MODELING THE EFFECT OF LAND USE CHANGE ON HYDROLOGY OF A FORESTED WATERSHED IN COASTAL SOUTH CAROLINA

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Abstract. Since hydrology is one of main factors controlling wetland functions, hydrologic models are useful for evaluating the effects of land use change on wetland ecosystems. We evaluated two process-based hydrologic models with different structures, MIKE SHE and DRAINMOD, using a 3-year (2003-05) dataset collected from a coastal South Carolina forested wetland watershed (WS80) on Santee Experimental Forest to evaluate the effects of land use change on hydrology of wetlands. The model performance was evaluated using the coefficient of determination ($\mathbf{R^2}$) and Nash-Sutcliffe model efficiency **(E)**. The two models were further tested by applying them for assessing effects of land use change on streamflow and water table in WS80 under four scenarios of converting forested watershed to varying proportions of cropland, 30, 40, 50 and 100%. Simulation results showed that, for both models, the outflow proportionally increases with an increase in the fraction (0 – 1.0) of agricultural land area with a rate ranging from 0.30 to 0.35. Depending on precipitation patterns, those values for a normal year represent a change in annual runoff of 64 – 69 mm for conversion from 50% of forestland to cropland, and an increase of 113 – 122 mm for a complete watershed conversion. The water table was predicted to increase by an average of 8 – 10 cm across the watershed for a complete land use conversion scenario. The change in runoff and water table due to converting forest to cropland is primarily a result of decreased evapotranspiration from croplands after conversion.

Key words: forest hydrology, land use change, stream flow, water table

INTRODUCTION

Despite the importance of wetlands, many of them have been converted in the last five decades primarily as a result of agriculture and urbanization. The land use change of wetlands influences hydrologic processes as well as water quality because wetlands affect the runoff, and the transport and exchange of materials between terrestrial and aquatic ecosystems. Understanding those impacts on material storage, interception, transport and transformation is needed to manage water quality and water resources.

The consideration of utilizing hydrologic models is needed to understand the effect of land use change on the hydrology of wetlands, to assess land use and management, and to manage water resources and quality. The development and application of hydrologic models in recent years reflect these merits (Amatya et al., 2008; Skaggs et al., 2004; Sun et al., 2000).

Although many hydrologic models have been developed in the past, they are mostly lumped based on spatially averaged conditions in a watershed (Sahoo et al., 2006) and mainly suitable for application in fields or watersheds with homogenous physical characteristics across space. The physically-based distributed hydrologic models utilize the physical characteristics of watersheds across space and time. The distributed models are considered to provide better results than lumped models. However, distributed models are difficult to calibrate due to a large number of input parameters (Boyle et al., 2000). Therefore, both types of hydrologic models are used depending on purpose and the characterizations of watersheds.

The objective of this study was to compare results from two hydrologic models (a physically-based distributed watershed scale MIKE SHE and a field scale DRAINMOD) for their simulations of streamflow and water table in a forested watershed on the southeast

Atlantic Coastal Plain with different cropland conversion scenarios, which is used to estimate the effects of land use change on the hydrology in wetland-dominated watersheds.

METHOD

Site Description

The study site is a 160 ha first-order watershed (WS80) located on the Santee Experimental Forest (SEF) (33.15ºN, 79.8ºW), 55 km northwest of Charleston, in Berkeley County, South Carolina. The details of the watershed, including hydrology, climate, soil, topography and vegetation, are described in many publications (Amatya et al., 2003; Hook et al., 1991; SCS, 1980; Sun et al., 2000a).

The weather parameters, including air temperature and precipitation, were observed within the watershed at hourly intervals. Daily potential evapotranspiration (PET) was estimated using the Penman-Monteith method (Monteith, 1965). The observation data for estimating daily PET was collected at SEF Headquarters, about 3 km away from the study site, at 30-minute intervals. Leaf biomass was used as the basis to calculate leaf area index (LAI). Water table depth data was provided by two automatic recording wells (WL40) at 4-hour intervals and 8 manual wells with biweekly measurements. An automatic Teledyne ISCO-4210 flow meter was used to measure stream flow at 10-minute intervals.

Hydrologic Models

Two hydrologic models, MIKE SHE (Abbott et al., 1986a and 1986b) and DRAINMOD (Skaggs, 1978) were used. MIKE SHE, a spatially and temporally explicit hydrologic model, is distributed to simulate the complete terrestrial water cycle. It is suitable for hydrologic modeling of watersheds with complex soil types, vegetation and conditions (DHI, 2005).

DRAINMOD is widely used to simulate the water balance in poorly drained soils. It includes methods to simulate subsurface and surface flows, irrigation, and control drainage. The details of DRAINMOD are described by Skaggs (1978).

Model Setup

The model framework for the hydrologic simulations was configured to predict outflow and water table elevation using watershed specific characterizations.

MIKE SHE: The simulation model was created with the flow model coupled with MIKE 11, which was used for simulating 1-D, 2-D and 3-D water movements in the watershed. The detailed model setup for this watershed is described by Dai et al. (2008).

DRAINMOD: A field scale version was used for comparison with a distributed watershed scale model. However, in order to obtain better simulated results from the field scale DRAINMOD, the watershed was divided into five subcatchments (Fig.1), C1 – C5, for this study based on the topography, soil properties and vegetation distribution. Large parts of C2, C3 and C4 contain wetlands, and C1 and C5 are primarily non-wet areas.

The main structure and parameterization of DRAINMOD was based on Harder et al. (2006) except for modifications to reflect the division of the watershed. Thus, the detention storage was changed to 10-50mm for the different subcatchments, and Kirkham's depth for flow to drains was changed to 10-40 mm. The drainage spacing for sub-catchments was set to their size of the subcatchments.

Model Calibration and Validation

Both models were calibrated and validated using 3-year observed flow and water table datasets from this watershed. The observed data in 2003 was used for calibration. The similar data in 2004 and 2005 was used for the validation. There were very substantial variations in flow and water table elevation due to large climatologic differences within these years. It is the large differences in outflow, water table and climate that are good for model calibration and validation.

The calibration and validation are evaluated by the coefficient of determination (squared correlation coefficient, $\mathbf{R^2}$) and model efficiency (**E**) (Nash and Sutcliffe, 1970).

Model Application

The calibrated and validated models were used to simulate the effect of four different land use change scenarios on streamflow and water table depth. The scenarios represented converting 30, 40, 50 and 100% of the forested land to cropland, using the assumption that maize was planted in May of every year and harvested in October of same year. PET for land use change was calculated based on the assumption that the albedo is 0.22 during crop growing period (July – September), 0.28 after harvest without tillage (October – April), 0.3 (0.32 for light color dry soils) from tillage to two weeks after planting, and then the albedo will be decreased step by step to 0.22 in July; and the stomata conductance is not

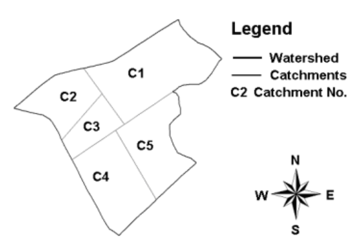

Fig.1 Sketch of sub-catchments for DRAINMOD.

included because empirical data is not available. The surface roughness for MIKE SHE was changed from 0.029 for forestland to 0.014 for cropland. The simulated results from both models will be used for the comparison of the performances of two different scales of models based on the values of $\mathbf{R^2}$ and **E**.

RESULT AND DISCUSSION

Model Calibration

The results showed that both of models were adequate in predicting the daily average and monthly outflows for the watershed; and both of the models are suitable for estimating the effect of land use change on the hydrology in the watershed. For daily average outflow, the calibration showed that the simulated results from MIKE SHE (2.04 mm/d) and DRAINMOD (1.94 mm/d) were in good agreement with the observation (2.01 mm/d). For the monthly average outflow, calibration produced high values of E (0.96 and 0.94) and R^2 (0.98 and 0.95) for comparison between the observed and the predicted. However, MIKE SHE was better than DRAINMOD in predicting daily stream flow based on E values (0.70 from MIKE SHE, 0.31 from DRAINMOD). The difference between both models for daily outflow may be related to the simulation precision of DRAINMOD; it gave a zero value for outflow during very low stream flow periods and over-predicted outflow during rainy periods (Fig.2).

Model Validation

The validation results of both models were similar to that from calibration. However, MIKE SHE over-predicted outflow for dry years (e.g., 0.42 mm/d compared to 0.3 mm/d measurement in 2004). This type of response may be related to an artifact in MIKE SHE which does not allow a river/stream to dry out (Lu et al., 2006). Moreover, annual precipitation was 962 mm in 2004, about 400 mm less than long-term average of 1350 mm, 700 mm less than 2003, and the stream ran dry for five months. MIKE SHE kept a very low flow in the stream bed during the dry period so that it overpredicted the outflow during the dry period. DRAINMOD underpredicted outflow for dry years (e.g., 0.16 mm/d compared to 0.3 mm/d measurement in 2004).

Effects of Land Use Change

The results from the scenario analysis of land use change showed that the outflow was affected by converting forested land to cropland (Fig.3), and proportionally increased with increase in the proportion (0.0 – 1.0) of cropland area at an average rate of 0.30 from MIKE SHE and 0.35 from DRAINMOD during the three-year period. Depending on precipitation patterns, conversion from forestland to cropland can increase outflow by 30 – 35%. For a normal climatic year (1350 mm precipitation), the annual outflow can be increased by 64 – 69 mm for a conversion of the forestland in the uplands (C1 and C5) on the watershed to cropland, and by 113 – 122 mm for a complete watershed conversion. These values were slightly higher than the values (40 and 90 mm for a conversion 50 and 100% of forestland to cropland) which were produced by DRAINMOD for Parker Tract pine forest watershed in North Carolina reported by Amatya et al. (2008).

Conversion from forestland to cropland may also influence water table depth. The water table change is closely related to topography. It can be decreased by 1 – 13 cm in wetland areas, but increased by 1 – 25 cm in the flat non-wetland areas. For a complete watershed conversion from forestland to cropland, the average water table across the watershed is predicted to increase by 8 cm using MIKE SHE and 10 cm using DRAINMOD. These results are lower than the values observed in a cypress-pine flatwoods watershed in Florida due to forest harvesting reported by Sun et al. (2000b).

CONCLUSION

The results from the model calibration and validation showed that both MIKE SHE and DRAINMOD were

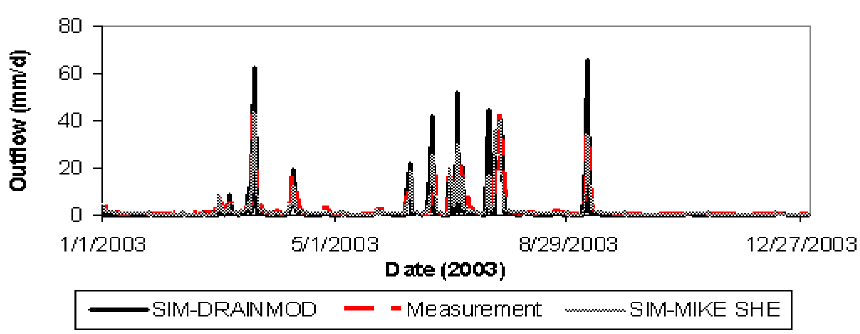

Fig. 2 Outflow observed vs. simulated by MIKE SHE and DRAINMOD for calibration.

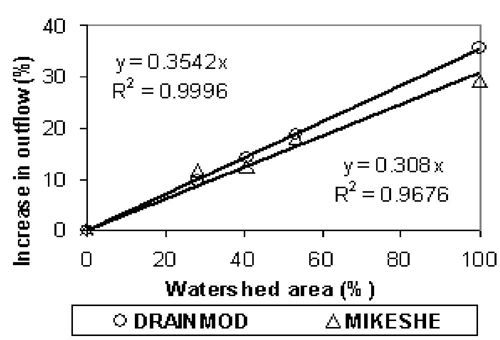

Fig.3 Effect of land use change on outflow.

applicable for assessing the effects of land use change although the distributed watershed scale MIKE SHE is better than the field scale DRAINMOD for assessing daily outflow and water table in this watershed. The results also showed that both outflow and water table were affected by the conversion from forestland to cropland; the changes were primarily due to decreased evapotranspiration from croplands.

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