	Final
ET Coefficients				
C_{int}	0.05	0.05	0.8	0.5
C1	0.3	0.05	1	0.3
C2	0.2	0.05	0.5	0.2
C3	20	5	30	12
A_{root}	0.5	0.1	1	0.25
Surface Manning Coefficient ($m^{1/3}/s$)	5	1	10	2
Horizontal Hydraulic Conductivity (m/s)	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-4}	3.6×10^{-5}
Vertical Hydraulic Conductivity (m/s)	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-4}	1.0×10^{-5}
Specific Yield	0.1	0.05	0.3	0.2

Figure 3-7 through Figure 3-15 showed both observed and simulated water table dynamics during the two-year calibration periods at 9 wells, which included 6 automatic paired wells and 3 upland manual wells (Figure 3-5). The 6 automatic wells had daily measurements except during some dry periods when the water table was lower than measurement range (Figure 3-7, Figure 3-8, Figure 3-10, Figure 3-11, Figure 3-13, and Figure 3-14). The three upland manual wells were recorded bi-weekly and there were no measurements available during some dry periods due to the same reason as the automatic wells (Figure 3-9, Figure 3-12 and Figure 3-15). Generally, the correlations between measurements and simulations ranged from 0.81 to 0.94 with ME values in a range of -0.34 m to 0.07 m and E values within -0.87 to 0.77. The calibration results showed that MIKE SHE could capture the temporal dynamics of water table variations as demonstrated by the high R values at this typical flatwoods site (Figure 3-7 through Figure 3-15). During the wet year of 1992, water tables were very close to the ground surface and water was ponded on the wetlands during most time of that year (Figure 3-7,

Figure 3-10, and Figure 3-13). On the uplands, water table periodically reached the ground surface but did not have ponded surface water as wetlands due to the higher elevations (Figure 3-8, Figure 3-9, Figure 3-11, Figure 3-12, Figure 3-14, and Figure 3-15). During the dry periods (June - October) in 1993, water table was much lower to the ground surface and most of the time there was no surface water on the wetlands. Overall, water table was closer to the ground surface in wetlands than in uplands under the dry conditions.

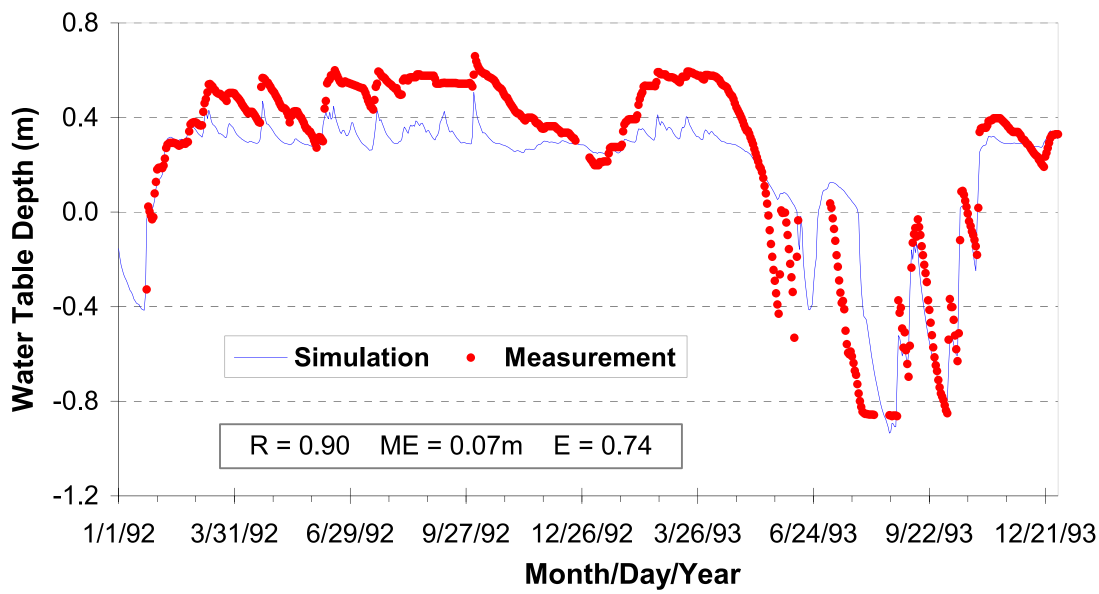

Figure 3-7. MIKE SHE model calibration at the K_Wet well in a NW block wetland during 1992-1993.

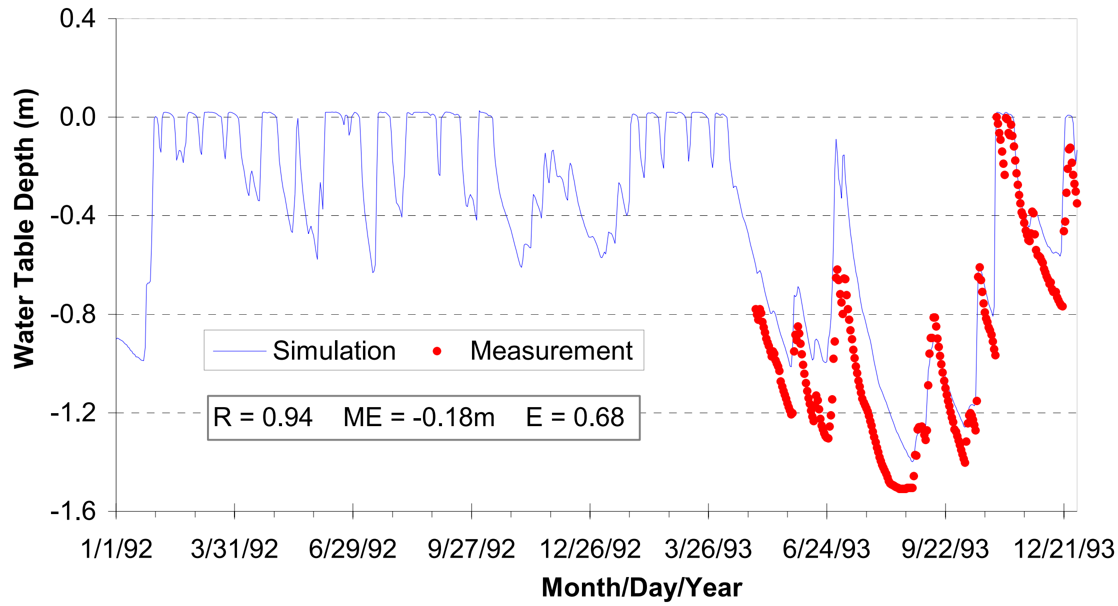

Figure 3-8. MIKE SHE model calibration at the K_Up well in a NW block upland during 1992-1993.

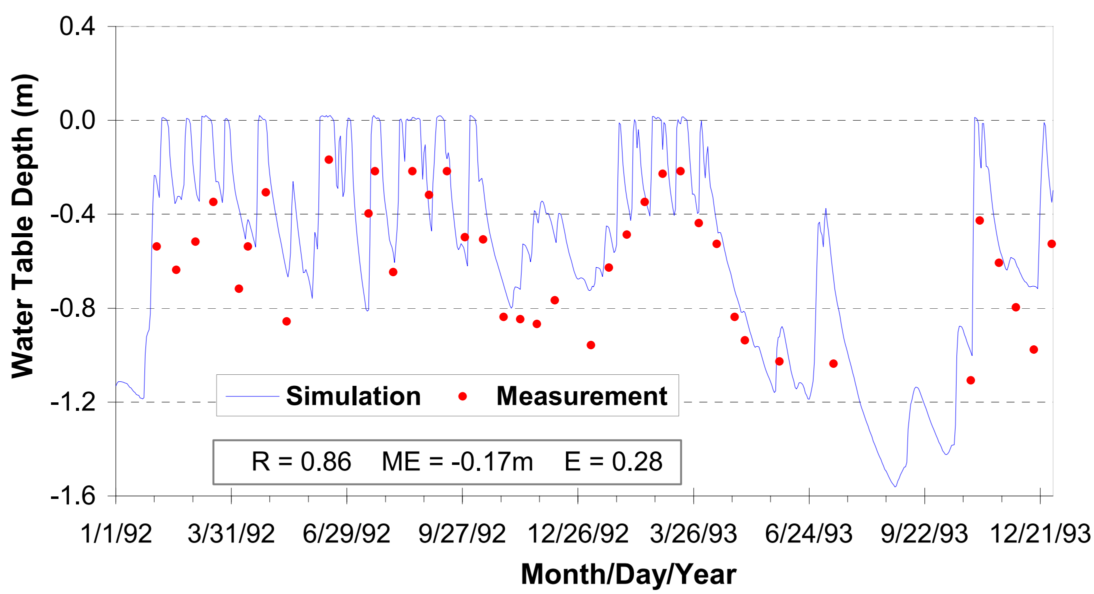

Figure 3-9. MIKE SHE model calibration at the K_Up_Manual well in a NW block upland during 1992-1993.

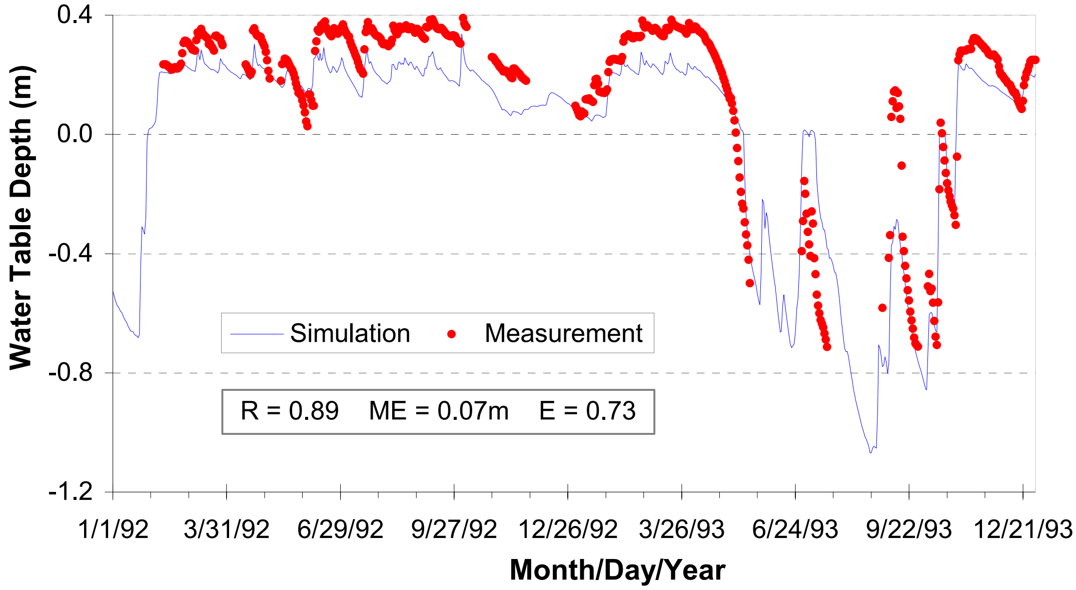

Figure 3-10. MIKE SHE model calibration at the N_Wet well in a SE block wetland during 1992-1993.

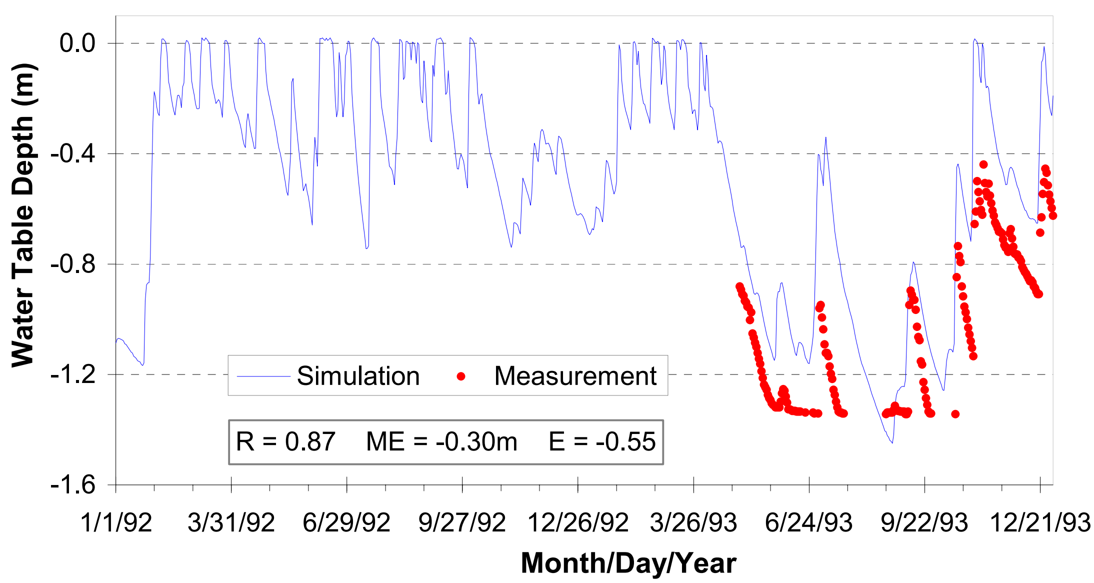

Figure 3-11. MIKE SHE model calibration at the N_Up well in a SE block upland during 1992-1993.

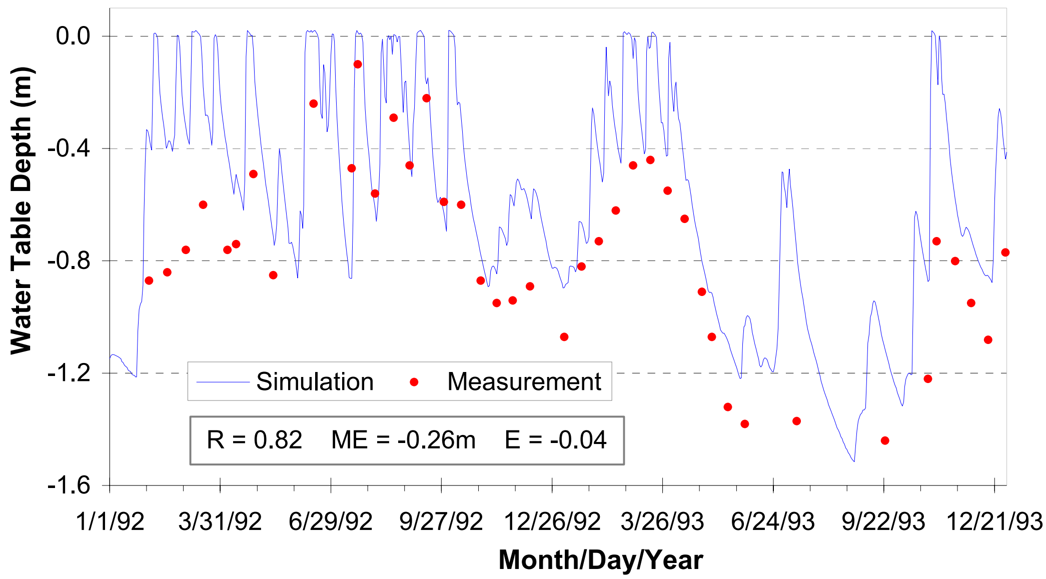

Figure 3-12. MIKE SHE model calibration at the N_Up_Manual well in a SE block upland during 1992-1993.

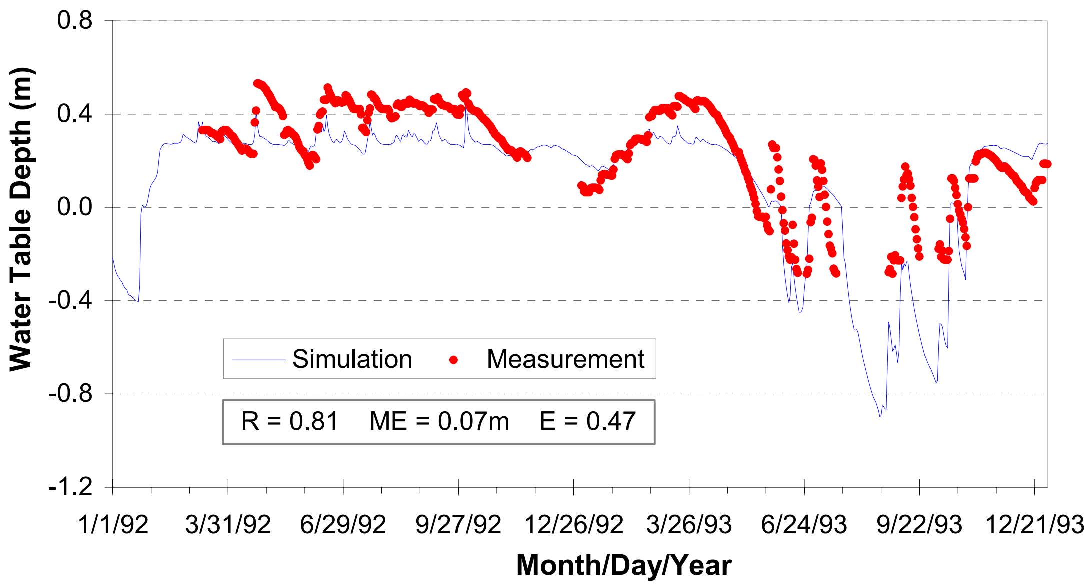

Figure 3-13. MIKE SHE model calibration at the C_Wet well in a SW block wetland during 1992-1993.

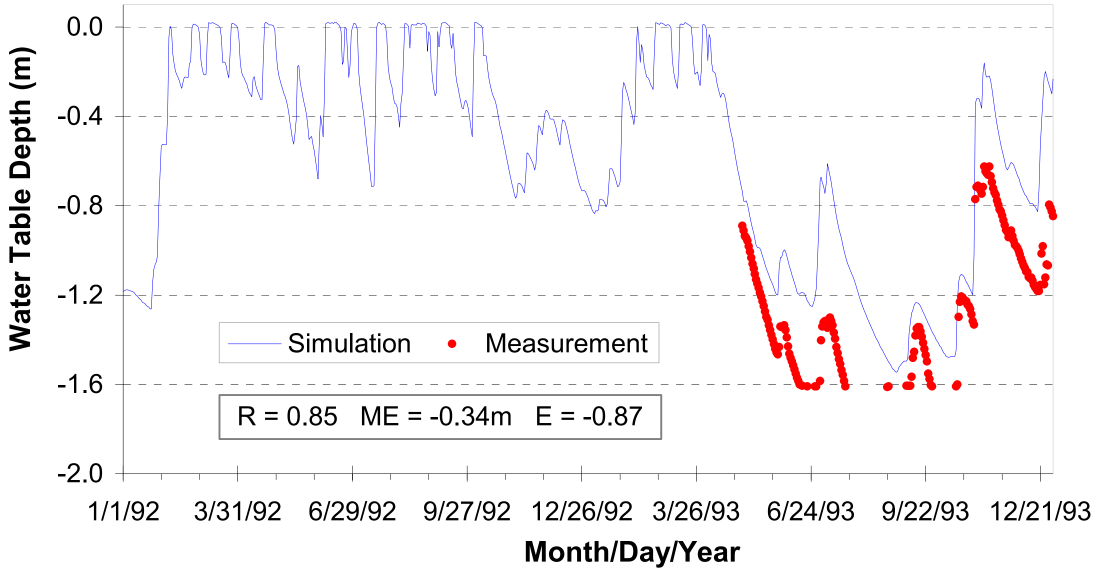

Figure 3-14. MIKE SHE model calibration at the C_Up well in a SW block upland during 1992-1993.

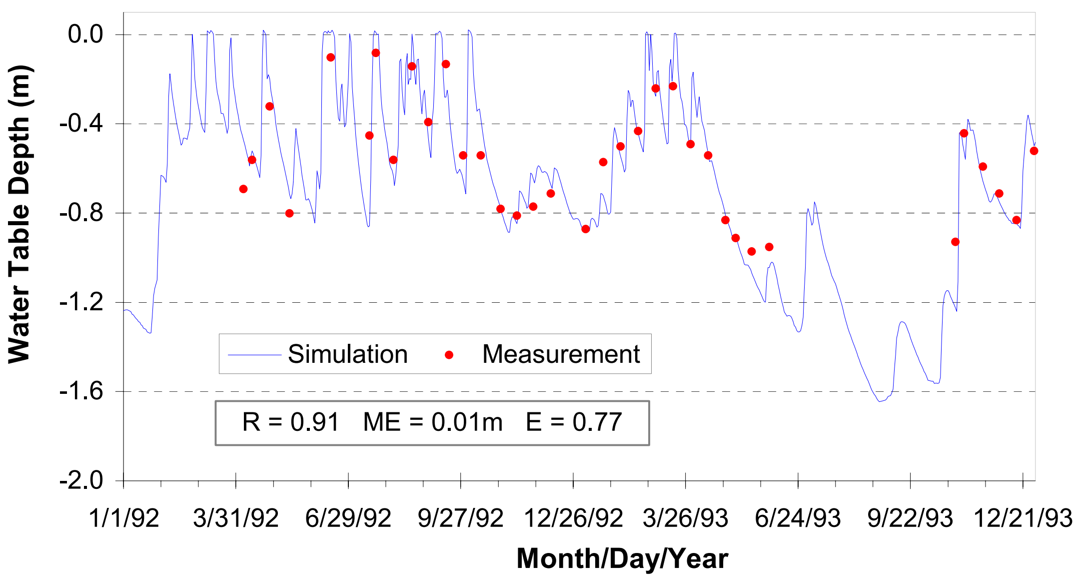

Figure 3-15. MIKE SHE model calibration at the C_Up_Manual well in a SW block upland during 1992-1993.

In general, the model underestimated water table depth in wetlands during wet periods but overestimated it in uplands during dry periods (Figure 3-7 through Figure 3-15). Discrepancies were more apparent in storm events when water table rose (Figure 3-10 and Figure 3-11) after a long drought period (i.e. 19993).

In addition to comparing temporal water table dynamics at nine individual locations as described above, spatial discrepancies between simulated and measured water table depths were also examined. One normal day with water table neither too high nor too low was selected. The date October 29, 1992 was chosen because it had moderate water table depth with complete measurements available over the landscape. A total of 123 wells had water table data on October 29, 1992. With the ESRI ArcView 3.3 software, the point features of these water table data were interpolated to create a grid surface using the method "IDW, nearest of neighbors, Numbers of neighbors: 3, power: 1, No barriers".

Simulated spatial water table data on October 29, 1992 were converted from the MIKE SHE text format to an Arcview grid format. Then this grid was imported into ESRI ArcView 3.3. Water table differences were defined as the interpolated measured water table depths subtracted the simulated water table depths. The grid subtraction calculations were performed in Arcview 3.3 (Figure 3-16).

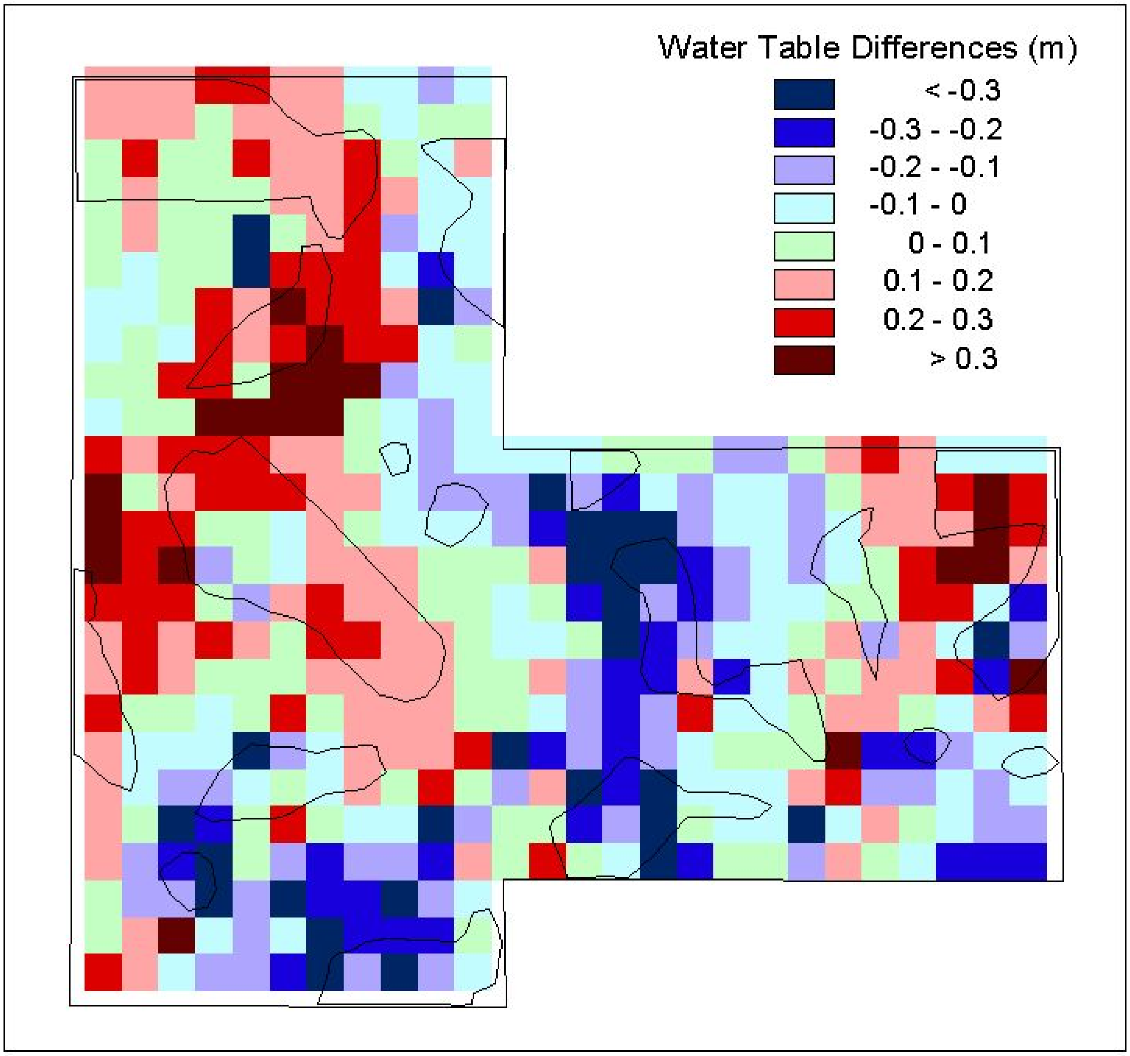

Figure 3-16. Spatial water table depth differences of measurements and simulations of water table depth on 10-29-1992 (30 m cell size; negative values indicate overprediction while positive values indicate underprediction).

Across the entire site, MIKE SHE underestimated water table depth at some locations (i.e. wetlands) and overestimated water table depth at the other locations (uplands). Generally, on October 29 1992, MIKE SHE underestimated water table depth at most of the wetlands, but overestimated water table depth at most of the uplands (Figure 3-16). The spatial inspection confirmed the general pattern observed during the comparisons of 9 individual wells. The discrepancies might be largely caused by inadequate representation of land topography at this flat landscape. The modeling cell size was set as 30 m. Thus, micro-landscape variations were likely not represented adequately in the modeling system. Well data were measured at particular points in the field, while the model simulated water table on a scale of 30 m × 30 m unit area. Furthermore, other spatial information was not likely represented adequately either, such as soil depth and soil hydraulic parameters.

Frequency analysis of the spatial discrepancies (Figure 3-17) showed that water table differences between measurements and simulations were in a normal distribution. There were about 38% of differences in the range of (-0.1 m, 0.1 m), 70% in the range of (-0.2 m, 0.2 m), and 90% in the range of (-0.3 m, 0.3 m). Overall, the discrepancies were in a reasonable error range.

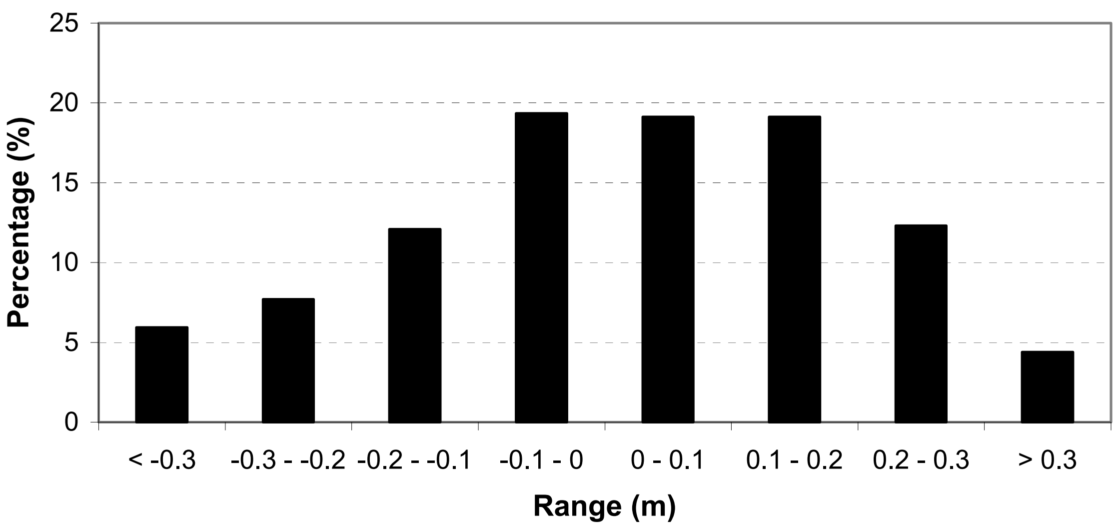

Figure 3-17. Distribution of spatial water table depth differences of measurements and simulations on 10-29-1992 (Negative values indicate overprediction while positive values indicate underprediction).

3.3.2 Model validation

Similarly, both temporal and spatial water table data collected from the study site were used to validate the MIKE SHE model. The model validation indicated the promising applicability of MIKE SHE at this flatwoods site (Figure 3-18 through Figure 3-26). Generally, there were high correlations between measured and simulated water table depths at these 9 various locations. R values varied from 0.73 to 0.91. ME values were in the range of -0.29 m to 0.15 m. E values ranged from -1.23 to 0.69. The validation showed that MIKE SHE performed reasonably well for the three years (1994-1996), especially for uplands. Similar model performances were achieved as those in the calibration. In general, the model underestimated water table depth in wetlands during wet periods.

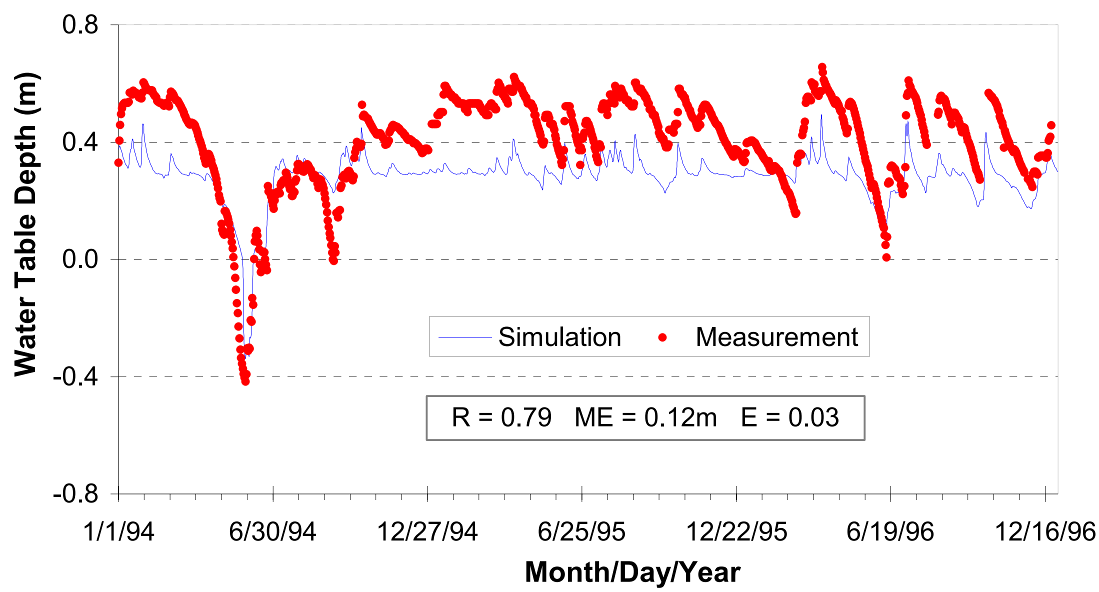

Figure 3-18. MIKE SHE model validation at the K_Wet well in a NW block wetland during 1994-1996.

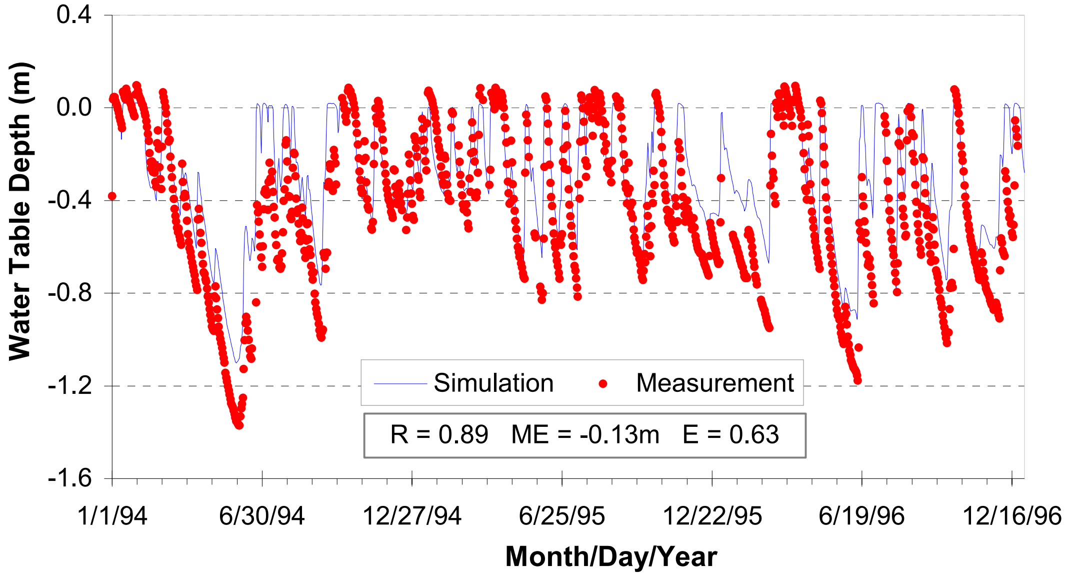

Figure 3-19. MIKE SHE model validation at the K_Up well in a NW block upland during 1994-1996.

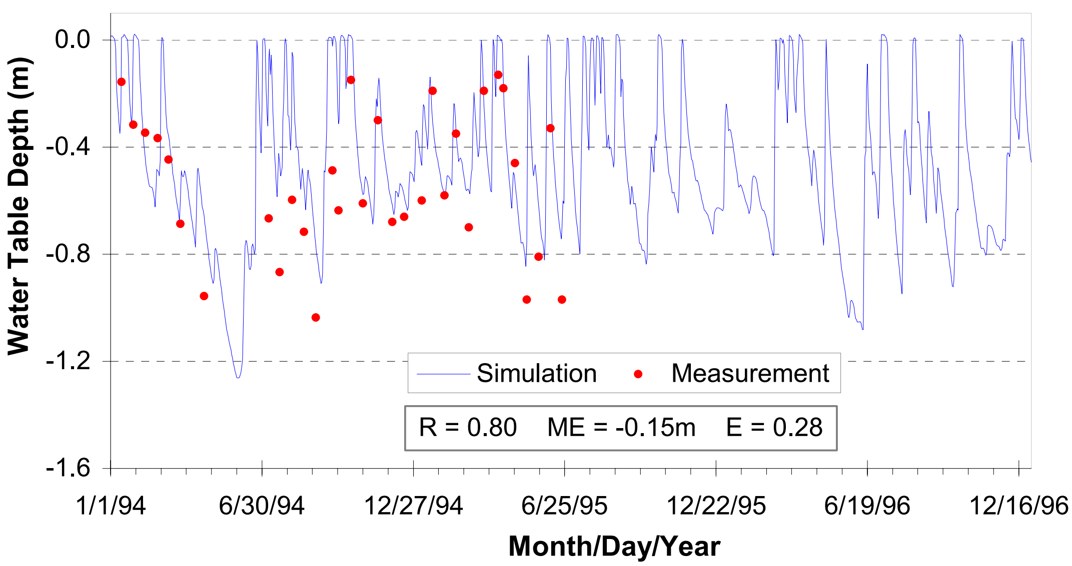

Figure 3-20. MIKE SHE model validation at the K_Up_Manual well in a NW block upland during 1994-1996.

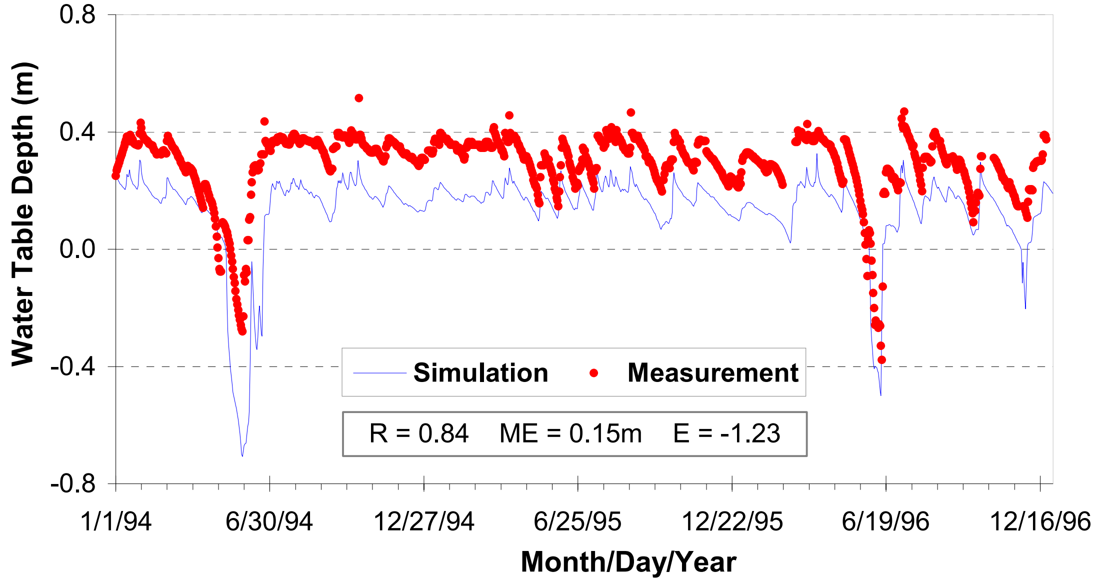

Figure 3-21. MIKE SHE model validation at the N_Wet well in SE block wetland during 1994-1996.

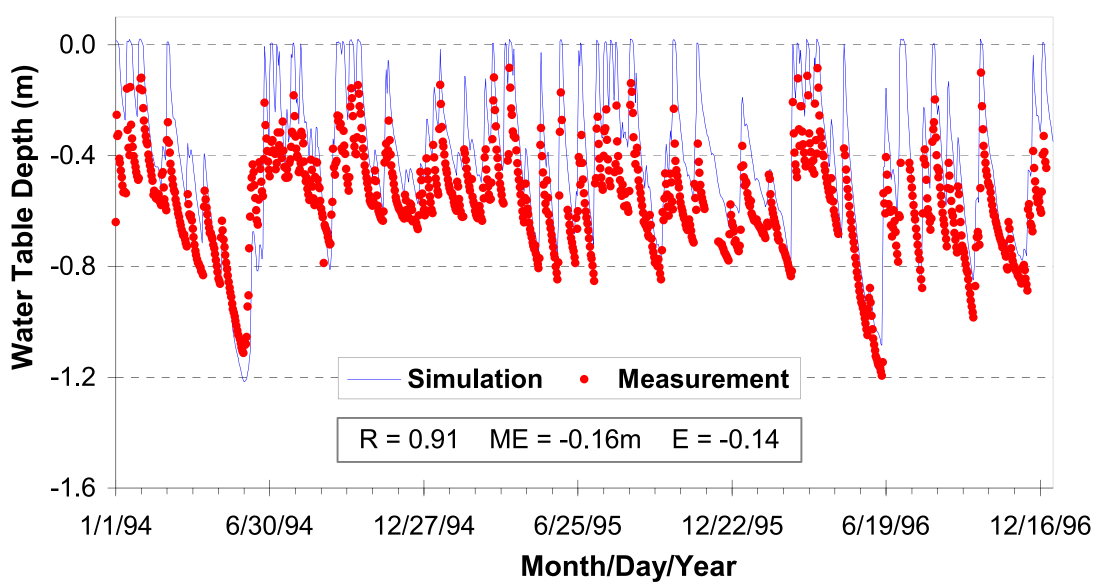

Figure 3-22. MIKE SHE model validation at the N_Up well in a SE block upland during 1994-1996.

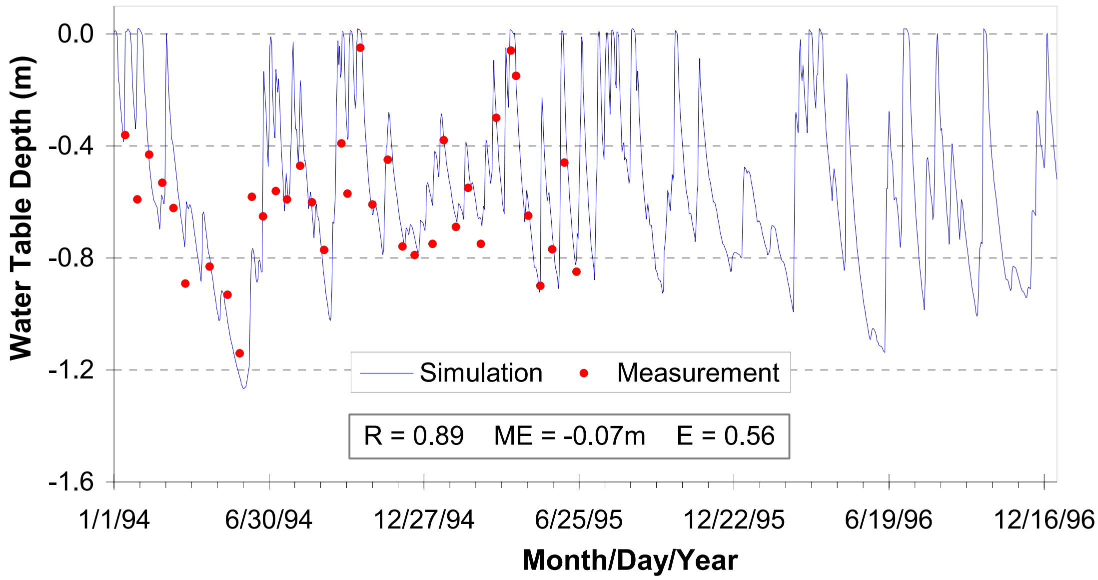

Figure 3-23. MIKE SHE model validation at the N_Up_Manual well in a SE block upland during 1994-1996.

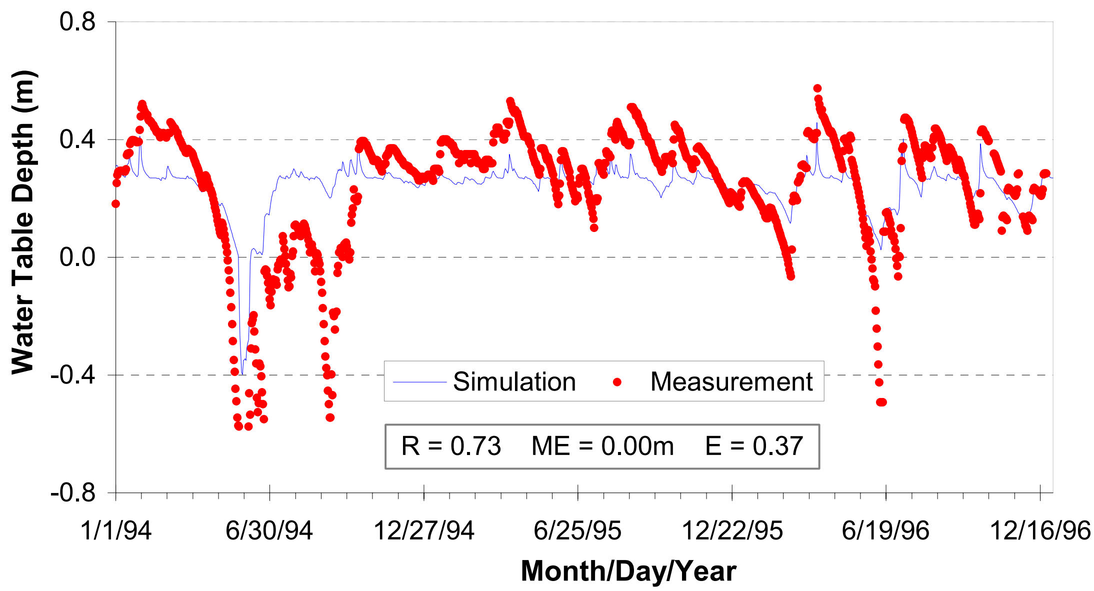

Figure 3-24. MIKE SHE model validation at the C_Wet well in a SW block wetland during 1994-1996.

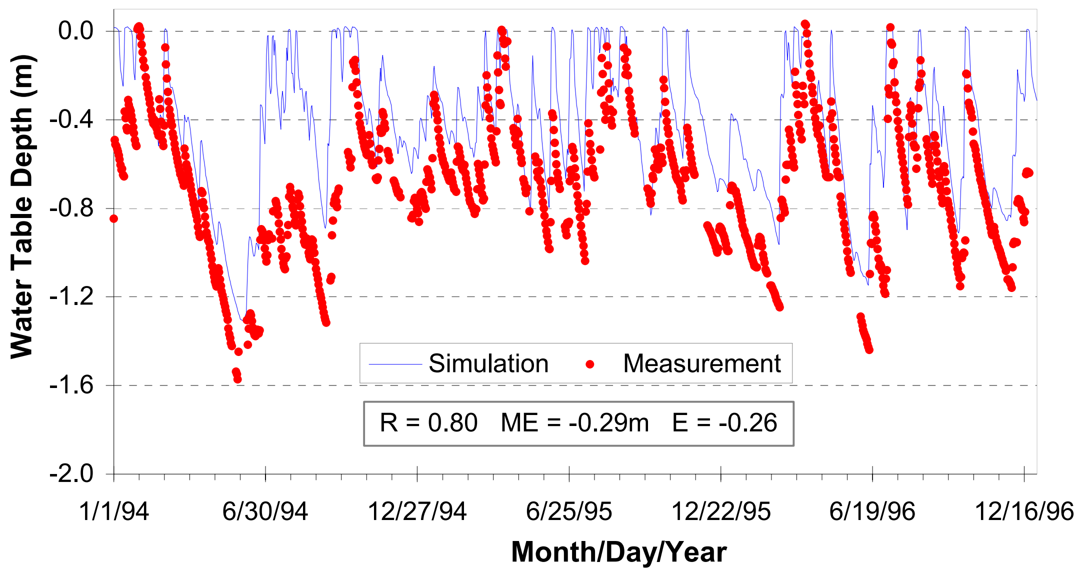

Figure 3-25. MIKE SHE model validation at the C_Up in a SW block upland well during 1994-1996.

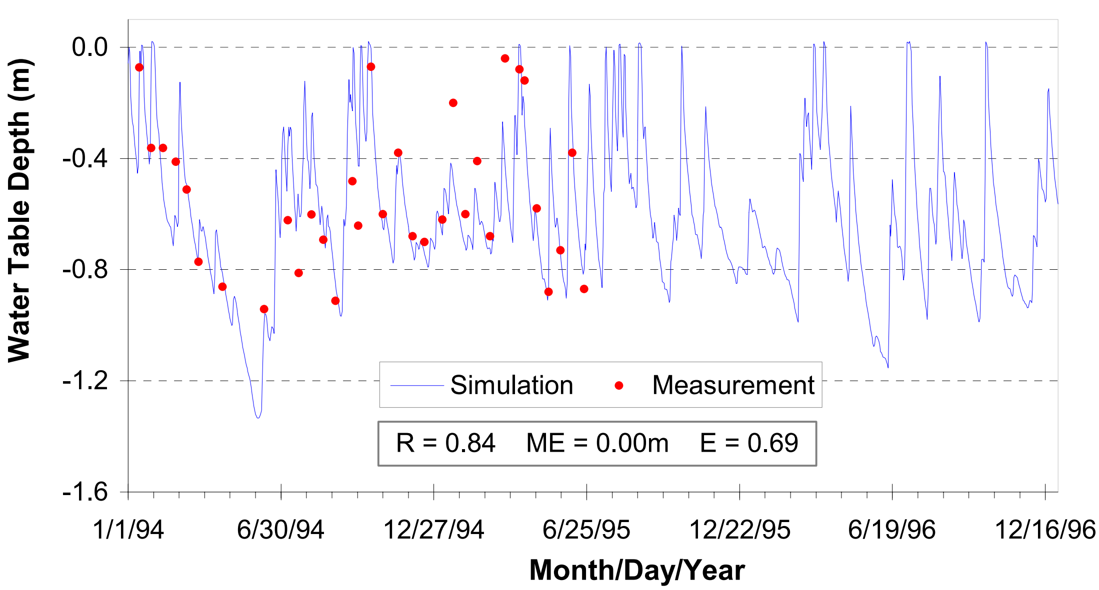

Figure 3-26. MIKE SHE model validation at the C_Up_Manual well in a SW block upland during 1994-1996.

Similar to the calibration, a normal day - March 11, 1994 - with moderate water table depth conditions was selected to examine the spatial water table depth discrepancies between measurements and simulations for the validation purpose (Figure 3-27). Again, with similar model performances in the calibration, MIKE SHE underestimated water table depth at some locations and overestimated it at the other locations. Generally, on 03-11-1994, MIKE SHE tended to overestimate water table depths across the flatwoods site.

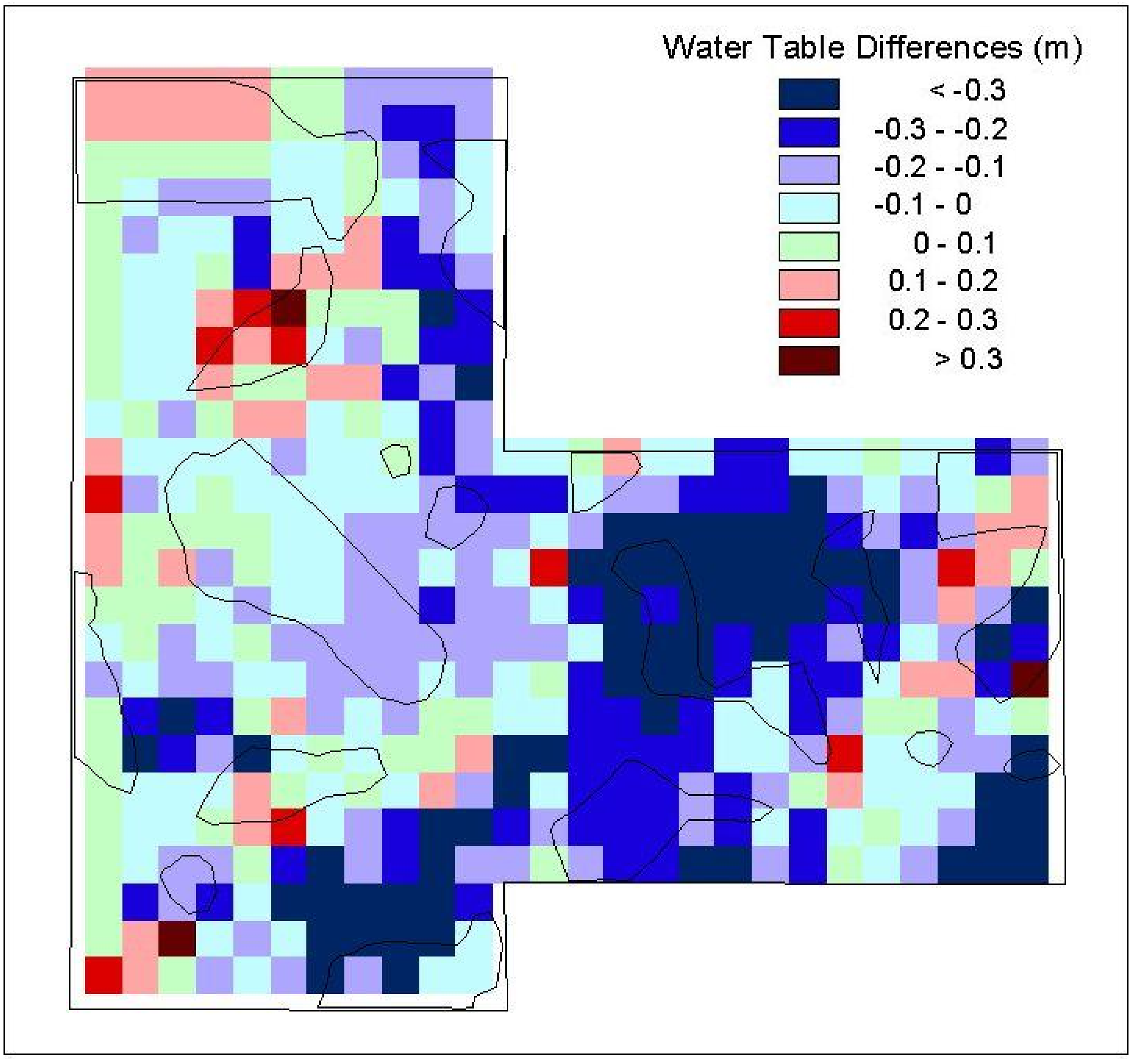

Figure 3-27. Spatial water table depth differences of measurements and simulations on 03-11-1994 (30 m cell size; negative values indicate overprediction while positive values indicate underprediction).

Frequency analysis of the spatial differences (Figure 3-28) confirmed that MIKE SHE mostly overestimated water table depth on 03-11-1994, because 73% of the discrepancies were less than zero. There were about 39% of the differences in the range of (-0.1 m, 0.1 m), 68% in the range of (-0.2 m, 0.2 m), and 85% in the range of (-0.3 m, 0.3 mm). Overall, the discrepancies were in a reasonable error range.

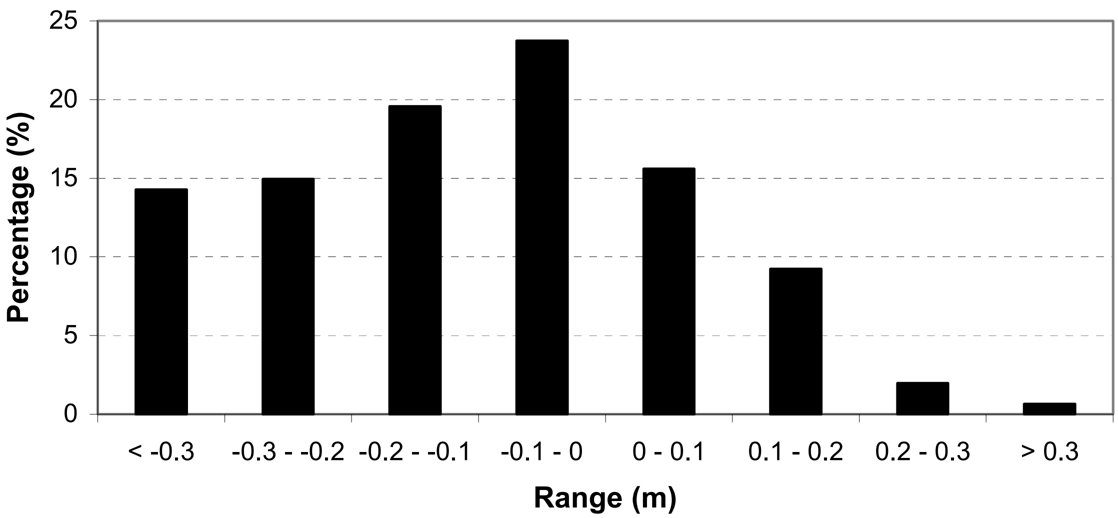

Figure 3-28. Distribution of spatial water table depth differences of measurements and simulations on 03-11-1994 (Negative values indicate overprediction while positive values indicate underprediction).

As a physically-based, distributed hydrologic model, MIKE SHE was able to simulate the interactive horizontal groundwater flow patterns (Figure 3-29, Figure 3-30 and Figure 3-31) between the wetlands and their surrounding uplands at this typical flatwoods landscape in Florida. The model identified three types of horizontal groundwater flow patterns: (1) Groundwater flows through the wetlands (Figure 3-29); (2) Groundwater flows into the wetlands (Figure 3-30); and (3) Groundwater flows out of the wetlands (Figure 3-31). Thus, the model simulations confirmed field observed groundwater flow patterns at this study site (Crownover et al., 1995).

On 01-10-1993, groundwater generally flowed through the wetlands in response to the general landscape topographic gradients (Figure 3-29). Groundwater was transmitted through the wetlands from the uphill side toward the downhill side. This flow pattern usually occurs during the wet periods and dry periods.

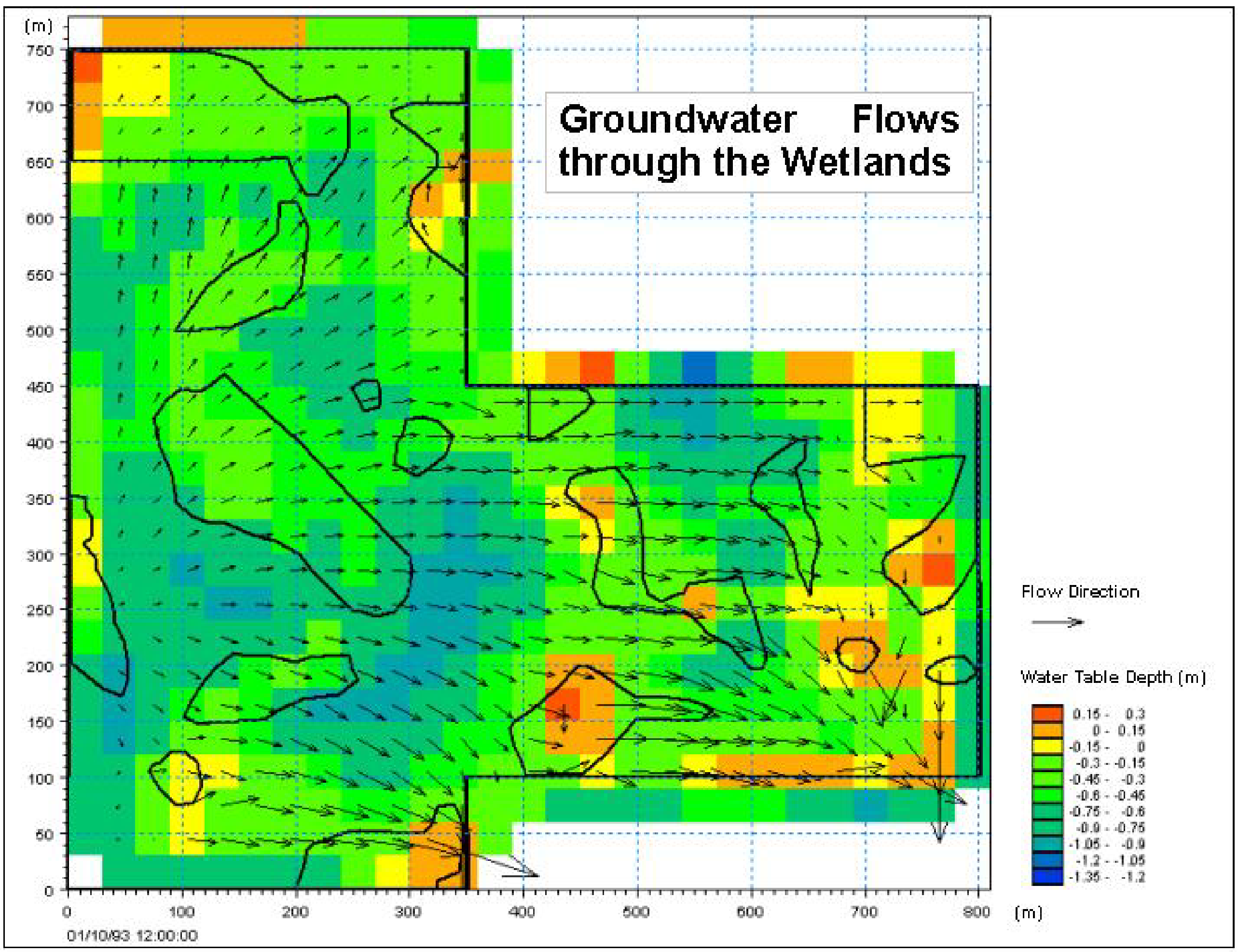

Figure 3-29. MIKE SHE simulated the flow pattern of groundwater flowing through wetlands on 01-10-1993 (30 m cell size; water table depth was defined as the distance of the water table to the ground surface; it was negative or positive when the water table was below or above the ground surface).

On 02-27-1993, a wet day, groundwater flowed from the surrounding uplands to the wetlands (Figure 3-30). Wetlands were recharged and served as the sinks of water from uplands. This flow pattern usually occurs under very wet conditions when the water table is high.

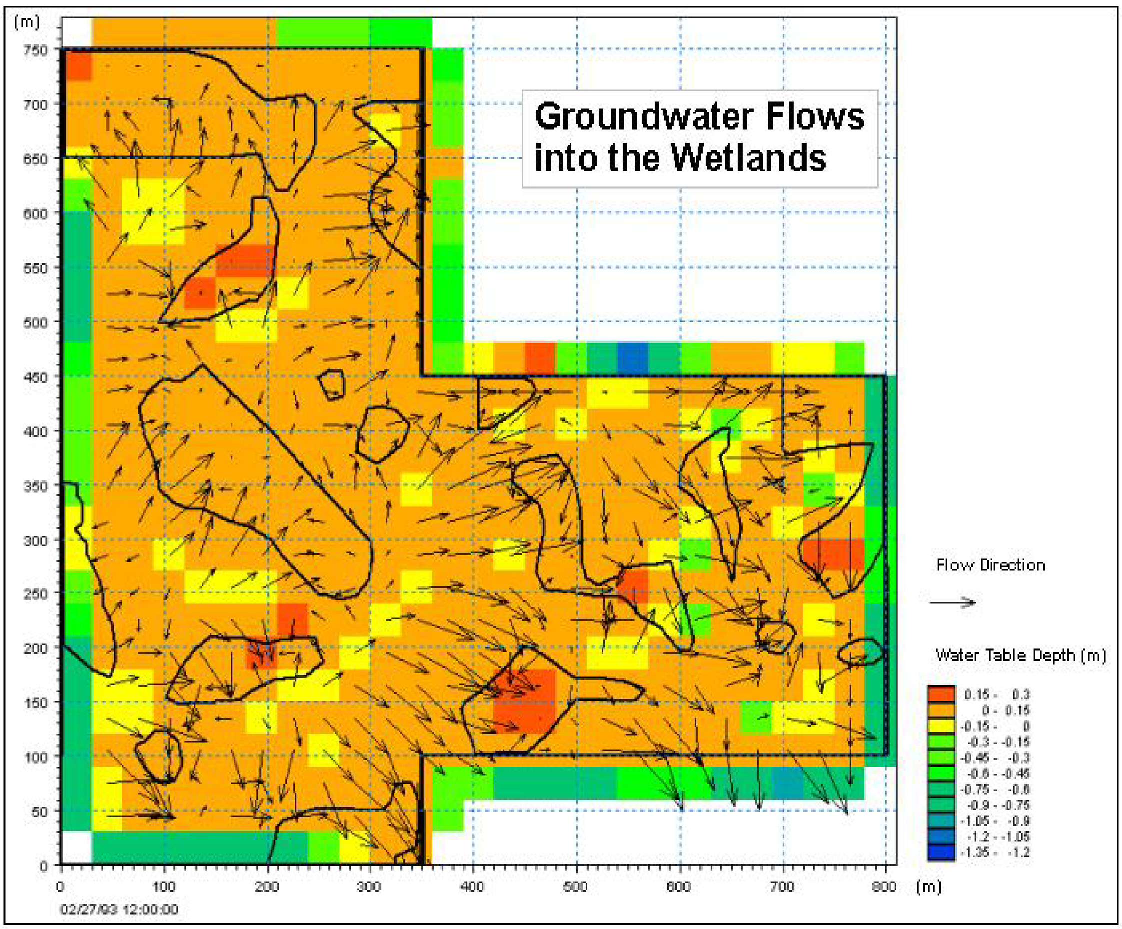

Figure 3-30. MIKE SHE simulated the flow pattern of groundwater flowing into wetlands on 02-27-1993 (30 m cell size; water table depth was defined as the distance of the water table to the ground surface; it was negative or positive when the water table was below or above the ground surface).

On 04-25-1993, a day of transition from wet to dry, groundwater flowed away from wetlands toward the surrounding uplands as indicated by the flow direction (Figure 3-31). This is most obvious for K wetland. Wetlands served as the sources of water to the uplands. This flow pattern usually occurs during the transition periods between wet and dry conditions.

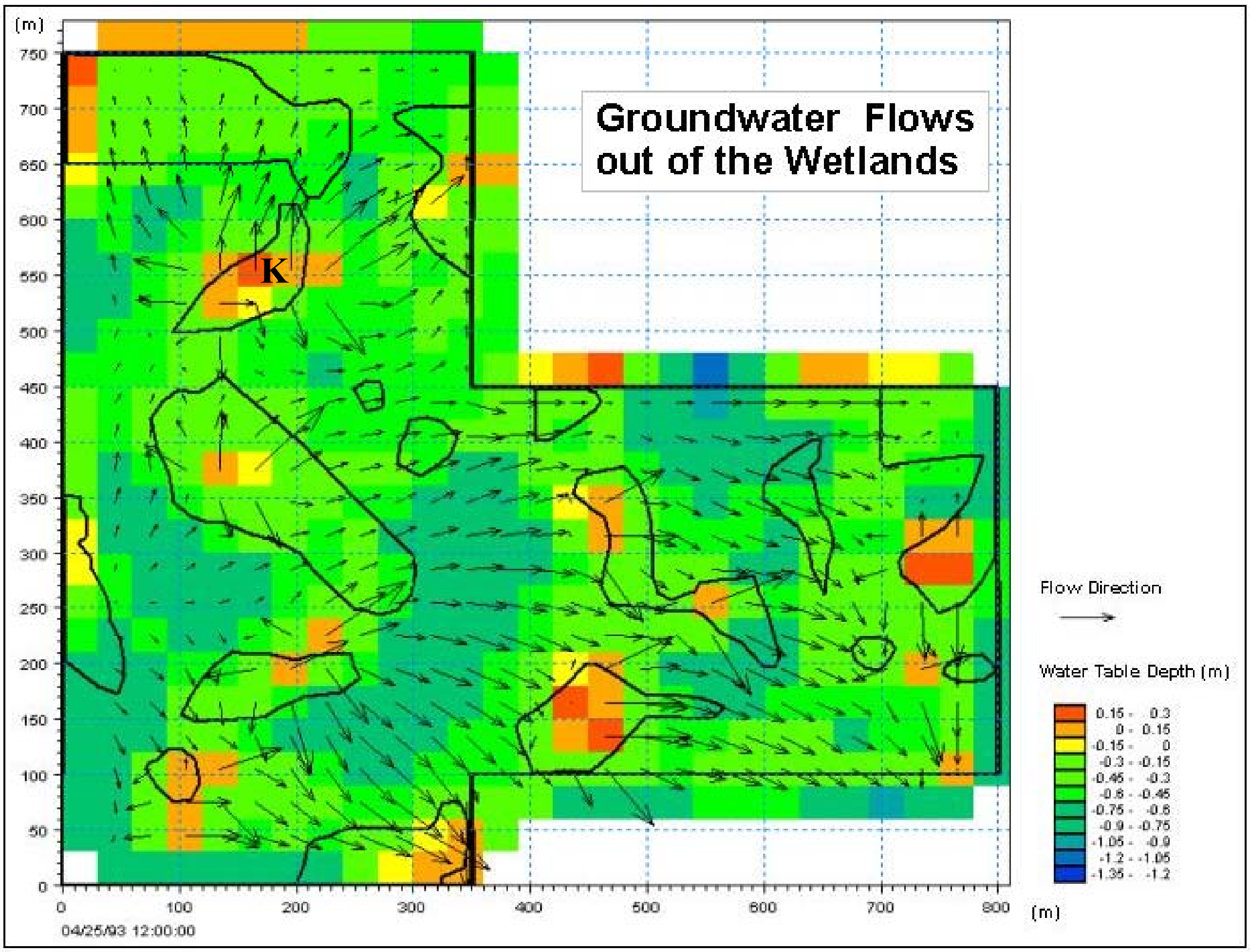

Figure 3-31. MIKE SHE simulated the flow pattern of groundwater flowing out of wetlands on 04-25-1993 (30 m cell size; water table depth was defined as the distance of the water table to the ground surface; it was negative or positive when the water table was below or above the ground surface).

The horizontal groundwater flow patterns were essentially governed by hydraulic gradients across the study site. During very wet periods when water table were both high in uplands and wetlands, hydraulic heads in uplands were higher than the heads in wetlands. Driven by hydraulic gradient, water moved from uplands into wetlands (Figure 3-30). This was a low-relief landscape. Water that moved into wetlands was mainly limited to the uplands adjacent to the wetlands rather than from the entire surrounding upland areas. This flow pattern was not common at this study site. Water mainly either flowed through the wetlands or flowed from wetlands toward the uplands (Crownover et al., 1995). When water table dropped lower, the general landscape topographic gradient played a dominant role in the hydraulic gradient. Thus, groundwater flowed through the wetlands from the uphill side toward the downhill side (Figure 3-29). When water table dropped further during the transitions from wet to dry conditions, water table dropped faster in uplands than in wetlands and resulted in higher water table in wetlands than in uplands. This was most likely resulted from the differential storage of water as surface water in wetlands and soil water in uplands as well as differential transpiration between vegetations in the wetlands and the uplands. Thus, hydraulic heads were higher in wetlands than in uplands. Driven by hydraulic gradient, groundwater flowed away from the wetlands toward the surrounding uplands (Figure 3-31). However, during dry periods when differential water storage in wetlands and in uplands was small, the general landscape topographic gradient dominated groundwater movement and resulted in the flow pattern of groundwater flowing through the wetlands (Figure 3-29).

These flow patterns were observed in the field (Crownover et al., 1995). However, the advantages of model simulations enabled us to examine the flow in more intensive time steps and spatial scales. Furthermore, model simulations could help quantify the flow between the wetlands and the uplands.

3.3.3 Model applications

In terms of water table variations, modeling results suggested that forest clearcut and climate change did not have much impact during the wet periods (Figure 3-32 and Figure 3-33). However, clearcut and climate change would affect water table during the dry periods. In the dry year 1993, the water table elevation was higher under the clearcut scenario than the base line. When temperature increased 2 °C or precipitation decreased 10%, water table dropped deeper than the base line scenario. It seemed that water table drop resulted from the TI scenario was slightly lower than that from the PD scenario, although the differences might not be significant. The effects were more apparent on 09-16-1993, for instance. This pattern could also be seen in the dry spring season of 1994.

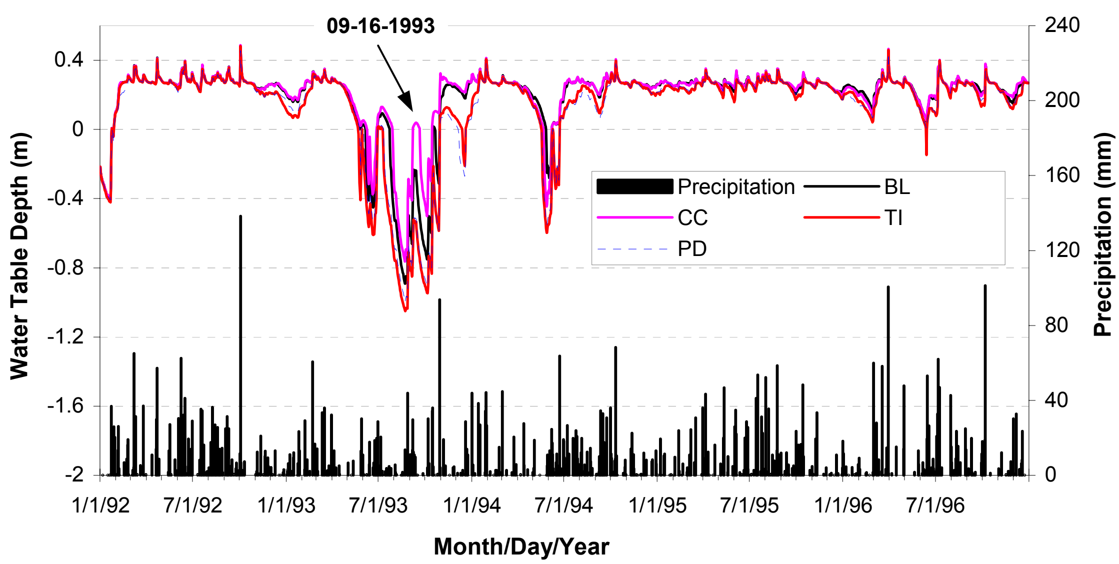

Figure 3-32. Impacts of clearcut and climate change on water table at C_Wet well in a SW block wetland during 1992-1996 (BL - base line; CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

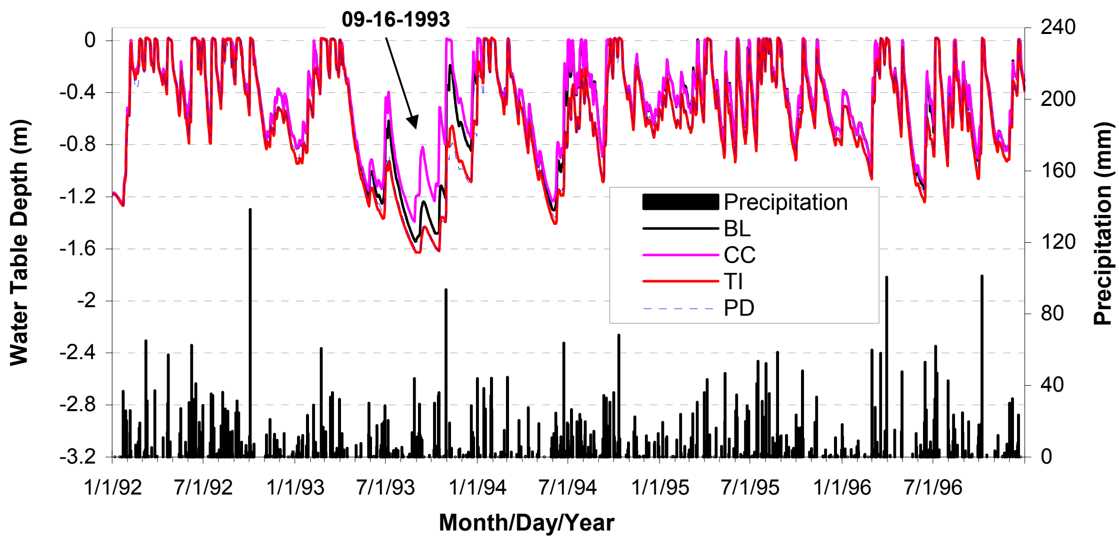

Figure 3-33. Impacts of clearcut and climate change on water table at C_Up well in a SW block upland during 1992-1996 (BL - base line; CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

Under the clear-cutting situation, ET was reduced due to the lack of leaves. Thus, it caused the rise of the water table. This was especially true during dry periods. When temperature was increased 2 °C, ET was increased due to the increase in driven energy and higher PET, thus water table dropped further. Under the 10% precipitation decrease scenario, the water input was less than the base line condition and recharge was decreased, thus the water table was lower. During the wet periods, the water table was close to the ground surface or even reached the ground surface. Water was sufficient for plant water use and satisfied the PET demand for most of the time. Thus, the impacts on water table level from forest management and climate change were minimum. However, during the dry periods when water table was well below the ground surface, the impacts were stronger and the effects were showed on the differences of the water table levels.

Impacts of the clearcut and climate change on ground water table were examined spatially on 09-16-1993 when it clearly showed the effects (Figure 3-34, Figure 3-35 and Figure 3-36). Most differences were in a range of 20 cm to 40 cm on that date. Spatial inspections confirmed that water table drop resulted from 2 °C temperature increase was slightly lower than that from 10% precipitation decrease.

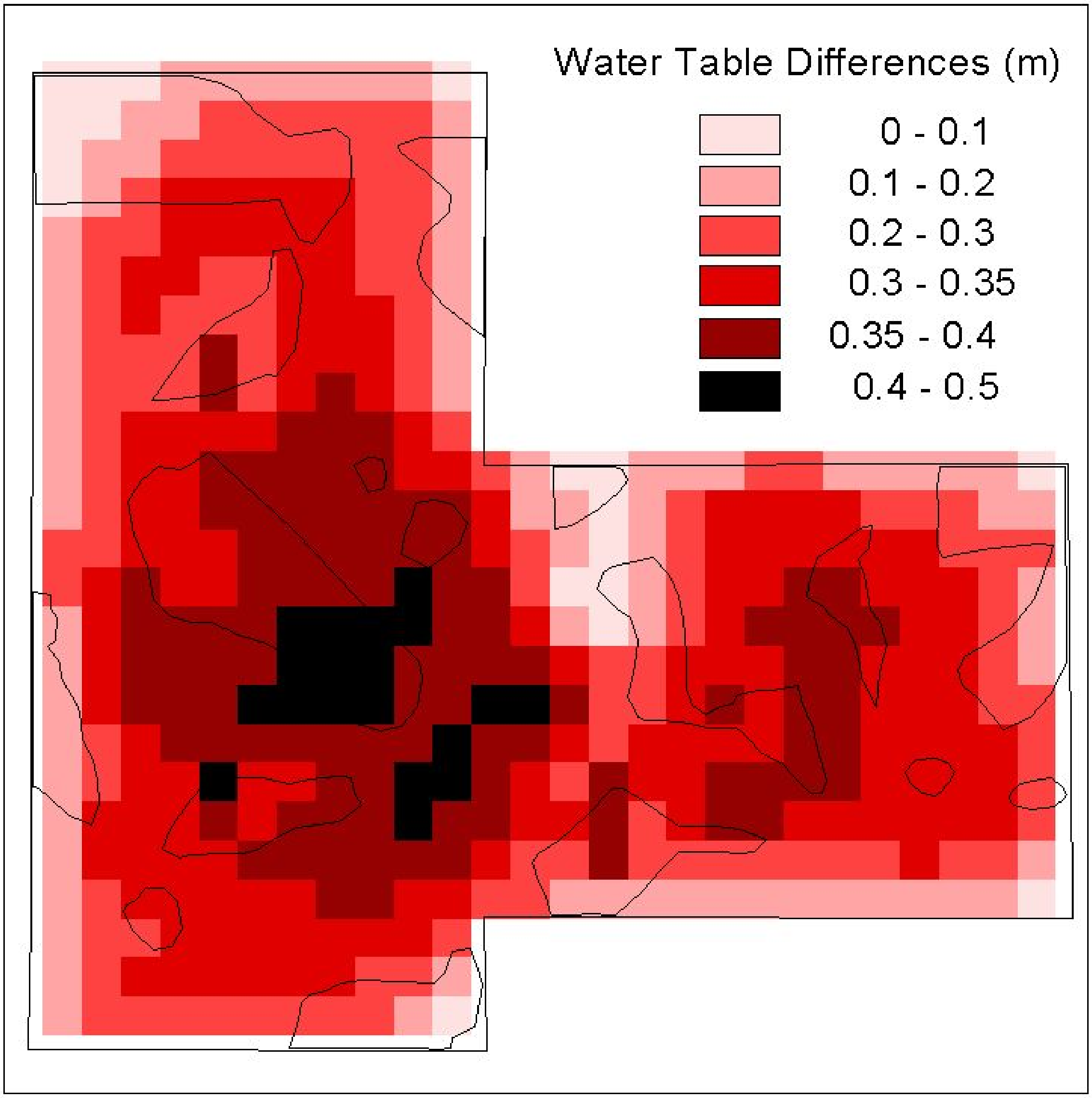

Figure 3-34. Water table rose as a result of clearcut on 09-16-1993 at Florida wetland site (30 m cell size; water table differences were defined as the water table depth after clearcut subtracted the water table depth before clearcut).

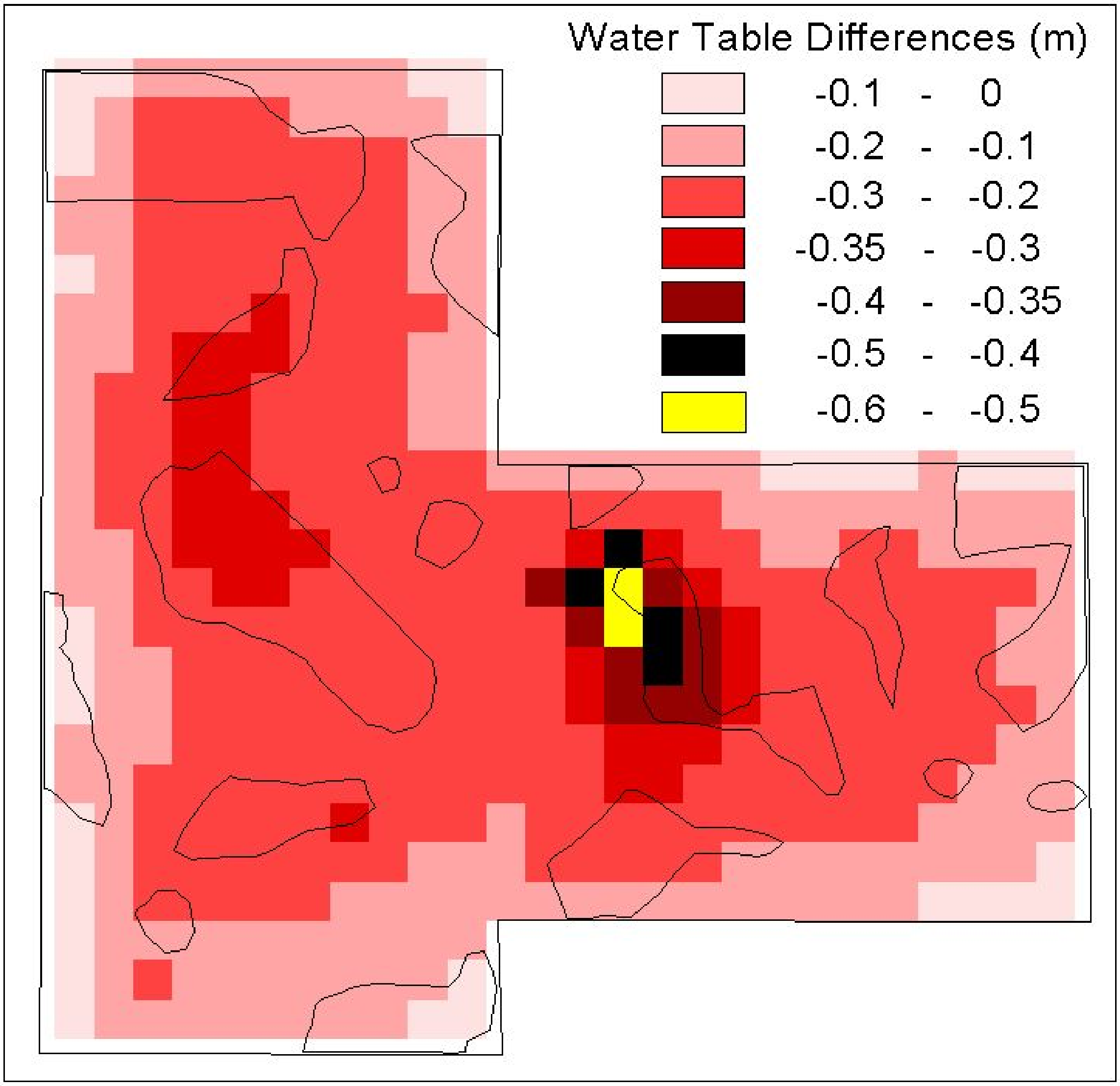

Figure 3-35. Water table dropped due to 2 °C temperature increase on 09-16-1993 at Florida wetland site (30 m cell size; water table differences were defined as the water table depth under 2 °C temperature increase subtracted the base line water table depth; negative values indicate that water table is lower than the base line under 2 °C temperature increase).

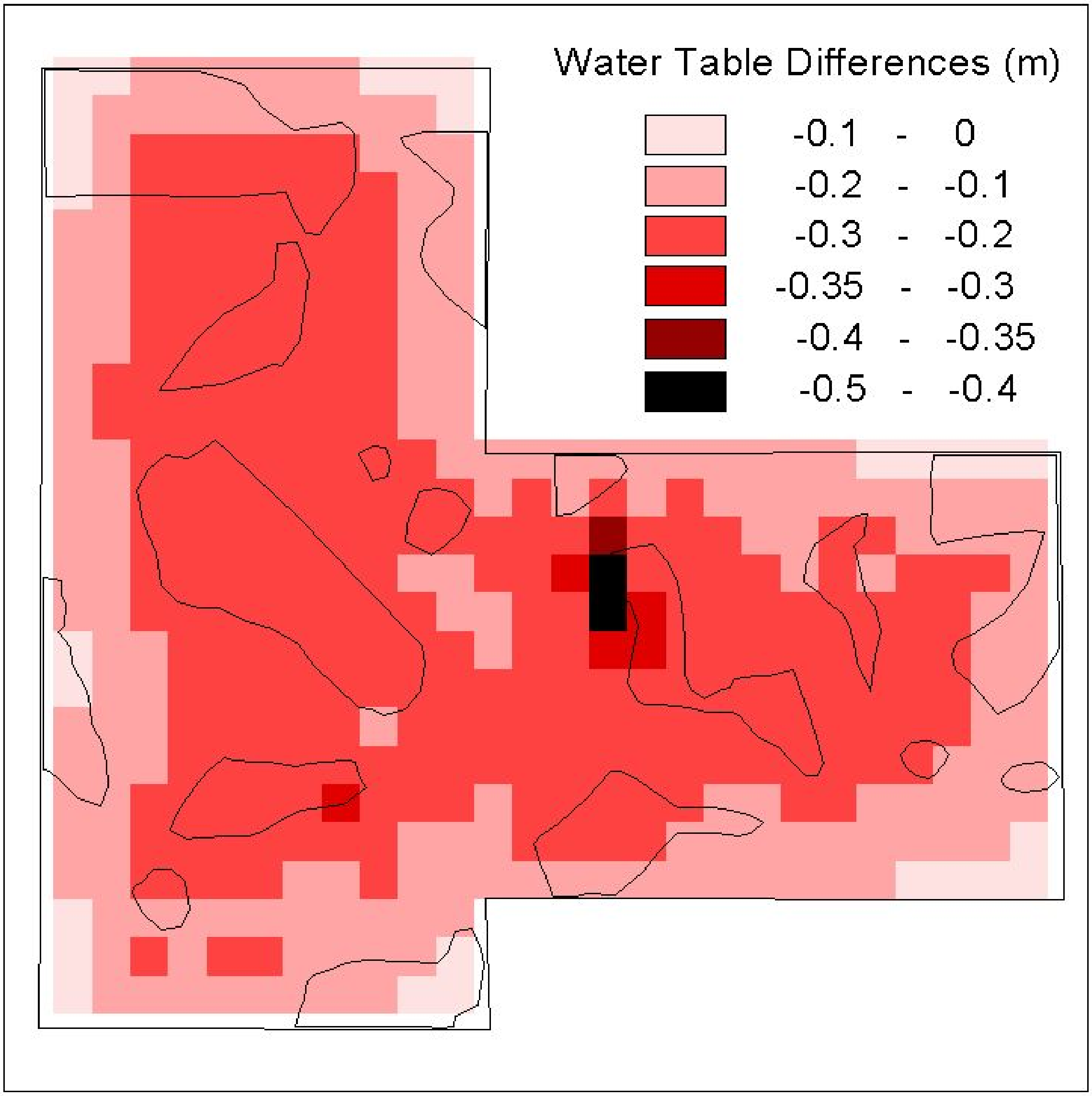

Figure 3-36. Water table dropped due to 10% precipitation decrease on 09-16-1993 at Florida wetland site (30 m cell size; water table differences were defined as the water table depth under 10% precipitation decrease subtracted the base line water table depth; negative values indicate that water table is lower than the base line under 10% precipitation decrease).

3.4 Summary

This study showed that MIKE SHE could be used to simulate hydrology at the Florida wetland site. Model calibration and validation results suggested that MIKE SHE had capabilities to simulate spatial hydrology at this typical Flatwoods landscape. Thus, it could be used as a tool to investigate hydrologic functions and responses to forest management and climate change at this type of landscape.

MIKE SHE identified three horizontal groundwater flow patterns at this study site. The model simulations confirmed field observations of interactive flow patterns between the wetlands and their surrounding uplands in this typical Flatwoods landscape. MIKE SHE had the advantages in presenting temporal flow dynamics spatially across the landscape and inspecting them in intensive time steps and spatial scales. Model simulations could also help quantify the flow between the wetlands and the uplands. These results further proved the applicability of the MIKE SHE model at this type of landscape.

The four application scenarios during the study period of 1992-1996 indicated that forest management and climate change would have impacts on the groundwater table during the dry periods. However, there were no significant impacts under the wet conditions for this Flatwoods landscape.

Chapter 4

Model Evaluation and Application at a Drained Pocosin Wetland in Eastern North Carolina

4.1 Objectives

The objective of this study is to apply a physically-based, distributed hydrologic model, MIKE SHE, to better understand hydrologic processes at a ditch-drained pocosin wetland and its responses to potential land disturbance (such as prescribed burning and vegetation management), and to test its sensitivity to potential climate variability and change.

4.2 Methods

4.2.1 Site description

The Alligator River study site is located on the coastal plain in eastern North Carolina (Figure 4-1). It is on the border of the United States Fish and Wildlife Service's Alligator River National Wildlife Refuge (ARNWR) and the Department of Defense's (DOD) Dare County Bombing Range (Rosenfeld, 2003). Defined by roads and ditches, the watershed is artificially delineated and has a size of 18 ha. The study site is generally characterized as high Pocosin with pond pine (*Pinus serotina*) and Loblolly-bay (*Gordonia lasianthus*) as dominant species (Figure 4-2). Pocosin is a Native American word meaning "swamp-on-a-hill" and is characterized by poorly drained organic soils (U.S. Fish and Wildlife Service, 2005; Rosenfeld, 2003).

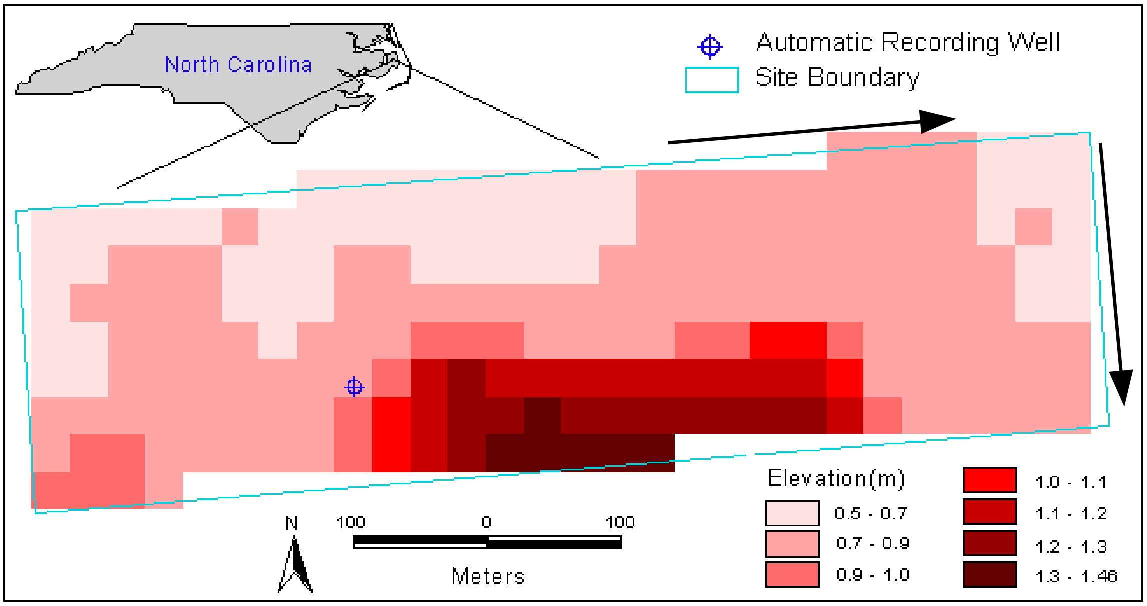

Figure 4-1. Location of Alligator River site in eastern North Carolina.

Figure 4-2. Road accesses to the Alligator River site (on the left side of the road).

ARNWR was established in 1984 to preserve and protect a unique wetland habitat type, the pocosin, and its associated wildlife species. The Refuge is about 152,000 acres, with the majority of the refuge being wetlands (high and low pocosin, bogs, fresh and brackish water marshes, hardwood swamps, and Atlantic white cedar swamps). ARNWR is perhaps best known for the reintroduction of endangered red wolves and as a home to one of the largest populations of black bears in the Mid-Atlantic States. The Refuge plays an important role in bird migration as well, including neo-tropical migrants and waterfowl. Surrounded by ARWNR, the DOD Dare County Bombing Range has similar ecological characteristics as the Refuge (U.S. Fish and Wildlife Service, 2005; Rosenfeld, 2003). ARNWR site was last disturbed in February 2000 by a prescribed burning, and the DOD site was last disturbed in March 1980 by a wildfire (Rosenfeld, 2003).

4.2.2 Data collection

An automatically recording well was installed inside the study plot to monitor the water table depth (Figure 4-1 and Figure 4-3). A data logger (Infinities USA, Inc.) was programmed to automatically record groundwater level in a one-hour interval. The data was manually downloaded in the field about once a month. This started in the summer of 2002 and ended in April 2005. Ditch-2 water level was measured approximately once a month during the site visit (Figure 4-3). Similar to the Florida wetland site, water table depth data were used for the MIKE SHE model calibration and validation at this study site.

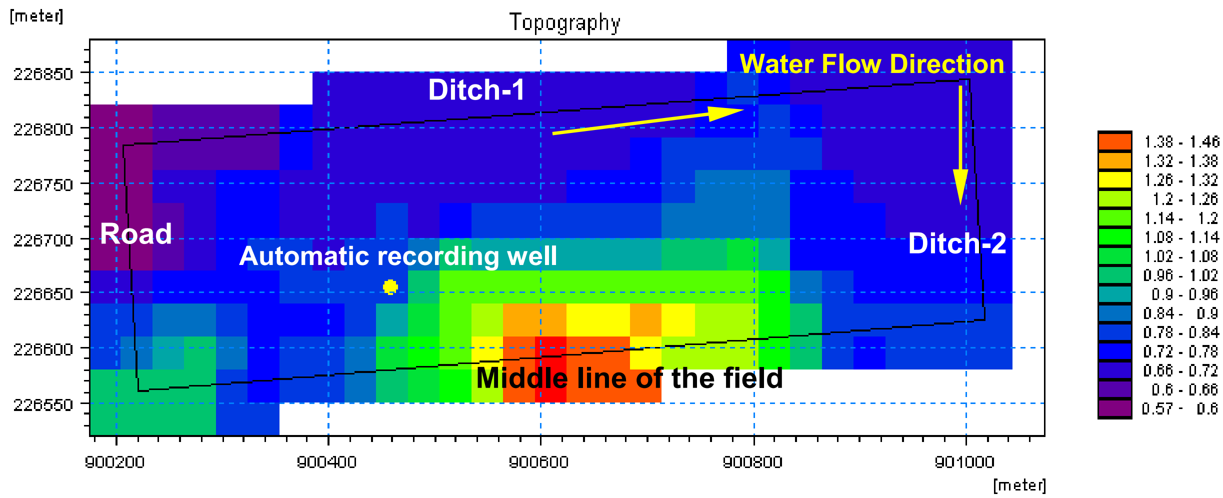

Figure 4-3. Boundary setup for the Alligator River site.

Leaf area index (LAI) measurement was also conducted about once a month using LI-COR LAI-2000 Plant Canopy Analyzer (LI-COR, 1992). One year (2004) LAI data were collected by the author for this site in monthly field measurements (Figure 4-4). The data were linearly interpolated between the measurements to derive daily values. The LAI dynamics were assumed to remain the same for each year during the study period (2002-2005).

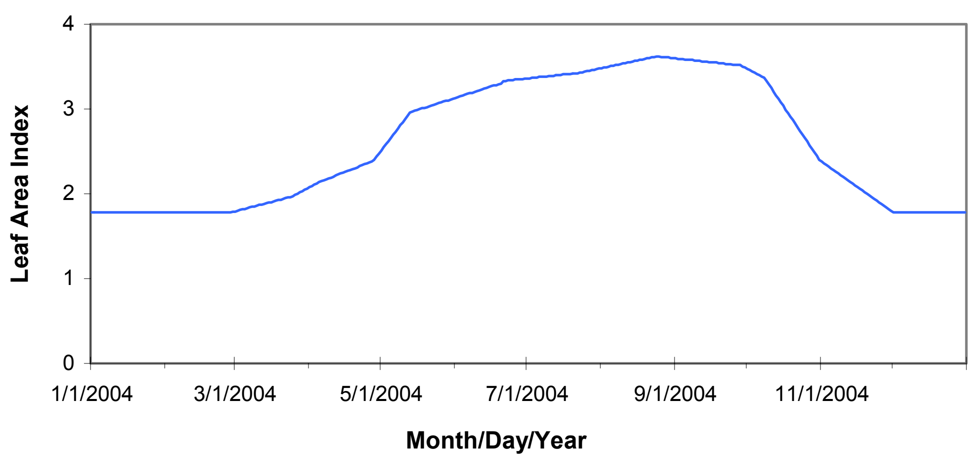

Figure 4-4. Forest Leaf Area Index (LAI) dynamics used by the MIKE SHE model at Alligator River site.

4.2.3 Model setup and parameterization

Similar to the Florida wetland site in the last chapter, data required to set up MIKE SHE model for the Alligator River site included: 1) Topography and landuse data - surface flow retention storage, Manning roughness number, and vegetation distribution (leaf area index (LAI) dynamics and rooting depth); 2) Soil data - soil depth, hydraulic properties such as conductivity, porosity, field capacity and wilting point; 3) Meteorological data - precipitation and air temperature; 4) Boundary conditions; and 5) Initial conditions (spatial water table depth and overland flow depth).

Elevation data were acquired from the USGS EROS Data Center's Seamless Data Distribution website (URL: http://seamless.usgs.gov/) in 30 m DEM resolution (Rosenfeld, 2003). The elevation data were processed by ESRI ArcView 3.3 software and organized as shape files, which were used directly as an input into the MIKE SHE model. Model grid cell size was set as 30 m, which was chosen to allow for an accurate representation of the site without placing excessive demands on model running time.

The18-ha study watershed was considered as one having a uniform vegetation represented by a set of parameters in the MIKE SHE. These included empirical constants for actual evapotranspiration (ET) - C1, C2, C3, C_{int} and A_{root}, and time series of measured LAI and rooting depth. LAI was assumed the same for each year during the study period (2002-2005). A rooting depth of 40 cm was used for vegetations across the entire study site.

Hourly rainfall and air temperature data (Figure 4-5) were requested from the ARNWR weather station, which is located near the study site. The Hamon potential evapotranspiration (PET) method (Hamon, 1963; Lu et al., 2005) was used to calculate daily PET (Figure 4-6) at this site with the calibrated coefficient (K_{pet}) as 1.0.

The soil was classified as the organic Belhaven series (SCS USDA, 1992). A soil pit was dug in the field (Figure 4-7). The soil profile indicated that the clay layer was about 1.7 m below the ground surface. The thickness of the clay layer is about 30 cm with a thick sand layer underneath it. The clay layer was considered as vertical simulation boundary. Thus, in the MIKE SHE modeling system, the soil depth was uniformly defined as 1.7 m below the ground surface across the study site. The thickness of the soil capillary fringe was set as 10 cm (Gillham, 1984).

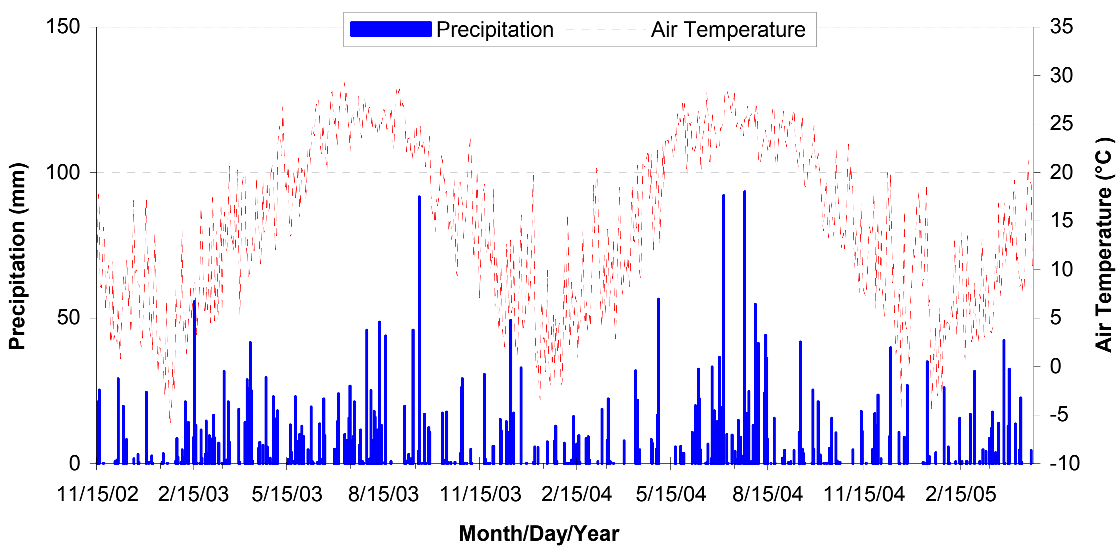

Figure 4-5. Daily precipitation and air temperature during the study periods (11-15-2002 to 04-24-2005) at Alligator River site in eastern North Carolina.

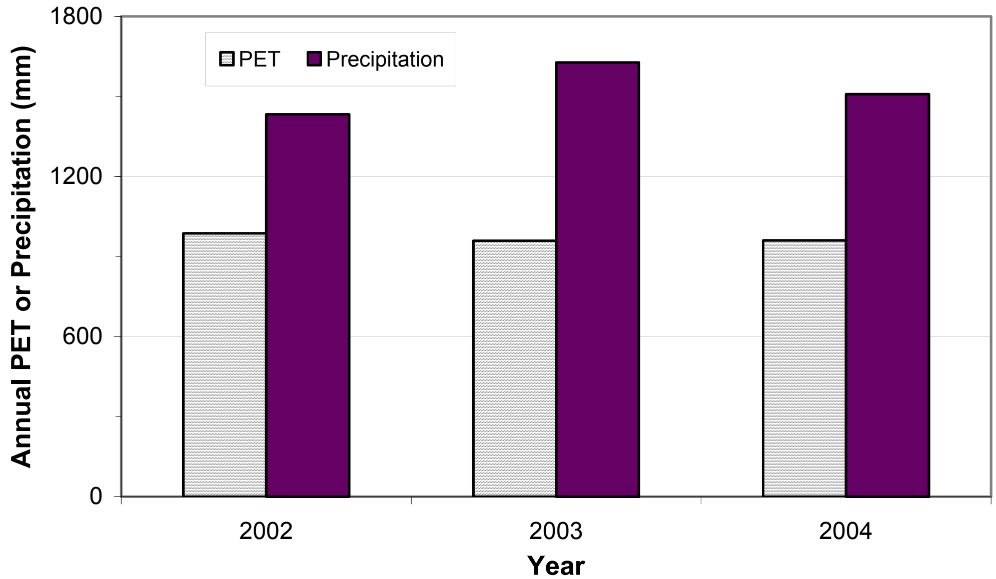

Figure 4-6. Annual PET and precipitation during the study period (2002-2004) at Alligator River site.

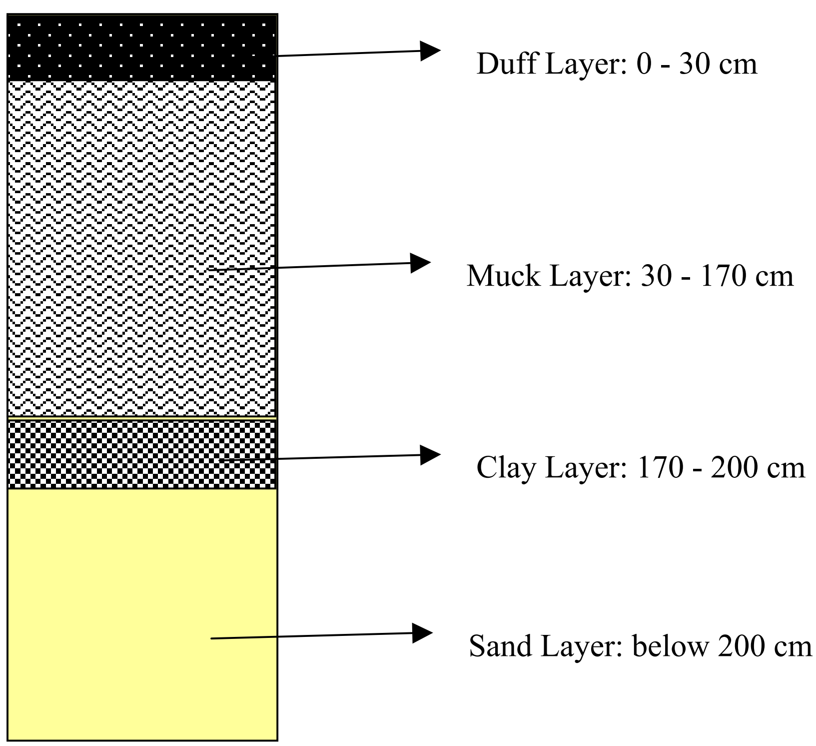

Figure 4-7. A soil profile recorded at Alligator River site.

The study plot was defined by the road and drained ditch systems (Figure 4-3). The “road” and the “middle line of the field” boundaries were set as “no-flux” boundaries, which indicated that there were no water interactions along these two boundaries. The other two ditch boundaries were set up using the water table elevation along the physical boundaries of the study plot.

As mentioned previously, “ditch-2” (Figure 4-3) water level was manually measured approximately once a month during the field trip from 2002 to 2005. To derive daily water table elevation for this boundary, the measured ditch water table elevation was correlated to the automatic recording well data, which was in hourly reading. Then the regression equation ($R^2 = 0.71$, n = 22) was applied to estimate the hourly “ditch-2” water table elevations.

“Ditch-1” (Figure 4-3) was divided at mid-point into two equal length sections. Referenced to the DEM elevations, the first section (left hand side) was set 10 cm higher than “ditch-2” water elevation, and the second section (right hand side) was set 5 cm higher than water elevation in “ditch-2”. Water was drained from the field into the ditches, and then it flowed from “ditch-1” to “ditch-2” (Figure 4-3). Water was carried out of the study plot through “ditch-2”, which joined the main ditch in the ditch systems.

Similar to the Florida wetland site, the “hot start” feature of the MIKE SHE model was used to set up initial conditions. First, the model was run, using starting water table elevations as 40 cm below the ground surface and 0 m depths of surface water across the entire site, to generate a ‘hot start’ file. Then, a new simulation run, using site conditions on 12-10-2003 as the “hot start”, was rerun. The same initial condition or “hot start” was applied to the rest of simulations at this study site.

4.2.4 Model calibration, validation and applications

Similar procedures as in the last chapter were used to conduct model calibration and validation. Water table data collected from the automatic recording well (Figure 4-1 and Figure 4-3) were used for model calibration and validation. The calibration period was from 11-15-2002 to 01-09-2004, and the validation period was from 04-29-2004 to 04-24-2005.

After model calibration and validation, the MIKE SHE model was applied to simulate four application scenarios during the time of November 2002 to April 2005. It was assumed that LAI was reduced to 0.1 for the entire site under the clear-cut conditions (Gholz and Clark, 2002; Clark et al., 2004).

4.3 Results and discussions

4.3.1 Model Calibration

Recorded water table depths at the automatic well were used to calibrate the MIKE SHE model during the time period of 11-15-2002 to 01-09-2004. Manual calibrations were conducted and the calibrated parameters were generated (Table 4-1 and Table 4-2). These calibrated parameters remained the same during the model validation period (April 2004 - April 2005).

Table 4-1. MIKE SHE calibrated parameters at Alligator River site.

Parameters	Parameter Values			
	Initial	Minimum	Maximum	Final
ET Coefficient - C_{int}	0.05	0.05	0.8	0.5
Surface Manning Coefficient ($m^{1/3}/s$)	5	1	10	7
Horizontal Hydraulic Conductivity (m/s)	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-3}	8.0×10^{-4}
Vertical Hydraulic Conductivity (m/s)	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-3}	7.8×10^{-4}
Specific Yield	0.1	0.1	0.4	0.3

Table 4-2. Calibrated parameters of Two-Layer Water Balance Method for the unsaturated zone simulation at Alligator River site.

Two-Layer UZ Parameters	Value
$\theta_{sat.}$ (Saturated water content)	0.65
θ_{fc} (Field capacity)	0.35
θ_{wp} (Wilting point)	0.25
Maximum infiltration rate (m/s)	7.8×10^{-4}
ET surface depth (cm)	10

Water table was quite shallow at this Alligator River site, as the measured water table varied within 0 cm to 40 cm below the ground surface (Figure 4-8). With R = 0.64, ME = -2 cm and E = -0.48, MIKE SHE generally captured the temporal dynamics of water table variations and achieved close estimates at this study site. However, the model overestimated water table depth during March through June of 2003 and underestimated it in July and early August of the same year. The rainfall was quite intensive through March and August of 2003. The discrepancies of water table depths between measurements and simulations might be caused by variations of soils data across the study site. The model was run using a uniform soil profile vertically and horizontally. In reality, however, soil parameters (such as conductivity, porosity and field capacity) were likely spatially heterogeneous. It might also be a result of errors in ET estimates. The model might underestimate ET during March through June and overestimate ET during July through early August. Also, local rainfall events might also cause input errors although the weather station is only approximately 10 miles from the study watershed. However, the discrepancies were generally within 10 cm - 20 cm, which seemed to be reasonable. MIKE SHE was able to simulate the water table dynamics. Overall, the model slightly overestimated water table depth at the automatic recording well with ME = -2 cm (Figure 4-8).

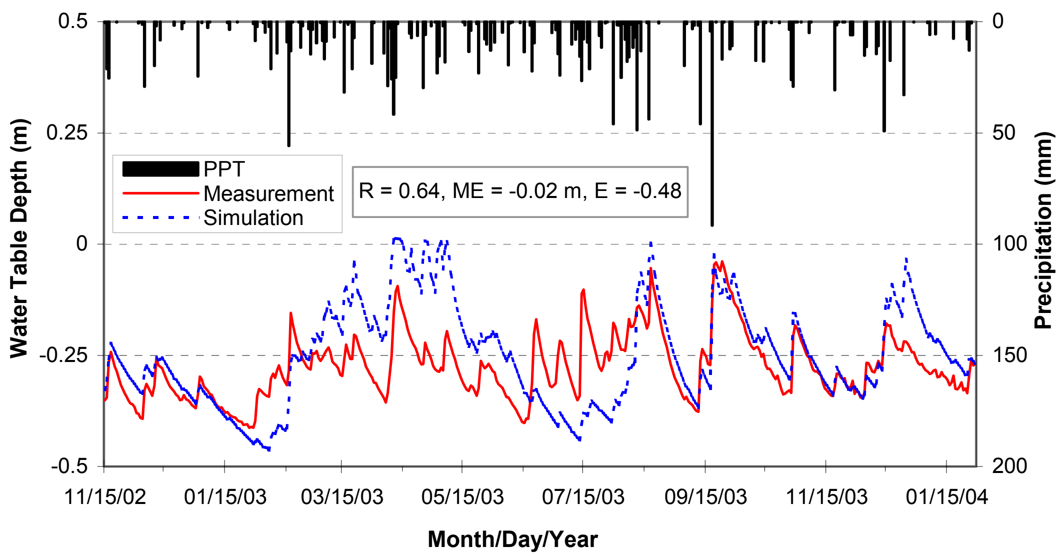

Figure 4-8. MIKE SHE model calibration at Alligator River site during the period of 11-15-2002 to 01-09-2004.

4.3.2 Model validation

Similar to the calibration, the model validation at the automatic recording well confirmed the reasonable performance of the MIKE SHE at the Alligator River site, in terms of water table dynamic simulations (Figure 4-9). Again, the measured water table depth generally varied within 0 cm to 40 cm below the ground surface. The validation period was drier than the calibration period, which was indicated by the measured water table depths at these two time periods. After a relatively dry winter, there was not enough rainfall to recharge the water table to the measurement level in the MIKE SHE model simulations. With R = 0.75, ME = 4 cm and E = -0.57, MIKE SHE could simulate the temporal dynamics of water table variations and achieved close estimates at this automatic well. Overall, the model slightly underestimated water table depth with ME = 4 cm. However, the discrepancies were generally within 10 cm.

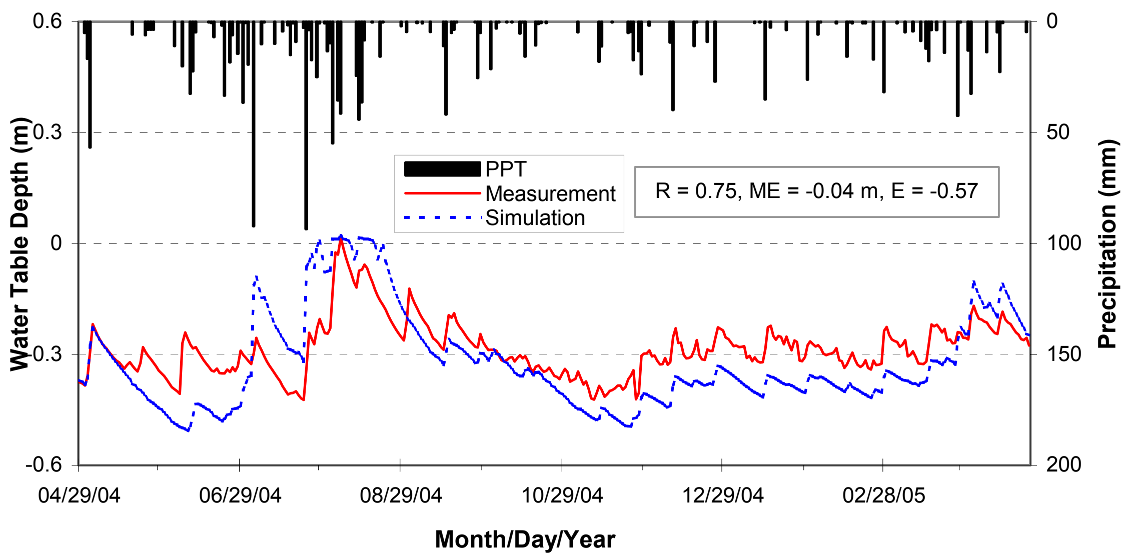

Figure 4-9. MIKE SHE model validation at Alligator River site during the period of 04-29-2004 to 04-24-2005.

4.3.3 Model Applications

In terms of water table variations, modeling results suggested that forest clearcut did not have any impacts during the study periods (Figure 4-10). This was likely due to the shallow water table at the Alligator River site. ET reached PET level no matter there was any forest coverage at the study site or not. Thus, even after forest clearcut, ET was the same as the pre-cutting amount.

However, the model did show that climate change consistently changed water table during the study periods (Figure 4-10). More specifically, when temperature increased 2 °C or precipitation decreased 10%, water table dropped deeper than the base line scenario, especially during the relatively low water table periods. Under the 10% precipitation decrease scenario, the water input was less than the base line condition and recharge was decreased, thus the water table was lower while ET was very likely remained the same as the base line. When temperature increased 2 °C, more energy was available to move the water out of the wetland and PET was higher than PET under the base line condition. So actual ET was higher due to 2 °C temperature increase. This resulted in lower water table than the base line condition. Generally, the water table drop resulted from 10% precipitation decrease was slightly lower than that from 2 °C temperature increase. This could be seen on 03-08-2003 (Figure 4-10).

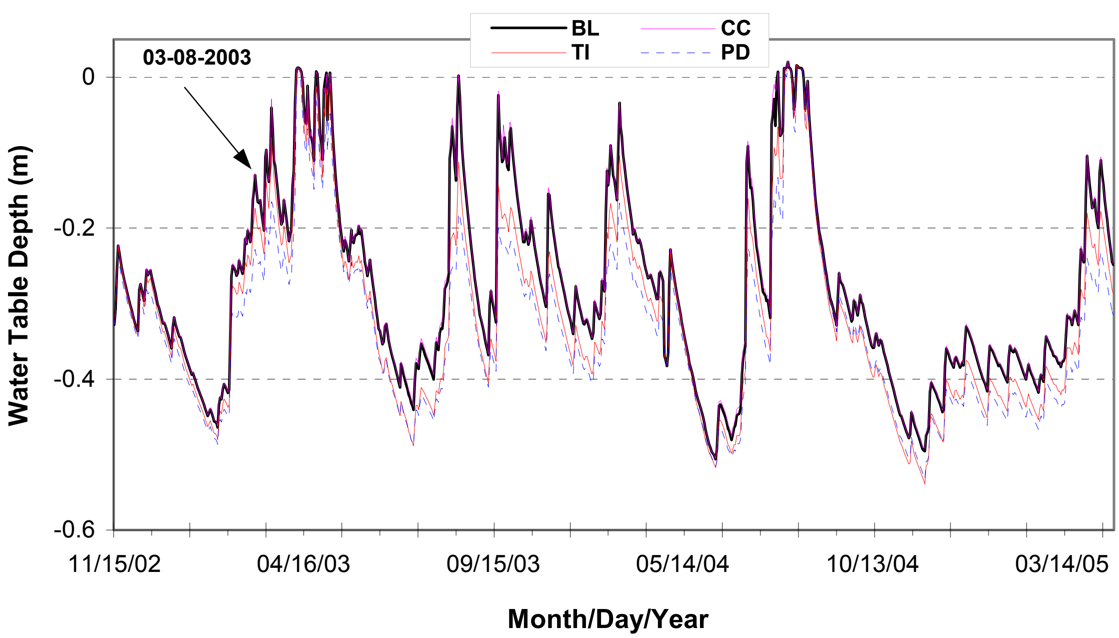

Figure 4-10. Impacts of clearcut and climate change on water table at the automatic well during 2002-2005 (BL - base line; CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

Climate change impacts on ground water table were examined spatially on 03-08-2003 when it clearly showed the effects of climate change (Figure 4-11 and Figure 4-12). Water table drop due to 2°C temperature increase was in a range of 0 cm to 6 cm, while the drop due to 10% precipitation decrease was in a range of 0 cm to 13 cm. Spatial inspections confirmed with point temporal comparisons that 10% precipitation decrease generally dropped water table down further than the case of 2°C temperature increase.

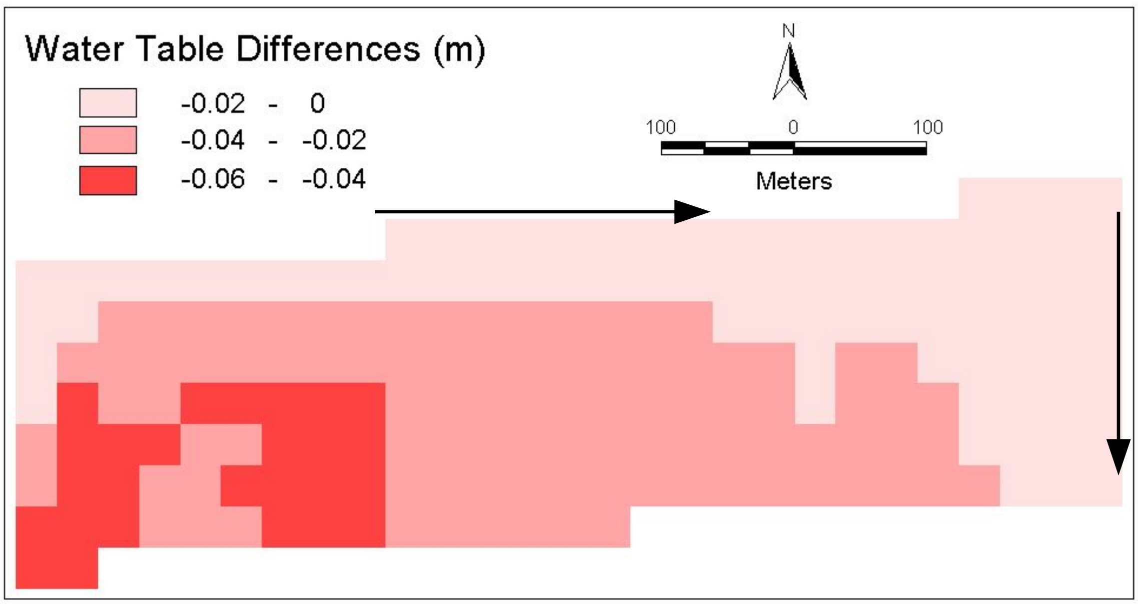

Figure 4-11. Water table dropped due to 2 °C temperature increase on 03-08-2003 at Alligator River site (30 m cell size; water table differences were defined as the water table depth under 2 °C temperature increase subtracted the base line water table depth; negative values indicate that water table is lower than the base line under 2 °C temperature increase).

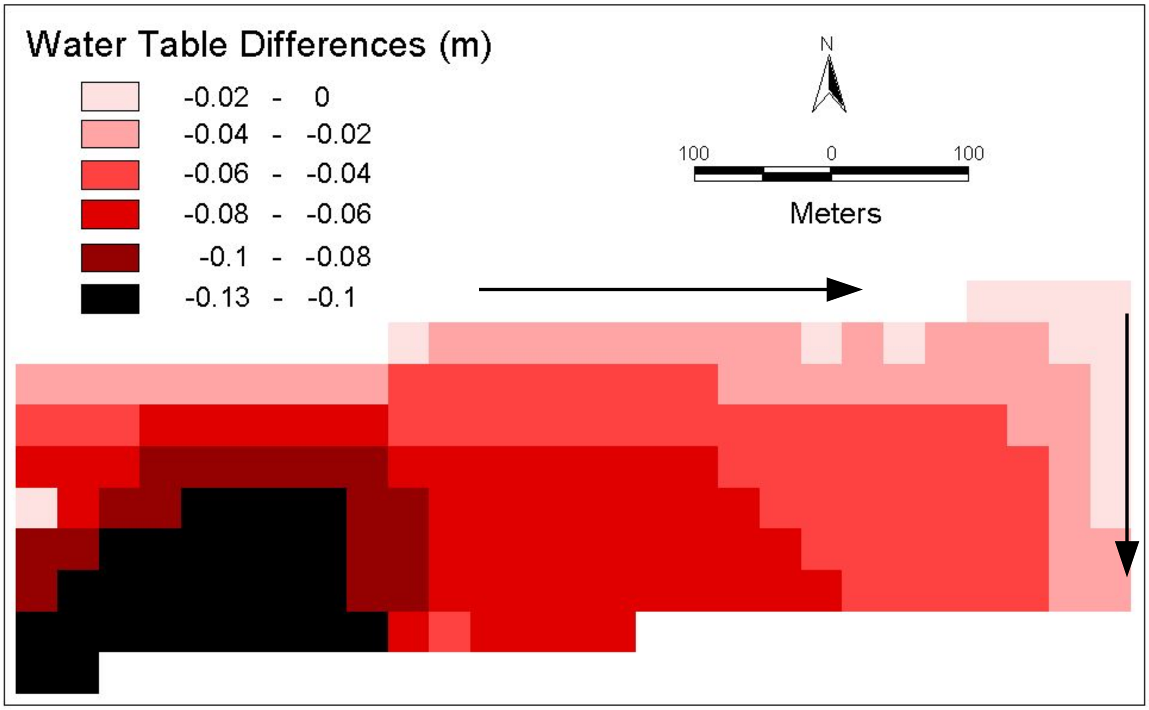

Figure 4-12. Water table dropped due to 10% precipitation decrease on 03-08-2003 at Alligator River site (30 m cell size; water table differences were defined as the water table depth under 10% precipitation decrease subtracted the base line water table depth; negative values indicate that water table is lower than the base line under 10% precipitation decrease).

4.4 Summary

This study showed that MIKE SHE had the capacity to simulate water table dynamics at the Alligator River pocosin wetland site. Thus, it could be used as a tool to investigate hydrologic functions and responses at this type of land condition.

The four application scenarios indicated that forest management had little impact on the water table at this study site. However, climate change, especially decrease in precipitation, would likely change groundwater table dynamics at this pocosin wetland, although the significance levels might depend on how severe the climate change would be.

Chapter 5

Model Evaluation and Application at an Undrained Lowland Watershed on the Lower Atlantic Coastal Plain in Eastern South Carolina

5.1 Objectives

The objective of this study is to apply a physically-based, distributed hydrologic model, MIKE SHE, to better understand the hydrologic processes of a low relief coastal forested watershed and its responses to potential land disturbance(such as prescribed fires and vegetation management), and to test its sensitivity to potential climate variability and change.

5.2 Methods

5.2.1 Site description

A lowland watershed was selected to test the MIKE SHE model. The 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 5-1). It is a first order forested watershed and has been used as a control watershed to conduct studies on hydrologic processes, water balances and forest management impacts (Sun et al., 2000c; Amatya et al., 2004; Harder, 2004). The watershed consists of an ephemeral stream as the main drainage pathway. The area has low topographic relief (< 4%) with surface elevation ranging from 3 - 10 m above mean sea level.

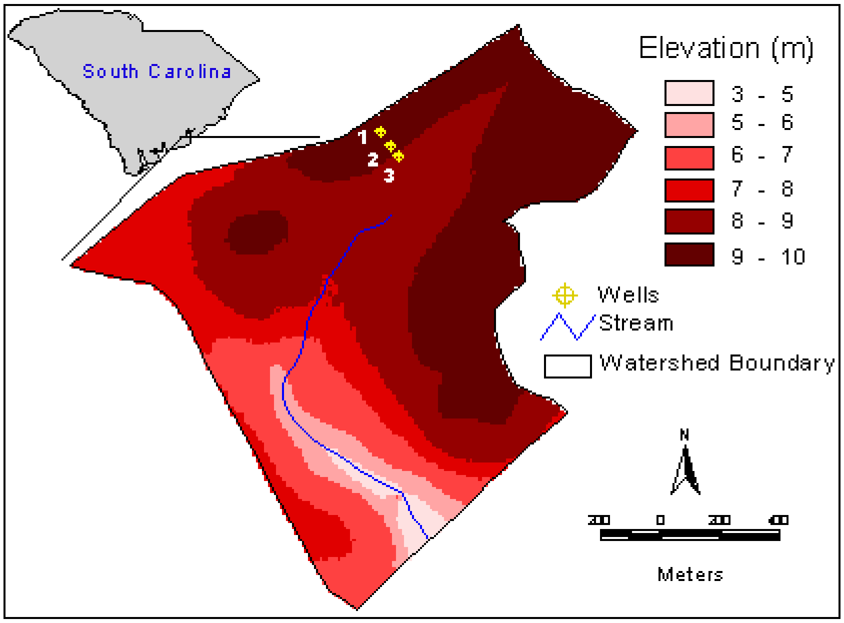

Figure 5-1. Watershed 80 within the Santee Experimental Forest in eastern South Carolina.

As a control watershed, watershed 80 has been relatively undisturbed for over eighty years, but it was damaged by Hurricane Hugo in 1989 (Harder, 2004). The Center for Forested Wetlands Research, USDA Forest Service has monitored the watershed since the 1960s. More details of the watershed can also be found in the Santee Experimental Forests Watersheds Metadata Report (Shepherd, 2004).

Originally, the watershed, with an area of 222 ha, was delineated in 1968 and was bounded by roads on all sides. The watershed was created by plugging a secondary outlet in the northeast side and diverting its flow to the main stream outlet via a drainage ditch dug. In November 2001, the secondary outlet was unplugged allowing the water to drain from two locations on the area previously designated as part of the watershed. A new delineation of the watershed was conducted in 2003 resulting in a new watershed size of 160 ha (Harder, 2004). And this study focused on the new delineation of the watershed with an area of 160 ha.

The vegetation coverage at this watershed is mainly composed of pine hardwood (39%), hardwood pine (28%) and mixed hardwoods (33%). Common 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 14-15 years old, regenerating after hurricane Hugo in 1989. 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 with low base saturation (Gartner and Burke, 1999). In addition, soils on WS80 are classified as somewhat poorly drained to poorly drained (SCS, 1980).

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 average temperatures are as low as 10 ºC in January and as high as 28 ºC in July. The long-term mean annual air temperature is 19.1 ºC. Approximately 23% of the WS80 is classified as wetlands (Sun et al., 2000c; Harder, 2004).

5.2.2 Data collection

Data for this study site were mainly acquired from the Center for Forested Wetlands Research, USDA Forest Service that maintained the study site. Field data were reported by Harder (2004).

5.2.3 Model setup and parameterization

Similar to the Florida wetland site and the Alligator River site, data required to run the MIKE SHE model at this study site 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 air temperature; 4) Boundary conditions; 5) Initial conditions; and 6) Stream network simulation setup with the coupling of MIKE 11 model (DHI, 2004b).

Watershed elevation data as DEM (Figure 5-1) were acquired from the GISDataDepot website (URL: http://data.geocomm.com/dem/) in 10 m spatial 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 scaled up to 50 m, which was selected to allow for an accurate representation of the watershed without placing excessive demands on model running time.

According to the vegetation coverage types, the160-ha watershed was classified as two forest types, which were represented by a set of parameters in the MIKE SHE vegetation database. These included empirical constants for actual evapotranspiration (AET) - C1, C2, C3, C_{int} and A_{root}, and time series of LAI and rooting depth. Measured LAI data were not available at this study site. LAI was assumed to be 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. The pine hardwood and hardwood pine were assigned to have the same LAI as those at the wetlands at the Florida wetland site. The mixed hardwoods were given the same LAI data as the uplands at the Florida wetland site (Liu, 1996).

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 with a calibrated coefficient (K_{pet}) of 1.2.

The soil characteristics were retrieved from lab testing and soil survey (Harder, 2004; SCS, 1980). The soil depth to the hydrologic restrictive layer (clay) was determined as 3 m deep below the ground surface across the entire watershed (Table 5-1). Three soil types were used (Figure 5-2). The thickness of the soil capillary fringe for all soils was set as 20 cm (Gillham, 1984). A simple two layer unsaturated zone model was used for this site (Yan and Smith, 1994; DHI, 2004a).

Table 5-1. Soil parameters used at the Santee watershed.

Two-Layer UZ Parameters	**Soil Types**		
	Wahee	**Meggett**	**Bethera**
θ_{sat} (Saturated conditions)	0.408	0.496	0.535
θ_{fc} (Field capacity)	0.384	0.458	0.464
θ_{wp} (Wilting point)	0.305	0.377	0.362
Infiltration rate (m/s)	4×10^{-4}	4×10^{-4}	4×10^{-4}
ET surface depth (cm)	20	20	20

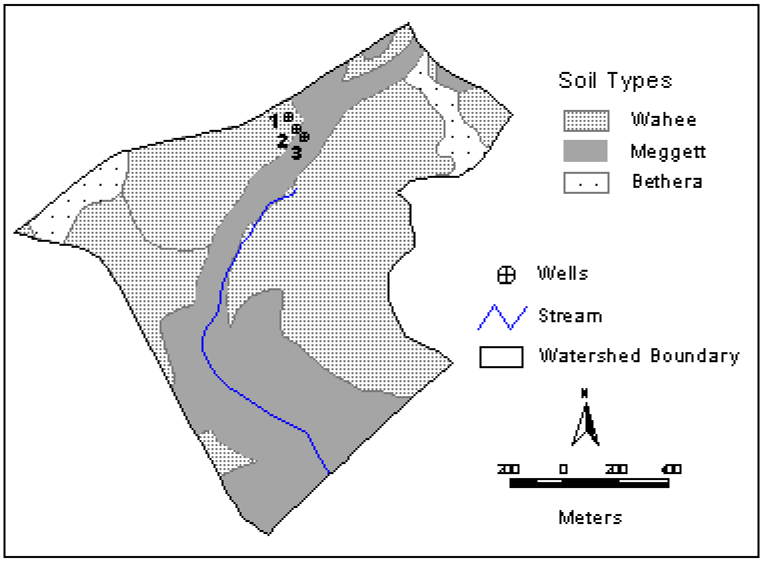

Figure 5-2. Three soil types used by the MIKE SHE model at Santee watershed.

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

First, the model was run using initial potential head, which was set 80 cm below the ground surface across the entire site, for generating a 'hot start' file. Then, a new simulation run, using the 'hot start' file as an initial condition, was conducted. The same initial condition was applied to the rest of simulations at this watershed.

MIKE 11 was coupled with MIKE SHE for streamflow simulations. The requirements for the model setup included: 1) Stream network; 2) Stream cross-sectional area; 3) Boundary conditions; and 4) Hydrodynamic parameters. A single ephemeral stream exists at this watershed and was delineated from the DEM data. Cross-sectional areas of the stream were estimated based on the field survey. Boundary conditions were set as zero inflow at the upstream open end and constant water level (2.3 m) at the watershed outlet.

5.2.4 Model calibration, validation and applications

Streamflow and three selected well water table data from this watershed were used for the MIKE SHE model calibration and validation. Daily streamflow data for 2003 and 2004 were acquired from the study site (Harder, 2004). The streamflow data in 2003 were used for MIKE SHE model calibration, and streamflow data in 2004 and three well water table data were used for MIKE SHE model validation.

For the model application, 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)

5.3 Results and discussions

5.3.1 Model calibration

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. Manual calibrations were conducted and the calibrated parameters were generated (Table 5-2). These calibrated parameters remained the same during the model validation period in 2004.

Table 5-2. MIKE SHE calibrated parameters at Santee watershed.

Parameters	Parameter Values			
	Initial	Minimum	Maximum	Final
ET Coefficient - C_{int}	0.05	0.05	0.8	0.5
Surface Manning Coefficient ($m^{1/3}/s$)	5	1	10	5
Horizontal Hydraulic Conductivity (m/s)	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-3}	8.0×10^{-4}
Vertical Hydraulic Conductivity (m/s)	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-3}	4.0×10^{-4}

Generally, the model could simulate the variations of the streamflow with R = 0.75, ME = 0.10 mm/day and E = 0.56 during the calibration (Figure 5-3). However, the model did not catch all the peak flows, especially for one large storm event (Hurricane Isabelle) in the mid of September of 2003. 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.

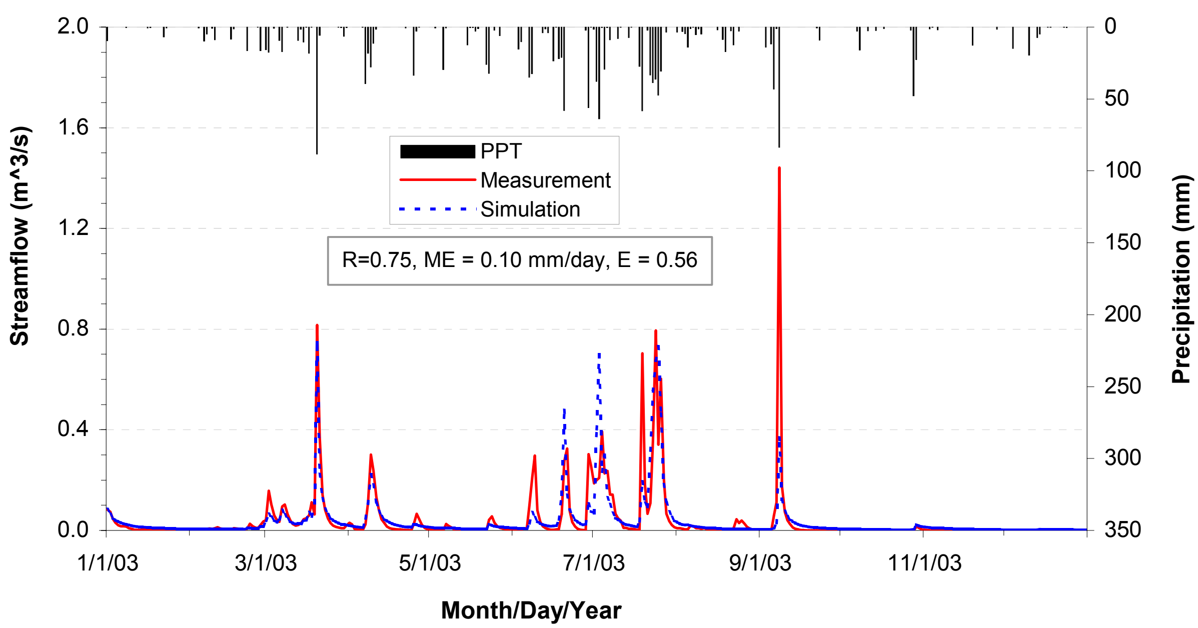

Figure 5-3. Calibration of MIKE SHE model with daily streamflow in 2003 at Santee watershed.

5.3.2 Model validation

The MIKE SHE model was validated with daily streamflow data in 2004 (Figure 5-4) and water table depth measured from the end of 2003 though 2004 (Figure 5-5, Figure 5-6 and Figure 5-7). 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 entire year, and there was no streamflow observed at all for entire five months - June, July, October, November, and December (Figure 5-4).

Overall, MIKE SHE simulated the streamflow dynamics with R = 0.75 under this extremely dry condition, but it over-predicted a peakflow rate in the late August (Figure 5-4). Contrary to the under-prediction during Hurricane Isabelle in calibration, the simulated peakflow rate (0.68 m^3/s) was much higher than the measurement (0.15 m^3/s). 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 dry 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.

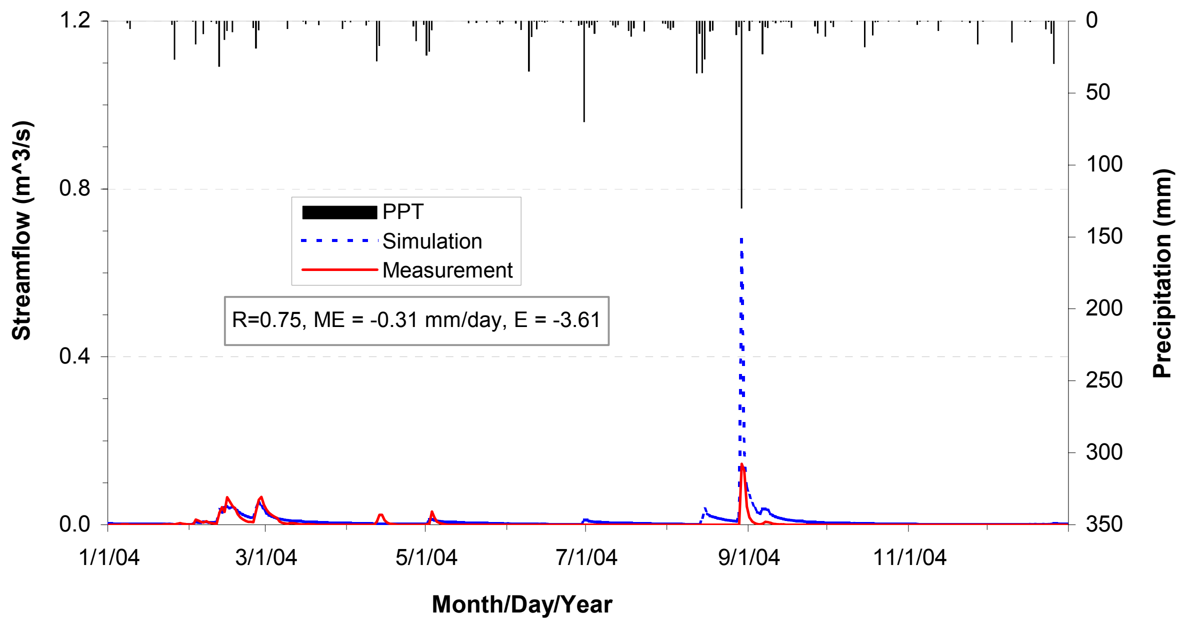

Figure 5-4. Validation of MIKE SHE model with daily streamflow in 2004 at Santee watershed.

A well transect, consisting of three wells (Figure 5-1) near the headwater area, was used for additional model validations. Well water table depths were measured by a bi-weekly schedule 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 5-4). However, it did not match as well for other two locations at well 2 (Figure 5-5) and well 3 (Figure 5-6) during dry periods.

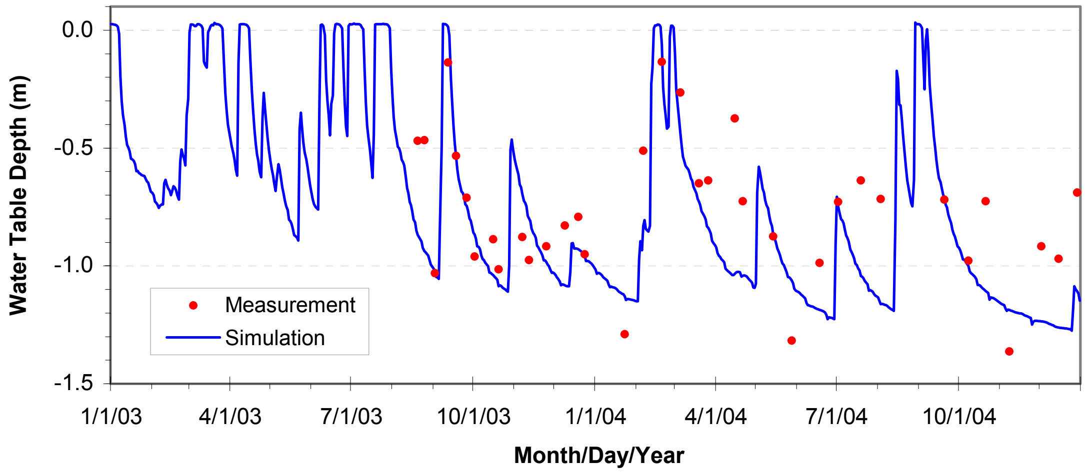

Figure 5-5. Validation of MIKE SHE model with water table depth at well 1 during October 2003 - December 2004.

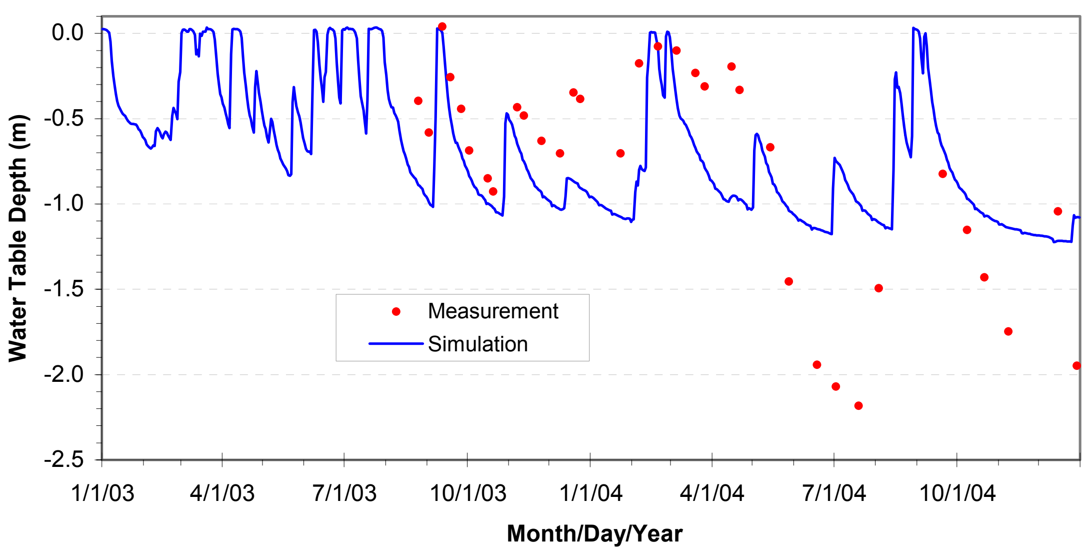

Figure 5-6. Validation of MIKE SHE model with water table depth at well 2 during October 2003 - December 2004.

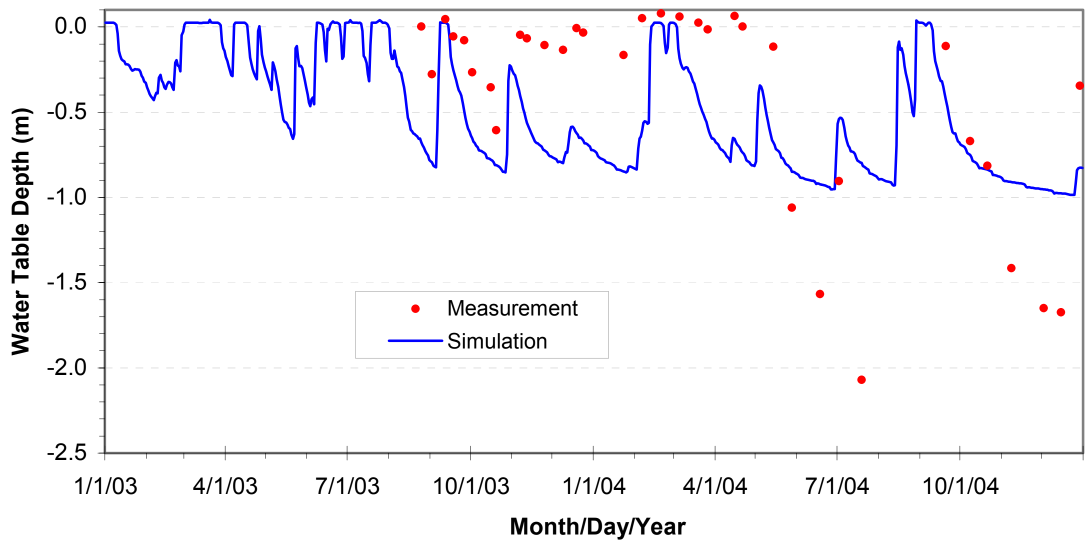

Figure 5-7. Validation of MIKE SHE model with water table depth at well 3 during October 2003 - December 2004.

According to the model simulation, overland flow had a big contribution to the annual total streamflow. The model 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 5-8). Most of the overland flow depths were within 2 cm to 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. Some cells had very high overland flow depth. This might be caused by inaccurate DEM representation. These cells were depressions surrounding by cells having higher elevations. Surface water had to fill these depressions before overland flow could be generated. Especially for several cells along the watershed boundary, their elevations were much lower (30 cm to 70 cm) than the surrounding cells. Water could not move out of the watershed with the closed watershed assumption. Thus, water had to fill to the level of the elevation of the surrounding cells before overland flow could be generated. 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.

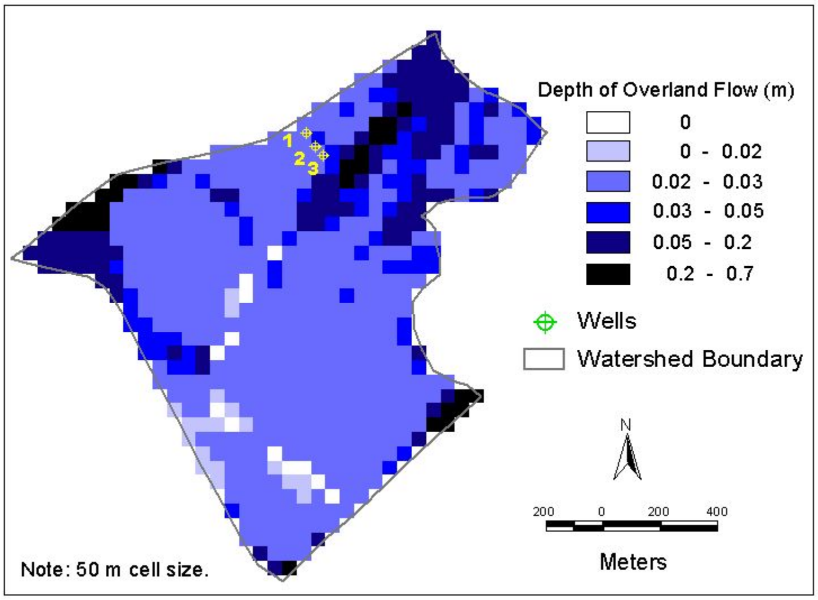

Figure 5-8. Spatial distribution of overland flow depth on 06-20-2003 at Santee watershed.

5.3.3 Model applications

After 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 5-9 and Figure 5-10). The simulation results suggested that clear-cut would raise the water table, especially during the dry periods, due to the decrease in ET. With 2 °C air temperature increase or 10% precipitation decrease, groundwater recharge would be reduced and thus resulted in lower water table (Figure 5-9).

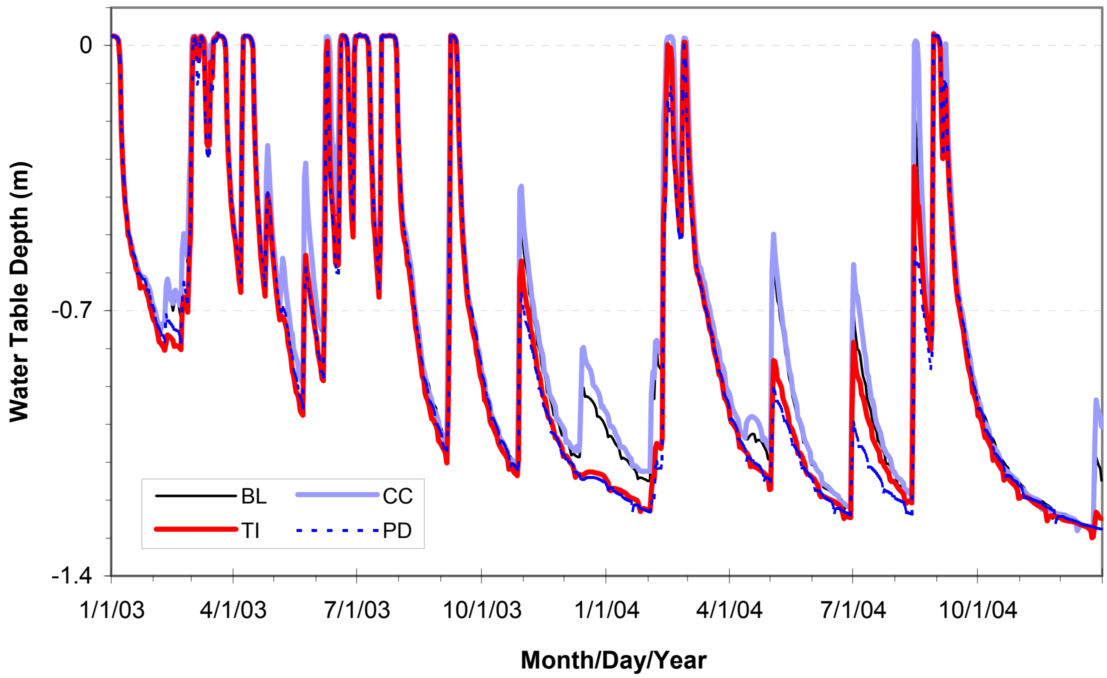

Figure 5-9. Impacts of clearcut and climate change on ground water table at well 1 during 2003-2004.

The model results indicated that clearcut would increase streamflow by 11 mm in 2003 and 16 mm in 2004, while the climate change scenarios would result in a significant decrease in streamflow (Figure 5-10). For both years, the magnitudes of water yield increase due to clearcut appeared to be much smaller than most literature suggested (Riekerk, 1989; 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 the model overestimated ET after clearcut.

However, large water yield responses to both climate change scenarios were found. A 10% decrease of precipitation resulted in approximately 20% to 30% reduction of streamflow. A 2 °C air temperature increase resulted in approximately 12% to 18% reduction of streamflow.

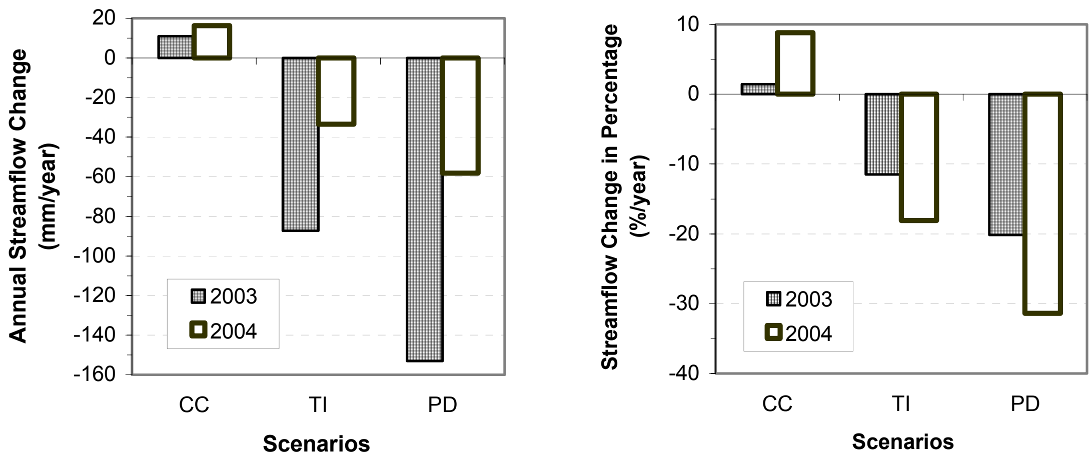

Figure 5-10. Impacts of clearcut and climate change on annual streamflow in total and percentage during 2003-2004 (CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

5.4 Summary

This study showed that MIKE SHE performed reasonably well in simulating daily streamflow at a coastal forested watershed in eastern South Carolina. Generally, the model simulations could capture the dynamics of the streamflow and water table variations at the study site. The modeling 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 two climate change scenarios have great potential impacts on streamflow and water table depth 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. It appeared that the model overestimated ET after clearcut. Future studies are needed to examine how the model describes ET processes under the new land use conditions. One option is calibrating ET parameters and PET calculation method that reflect the management practices on PET.

Chapter 6

Model Evaluation and Application with an Upland Watershed at the Appalachian Mountains in Western North Carolina

6.1 Objectives

The objective of this study is to apply a physically-based distributed hydrologic model, MIKE SHE (coupling with MIKE 11), to better understand the hydrologic processes of a steep slope mountainous forested watershed and its responses to potential land disturbance (such as prescribed fires and vegetation management), and to test its sensitivity to potential climate variability and change.

6.2 Methods

6.2.1 Site description

Coweeta Watershed 2 was selected for model evaluation and application for the upland conditions. This watershed is located at the USDA Forest Service Coweeta Hydrologic Laboratory and Long Term Ecological Research (LTER) Center (Coweeta) in western North Carolina in the southern Appalachian (35°03′N, 83°25′W). The 2185 ha 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 knowledge and information on forest hydrology and the effects of forest management on hydrology have been generated from the research facility (Hewlett, 1961; Hibbert and Troendle, 1988; Helvey and Patric, 1988; Swank and Douglas, 1974; Swank, 1988; Swank et al., 1988; Swift et al., 1975; Swift, 1988).

The 12-ha Watershed 2 (Figure 6-1) is one of Coweeta's control watersheds, and it has not been disturbed since it was clear-cut back in 1927. The paired treatment watershed is the 16-ha Watershed 1, which is located adjacent to Watershed 2. The paired watersheds have contributed to the understanding of basic hydrologic processes and forest conversion effects since they were gaged in 1934 (Swank and Crossley, 1988; Swift et al., 1988; Gaskin et al., 1989). Hydrologic modeling studies have been conducted at these paired watersheds (Vose and Swank, 1992; Vose and Maass, 1999; Yeakley, 1993). Yeakley et al. (1998) conducted a hillslope soil moisture gradient study at watershed 2. The results indicated that hillslope soil moisture gradient was restricted to upper soil layers, with deeper hillslope moisture gradients occurring only with sufficient drought. Their study also showed that topographic features had more control over hillslope soil moisture during drier periods while variations in soil water storage properties were more important during wetter periods. Both watersheds also served as field sites for a fuel load mapping strategy project (Rosenfeld, 2003).

In particular, Watershed 1 has undergone a series of experiments, including prescribed burning, clear-cut and eastern white pine (*Pinus strobus L.*) conversion from hardwoods, to help understand the impacts of the disturbance on hydrology (Swank and Douglass, 1974; Swank and Crossley, 1988; Swank, 1988; Swank et al., 1988). Fifteen years after white pine conversion from mature deciduous hardwoods at Watershed 1, annual streamflow was found to be 200 mm (20%) less than expected for a hardwood cover (Swank and Douglass, 1974). In the following 9 years, annual streamflow reductions were found to be in a range of 100 mm to 200 mm, depending on annual precipitation (Swank et al., 1988).

The climate in Coweeta is classified as marine, humid temperate with water surplus in all seasons. At Watershed 2, mean annual precipitation is about 1772 mm with evenly annual distribution. The mean annual streamflow is around 854 mm, which is 48% of precipitation. Long-term monthly average air temperature is as low as 3.3 °C in January and is as high as 21.6 °C in July (Swift et al., 1988). The watershed has an average slope of 23 ° with a maximum of 49 °, and elevations range from 710 m at the watershed outlet to 1007 m at the ridge top of the watershed. With a south-southeast aspect, the 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 for in this watershed are reported as Chandler and Fannin (Swank and Crossley, 1988; Rosenfeld, 2003).

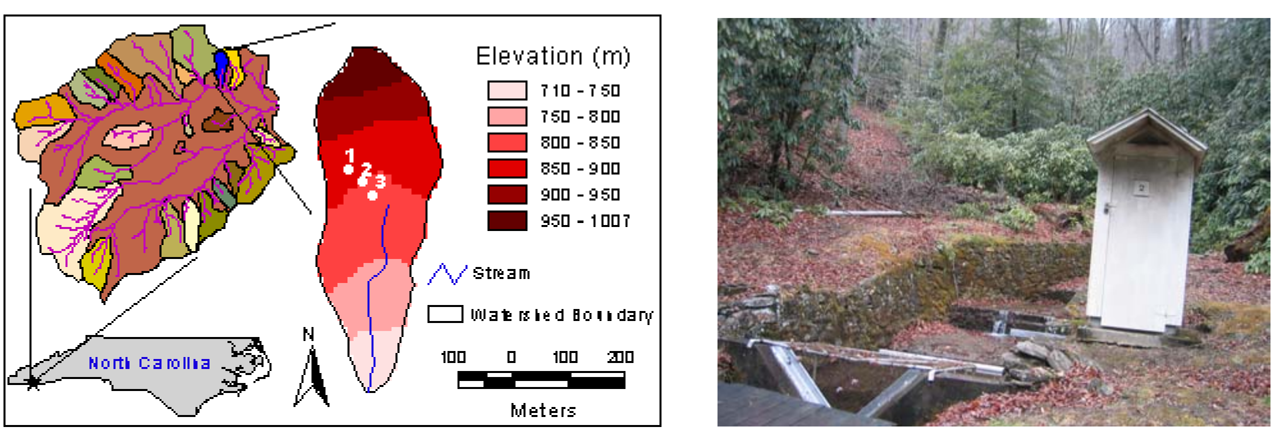

Figure 6-1. Location of the study watershed (Watershed 2) at Coweeta Hydrologic Laboratory in southern Appalachian Mountains, western NC.

6.2.2 Data collection

Historical climate and streamflow data were requested from Watershed 2. Watershed characteristics, soils, and vegetation were derived from the published literature. Coupling with MIKE 11, MIKE SHE model was calibrated and validated with the daily streamflow measured at the watershed outlet. Stream network and stream cross-section survey were conducted for model parameterization.

6.2.3 Model setup and parameterization

Similar to the Santee site in South Carolina described in the last chapter, data required to run the MIKE SHE model at this study site included: 1) Watershed topography and landuse data - surface flow retention storage, Manning roughness number, and vegetation distribution (leaf area index (LAI) dynamics and rooting depth); 2) Soil data - soil depth, hydraulic properties (soil moisture release characteristics); 3) Meteorological data - precipitation and air temperature; 4) Boundary conditions; 5) Initial conditions; and 6) Stream network simulation setup with the coupling of MIKE 11 model (DHI, 2004).

Watershed elevation data (Figure 6-1) were acquired from Coweeta in a 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 scaled up to 20 m to allow for an accurate representation of the watershed without placing excessive demands on model running time. The surface detention storage was set as 15 mm.

Published LAI data for this watershed were found in Vose and Swank (1992). Linear interpolation between winter LAI (0.5) and summer LAI (5) was assumed (Figure 6-2). LAI was assumed the same for each year during the study period (1985-1990). A rooting depth of 80 cm was used for vegetations across the entire watershed (Yeakley, 1993).

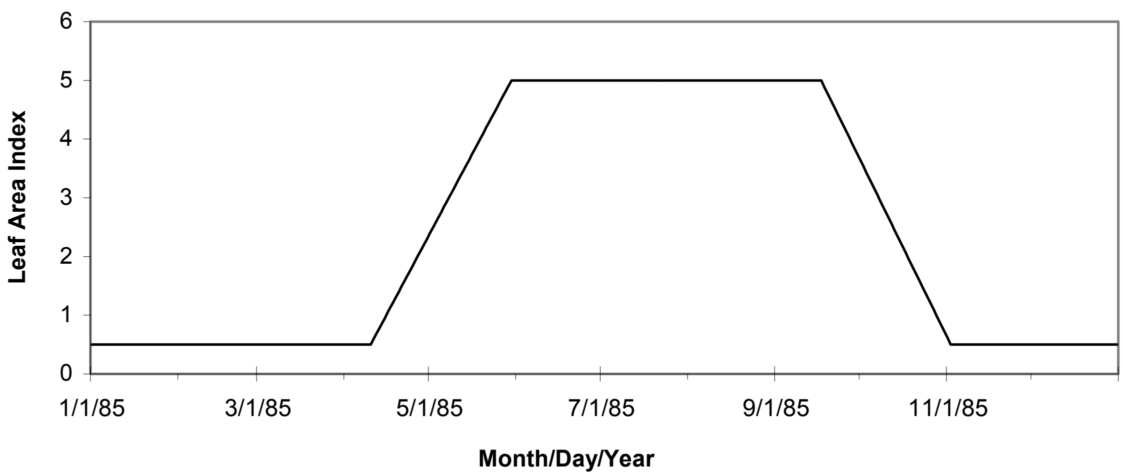

Figure 6-2. Forest Leaf Area Index (LAI) dynamics used by the MIKE SHE model for Watershed 2 (from Vose and Swank, 1992).

Hourly rainfall and daily air temperature data were acquired from Coweeta for the study period 1985-1990. The Hamon potential evapotranspiration (PET) method (Hamon, 1963; Lu et al., 2005) was used to calculate daily PET with the calibrated coefficient (K_{pet}) as 1.3. Daily streamflow data for the period of 1985-1990 were acquired from Coweeta. The unit of streamflow data was in $ft^3/(s.mi^2)$. It was converted into m^3/s and area depth unit in mm/day. The streamflow data were used for MIKE SHE model calibration and validation at this watershed.

Measured soil moisture release characteristics for soils in Watershed 13, a nearby watershed in Coweeta, were used as model inputs (Huff and Swank, 1985; Table 6-1). Soil porosity and saturated hydraulic conductivity parameters used by previous modeling studies (i.e. PROSPER) (Goldstein et al., 1974; Vose and Swank, 1992; Table 6-2) were adopted by this study. Hydraulic conductivity and matric potential relations for unsaturated zones were developed by the van Genuchten method (1991; Table 6-2). The soil data were available for three layers: 0 - 30 cm, 30 - 90 cm and 90 - 180 cm. The soil characteristics below 1.8 m depth were assumed to have the same properties as the 90 - 180 cm layer. The soil depth to bedrock was estimated by field experience and calibrated in this study. A final 3 m depth was determined as described later.

Table 6-1. Soil moisture and suction used by the MIKE SHE model at Watershed 2 (from Huff and Swank, 1985).

Soil Depth	Moisture content (cm^3/cm^3) at indicated soil suction value (kPa)							
(cm)	2	4	6	103.5	207	414	828	1628
0 - 30	0.412	0.36	0.332	0.2	0.169	0.141	0.117	0.096
30 - 90	0.387	0.336	0.311	0.265	0.238	0.207	0.173	0.138
90 - 180	0.360	0.312	0.298	0.241	0.212	0.187	0.157	0.127

Table 6-2. Soil and hydraulic properties for the MIKE SHE model at Watershed 2 (from Vose and Swank, 1992; van Genuchten et al., 1991).

Soil depth (cm)	Porosity (cm^3/cm^3)	Field Capacity (cm^3/cm^3)	Ks (m/s)	α	n
0 - 30	0.610	0.29	1.6×10^{-4}	0.145	2.68
30 - 90	0.500	0.30	1.9×10^{-5}	0.115	1.474
90 - 180	0.499	0.28	1.0×10^{-5}	0.075	1.89

The watershed was assumed as a closed watershed, and there was no leakage through the lateral and vertical watershed boundaries. In other words, water only moved out of the watershed through evapotranspiration and streamflow at the watershed outlet.

The model was first run with the assumption that the water table depth was 2 m below the ground surface across the entire watershed, and 0 m depth of overland flow and streamflow to generate a ‘hot start’ file. Then, a new simulation run, using the ‘hot start’ file of date 12-25-1988 as an initial condition, was conducted. The same initial condition was applied to the rest of simulations at this study site.

MIKE 11 was coupled with MIKE SHE for streamflow simulations. The requirements for the model setup included: 1) Stream network; 2) Stream cross-sectional area at selected sections; 3) Boundary conditions; and 4) Hydrodynamic parameters (such as Manning coefficient). A single perennial stream exists at this watershed. Stream network was surveyed in the field, and cross-sectional areas were measured. Boundary conditions were set as zero inflow at the upstream open end and constant water level (711 m) at the watershed outlet.

6.2.4 Model calibration, validation and applications

Daily streamflow data (1985-1990) from this watershed were used for model calibration and validation. Years 1988 and 1990, which were historically a dry year and a wet year respectively, were used for model calibration to cover two extreme hydrologic years. The rest of the data, including three dry years (1985-1987) and one wet year (1990), were used for model validation.

Similar to the previous three study sites, after model calibration and validation were conducted, MIKE SHE was applied to simulate a base line and three hypothetical scenarios for the study period (1985-1990). 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 remained unvegetated during 1985 - 1990 with LAI reduced to 0.75 in the summer and 0.5 in the winter for the entire watershed (Swift and Swank, 1975).

6.3 Results and discussions

6.3.1 Model calibration

The MIKE SHE model was calibrated against the daily streamflow data from the watershed in 1988 and 1989. Compared to the long-term annual average precipitation of 1770 mm at the watershed, 1988 (1267 mm) was a dry year and 1989 (2341 mm) was a wet year. Manual calibrations were conducted and the calibrated parameters were achieved based on the graphical inspections and statistical parameters (Table 6-3). These calibrated parameters remained the same during the model validation and scenario simulations.

Table 6-3. MIKE SHE calibrated parameters at Coweeta Watershed 2.

Parameters	Parameter Values			
	Initial	**Minimum**	**Maximum**	**Final**
ET Coefficients				
C_{int}	0.05	0.05	0.8	0.5
C1	0.3	0.05	1	0.3
C2	0.2	0.05	0.5	0.1
C3	20	5	30	30
A_{root}	0.5	0.1	1	1
Soil depth (m)	1.8	1.8	6	3
Surface Manning Coefficient ($m^{1/3}/s$)	5	1	10	6

Generally, the model could simulate the variations of streamflow with R = 0.88, ME = -0.04 mm/day and E = 0.74 (Figure 6-3). The model mostly simulated the streamflow within a 1 mm/day discrepancy from the measurements, and the simulations had a good correlation with the measurements (Figure 6-4 and Figure 6-5). The biggest differences were found in January of 1988 and the summer of 1989. Approximately a 7 mm/day difference in the early 1988 might be partly caused by the initial condition setup in the MIKE SHE modeling system. The base line simulation run from 1985 to 1990 showed that the difference was reduced to 5 mm/day. Another reason was likely that the rainfall intensity represented in the MIKE SHE modeling system was lower than that in the reality. Rainfall intensity data was recorded at about 30 minutes to 1.5 hours intervals for that storm. In the MIKE SHE modeling system, it was assumed that rainfall intensity was uniform during those 30 minutes or 1.5 hours periods, depending on the rainfall records. However, big variations of rainfall intensity might exist during those periods and thus resulted in bigger discrepancies between the simulations and measurements. The largest discrepancy in the summer of 1989 might be due to the relatively shallow soil depth setup in the MIKE SHE modeling system. Since there was no soil data available for the soil below 1.8 m depth at this watershed, the soil depth was calibrated to be 3 m, and it was distributed uniformly across the entire watershed. In reality, the soil depth is very likely to be variable across the watershed. Attempts were conducted by Cweeta to investigate the weathered profile depth throughout the Coweeta Basin. However, a relationship between the depth to bedrock and the percentage of distance between stream and ridge was not found (Yeakley, 1993; Miner, 1968). We suspected that the depth to bedrock was deeper than 3 m depth in some areas (Vose and Maass, 1999), however, there was no such soil and hydrologic data available. With a 3 m soil depth, soil storage might be underestimated.

The variable source area was rather large during the big storms in June and July of 1989. Model simulations showed that many cells were saturated adjacent to the stream. After the storms, variable source area shrinked and resulted in much less streamflow than the measurements.

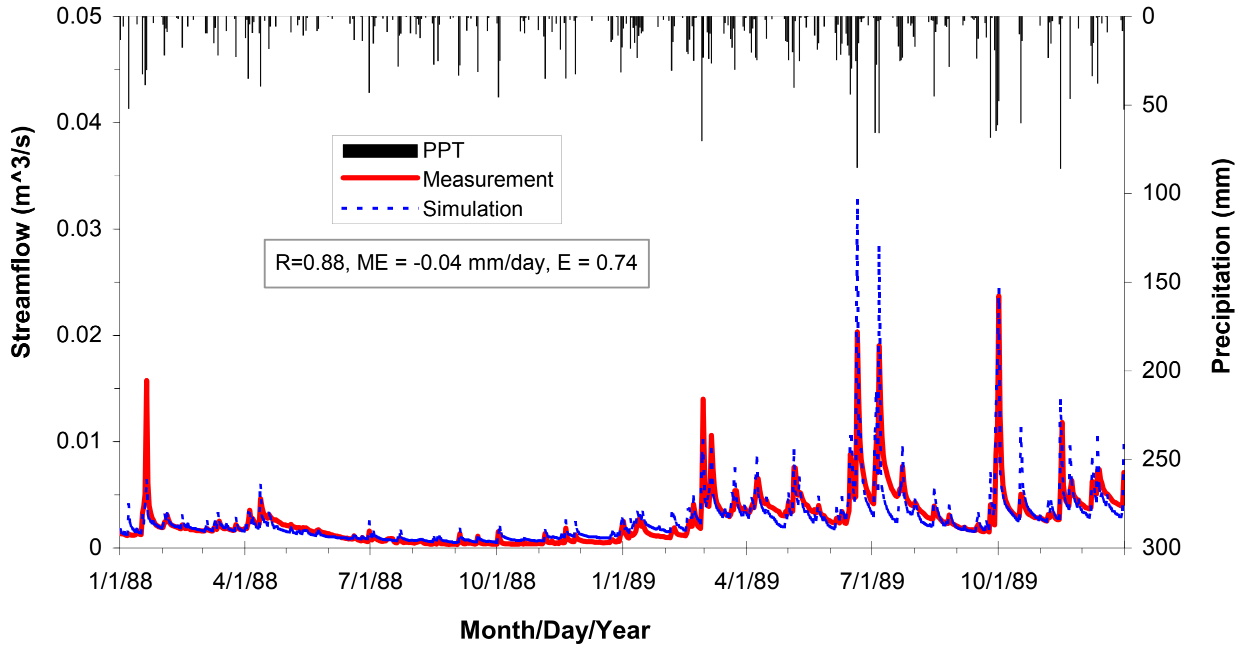

Figure 6-3. Model calibration with daily streamflow during 1988-1989.

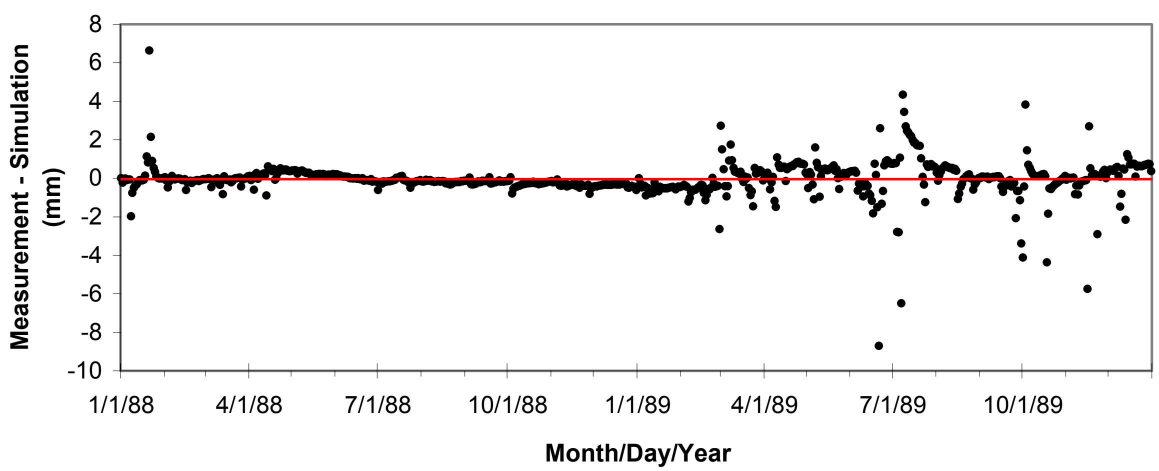

Figure 6-4. Daily streamflow differences of the simulation and measurement during the calibration period (1988-1989).

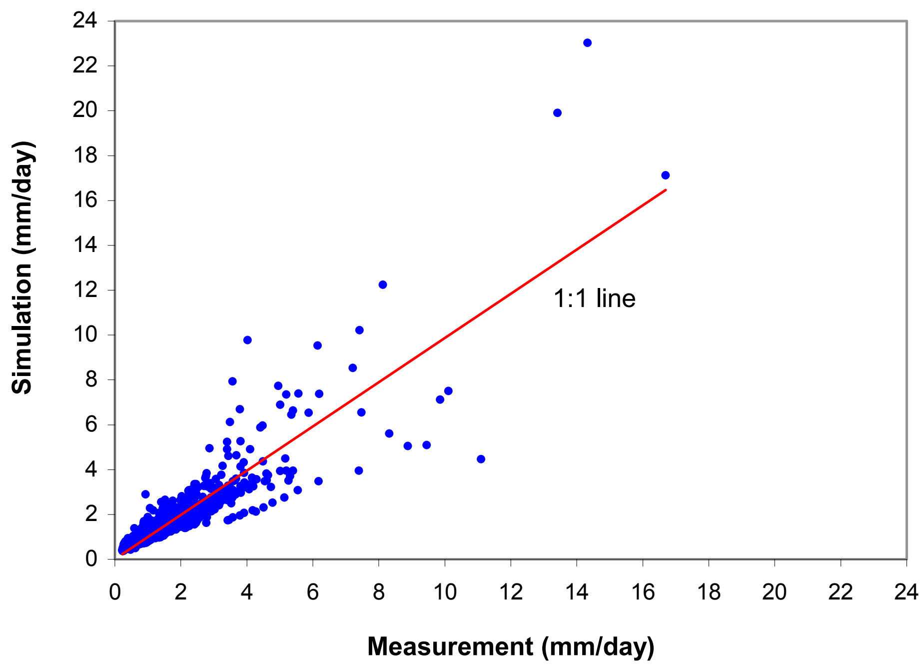

Figure 6-5. Daily streamflow of the simulation and measurement during the calibration period (1988-1989).

On the annual basis, the model slightly over-predicted streamflow by 31 mm in 1988, but the streamflow in 1989 came to an almost identical value of 1019 mm as the measurement (Figure 6-6). Thus, during the calibration period, cumulative streamflow was very close to the measurement with a discrepancy of 32 mm, which was 2.4% of the measurement.

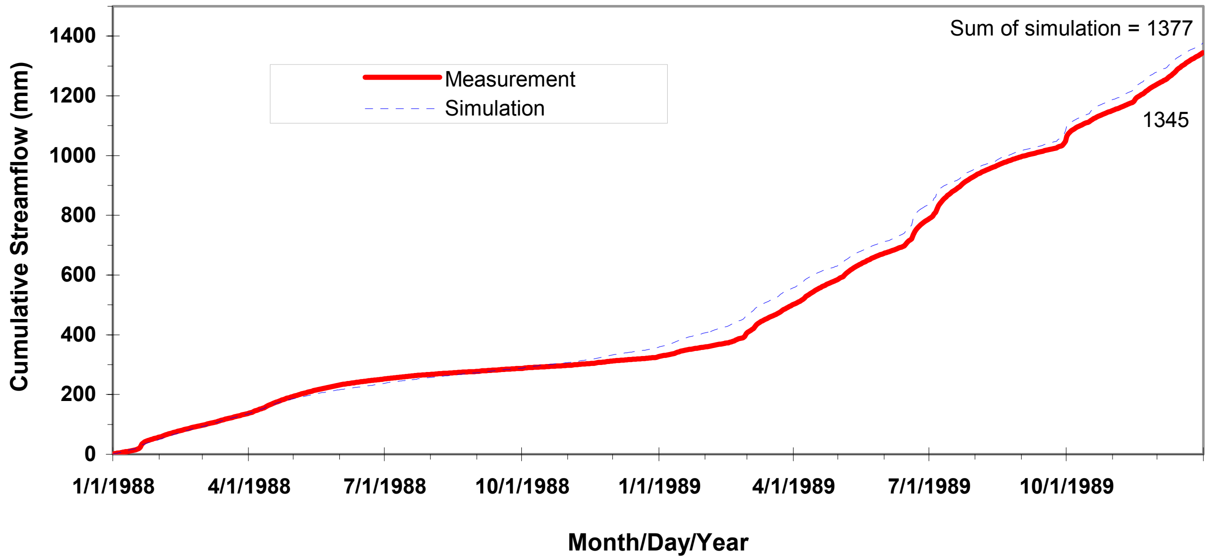

Figure 6-6. Cumulative streamflow of the simulation and measurement during the calibration period (1988-1989).

6.3.2 Model validation

The MIKE SHE model was validated with the daily streamflow data recorded in 1985-1987 and 1990. Compared to the long-term annual average precipitation at the watershed, 1985-1987 were dry years and 1990 was a wet year. According to Gaskin et al. (1989), during the period of October 1985 to November 1986, the watershed experienced a precipitation deficit of 734 mm. Similar to the calibration, the model generally could catch the streamflow dynamics with R = 0.85, ME = 0.04 mm/day and E = 0.72 (Figure 6-7). With a good correlation with the measurements, simulated streamflow values were in a reasonable range of the measurements except during the big storms in February and March of 1990 (Figure 6-8 and Figure 6-9).

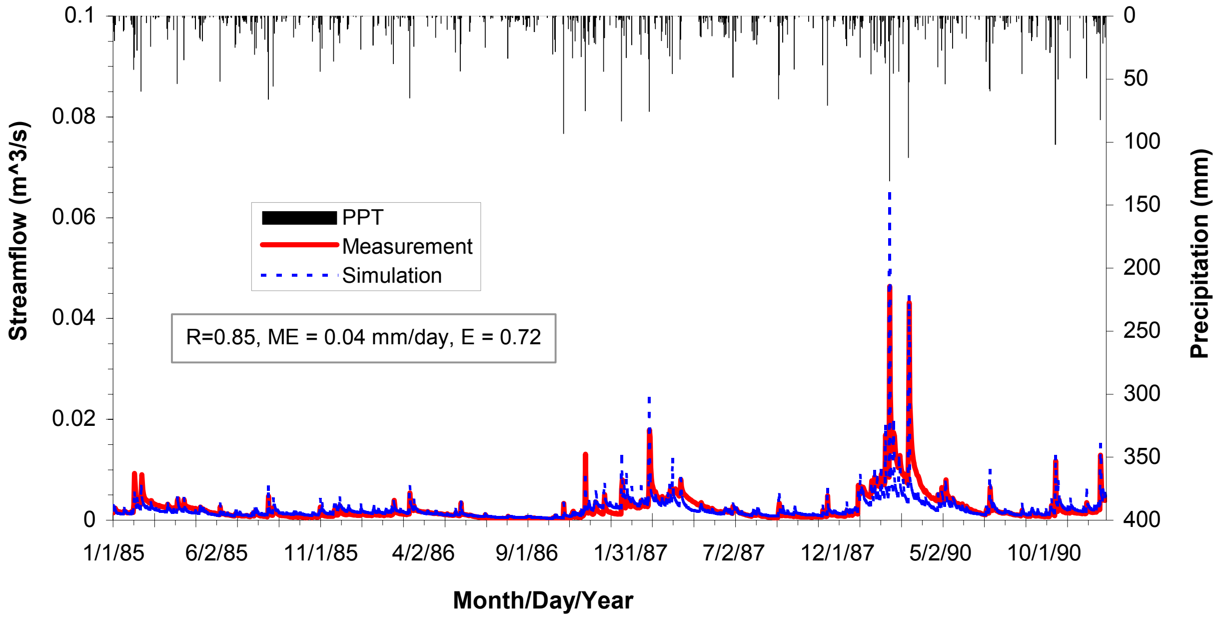

Figure 6-7. Model validation with daily streamflow during 1985-1987 and 1990.

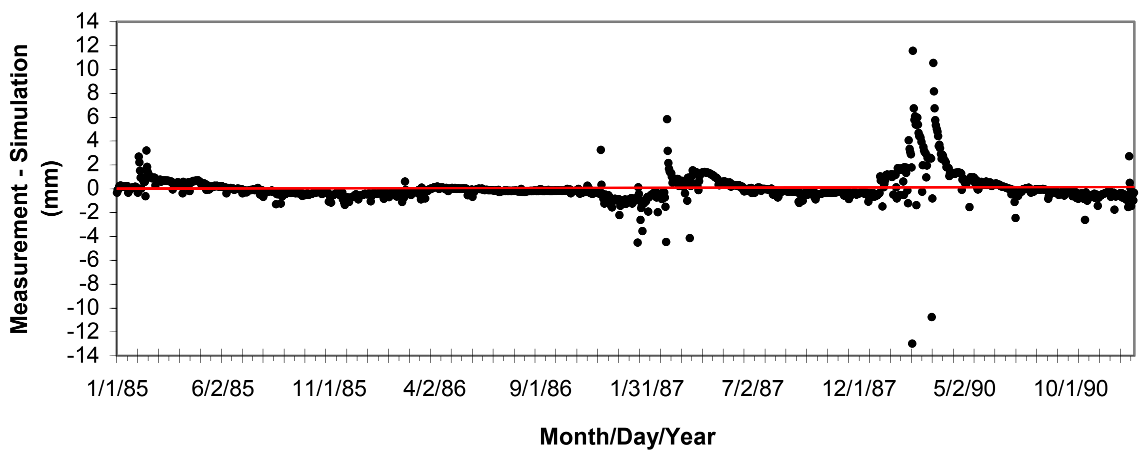

Figure 6-8. Daily streamflow differences of the simulation and measurement during the valibration period (1985-1987 and 1990).

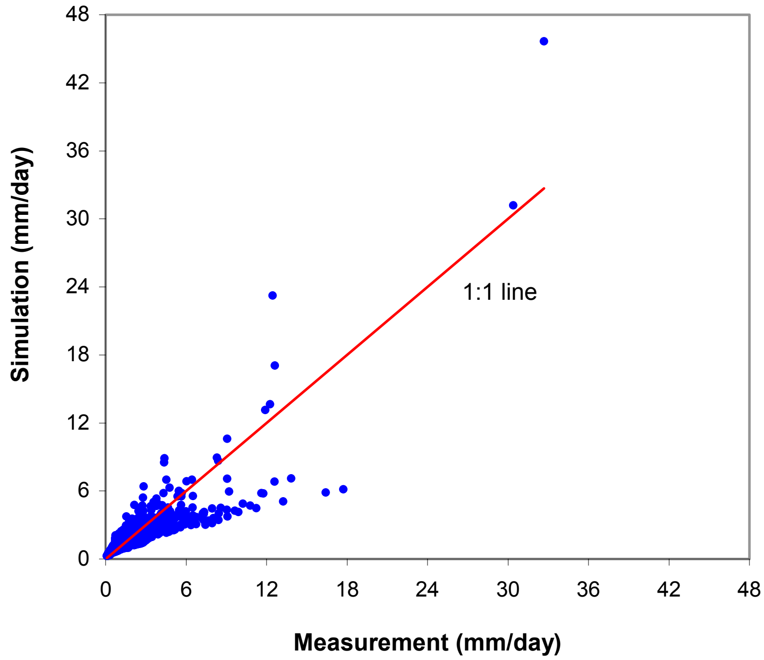

Figure 6-9. Daily streamflow of the simulation and measurement during the valibration period (1985-1987 and 1990).

On 02-16-1990, the daily rainfall was 131 mm, the largest storm during the study period of 1985 –1990, with 20 mm rainfall on the previous day and no rainfall at all on the next day (Table 6-4). The measured streamflow data were 33 mm on that day and 18 mm on the next day. The MIKE SHE model predicted corresponding values of 46 mm and 6 mm, respectively. A month later, on 03-16-1990, the daily rainfall amount was 112 mm with 3 mm on the previous day and 52 mm on the next day. The measured streamflow data were 12 mm on that day and 30 mm on the next day. The MIKE SHE model predicted corresponding values of 23 mm and 31 mm, respectively. Daily discrepancies might be large. However, the differences were still in a small range for the total discharge (Table 6-4).

Table 6-4. Daily streamflow validation during two big storms in 1990.

Storm	Date	Precipitation (mm)	Measured Streamflow (mm)	Simulated Streamflow (mm)	Measurement – Simulation (mm)
Storm1					
	2/14/1990	0	6	3	3
	2/15/1990	20	6	4	2
	2/16/1990	131	33	46	-13
	2/17/1990	0	18	6	12
	Total	**151**	**63**	**59**	**4**
Storm 2					
	3/14/1990	0	5	3	2
	3/15/1990	3	5	3	2
	3/16/1990	112	12	23	-11
	3/17/1990	52	30	31	-1
	3/18/1990	0	16	6	10
	Total	**167**	**68**	**66**	**2**

On an annual basis, the model slightly over-predicted streamflow in the early 1985, but it came to a very close agreement with the measurement by the end of the year (Figure 6-10). The model consistently over-predicted streamflow in the next two dry years - 1986 and 1987. In 1990, a wet year during the validation period, however, the model under-predicted the streamflow by 193 mm, the biggest discrepancy during the six-year study period. Thus, by the end of the validation period, cumulative streamflow was still in a good agreement with the measured data with a discrepancy of 55 mm, which was only 2.3% of the measurement.

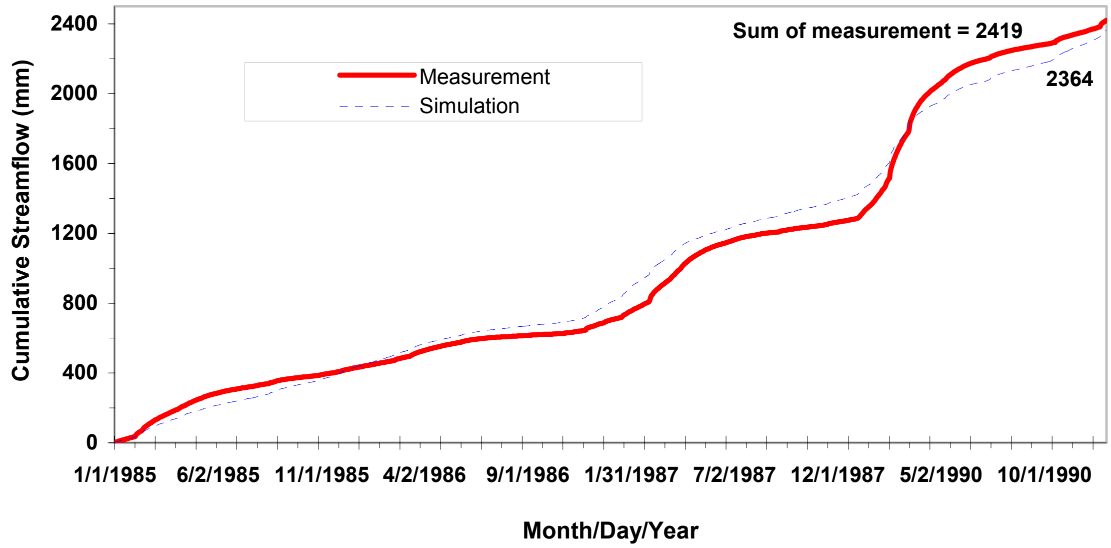

Figure 6-10. Cumulative streamflow of the simulation and measurement during the valibration period (1985-1987 and 1990).

The validation clearly showed that the model had a tendency of over-predicting streamflow in a dry year and under-predicting it in a wet year, but the model had a good agreement overall. This pattern was also valid if the entire calibration and validation period was considered. The model over-predicted total streamflow during the calibration period and under-predicted it during the validation period. Thus, overall, the model performed well for this multiple-year simulation.

Similar to the Santee site in the last chapter, a transect, running through three locations near the headwater area (Figure 6-1), was used to illustrated the ground water table dynamics relative to the ground surface during the study period (Figure 6-11). During dry seasons, the water table was far below the ground for all cells. With the rainfall recharge during wet seasons, however, the water table rose up and could reach the ground surface for extreme wet periods in 1987 and 1988. However, even for stream cells, saturation was not common in 1985. The model results showed that a ground water table gradient existed along the transect. If a location was nearer to the stream, the closer its water table was to the ground surface. This pattern was also spatially simulated by the model (Figure 6-12).

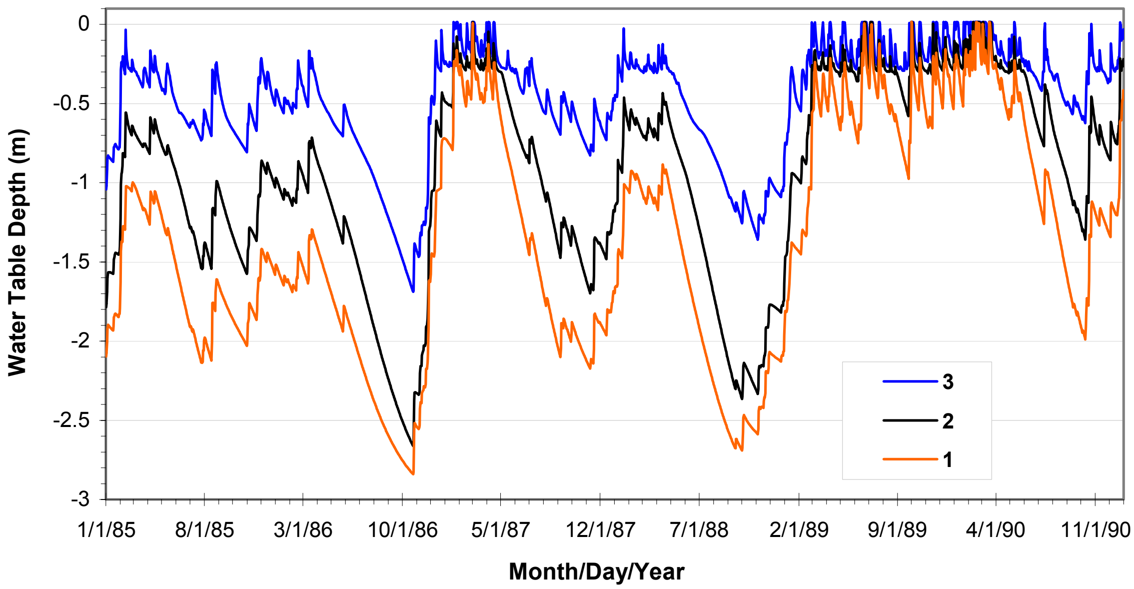

Figure 6-11. Model simulations of temporal water table dynamics across a transect near headwater during 1985-1990.

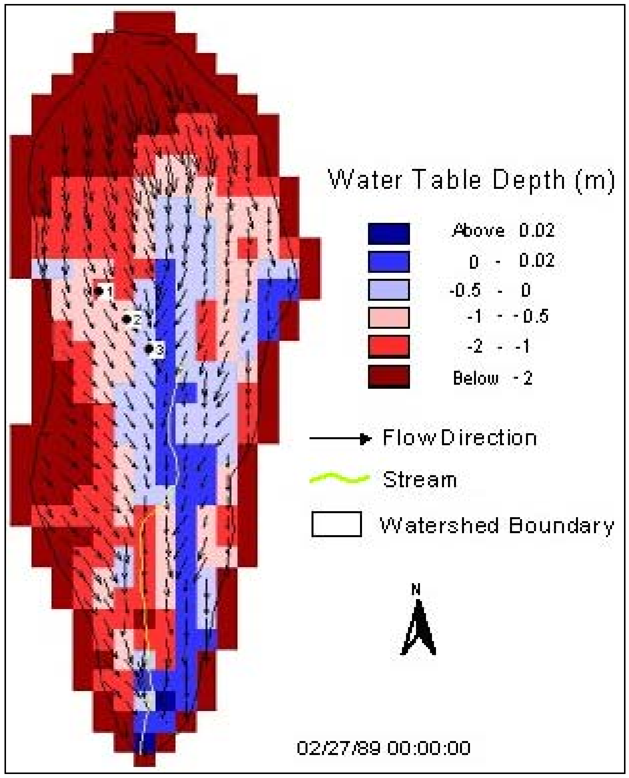

Figure 6-12. Model simulations of spatially distributed water table depth and flow direction on 02-27-1989 (20 m cell size).

6.3.3 Model applications

After the model calibration and validation were performed, MIKE SHE was applied to simulate the base line and evaluate the effects of three hypothetical scenarios on streamflow during 1985-1990. The model results confirmed the measurements that there was a big variation of annual streamflow from this small watershed in the wet years and the dry years (Figure 6-13). Annual streamflow can double and even triple in a wet year when it was compared to a try year. The model results also suggested that clear-cut would increase streamflow, while the climate change scenarios would result in decrease of streamflow (Figure 6-14).

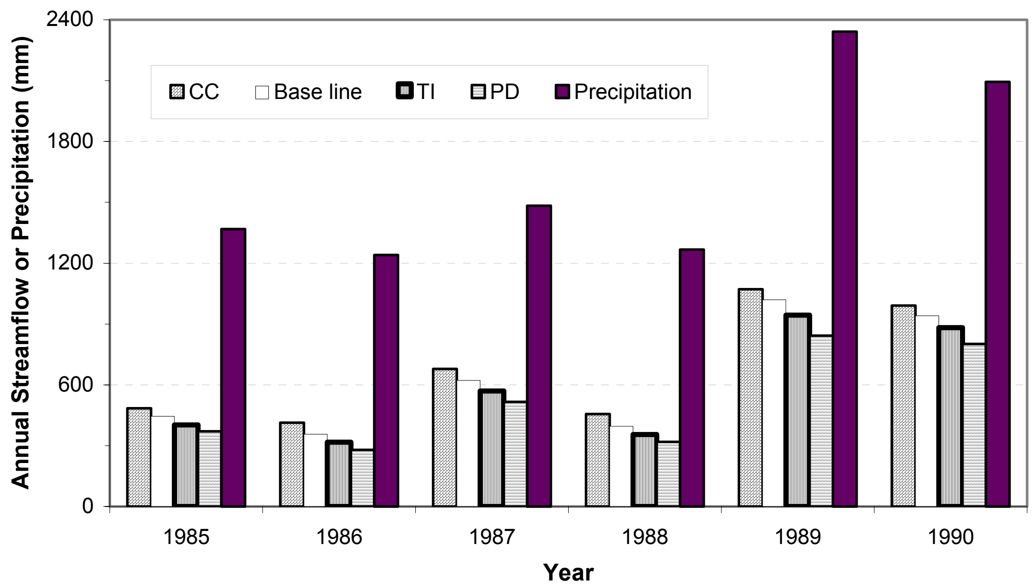

Figure 6-13. Annual streamflow responses to the impacts of clearcut and climate change during 1985-1990 (BL - base line; CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

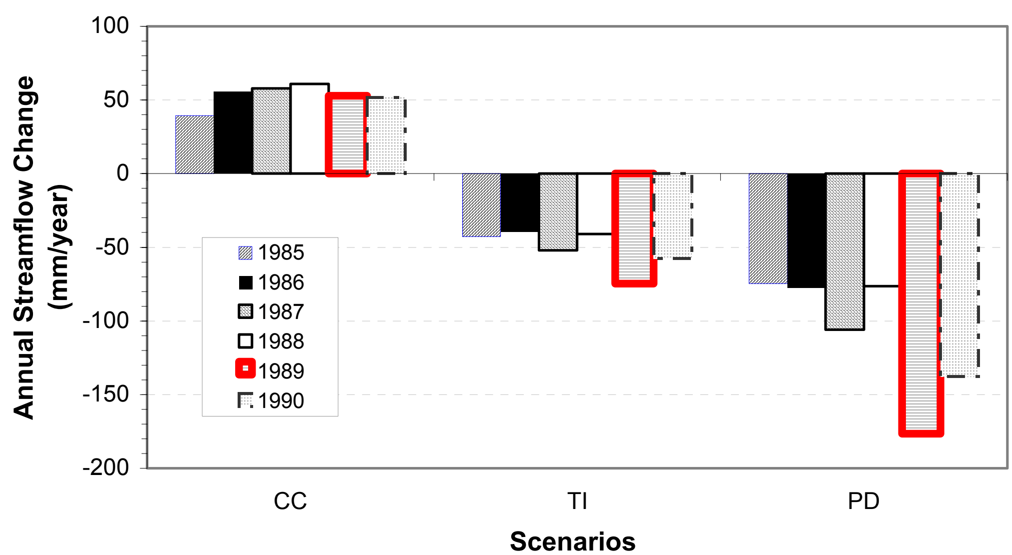

Figure 6-14. Impacts of clearcut and climate change on annual streamflow in terms of differences to the base line during 1985-1990 (CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

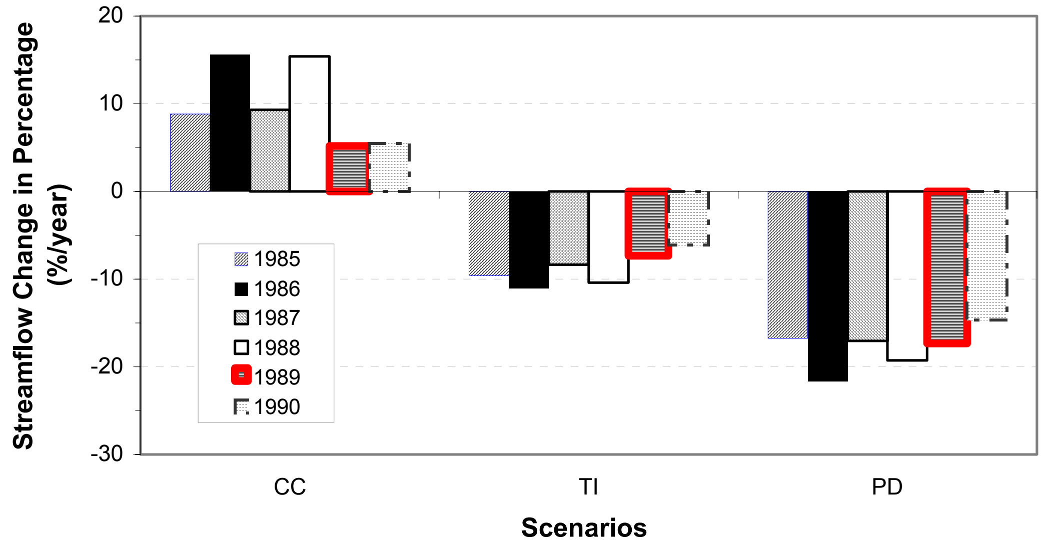

Figure 6-15. Impacts of clearcut and climate change on annual streamflow in terms of differences in percentages of the base line during 1985-1990 (CC - clearcut; TI - 2 °C temperature increase; PD - 10% precipitation decrease).

The magnitudes of streamflow increase due to clear-cut appeared no difference between the dry years and wet years (Figure 6-14). Thus, the percentage of the increase was greater in a dry year than a wet year (Figure 6-15). For the climate change scenarios, the magnitudes of streamflow decrease were larger in a wet year than in a dry year (Figure 6-14). However, there were not much different in terms of the percentages (Figure 6-15).

During the 6-year study period, the magnitudes of streamflow increase due to clearcut were in a range of 39 mm to 61 mm. These values were considered too small when compared to most literature (Swank et al., 1988; Sun et al., 2004) and modeling studies (Swift et al., 1975; Sun et al., 2004), which indicated that clearcut would increase streamflow by 260 mm to 410 mm. Under-estimating hydrologic responses was explained by the over-estimation of ET under harvesting conditions. Similar to the Santee watershed, the model results showed that ET of the clearcut scenario remained similar to the base line after the watershed was harvested. At location 2 near the headwater (Figure 6-1 and Figure 6-12), for instance, average ET reduction due to clearcut was only 79 mm/year with a range of 27 mm to 103 mm during 1985 - 1990. The model might have over-estimated soil evaporation under the optimum soil moisture conditions in Coweeta. In reality, however, harvested forest floors were generally covered by litter and other residual materials that may greatly prevent large amount of soil moisture loss by soil evaporation. Future studies are needed to examine how the model describes evapotranspiration processes under harvesting conditions.

Larger streamflow responses to the PD scenario were found (Figure 6-14 and Figure 6-15). The PD scenario resulted in 75 - 177 mm streamflow reduction. Thus, the model simulations indicated that 10% decrease of precipitation would result in 15 - 22% reduction of streamflow. The 2 °C air temperature increase would result in 39 - 75 mm or 6 - 11% streamflow decrease.

6.4 Summary

This study showed that the MIKE SHE/MIKE 11 modeling system could be used to simulate streamflow at a steep Appalachian mountainous watershed. Generally, the model simulations could capture the dynamics of the streamflow variations at this small watershed. The model simulations indicated that climate change in both air temperature (2 °C increase) and precipitation (10% decrease) will have potential to reduce streamflow by 6% to 22%. However, in the harvesting simulation, the magnitudes of streamflow increase due to clearcut appeared much smaller than most literature suggested. Thus, future studies are needed to examine how the model describes ET processes under the land use change conditions. A process-based ET model is needed to fully describe the soil evaporation processes under harvested conditions. Litter interception and its effects on soil evaporation need to be considered in order to predict ET more accurately for forested conditions.

Chapter 7

Discussion and Conclusions

Due to significant physiographic and climatic gradients, documented in over half century of studies across the southeastern U.S., empirical data suggested that hydrologic pathways and processes vary greatly from the coastal plain to the mountainous uplands. The coastal plain is a ground water dominated system with a shallow water table, while the mountainous upland is a hillslope controlled system (Sun et al., 2004). It was hypothesized that different regions have different hydrologic responses to forest management and climate change because of different topography, climate, soil, and vegetation conditions. The hydrologic impacts of climate change and forest management practices are complex, and a computer simulation model was selected as a tool to test the hypothesis and conduct this study.

This study was the first attempt to apply a single advanced, distributed hydrologic model to simulate the watershed hydrologic process and its responses to forest management and climate change in two contrasting regions in the southeastern U.S. Four watersheds, one in the Appalachian mountainous upland and three in the lower coastal plain, were selected as research sites to conduct the study. A physically-based, distributed hydrologic modeling system, MIKE SHE/MIKE 11, was chosen as a research tool to carry out the task. Similar procedures were applied at the four study watersheds.

The model was first evaluated at the four study sites with long-term data representing the best forest hydrology research in the southeastern U.S. The results indicated that different hydrologic processes were simulated adequately by the model in these two contrasting regions. Then, the model was applied to simulate the hydrologic impacts of forest management and climate change at these four study watersheds. Four simulation scenarios were performed at each site. These included the base line, clearcut, 2 °C temperature increase, and 10% precipitation decrease scenarios. Water table level and streamflow amount were selected as responses to test the forest management and climate change impacts.

7.1 Hydrologic responses

7.1.1 Forest management impacts

A clearcut was one forest management practice represented in this study. It was difficult to quantify soil parameter changes under this scenario, thus, LAI reduction was the only change. Water table responses were investigated in the three wetland-dominated watersheds, while streamflow responses were examined both on the coastal plain and on the mountainous upland.

Generally speaking, model simulations suggested that forest removal would cause water table levels to rise. However, the results indicated that there were no significant impacts on wetland water table levels during wet periods. The impacts could be pronounced during the dry seasons as water table levels rose at the Flatwoods sites and the Santee watershed due to the clearcut. These seasonal impact patterns agreed with similar field studies (Sun et al., 2000a; Riekerk, 1989; Bliss and Comerford, 2002) although the response magnitude from this study might not be similar.

Several factors may have contributed to the water table response. Canopy interception and plant transpiration were reduced under the clearcut due to the remove of leaf biomass. Therefore, ET was decreased and more water was available to recharge the groundwater, particularly during dry periods. During wet periods, however, water table levels were close to or even at the ground surface. Therefore, there was sufficient water for plant use, and PET demand was satisfied most of the time. The impacts on water table levels due to the clearcut were minimum, but they were stronger during the dry periods when the water table was well below the ground surface.

These seasonal impact patterns did not occur at the Alligator River Pocosin wetland. This was likely due to the fact that it is a very wet site with water table within 40 cm below the ground surface year round. If more data were available for this site, especially for a dry year, impacts might be detected. Long-term monitoring data are critical for wetland hydrologic studies.

Streamflow responses to clearcut were detected at watersheds on the coastal plain and on the mountainous upland. At the Santee watershed, the clearcut scenario would increase streamflow by 11 mm in 2003 and 16 mm in 2004, representing 1% and 9% of the base line streamflow, respectively. Again, this response is considered rather low. At Coweeta Watershed 2, during the six-year study period of 1985-1990, streamflow increase resulted from clearcuts ranged from 39 mm to 61 mm, 5% to 16% of the base line streamflow. Streamflow increase was caused by ET decrease, because the loss of leaves made more water available for stream channel and annual streamflow.

At each watershed, the absolute magnitude of streamflow increase due to clearcut appeared no different between a dry year and a wet year, but the percentage increase was greater in a dry year than in a wet year. The absolute magnitudes and percentages of streamflow increase were slightly higher at the Coweeta watershed than at the Santee watershed. However, these small differences might not be significant. Furthermore, the Santee watershed had only two years of data for the clearcut simulations. These two years were one wet year (300 mm surplus in precipitation compared to the long-term average) and one dry year (409 mm deficit in precipitation compared to the long-term average). More data will be available in the future, as this watershed is under long-term monitoring. The Coweeta watershed had six years of data with which to evaluate the clearcut impacts, including two wet years and four dry years.

However, the absolute magnitudes of streamflow increase at the two watersheds were considered very small when compared to literature (Swank et al., 1988; Riekerk, 1989; Sun et al., 2004) and modeling studies (Swift et al., 1975; Sun et al., 2004) that indicated clearcut would increase streamflow by 260 mm to 410 mm. Underestimation of hydrologic responses was caused by the over-estimation of ET under harvested conditions in the MIKE SHE modeling system. This study revealed that MIKE SHE over-predicted soil evaporation from harvested lands under the optimum soil moisture conditions in Coweeta and Santee. In reality, however, litter and forest residuals generally cover harvested forest floors. Therefore, they may greatly prevent a large amount of soil moisture loss by soil evaporation. Thus, this study suggested a process-based ET model is needed to fully describe the soil evaporation processes under forest harvest conditions. Litter interception and its effects on soil evaporation need to be considered to predict ET more accurately for forest harvest conditions.

Because ET was over-estimated by MIKE SHE under the forest harvest conditions, the impacts of the clearcut on wetland water table levels were likely more pronounced than the magnitudes that were presented in this study during the dry periods. It is unlikely that impacts during the wet periods would differ significantly.

PET is not a very clear concept (Lu et al., 2005; Nokes, 1995). PET for harvested conditions is unknown before calibration. MIKE SHE performance is sensitive to the PET method used (Vazquez and Feyen, 2003). This study did not calibrate PET model for harvested conditions. Generally, PET for harvested conditions is considered less than PET for forested conditions. However, it is difficult to quantify PET for harvested conditions. Grace and Skaggs (2006) used the Penman-Monteith method (Monteith, 1965) to calculate PET for forested conditions and for a fifth row thinning condition in eastern North Carolina. PET was reduced by 20% to 29% due to the thinning (Grace and Skaggs, 2006).

Another clearcut scenario was simulated at the Coweeta Watershed 2 with base line PET decreased by 20% in addition to LAI reduction. The results showed that the streamflow increased much more than under the clearcut scenario that used the base line PET (Figure 7-1 and Figure 7-2). Over a six-year average, streamflow increased 64 mm/year more than under the clearcut scenario, which corresponds to an average of 11% more than the clearcut scenario. PET for harvested conditions might be lower than that for thinning conditions. In that case, streamflow was expected to increase more due to clearcut. However, it is difficult to estimate PET for harvested conditions.

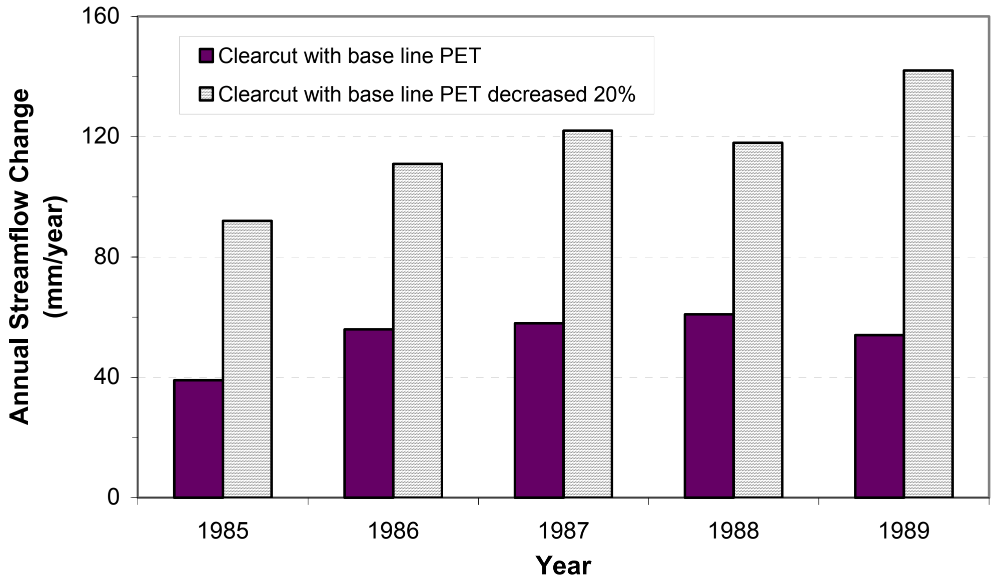

Figure 7-1. Impacts of two clearcut scenarios on annual streamflow in terms of differences to the base line during 1985-1990 at the Coweeta Watershed 2.

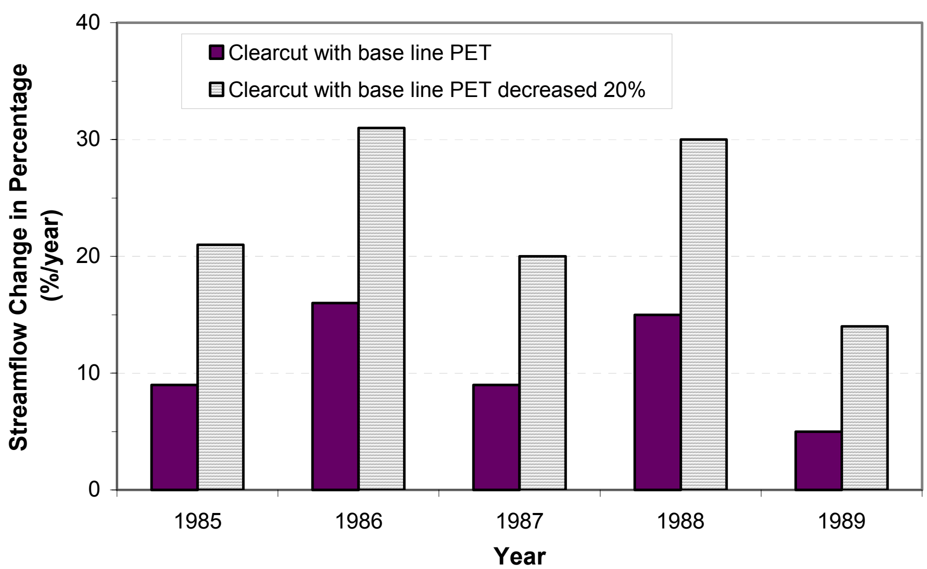

Figure 7-2. Impacts of two clearcut scenarios on annual streamflow in terms of differences in percentages of the base line during 1985-1990 at the Coweeta Watershed 2.

7.1.2 Climate change impacts

Similar to the impact evaluations under the clearcut scenario, water table responses to the climate change scenarios (2 °C temperature increase and 10% precipitation decrease) were inspected at the three wetlands, while streamflow responses were investigated on the coastal plain and on the mountainous upland.

The simulation results suggested that there were no significant impacts on water table levels under the wet conditions. However, the impacts could be pronounced under the dry conditions as water table levels dropped due to a 2 °C temperature increase or a 10% precipitation decrease at the three wetland watersheds. Although these seasonal impact patterns were similar for both climate change scenarios, the mechanisms were different. When temperature was increased 2 °C, ET was increased due to the increase in driven energy (PET). Therefore, water table levels dropped lower than the base line as more water was lost through ET. However, when precipitation was decreased 10%, the water input was less than the base line condition and recharge was decreased. Therefore, the water table was lower than the base line. Thus, a 2 °C temperature increase resulted in more water loss from the wetlands than the base line, while a 10% precipitation led to less water recharge to the wetlands. During the wet periods, water table levels were close to the ground surface or at the surface. Therefore, the impacts on water table level due to either a 2 °C temperature increase or a 10% precipitation decrease were minimal. However, during dry periods when the water table was well below the ground surface, the impacts were stronger and the effects were detected by variations of the water table.

Thus, this study indicated that forest management and climate change would have potential impacts on wetland water table and hydroperiod, the fluctuation of the water table over time. Therefore, forest management and climate change will likely affect wetland hydrology, which is an important characteristic of wetlands (Skaggs et al., 1994). Furthermore, the change in hydroperiods might result in changes in wetland biogeochemical cycles (Sun et al., 2006b).

This study suggested that climate change would have potentially large impacts on streamflow on the coastal plain and mountainous uplands of the southeastern U.S. Both climate change scenarios resulted in streamflow reduction in the Coweeta and the Santee watersheds. However, the causes were different for the two climate change scenarios: streamflow reduction was caused by ET increase under the 2 °C temperature increase scenario and by less water contribution to the stream channel under the 10% precipitation decrease scenario.

The absolute magnitudes of streamflow reduction were larger in a wet year than in a dry year for both watersheds under both climate change scenarios. At the Santee watershed, a 10% decrease in precipitation resulted in 153 mm and 58 mm streamflow decreases in a wet year and a dry year, respectively; the 2 °C air temperature increase resulted in 87 mm and 34 mm streamflow decreases in a wet year and a dry year, respectively. On the other hand, at the Coweeta watershed, a 10% precipitation decrease resulted in a range 138 to 177 mm and 75 to 106 mm streamflow decreases in the wet year and the dry year, respectively; the 2 °C air temperature increase resulted in a range of 58 to 75 mm and 39 to 52 mm streamflow decreases in the wet year and the dry year, respectively.

At the Santee watershed, simulation results indicated that streamflow reduction percentages were higher in a dry year than in a wet year due to climate change. A 10%

precipitation decrease resulted in 20% and 31% mm streamflow decreases in a wet year and a dry year, respectively; a 2 °C air temperature increase resulted in 12% and 18% streamflow decreases in a wet year and a dry year, respectively. At the Coweeta watershed, however, it appeared that streamflow reduction percentages were not much different between the wet year and the dry year. A 10% precipitation decrease resulted in a range of 17% to 22% and 15% to 17% streamflow decreases in the wet year and the dry year, respectively; a 2 °C air temperature increase resulted in a range of 8% to 11% and 6% to 7% streamflow decreases in the wet year and the dry year, respectively. Across the two watersheds, the absolute magnitudes of streamflow reduction were similar in wet and dry years. However, the streamflow reduction percentages were higher in the Santee watershed than in the Coweeta watershed if a wet year or a dry year was compared between the two watersheds. These results seemed to suggest that the Santee watershed was more sensitive to climate change than the Coweeta watershed. However, the Santee watershed had only two years of data for the climate change simulations, while the Coweeta watershed was better represented with six years of data.

7.2 Model performance

As a distributed, physically-based hydrologic modeling system, MIKE SHE integrates surface and ground water simulations. The model simulates the full hydrologic cycle characteristics of a forest ecosystem, including ET and vertical soil water movement in the unsaturated zone to the groundwater. Therefore, it could be applied to both lowland and upland conditions. Furthermore, MIKE SHE has been intensively reviewed and widely used for various projects in the literature (Thompson et al., 2004;

Sonnenborg, 2003; Vazquez and Feyen, 2003; Xevi et al., 1997). Based on independent reviews, MIKE SHE has consistently received the top rank (El-Nasr et al., 2005; Tague et al., 2004; Yang et al., 200; Camp Dresser and McKee Inc., 2001).

The model has a Windows-based user-friendly interface. It is relatively easy to set up and run the model. MIKE SHE has the advantage of GIS linkage. It is tightly integrated with ESRI's ArcView GIS file formats, and ArcView can be used for both pre-processing of input data and post-processing of output data. Therefore, it is easy to manipulate and manage the distributed data. Data can also be directly copied and pasted between MIKE SHE time series and Microsoft Excel, which helps to prepare input data and extract output data. Furthermore, MIKE SHE has elaborate result viewers, which can be used to explore the response surface of a simulation. These include the utilities to animate a time-series of spatially distributed results. Thus, it helps visualize the dynamics of hydrologic processes. These are great assets for a modeler to not only review and present the simulation results, but also to understand the underlying hydrologic processes.

Generally, MIKE SHE performed reasonably well for forested watersheds in both uplands and wetlands. It captured variations in water table dynamics temporally and spatially in wetlands. It also caught streamflow dynamics at watersheds in both the coastal plain and the mountainous uplands. MIKE SHE confirmed field observations of horizontal groundwater flow patterns between the wetlands and the surrounding uplands in a typical Flatwoods landscape (Crownover et al., 1995). MIKE SHE had the advantages in presenting temporal flow dynamics spatially across the landscape and inspecting them in intensive time steps and spatial scales. Model simulations could also help quantify the flow. Streamflow simulations performed relatively better at the high gradient watershed than the one on flat land. However, more field data are needed to evaluate streamflow simulations at the Santee watershed, as long-term monitoring data are critical for model evaluation and application.

As a comprehensive, integrated hydrologic model, MIKE SHE requires extensive physical input parameters. In many cases, some of the parameters are not available. It is difficult if not impossible to obtain all the detailed spatial features (e.g., depth to the bedrock or the confining layer) as inputs for the model. The availability of the computational resources (speed and memory), especially computer speed, will limit detailed representations of the modeling system. It can take a long time to run a single simulation, depending on the options selected, the size of the study area, time periods of the simulation, etc. At the 12-ha Coweeta Watershed 2, for instance, it took approximately 24 hours to run a six-year (1985-1990) simulation with 20 m cell size on a computer with Pentium 4 CPU 1.7 GHz processor and 1 GB of random access memory.

Because MIKE SHE is commercial software, source code is not available for users to modify in order to meet the specific needs of individual projects. Model usage assumes and requires that users have a hydrology background, which makes it challenging for new users to apply the model, and the learning curve can be steep.

In terms of model mechanisms, MIKE SHE only simulates vertical unsaturated water movement. Under forested conditions, lateral unsaturated flow can be high and cannot be ignored, especially for steep slope watersheds on mountainous uplands. The empirical ET model of the Kristensen-Jensen method was developed from an agricultural field; it raises concerns for applications under forested conditions. Furthermore, ET models in MIKE SHE do not differentiate tree species for ET estimates. This might cause some errors in ET calculations. According to the Ewers et al. (2002) study in northern Wisconsin, canopy transpiration cannot be estimated by LAI alone. Their study results showed that different tree species might have different transpiration rates.

This study showed that MIKE SHE over-predicted soil evaporation from harvested lands. A process-based ET model is needed to fully describe the soil evaporation processes under harvested conditions. Litter interception and its effects on soil evaporation need to be considered in order to predict ET more accurately for forested conditions. It seems that MIKE 11 could not simulate discontinuous streamflow conditions at a head watershed with only an ephemeral stream.

7.3 Future study

This study was the first attempt to apply a state-of-the-art hydrologic model to simulate hydrologic processes and responses to forest management and climate change in two contrasting regions in the southeastern U.S. More work is needed based on the current study.

First, MIKE SHE needs improvements in ET simulation. Model sensitivities to different PET methods need to be evaluated (Vazquez and Feyen, 2003). In a recent release, a Soil Vegetation Atmosphere Transfer model has been added to simulate ET in the MIKE SHE modeling system (Graham and Butts, 2005). The primary advantage of this model is that AET is calculated directly from standard meteorological and vegetation data, and PET is not a required input. However, evaluation of this ET model is needed.

Long-term monitoring data are critical for the hydrologic model evaluation and application. Therefore, more field data collection and monitoring are needed, especially for both the Santee and Alligator River sites. These include model parameters such as soil properties and hydrologic variables such as spatial water table distribution and streamflow.

The climate change scenarios were simplified as a fixed 2 °C temperature increase and 10% precipitation decrease in this study. Future research might consider using climate change scenarios generated by global circulation models (GCMs), such as CGCM1 or HADCM2, to feed the model. In the future, it might be possible to link the hydrologic model with an ecological model. Therefore, the biological feedback (e.g., stomata conductance, water use efficiency) due to climate change, as well as CO_2 and O_3 impacts on the ET processes, can be simulated. It is generally believed that climate change will affect LAI and other vegetation parameters (Hanson et al., 2005).

This study only investigated clear cutting as a forest management practice, and the only change after harvesting was the reduction of LAI. In the future, soil physical property (e.g., porosity and conductivity) change due to clear cutting might be considered to better represent real world situations. Furthermore, more management scenarios should be examined. For instance, prescribed burning can also be simulated by the MIKE SHE model. Based on fire intensity, prescribed burning can be represented by changes in LAI, floor litter, soil porosity, infiltration rate, and hydrologic conductivity. With a sound ET method, MIKE SHE can be used to evaluate the afforestation and forest conversion effects. Eventually, the model can be used as a management tool for land managers to assess hydrologic responses to land management.

The combined impacts of climate change and forest management practices can also be investigated by using the MIKE SHE model. These will address questions about management impacts on hydrology under a changing climate.

The MIKE SHE model might also be applied to evaluate seasonal impacts of forest management and climate change on streamflow, a research area that is lacking quantitative information (Brown et al., 2005). MIKE SHE could be a useful tool to address this knowledge gap.

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