EVALUATING THE SWAT MODEL FOR A LOW-GRADIENT FORESTED WATERSHED IN COASTAL SOUTH CAROLINA

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ABSTRACT. *Modeling the hydrology of low-gradient forested watersheds on shallow, poorly drained soils of the coastal plain is a challenging task due to complexities in watershed delineation, microtopography, evapotranspiration, runoff generation processes and pathways including flooding and submergence caused by tropical storms, and complexity of vegetation species. The main objective of this study was to calibrate and validate the GIS-based spatially distributed hydrologic model SWAT for the 72.6 km² low-gradient, third-order Turkey Creek watershed within the Francis Marion National Forest in the South Carolina Coastal Plain. Model calibration used GIS spatial data of the watershed and 2.75 years (2005-2007) of streamflow and climate data, and the model was validated with 2.5 years (2008-2010) of data. Based on limited field measurements, results showed that the SWAT model with an improved one-parameter "depletion coefficient" for plant evapotranspiration in the SCS curve number (CN) estimate can predict the daily and monthly streamflow processes of this watershed reasonably well and better than the CN method. The model performance was "good" (E = 0.68; RSR = 0.56) to "very good" (E = 0.90; RSR = 0.31) for the monthly calibration and validation periods but only "satisfactory" (E = 0.59; RSR = 0.64) to "good" (E = 0.70; RSR = 0.55) for the daily calibration and validation periods. Better predictions were found for the validation period that included two wetter years than the calibration with two drier years. The model's predictions of the zero or near-zero flow days of summer were also in agreement with the measurements for 60% of the time. However, it was concluded that the refined SWAT model was still unable to accurately capture the flow dynamics of this forest ecosystem with shallow, high water table soils for events preceded by wet saturated conditions during the dry summer and wet winter periods, warranting further investigations on these forest systems. The five-year average annual runoff coefficient of 19% with a baseflow amount of 27%, on average, of the runoff (streamflow) and ET of 987 mm predicted by the model were found reasonable compared to the estimated values and other published data for the region. Further improvements in estimates of forest potential evapotranspiration, rainfall spatial variability, and antecedent moisture as a function of water table should reduce uncertainties in flow predictions, allowing the model to be used in hydrologic impact assessments of land use change, land management practices, and climate change in coastal landscapes.*

Keywords. *Baseflow, Evapotranspiration, Poorly drained soils, Rainfall variability, Santee Experimental Forest, Streamflow, Water balance, Water table.*

Understanding the hydrologic processes of a region's relatively undisturbed forest ecosystems is vital to reliable assessments of the water quantity and quality impacts of other developing watersheds in the region. For this purpose, researchers conduct studies of undisturbed ecosystems using a monitoring and/or modeling approach to build a reference database of key water balance components such as runoff, groundwater, and evapotranspiration (ET). This is especially true for the Atlantic coastal plain (La Torre Torres et al., 2011; Dai et al., 2010; Harder et al., 2007; Bosch et al., 2004), where a legacy of land management practices (e.g., rice plantations, river channelization, dam development, drainage of wetlands, conversion of bottomlands to pine plantations) and ongoing rapid development due to urbanization threaten aquatic ecosystems (Hupp et al., 2009; Trettin et al., 2008; Amatya et al., 1997). Potential impacts from climate change and rising sea level warrant closer attention to these coastal forest ecosystems (Scavia et al., 2002). However, due to limited resources for long-term monitoring (Amatya and Skaggs, 2011), researchers are increasingly inclined toward the development and application of models (Amatya et al., 2011) to better quantify the complex interrelationships between topography, soil, vegetation, and land use (Wu and Xu, 2006; Tian et al., 2012; Vazquez-Amabile and Engel, 2005). Furthermore, these validated models, as decision making tools (Hashemi and O'Connell, 2010; Rao et al., 2007; Choi et al., 2005), are useful in providing insights on alternative best management practices designed to avoid, reduce, or mitigate the negative impact of anthropogenic activities on water quantity and quality (Amatya et al., 2004; Dai et al., 2010; Bosch et al., 2004; Fernandez et al., 2007; Francos et al., 2001).

The Soil and Water Assessment Tool (SWAT), a widely used watershed-scale, distributed model, was originally developed to evaluate the impacts of land management practices on hydrology and water quality (Arnold et al., 1998).

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SWAT has found wide applications for various purposes in various geographic regions around the world (Tuppad et al., 2011; Douglas-Mankin et al., 2010; Gassman et al., 2007). The drainage areas where SWAT has been applied for hydrologic calibration have varied from 7.2 km^2 to as large as 444,185 km^2 (Douglas-Mankin et al., 2010).

SWAT has been used and applied under a variety of low-gradient conditions worldwide, with various results. For example, Watson et al. (2009) made several modifications to the SWAT model (SWATBF) to better represent processes occurring within forested watersheds on the boreal plain in Canada. Although the authors reported that SWATBF did not perform as well for the validation period compared to the calibration period, it has the potential to be used as a tool by forest managers for predicting the effects of land use change on the boreal plain provided that it can be satisfactorily validated. Francos et al. (2001) found a good agreement between measured and predicted values when they applied SWAT in an agricultural watershed in the coastal plain of Finland. In the U.S., recent studies by Bosch et al. (2004, 2010) and Feyereisen et al. (2007) were conducted on low-gradient coastal watersheds of the Atlantic coastal plain, but the sites were dominated by agricultural land use. Although SWAT was able to simulate general streamflow trends, discrepancies were observed in the simulated runoff hydrographs (Bosch et al., 2004) and winter months, and extreme events were overestimated while summer months were underestimated (Bosch et al., 2010). Similarly, Feyereisen et al. (2007) noted that SWAT's predictive capabilities were less suited for predicting streamflows during drier conditions. In their comparative study of SWAT and AGNNPS models, Sadeghi et al. (2007) reported that both SWAT and AnnAGNPS performed well for simulating hydrologic conditions for a 1036 km^2 agricultural watershed in Cheasapeake Bay, Maryland. In another study, Wu and Xu (2006) applied SWAT on three mixed land use but predominantly forested, low-gradient watersheds in coastal Louisiana. Based on the results of a two-year calibration and 10 to 20 years of validation data for all these three watersheds, the authors demonstrated that SWAT is capable of simulating hydrologic processes for medium- to large-scale coastal lowland watersheds. They also found the model sensitive to Manning's roughness coefficient for the main channel as well as the SCS curve number and soil evaporation compensation factor for these coastal watersheds. The watersheds studied by Wu and Xu (2006) had no more than 67% forested area, with the remaining percentages varying from 31% to 39% for agricultural land and from 1% to 5% for urban areas. Most recently, SWAT was used to assess the hydrologic and water quality impacts of forest harvesting at the upper Pearl River watershed, comprised primarily of forest vegetation (72%), in east central Mississippi (Khanal et al., 2011). However, much of the land in the southeastern coastal plain region is covered by forests (Sun et al., 2002) that are being cleared for development.

There have been limited studies on SWAT's application on low-gradient watersheds (Lam et al., 2010; Wu and Xu, 2006), especially on the forested watersheds of the southeastern coastal plain in the U.S. The low-gradient southeastern coastal plain watersheds are characterized by slow-moving streams and high annual precipitation with semi-tropical, humid conditions, with a significant presence to dominance of poorly drained shallow water table soils, including riparian areas, floodplains, and wetlands affecting the runoff generation process (LaTorre Torres et al., 2011). The runoff on these landscapes is generally dependent on the shallow water tables and saturation of the upper soil as a result of interaction of precipitation and ET with the complex surface and subsurface features. Recognizing the importance of an accurate knowledge of the shallow water depths in the hydrologic models, Moriasi et al. (2011) recently incorporated a shallow water table depth algorithm, called the modified DRAINMOD (Skaggs, 1978) approach, in the SWAT model. The authors reported encouraging results in predicting water table depths for a watershed comprising only 35% forest in southeast Indiana.

The main objective function of this study was to test the capability of the SWAT model to predict daily, monthly, and annual streamflow in the Turkey Creek watershed, an area of 72 km^2 dominated by poorly drained forested land in the Atlantic lower coastal plain. The testing uses a calibration and validation approach using streamflow and weather data collected continuously since early 2005. This study is distinct because, to our knowledge, the widely used SWAT model has not yet been tested on fully forested, less disturbed, medium-scale watersheds on the low-gradient poorly drained soils of the coastal plain, and because the results could lead to development of modeling applications that provide a better understanding of the hydrology of a fully forested system as a reference in the low-gradient coastal plain.

Materials and Methods

Site Description

Turkey Creek watershed is in the Francis Marion National Forest on the coastal plain of South Carolina (fig. 1). The U.S. Forest Service established a stream gauging station in Turkey Creek in 1964 and monitored the watershed until 1984. The upland pine forest was the most heavily affected area by Hurricane Hugo in 1989. Nevertheless, researchers recognized the importance of stream gauging and other hydro-meteorological data from a forested coastal watershed as a reference in a rapidly changing coastal environment. As a result, in 2004, the U.S. Forest Service renewed interest in the Turkey Creek watershed by installing, in cooperation with the College of Charleston and the U.S. Geological Survey (USGS), a real-time streamflow gauging station, including a rain gauge (http://waterdata.usgs.gov/sc/nwis/uv?site_no =02172 035) approximately 800 m upstream of the previous gauging station. This completed the development of a multi-scale gauging network that includes three other smaller watersheds inside the Santee Experimental Forest (boundary shown in red in fig. 1), providing a basis for a large-scale ecohydrological monitoring and modeling program (Amatya and Radecki-Pawlik, 2007).

The Turkey Creek watershed is a third-order stream system draining an area of approximately 7,260 ha and located about 60 km northwest of Charleston near Huger, in Berkeley County, South Carolina (33° 8′ N, 79° 48′ W) (fig. 1). Turkey Creek has perennial flow except in extremely dry seasons, such as the summer of 2007. There are indications of hydrologic modifications due to rice culture and channelization, the extent of which has not been fully realized or determined. Most of these hydrologic changes have not been maintained for many decades to centuries, so they are generally no longer

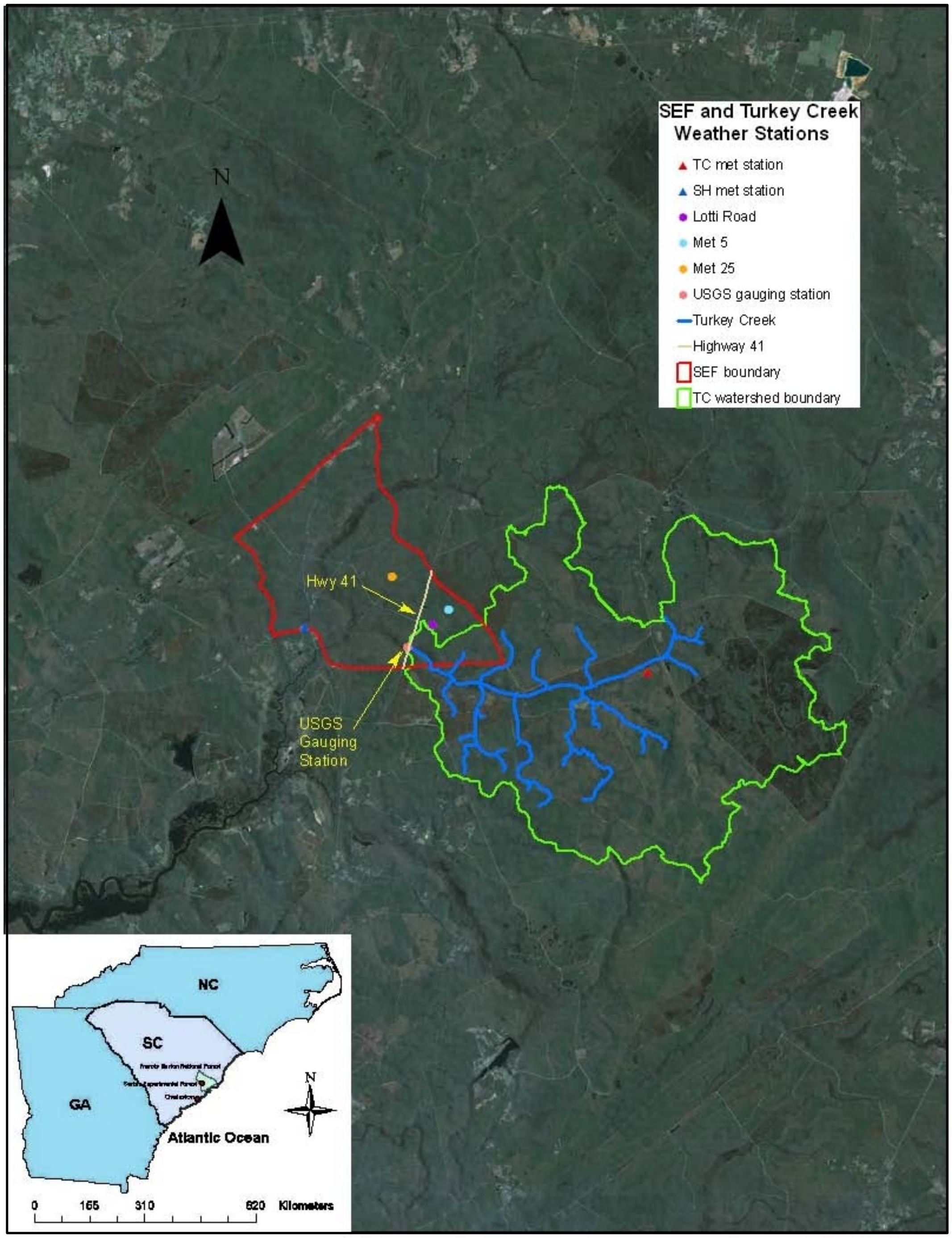

Figure 1. Location of the Turkey Creek watershed in the Francis Marion National Forest in coastal South Carolina and the watershed boundary with stream hydrography. Also shown are the monitoring stations in and around the watershed.

functional. The main channel has braided in some locations, which is anastomosed and stable with mature root systems of bottomland species such as bald cypress and tupelo gum along the streambanks and in some locations in the channel. Sand is the dominate substrate material.

The study watershed is located within the USGS quadrangle maps of Huger (NE), Bethera (SE), Shulerville (SW and SE), and Ocean Bay (NW and NE) with the approximate coordinate ranges of 610400 to 628600 easting and 3658500 to 3670500 northing. Located within a 12-digit hydrologic unit code (HUC 030502010301) of the Catawba-Santee basin (Eidson et al., 2005) at the headwaters of East Cooper River, a major tributary of the Cooper River, which drains to the Charleston harbor system, Turkey Creek (WS 78) is typical of other watersheds in the south Atlantic coastal plain, where rapid urban development is taking place. The topographic elevation of the watershed varies from about 2.0 m at the stream gauging station to 14 m above mean sea level. The subtropical climate is characteristic of the coastal plain, with hot and humid summers and moderate winter seasons. Accordingly, the minimum and maximum air temperatures, based on a 50-year (1951-2000) record at the Santee Experimental Forest, which is adjacent to Turkey Creek, were recorded as -8.5°C and 37.7°C, respectively, with an average daily temperature of 18.4°C (Harder et al., 2007). Annual rainfall at the site varied from 830 to 1940 mm, with an average of 1370 mm based on the 50-year (1951-2000) average. Seasonally, the winter is generally wet, with low-intensity, long-duration rain events, and the summer is characterized by short-duration, high-intensity storm events; tropical depression storms are not uncommon.

Land use within the watershed is comprised of 44% pine forest, mostly loblolly (*Pinus taeda* L.) and longleaf (*Pinus palustris*) pine, 35% thinned forest, 10% forested wetlands, 8% mixed forest, and 3% agricultural, roads, open areas, and impervious areas (Haley, 2007). The watershed was heavily impacted by Hurricane Hugo in September 1989, and the forest canopy was almost completely destroyed (Hook et al., 1991). Most of the current forests on the watershed are a mixture of remnant large trees and natural regeneration, which is approximately 21 years old. The watershed is dominated by poorly drained soils of the Wahee series (clayey, mixed, thermic Aeric Ochraquults) mostly on the northern part or right bank (looking downstream) of the stream and Lenoir series (clayey, mixed, thermic Aeric Paleaquults), with shallow argillic horizons with less than 3 m depth (SCS, 1980) mostly on the southern part (left bank) of the stream. The watershed also contains small areas of somewhat poorly and moderately well-drained sandy and loamy soils such as Lynchburg (thermic Aeric Paleaquults), Goldsboro (thermic Aquic Paleudults), and Rains (thermic Typic Paleaquults). Soils in the streambed and riparian buffers are comprised of the Meggett series (thermic Typic Albaqualfs) (SCS, 1980). Current management practices on the majority of the watershed include forestry, biomass removal for reducing fire hazards, prescribed fire and thinning for restoration of native longleaf pine, and habitat management for red-cockaded woodpeckers (*Picoides borealis*), an endangered species (http://ecos.fws.gov/speciesProfile/profile/speciesProfile.action?spcode=B04F). Some information on minor silvicultural management, such as thinning of some forest stands, was obtained from the U.S. Forest Service Ranger District Office at Witherbee, South Carolina. The watershed is also used for recreational purposes such as hunting, fishing, bird watching, hiking, kayaking, biking, historical tours, horse riding, all-terrain vehicle (ATV) use, and agriculture based on our field information.

Hydro-Meteorological Monitoring

Rainfall

At present, there are two automatic tipping-bucket rain gauges in the study watershed. One rain gauge (model TR-525USW, Texas Electronics, Inc., Dallas, Tex.) with a CR10X datalogger (Campbell Scientific, Logan Utah) is located near the middle, large open area of the Turkey Creek (TC) watershed, and the USGS rain gauge (Waterlog H-340, Design analysis Associates, Inc., Logan Utah) is linked with the new streamflow monitoring station at the main outlet of the watershed (fig. 1). There are also four automated gauges around the watershed. Three of these gauges (model RG2M tipping bucket with Onset HOBO event datalogger, Onset Computer Corp., Bourne, Mass.) are located at the Lotti, Met 5, and Met 25 stations, and the fourth gauge (model TR-525USW, Texas Electronics, Inc.) with a Campbell Scientific CR10X datalogger is at the Santee Experimental Forest (SEF) headquarters (SH), located about 5 km west of the watershed outlet (fig. 1). Data from each of the automatic rain gauges were verified and calibrated using an adjacent manual rain gauge (Amatya et. al., 2009). The manual gauges at SH, Met 5, and Met 25 are 0.20 m diameter metallic cylinders (standard U.S. Weather Bureau type), and those at TC and Lotti are 0.10 m diameter plastic cylinders.

Streamflow

A new real-time USGS stream gauging station was established at the main outlet of the watershed near the bridge on Hwy 41 (fig. 1) to collect stage heights every 15 min using a datalogger (SatLink–2 interfaced with Sutron Model 8210, Sutron Corp., Sterling, Va.) connected to the pressure transducer at the bottom of the stream (Amatya and Radecki-Pawlik, 2007). Flow rates were calculated using a stage-discharge relationship developed by the USGS using frequent *in situ* manual velocity measurements with a Marsh-McBirney flowmeter (Hach Co., Loveland, Colo.) at the stream cross-section where the stage transducer is located. The 15 min flow rates ($ft^3\ s^{-1}$) were integrated to obtain the mean daily outflow rates ($m^3\ s^{-1}$) and daily total (mm) at the watershed outlet (Amatya et al., 2009). Daily streamflow (mm) was used with a SWAT-recommended baseflow program that uses an auto-filter technique (Arnold and Allen, 1999) to estimate daily baseflow.

Weather Parameters

Climate data measurements from two complete automated weather stations were available at and around the study site. The first station (SH) is a long-term weather station established in 1946 (with just manual rainfall and temperature) at the Santee Experimental Forest (SEF) headquarters. Currently, a Campbell Scientific weather station (installed in 1996) with a CR10X datalogger has been recording continuous half-hour data of air temperature and relative humidity (model HMP45C, Vaisala, Inc., Woburn, Mass.), wind speed and direction (model 034A, Met One Instruments, Grants Pass, Ore.), solar radiation (model LI200X, Campbell Scientific), and net radiation (model Q7.1, Radiation and Energy Balance Systems, Inc., Bellevue, Wash.). The second station (TC), also a Campbell Scientific weather station with a CR10X datalogger, was installed in a large, open area in the middle of the Turkey Creek watershed in October 2005 to measure precipitation (model TR-525USW, Texas Electronics, Inc.), air temperature and relative humidity (model HMP45C, Vaisala, Inc.), wind speed and direction (model 034B, Met One Instruments), and solar radiation (model LI200X, Campbell Scientific) on a half-hourly basis (Amatya and Trettin, 2007; Amatya et al., 2009).

SWAT Model

The Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) is a watershed-scale model developed to quantify the impact of land management practices on the hydrology and water quality in large watersheds. This public domain model, supported by the USDA Agricultural Research Service, couples GIS spatial data characterizing a watershed with a distributed parameter hydrological model to predict hydrologic processes including surface runoff, percolation, deep aquifer flow, evapotranspiration (ET), and channel routing. This assessment tool uses continuous time and distributed parameters to improve the model's predictions of hydrologic processes. The model is able to simulate a variety of environmental factors including hydrology, weather, crop growth, soil temperature, nutrients, and sedimentation (Wu and Xu, 2006). SWAT is particularly useful in large watersheds with a variety of soils and land use conditions when making predictions over long periods of time. This study used the 2005 version of the ArcView SWAT model (Neitsch et al., 2005) for hydrologic modeling analysis.

The USDA Natural Resources Conservation Service (NRCS) curve number method was used to calculate surface runoff and infiltration (SCS, 1986). It is based on the soil type, land use and management practices, and antecedent moisture condition with respect to the rainfall amount. Given a rain event, the CN method estimates the amount of infiltration and surface runoff in a given area. Larger CN corresponds to greater surface runoff and less infiltration. The traditional CN approach in SWAT is linked with the available water capacity of the soil for soil moisture accounting in continuous simulation. However, for shallow soils and soils with low storage, as are often found in low-gradient coastal landscapes, this method generally seems to overpredict runoff and thus has limitations in simulating watershed response (Kannan et al., 2007). A different methodology, proposed by Kannan et al. (2007) and also available as an option in newer versions of SWAT, links the CN method with a one-parameter soil moisture depletion curve to account for antecedent soil moisture conditions in surface runoff calculations during continuous simulation. The depletion coefficient is related to PET, precipitation, and runoff in the curve number method (Santhi et al., 2008). By calculating daily CN by this method, the runoff value is less dependent on soil water storage and more dependent on antecedent climate (Neitsch et al., 2004). This method was shown to simulate hydrology realistically for shallow soil conditions (Kannan et al., 2007; Amatya et al., 2008) and was, therefore, tested in this low-gradient forested watershed with shallow water tables (Amatya et al., 2009).

Model Parameterization

GIS-Based Watershed Spatial Data

Delineation of the watershed boundary, followed by further discretization into subwatersheds, was conducted using the 2005 USGS enhanced 1:24,000 true 10 m horizontal, 1 m vertical digital elevation model, geo-referenced stream layer, and aerial photographs. The stream layer was further modified and digitized based on field surveys and verifications, especially for the headwaters with the extension of channels and tributaries (Haley, 2007). This additional channel information was believed to contribute to accurate streamflow routing in the SWAT model. A total of 39 subwatersheds were delineated using the automatic delineation tool in AVSWAT, with an average subwatershed size of 186 ha, i.e., 2.6% of the total area.

Table 1. Distribution of land use defined with SWAT.

Land Use Type	Area (km^2)	Percent
Watershed area	72.64	100.00
Agriculture land (AGRL)	0.71	1.00
Evergreen forest (FRSE)	49.00	67.42
Mixed forest (FRST)	5.84	8.04
Deciduous forest (FRSD)	8.16	11.24
Forested wetland (WETF)	7.55	10.4
Open fields (PAST)	0.36	0.5
Urban (transportation and residential)	1.02	1.4

The GIS-based land use layers (La Torre Torres, 2008) were developed by digitizing a 2005 National Agriculture Imagery Program (NAIP) aerial photo at 1:1500 scale (Haley, 2007). Based on these data, the total watershed area of 7260 ha was comprised of 97% forests and forested wetlands and 3% crops, roads, and open area. Pine and pine-hardwood mixed forest covered more than 87% of the area. Details of forest types and their distribution per the data obtained from the Francis Marion National Forest were presented by Haley (2007). The model can differentiate between five main forest categories: deciduous, evergreen, mixed, wetland, and mixed wetland. Within the model, the different types of urban development such as ditches and gravel, dirt, and paved roads can only be placed under one land use, which is referred to as transportation (Haley 2007). A breakdown of the land use distribution defined within the SWAT model setup is presented in table 1.

Information on major soil types, soil hydrologic groups, and soil layer properties was obtained from the NRCS 1:24,000-scale SSURGO database (table 2). Details of other soil types are given elsewhere (Haley, 2007). The percentages of each soil hydrologic group vary significantly within the watershed, with over half (62%) of the soils belonging to hydrologic group D, with the highest runoff generation potential. While some physical properties of the dominant soil series like Wahee, Lynchburg, Lenoir, Goldsboro, and Rains were obtained by field and laboratory measurements (Callahan, 2009), other properties, such as available water capacity, used SWAT default values. The combinations of land use and soil type generated 216 hydrologic response units (HRUs). Soil and land use layers could be used with the SWAT model to determine the curve number (CN) distribution for each of the HRUs throughout the watershed that are used in generation of surface runoff. However, CNs for each HRU were developed using the ArcCN-Runoff tool (Zhang and Huang, 2004), an extension of ESRI's ArcGIS software, since more

Table 2. Soil descriptions along with updated saturated hydraulic conductivities (K_{sat}) values.

Symbol	Hydrologic Group	Name	Texture	Drainage Class	K_{sat} (mm h^{-1})
GoA	B	Goldsboro	Loamy sands, 0% to 2% slopes	Moderately well drained	9
Ly	C	Lynchburg	Fine sandy loam	Somewhat poorly drained	25
Ra	D	Rains	Fine sandy loam	Poorly drained	25
Be	D	Bethera/Coxville	Loam	Poorly drained	23
Le	D	Lenoir	Fine sandy loam	Somewhat poorly drained	9
Mg	D	Meggett	Loam	Poorly drained	23
Wa	D	Wahee	Loam	Somewhat poorly drained	9
Ct	C	Chipley-Echaw complex	Sandy to loamy sand	Somewhat poorly drained to moderately well drained	628

detailed land use data, including some wetlands and ponded areas, were available.

Weather Data

Precipitation data were adopted directly from the Lotti rain gauge (33° 8′ 12″ N, 79° 46′ 36″ E) at the northern boundary near the watershed outlet (Amatya et al., 2009), while data on maximum and minimum temperature, solar radiation, wind speed, and relative humidity for 2005 were collected from the nearby Santee Experimental Forest (SEF) headquarters station (SH; 33° 8′ 11″ N, -79° 48′ 52″ W) (fig. 1). Weather data for the rest of the period until June 2010 were obtained from the on-site weather station (TC) after its establishment. The weather data measured at these stations were used to calculate Penman-Monteith (Monteith, 1965) based daily potential evapotranspiration (PET) for a standard grass reference (Amatya et al., 2009; Licciardello et al., 2011) to input directly into the SWAT model.

Model Simulation

The model simulation process was comprised of three main steps: (1) initial model simulation with GIS spatial data and SWAT default parameters, (2) manual calibration, and (3) manual validation. A total of 33 months (April 2005 to December 2007) of weather and streamflow data, which includes a wet year (2005) and a dry year (2007), were used for calibration. Similarly, 30 months (January 2008 to June 2010) of data, which includes a normal year (2008 with a dry spring and wet fall), a wet year (2009), and a wet winter-spring (2010), were used for validation.

Guidelines provided by Luzio et al. (2002) were used for the SWAT model calibration analysis. These guidelines suggest at least a year of "warm up" model simulation results, which are not actually used, to account for instability in the soil water balance computations caused by the initial conditions. Therefore, a two-year warm-up period was used to simulate results for the 2005-2010 period analyzed in this study. The weather parameters measured in 2005-2006 were used for simulation of the two previous years (2003 and 2004) as the warm-up period (Luzio et al., 2002). These results were then discarded, and only the predicted daily streamflows from April 2005 to December 2007 were used for the calibration analysis, as the data from January to March 2005 were somewhat questionable. Similarly, flow data for July 4, 2005, were also excluded due to an artificial gauge submergence that occurred when the stage was artificially high due to blockage upstream of the gauge. The calibration processes involved repetitive analysis of the simulated watershed response, which includes precipitation, evapotranspiration, water yield, and contributions from surface flow and baseflow, which are compared with the measured data (primarily streamflows) for evaluating the performance of the model for the selected set of crucial input parameters. The average annual watershed water balance parameters obtained from the SWAT-simulated output for Turkey Creek watershed were first calibrated for fractions of surface runoff and baseflow (per Amatya et al., 2009). Similarly, the simulated mean annual baseflow and ET components were calibrated based on the estimated values obtained by the methods of Arnold and Allen (1999) and Amatya and Trettin (2007), respectively. Once these values were predicted in an acceptable range, as expected, the calibration was extended to predict streamflow at the watershed outlet on an annual, monthly and daily basis.

The initial calibration parameters were primarily selected based on the SWAT literature for coastal watersheds (Veith et al., 2010; Feyereisen et al., 2007; Wu and Xu, 2006; Bosch et al., 2004) and our modeling experience. The manual calibration of input parameters for obtaining acceptable streamflow predictions for 2005-2007 in this low-gradient forested watershed included a nine-month wet period in 2005 and a very dry year in 2007. Table 3 lists the calibration input parameters used in SWAT for the study watershed, based on the sensitivity analysis conducted by Haley (2007). We also calibrated the soil moisture depletion coefficient (CNCOEFF) in the modified CN approach suggested by Kannan et al. (2007). The CNCOEFF parameter value of 0.1 (table 3), which is below the suggested range of 0.5 to 1.5, was found to provide a better calibration for the proportion of surface runoff and baseflow for this watershed. The weighted CN values obtained by Haley (2007) were also reduced by 10% in the final calibration to better match the surface runoff generated by the primarily shallow saturated soils in this type of low-gradient forested watershed (Harder et al., 2007). The new calibrated CNII values (average condition) for the 213 HRUs delineated for this coastal forested watershed ranged from 29.7 to 88.2 with an average of 69.3. The 10th percentile CN value was 54.9, indicating that only about 21 HRUs had assigned values below this value. Similarly, only 10% of the 213 HRUs had values exceeding 82.6, as shown by the 90th percentile. These CNII values are consistent with the published range (SCS, 1986) for good condition forests on poorly drained soils. The ranges of the calibrated values presented here are also similar to the values obtained by La Torre Torres (2008) with an optimization method using storm event data from 13 years (1964-1976) of historic data at the site.

The maximum rooting depth of 1000 mm for the matured and regenerated vegetation since the effects of Hurricane Hugo in 1989 is consistent with other published literature in which an effective rooting depth of 50 to 60 cm was used for this type of forest vegetation in the South Carolina coastal plain (Dai et al., 2010). Similarly, a maximum canopy leaf area index (LAI) of 5.0 m^{-2} m^{-2} and storage capacity of 0.5 mm were used for this pine and hardwood mixed forest, consistent with the Dai et al. (2010) study. A value of 0.20 for Manning's overland surface runoff coefficient was assumed

Table 3. New calibration parameters input into the Turkey Creek SWAT model.

Parameter	Description	Final Calibrated Value
CN	Curve number	Reduced by 10%
CNCOEF	Plant ET curve number coefficient	0.1
ESCO	Evaporation soil compensation factor	0.70
GW_REVAP	Groundwater "revap" coefficient	0.02
RDPTHMAX	Maximum root depth (mm)	1000
CH_N(1)	Manning's roughness in main channel	0.1
CH_N(2)	Manning's roughness in tributaries	0.15
OV_N	Manning's roughness in overland flow	0.2
SOL_AWC	Soil available water content	0.4
ALPHA	Alpha baseflow	0.048
GW_DELAY	Groundwater delay (days)	10
SURLAG	Surface runoff lag coefficient	1
CNMAX	Maximum canopy storage (mm)	0.50

for the forest surface, with litter, understory vegetation, depressions, fallen tree limbs, branches, etc. (McCuen, 1989). Similar procedures were used for determining Manning's roughness coefficient for stream channels and tributaries. All other input parameters are presented in table 3.

After a satisfactory calibration, the model was further validated with 2.5 years (January 2008 to June 2010) of data using the same set of input parameters used for the calibration. The validation process also included evaluation of the model's performance in predicting stream outflows on a daily, monthly, and annual basis. The final parameters used in both the calibration and validation are presented in table 3. Furthermore, the model-predicted annual baseflow and ET were compared with estimated values. The model performance for both the calibration and validation periods was evaluated using the methods described in the following section.

Evaluation of Model Performance

Model-predicted stream outflows at the outlet of the watershed (the location of the stream gauging station) were used for evaluation of the model performance. In this study, in addition to the graphical plots and tabular results, three standard statistical techniques, Nash-Sutcliffe coefficient (E), RMSE of observations standard deviation ratio (RSR), and percent bias (PBIAS), recommended by Moriasi et al. (2007), and the widely used coefficient of determination (R^2) were used to test and evaluate the accuracy of the model simulations. In general, model simulation was judged satisfactory for $E > 0.50$ and $RSR < 0.70$, and if PBIAS was within $\pm 25\%$ (Moriasi et al., 2007). These statistics were computed using monthly and daily observed streamflow values (mm) and the monthly and daily water yields (mm) predicted by SWAT at the main watershed outlet. These criteria are widely used for calibration and validation of hydrologic models using streamflow (Veith et al., 2010; Dai et al., 2010; Tian et al., 2012), although several researchers use only the E and PBIAS statistics (Fernandez et al., 2007; Bosch et al., 2004).

Results and Discussion

The average annual water balance parameters simulated for water yield (= surface runoff + baseflow), REVAP (flow from a shallow aquifer to the soil/root zone), and evapotranspiration were 343 mm (= 261 mm + 82 mm), 9 mm, and 973 mm, respectively, for the measured mean annual rainfall of 1325 mm and estimated PET of 1128 mm for the 2005-2009 period. The simulated average baseflow (82 mm), comprising of 24% of streamflow, was comparable to 28% estimated using the method of Arnold and Allen (1999) for the 2005-2009 period (Amatya et al., 2009). The simulated baseflow is also consistent with that obtained by La Torre Torres et al. (2011) using the hydrograph separation method of Swindel et al. (1983) with historic storm event data for the site. Similarly, the predicted ET of 973 mm is similar to the Thornthwaite water balance-based average ET of 988 mm for 2005-2008 (Amatya et al., 2009) and the long-term (1964-1976) historical average ET of 983 mm obtained by various empirical methods that used canopy cover, latitude, elevation, precipitation, and PET for this site (Amatya and Trettin, 2007). The simulated ET of 973 mm, similar to the value obtained by a water balance study by Harder et al. (2007) in an adjacent first-order forested watershed, was 87.5% of the average annual PET of 1128 mm and 75.5% of the average annual rainfall.

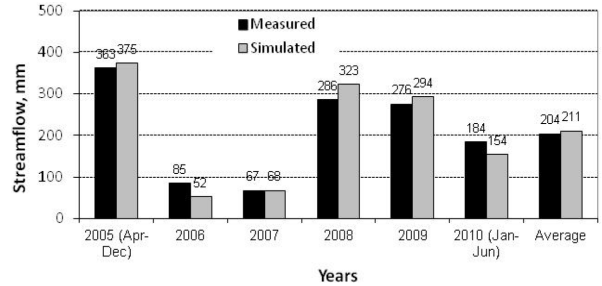

Figure 2. Measured and SWAT predicted annual stream outflows at the Turkey Creek watershed outlet.

The results of annual streamflow predicted by SWAT for 2005-2010, covering both the calibration and validation periods, are compared with the measured data in figure 2. The comparison excludes January to March data in 2005 as the measured data were not as reliable.

Calibration Period (Apr. 2005 to Dec. 2007)

The model only slightly overpredicted the annual flows in the wet year of 2005 (rain of 1186 mm for nine months) as well as the dry year of 2007 (rain of only 982 mm). However, the flow in 2006 with rainfall of 1218 mm was underpredicted (52 mm) by 38.7% compared to the measured flow (85 mm), indicating no systematic modeling error with consistent over- or underpredictions. The overpredictions of the measured flows by only 3.2% in 2005 and 0.7% in 2007 are considered very good (Moriasi et al., 2007). The mean PBIAS for the entire calibration period was 11.6%, which was mostly biased due to 38.7% underprediction in 2006 alone. One of the reasons for the large underprediction in 2006 is due to overprediction of ET (1086 mm), possibly as a result of the high value of PET of 1230 mm estimated for that year. Such an error may likely be caused by the use of the Penman-Monteith PET estimated values based on the extrapolated net radiation using a solar and net radiation relationship from the nearby Santee Experimental Forest weather station (SH). Net radiation data were not measured at the weather station on the study site (TC) itself. This is consistent with the recent observations by Licciardello et al. (2011), who demonstrated that SWAT was more sensitive to the PET parameter than to the six other parameters impacting surface runoff in a small Mediterranean watershed. The authors also showed the sensitivity of the net radiation estimating methods for the Penman-Monteith PET on the SWAT-predicted runoff. In addition, there is always an inherent error caused by the rainfall spatial variability in a watershed modeling study.

The data in figure 3 represent the monthly predicted outflows compared with the measured data for the 33-month (2005-2007) calibration period and 30-month (2008-2010) validation period. The model predictions of streamflow generally followed the pattern of measured monthly flows, with some overpredictions in most of the months in the wet year of 2005 and underpredictions in most months in relatively dry year of 2006, except for wet January. The largest flow underprediction in 2006 occurred in February when the preceding months were wet. However, the model accurately predicted all near-zero flows from May to August 2006 and all monthly flows, including summertime near-zero to zero flow, for the

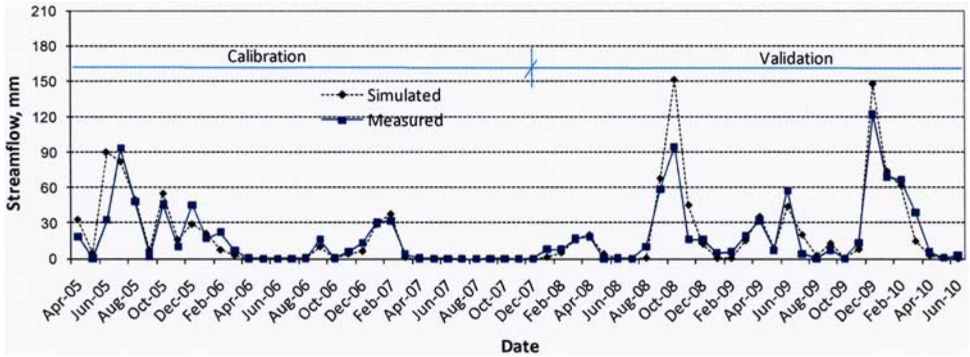

Figure 3. Measured and SWAT predicted monthly stream outflows at the Turkey Creek watershed outlet.

dry year of 2007, except for February, which was overpredicted by about 20%.

A close examination of monthly rainfall from April to August in 2006 and 2007 revealed that the watershed received only 587 mm and 488 mm of rain, respectively, compared to 695 mm for the long-term average for the same period. This was also supported by the data from groundwater wells at the study site, which had water tables as deep as 2.5 m, creating large soil storage in a well drained soil, as identified by Amatya et al. (2009). These results clearly demonstrate that the modified CN method (Kannan et al., 2007) in this study dramatically improved the predictions for the near-zero flow months of both 2006 and 2007 compared to earlier studies (Amatya et al., 2008; Haley, 2007), which found a larger underprediction of flow for the event of September 2006 and overprediction for the events of August to September 2007. Although the E and RSR statistics in the earlier studies were similar to ours, their PBIAS was about 15% and three times higher than ours for the calibration and validation periods, respectively. The flow overpredictions of 2005 may be partially attributed to both the rainfall and the PET data used from the Santee Experimental Forest weather station (SH), which is about 8 km to the west from the center of the site (fig. 1) and has generally higher rainfall than the nearby gauges (Amatya et al., 2009). These data from the SH site were used because the weather station (TC) at the study site was not installed until October 2005. The effects of minor forest removal by thinning of approximately 141 ha in 2006 and 85 ha in 2007, both of which were less than 3% of the total watershed area, were ruled out based on Stednick (1996), who reported that for the Eastern Coastal Plain hydrologic region, as a conservative estimate, 45% of the catchment must be harvested for a measurable increase in annual water yield.

Based on Moriasi et al. (2007), the model performance for predicting monthly streamflows was "good" for the calibration period (2005-2007) without the three months (January to March) and one day (July 4) in 2005 with measured streamflows. This is supported by the R^2 value of 0.76, E of 0.68, RSR of 0.56 (<0.70), and PBIAS of less than 10% (table 4). A negative PBIAS value for both the calibration and validation periods indicates an overestimation bias. On a year-to-year basis, the model performed best in the dry year of 2007, and the years 2005 and 2006 could be judged only as satisfactory. Based on our nearly three-year-limited calibration data, these results are contrary to those obtained by Feyereisen et al. (2007), who obtained poorer results (E = 0.59) for seven dry years than for three wet years (E = 0.89) for a 16.9 km^2 mixed land use watershed with 65% forest in the coastal plain of Georgia.

Simulation results for daily flow are presented in figure 4, which again excludes the measured data for January to March and July 4, 2005. It is evident that the model was able to capture most of the daily flow events for the calibration period (2005-2007), including the long dry days from May to August 2006 and from May to December in the dry year of 2007. The major discrepancies were observed in June to July 2005, when the model severely overpredicted the daily flows in June and underpredicted the events in February, and the early September event in 2006 when the model barely captured an event with a peak flow rate of near 4 mm d^{-1} that occurred after a long dry (near-zero flow) period from May to August. SWAT probably was unable to accurately simulate the February events, which occurred soon after wet events in January. Similarly, it is likely that the model did not capture the need to replenish the water table and wetland storage due to the large rain events after the dry periods in early September. Measured water tables on the watershed were at or near the surface soon after this September event (not shown). Input of literature-based soil hydraulic properties, such as AWC, might have also partially affected these predictions. Another possible reason for the underprediction may be that the spatial variability of rainfall was not considered here. For example, the rain in August 2006 was about 27 mm lower than that recorded by the nearby TC gauge. Similarly, the Penman-Monteith PET values estimated using net radiation extrapolated from a relationship from the nearby SH site might also have partially influenced the results, as SWAT surface runoff is very sensitive to the PET parameter (Licciardello et al., 2011).

Furthermore, the calculated flows obtained by using the rating curve method itself may have some errors, especially

Table 4. Calculated SWAT model performance evaluation statistics for the monthly streamflows.

Monthly	R^2	E	RSR	PBIAS (%)
Calibration (April 2005 to Dec. 2007)				
2005	0.54	0.41	0.68	-3.22
2006	0.64	0.52	0.69	38.68
2007	0.98	0.97	0.16	-0.68
All data	0.76	0.68	0.56	-7.75
Validation (Jan. 2008 to June 2010)				
2008	0.96	0.90	0.31	-13.1
2009	0.95	0.91	0.30	-6.5
2010	0.91	0.87	0.36	16.65
All data	0.94	0.90	0.31	-3.56

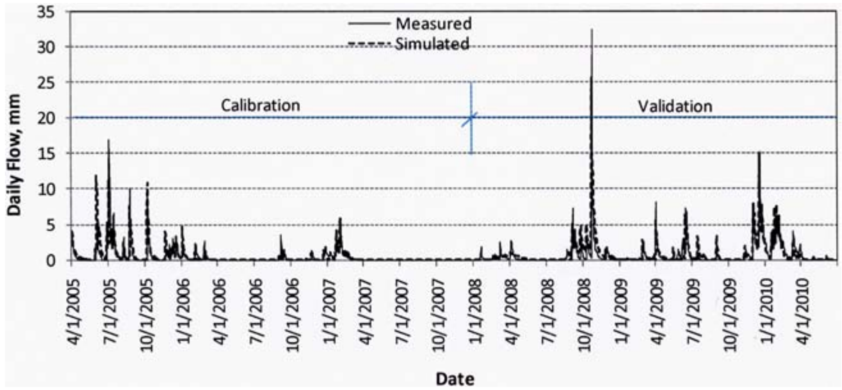

Figure 4. Measured and SWAT predicted daily stream outflows at the Turkey Creek watershed outlet.

when extrapolated out of its range (Harmel et al., 2006). Some other possible reasons for the discrepancy in 2006 may be the effect of somewhat higher estimated PET, as well as the spatial variability of rainfall during the summer-fall periods (Amatya et al., 2006; Chaubey et al., 1999). For example, the total rainfall measured at the TC gauge on the watershed was 40 to 50 mm less than at the SEF gauge in 2006. Most importantly, the fact that the water table was at or near the surface in four of the six groundwater wells in early days of September 2006 due to repeated rain events in August on the study site (Amatya et al., 2009) may have saturated these soils, in which case the improved CN method with a depletion coefficient (Kannan et al., 2007) might have failed to describe the runoff process for this saturated condition. In addition, the model's predictions of flow occurring a day earlier in most events than the measurements might have yielded some discrepancies consistent with the observations of Bosch et al. (2004), who also reported that a one-day time lag between the observed and simulated time to peak was the primary cause of large errors in daily flow simulations.

Overall, the simulated total cumulative daily flow of 494 mm for the 2005-2007 calibration period was only 4% lower than the measured cumulative value of 515 mm. The simulated mean and standard deviation of the daily flow of 0.48 and 1.29 mm d^{-1}, respectively, for the calibration period were close to the corresponding measured mean values of 0.45 mm d^{-1} and 1.25 mm d^{-1}, indicating good agreement of the distribution of simulated daily flow with the measurements.

As expected, the calculated performance statistics were somewhat poorer for the daily predictions (table 5) than for the monthly periods (table 4). However, the calculated R^2 and E statistics of 0.64 and 0.59, respectively, together with the RSR and PBIAS values (<10%) obtained for predicting daily flows during the 2005-2007 calibration period (table 5) indicate that the model performed satisfactorily based on the evaluation criteria suggested by Moriasi et al. (2007). The negative PBIAS, indicating an overprediction, was similar to the value obtained for the monthly periods (table 4).

Table 5. Calculated SWAT model performance evaluation statistics for the daily streamflows.

Daily	R^2	E	RSR	PBIAS (%)
Calibration (April 2005 - Dec. 2007)				
2005	0.61	0.56	0.66	-22.6
2006	0.36	0.27	0.85	38.7
2007	0.74	0.62	0.62	-0.7
All data	0.64	0.59	0.64	-7.8
Validation (Jan. 2008 - June 2010)				
2008	0.73	0.72	0.53	-13.1
2009	0.68	0.60	0.63	-6.5
2010	0.77	0.69	0.56	16.7
All data	0.70	0.70	0.55	-3.3

One reason for higher statistics is due to several days of zero and near-zero flows that the model was able to predict well. Although these evaluation statistics, especially the E values, were lower than those obtained by Wu and Xu (2006) for coastal Louisiana watersheds and by Watson et al. (2009) for a forested watershed on the Canadian boreal plain, they were higher than those reported by Feyereisen et al. (2007) for a watershed in coastal Georgia. None of these studies used the modified CN approach with a depletion coefficient. These results showed that the CN approach modified with a depletion parameter to continuously account for the soil moisture represented by PET and rainfall can better describe the runoff generation on shallow water table soils. In this study, we used this method as a calibration parameter for the baseflow and surface runoff portions of the total runoff generation process. Although a value in the suggested range of 0.5 to 2.0 (Kannan et al., 2007) could have been used for total streamflow calibration, a value of 0.1 was found to provide a better calibration for the proportion of surface runoff and baseflow as well as the total streamflow for this watershed with high water table soils where saturation-excess rainfall dominates the runoff.

Validation Period (Jan. 2008 to June 2010)

The SWAT-predicted annual streamflows for 2008, 2009 and the first half of 2010 are shown in figure 2. As in the calibration period, the model again overpredicted in 2008 and 2009 and underpredicted in 2010, indicating no systematic error for the validation period as well. The overprediction in 2008 could be related, in part, to the two years of dry conditions in 2006 and 2007. The overprediction was as high as only 13.1% in 2008, and the underprediction was 16.7% in 2010, with an overall overprediction of only 1% for the 2008-2010 validation period. The year 2009 yielded the best prediction, with only a 6.5% overprediction. These results were much better than those for the calibration period, which had two relatively dry years compared to the validation period, in which both 2008 and 2009 exceeded the long-term average rainfall of 1380 mm.

A comparison of the SWAT-predicted and measured monthly streamflow for the 30-month (January 2008 to June

2010) validation period is shown in figure 3. The model accurately predicted the streamflows for most of the months, except for some overpredictions in the wet months (e.g., October and November of 2008 and July and December of 2009) and some large underpredictions (e.g., February of 2008, June of 2009 and March of 2010). The overpredictions were consistent with the observations of Bosch et al. (2010), who attributed these discrepancies in flow predictions either to underestimation of extreme events in the field observations or to poor tracking of seasonal variations in water table elevation, ET, or soil water storage, as discussed earlier for the September 2006 event of the calibration period with antecedent soil moisture conditions. In the case of October 2008, the measured flows for the very large events of days 297-299 were extrapolated from the adjacent first-order watershed (Dai et al., 2010). Other possible explanations may be the effect of the PET values estimated using the net radiation relationship from the nearby Santee Experimental Forest (SEF) weather station (SH). The effect of rainfall variability was ruled out, as the rainfall amounts for September to December 2008 were similar at all nearby gauges. However, some overpredictions in July and September 2009 may have been due to the effect of rainfall variability, when the rain at the site was somewhat higher than at the nearby gauges, as well as extrapolation of radiation data from the SH site. At the same time, the underprediction in August 2008 may have been due to the variability of rainfall when the study site gauge received substantially less (by 50 mm or more) rainfall in earlier July than the surrounding gauges, resulting in drier simulated conditions.

Small underpredictions of about 5 mm were observed in January and February 2009, when the model predicted zero or near-zero flows for most measured daily flow rates of 0.2 mm or less. Again, these are the months with water tables near the surface and with wet antecedent conditions, such as February 2006, explained earlier. These underpredictions, including a large one by as much as 25 mm in March 2010, with low PET demands and small rainfall variability may also be due to the fact that the modified CN method (Kannan et al., 2007) using the depletion coefficient cannot adequately predict runoff generation on this poorly drained site with shallow water table dynamics. Measured water table depths during February and March 2010 were either ponded or near the surface at some well locations (not shown). Future study should consider using a version of SWAT that not only uses the modified CN method with a depletion coefficient but that is also modified with a procedure for predicting water table depth (Vazquez-Amabile and Engel, 2005). Greater attention to water table depth and potential water storage of wetlands and saturated or ponded areas could help reduce overestimation of runoff when predicting flow from dry to wetter periods and reduce underestimation for events preceding wet antecedent conditions in these poorly drained lowland landscapes.

The model performance E values for the validation period were much higher, ranging from 0.87 for 2010 to 0.91 for 2009, than for the calibration period (table 4). Similarly, the RSR values were equal to or less than 0.36, and the PBIAS ranged from 6.5% to 13.1% overprediction and 16.7% underprediction. On average for the 2008-2010 validation period, the E value of 0.90, PBIAS of 3.6%, and RSR of 0.31 indicate much better predictions than that for the calibration period, and the model performance was considered "very good" based on the Moriasi et al. (2007) criteria. Consistent with Feyereisen et al. (2007), the model performance was very good, with an E value of 0.90 or higher, for both 2008 and 2009, which had higher than normal rainfall. These E values in our validation period were higher than the values (0.81 to 0.87) obtained by Wu and Xu (2006) for three coastal watersheds in Louisiana and also higher than the value of only 0.44 reported by Watson et al. (2009) for a forested watershed in the Canadian boreal plain, suggesting that the model predictions in this study are better than those published data.

The daily flow predictions for the validation period are shown together with the calibration period in figure 4. The model clearly was able to simulate all flow events during both wet and dry periods, although there were only a few months with near-zero flow in the validation period. The largest discrepancy in daily flows occurred during the wettest event of October 25 to 27 in 2008 and some other wet events. On a cumulative basis, the 30-month simulated daily cumulative flow of 771 mm was just 3.6% higher than the measured value of 746 mm. The simulated mean and standard deviation were 0.85 and 1.93 mm d^{-1}, respectively, compared to the measured values of 0.82 and 2.23 mm d^{-1}.

The model performance statistics for prediction of daily flows are shown in table 5. The E values varied from 0.60 in 2009 to 0.72 in 2008 with an overall average of 0.70 for the 2008-2010 validation period, which are similar to or slightly lower than the values obtained by Wu and Xu (2006) but much higher than that reported be Watson et al. (2009) for daily flows in a forested watershed in the Canadian boreal plain. Although the model performance could be judged "very good" on year-by-year basis for the validation period, the PBIAS values for 2008 and 2010 were those suggested for the "good" category per Moriasi et al. (2007).

Francos et al. (2001) noted that their SWAT simulation results for daily flows for a coastal basin in southern Finland were deemed satisfactory with E = 0.65, taking into account that errors in the peak flows have an overwhelming effect, decreasing the overall efficiency results. One reason for poor model performance in some years is the uncertainty in the measured streamflow data itself, especially during very large storm events when data are extrapolated out of the range of the rating curve or from a nearby watershed. Flow measurements are often difficult during high-flow events in coastal streams due to wide floodplains and sometimes multiple channels, woody debris, and vegetation density across the floodplain. Some of this is reduced when gauging stations are located at bridge sites, such as the one at this study site. There is usually some road filling and other channel modifications that force the wide, multi-channel streams with broad floodplains through a confined location that is easier to measure, but this may also cause backwater and other conditions that can affect the instantaneous measurements, as happened on July 4, 2005.

Conclusions

Based on limited field-measured data, results of the 2.75-year (April 2005 to December 2007) calibration and 2.5-year (January 2008 to June 2010) validation analyses showed that the SWAT model with an improved one-parameter depletion coefficient for adjusting the curve number (CN) based on plant ET is capable of predicting the monthly and daily streamflow processes of a 72.6 km^2 low-gradient forested watershed in coastal South Carolina reasonably well. We conclude that our model predictions of monthly flows are "good" for the overall 2005-2007 calibration period and "very good" for the 2008-2010 validation period. Extending the same criteria for daily time steps, the model's performance for daily flow predictions was "satisfactory" for the calibration period and "good" for the validation period. The annual percent bias varied from 0.7% overprediction in 2007 to 38.7% underprediction in 2006, with an average of only 1% over the entire 2005-2010 study period. On average, the annual water balance components estimated by the model were reasonable for the less-disturbed forest site on shallow poorly drained soils with an average annual streamflow of 211 mm (19% of the mean rainfall) and ET of 973 mm. The simulated mean annual baseflow of 27% of the streamflow was also consistent with estimated data. Based on our results, it is recommended that the alternative CN approach with a one-parameter depletion coefficient (Kannan et al., 2007) based on evaporation for soil moisture accounting be used for simulating the hydrology of low-gradient watersheds where surface runoff is dominant. This method has an advantage over the traditional CN approach in that it can control the amount of infiltration (for subsurface flow) and surface runoff without affecting ET. The study also showed that the calibrated depletion coefficient may be outside the suggested range, depending on the calibration of surface flow and baseflow for these low-gradient watersheds.

However, it was also concluded that the refined SWAT model was not able to accurately capture the daily flow dynamics of this forest ecosystem in shallow, high water table soils for dry summer and wet winter events with wet saturated antecedent conditions (e.g., February and September 2006), and this warrants further investigation of these shallow soil systems, particularly in forests. Accordingly, we hypothesize that use of the extrapolated net radiation for estimating grass-reference Penman-Monteith PET instead of forest-reference PET might have introduced some errors in simulating the daily and seasonal ET and for that matter streamflow (Licciardello et al., 2011; Sun et al., 2010). Other errors may have been due to rainfall spatial variability, especially during the summer periods, and discrepancies in soil hydraulic properties that were not measured. ET is a major component of the forest hydrologic cycle, and a realistic simulation of forest ET is critical to overall water balance simulation. A review of current hydrologic models indicates that ET is weakly quantified for forested catchments due to lack of specific vegetation data, such as leaf area index (LAI), stomatal conductance, rooting depth, and soil moisture. It is important to accurately characterize these and other parameters, such as net radiation (albedo), and the processes they control, if models are to be applied to address issues of land use, climate change, and impacts of BMPs.

It is also recommend that future studies using the SWAT model should consider longer-term data and additional enhancements in field calibration, such as aerially distributed rainfall; Manning's roughness for the surface, stream, and tributaries; and available soil water capacity. These enhancements should provide better results for both the wet and dry periods, on both monthly and daily temporal scales. Furthermore, the current SWAT-GIS modeling effort should be expanded to use more accurate digital elevation models (DEMs) obtained from light detection and ranging (LiDAR) for watershed and drainage network delineation, and test the model's internal consistency by using multi-validation results of subwatershed streamflows, soil moisture, and/or shallow groundwater (Dai et al., 2010) for distributed hydrologic models such as SWAT.

Although we believe that this work adds to the existing limited knowledge on SWAT modeling of low-gradient forested watersheds, improvements such as those outlined above should substantially improve the predictive capability of the SWAT model for future work. These improvements will provide better understanding of the hydrologic dynamics and watershed response to land use change and climate variability and allow accurate quantification of total maximum daily loads (TMDLs) for various pollutants in the Turkey Creek watershed and similar low-gradient forested watersheds in the rapidly urbanizing coastal landscapes.

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References

Amatya, D. M., and A. Radecki-Pawlik. 2007. Flow dynamics of three forested watersheds in coastal South Carolina, U.S.A. *Acta Scient. Polonorum - Formatio Circumiectus* 6(2): 3-17.

Amatya, D. M., and R. W. Skaggs. 2011. Long-term hydrology and water quality of a drained pine plantation in North Carolina. *Trans. ASABE* 54(6): 2087–2098.

Amatya, D. M., and C. C. Trettin. 2007. Annual evapotranspiration of a forested wetland watershed, SC. ASABE Paper No. 072222. St. Joseph, Mich.: ASABE.

Amatya, D. M., R. W. Skaggs, J. D. Gregory, and R. Herrmann. 1997. Hydrology of a forested pocosin watershed. *J. American Water Resour. Assoc*. 33(3): 535-546.

Amatya, D. M., G. M. Cheschier, G. P. Fernandez, R. W. Skaggs, and J. W. Gilliam. 2004. DRAINWAT-based methods for estimating nitrogen transport on poorly drained watersheds. *Trans. ASAE* 47(3): 677-687.

Amatya, D. M., M. Miwa, C. A. Harrison, C. C. Trettin, and G. Sun. 2006. Hydrology and water quality of two first-order forested watersheds in coastal South Carolina. ASABE Paper No. 062182. St. Joseph, Mich.: ASABE.

Amatya, D. M., E. B. Haley, N. S. Levine, T. J. Callahan, A. Radecki-Pawlik, and M. Jha. 2008. Calibration and validation of the SWAT model for a forested watershed in coastal South Carolina. ASABE Paper No. 083912. St. Joseph, Mich.: ASABE.

Amatya, D. M., T. J. Callahan, C. C. Trettin, and A. Adecki-Pawlik. 2009. Hydrologic and water quality monitoring on Turkey Creek watershed, Francis Marion National Forest, SC. ASABE Paper No. 095999. St. Joseph, Mich.: ASABE.

Amatya, D. M., M. K. Jha, A. E. Edwards, T. M. Williams, and D. R. Hitchcock. 2011. SWAT-based streamflow and embayment modeling of karst-affected Chapel Branch watershed, South Carolina. *Trans. ASABE* 54(4): 1311-1323.

Arnold, J. G., and P. M. Allen. 1999. Automated methods for estimating baseflow and groundwater recharge from streamflow records. *J. American Water Resour. Assoc*. 35(2): 411-424.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrological modeling and assessment: Part I. Model development. *J. American Water Resour. Assoc.* 34(1): 73-89.

Bosch, D. D., J. M. Sheridan, H. L. Batten, and J. G. Arnold. 2004. Evaluation of the SWAT model on a coastal plain agricultural watershed. *Trans. ASAE* 47(5): 1493-1506.

Bosch, D. D., J. G. Arnold, M. Volk, and P. M. Allen. 2010. Simulation of low-gradient coastal plain watershed using the SWAT landscape model. *Trans. ASABE* 53(5): 1445-1456.

Callahan, T. J. 2009. Soil water properties of dominant soils on Turkey Creek watershed, Francis Marion National Forest, South Carolina. Personal communication.

Chaubey, I., C. T. Haan, J. M. Salisbury, and S. Grunwald. 1999. Quantifying model output uncertainty due to spatial variability of rainfall. *J. American Water Res. Assoc*. 35(5): 1113-1123.

Choi, J. Y., B. A. Engel, and R. L. Farnsworth. 2005. Web-based GIS and spatial decision support system for watershed management. *J. Hydroinformatics* 7.3: 165-174.

Dai, Z., C. Li, C. C. Trettin, G. Sun, D. M. Amatya, and H. Li. 2010. Bi-criteria evaluation of the MIKE SHE model for a forested watershed on the South Carolina coastal plain. *Hydrol. Earth Syst. Sci.* 14(6): 1033-1046.

Douglas-Mankin, K. R., R. Srinvasan, and J. G. Arnold. 2010. Soil and Water Assessment Tool (SWAT) model: Current developments and applications. *Trans. ASABE* 53(5): 1423-1431.

Eidson, J. P., C. M. Lacy, L. Nance, W. F. Hansen, M. A. Lowry, and N. M. Hurley Jr. 2005. Development of a 10- and 12-digit hydrologic unit code numbering system for South Carolina, 2005. Washington, D.C.: USDA Natural Resources Conservation Service.

Fernandez, G., G. M. Chescheir, R. W. Skaggs, and D. M. Amatya. 2007. Application of DRAINMOD-GIS to a lower coastal plain watershed. *Trans. ASABE* 50(2): 439-447.

Feyereisen, G. W., T. C. Strickland, D. D. Bosch, and D. G. Sullivan. 2007. Evaluation of SWAT manual calibration and input parameter sensitivity in the Little River watershed. *Trans. ASABE* 50(3): 843-855.

Francos, A., G. Bidoglio, L. Galbiati, F. Bouraoui, F. J. Elorza, S. Rekolainen, K. Manni, and K. Granlund. 2001. Hydrological and water quality monitoring in a medium sized coastal basin. *Phys. Chem. Earth B* 26(1): 27-52.

Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Trans. ASABE* 50(4): 1211-1250.

Haley, E. B. 2007. Field measurements and hydrologic modeling of the Turkey Creek watershed, South Carolina. MS thesis. Charleston, S.C.: College of Charleston.

Harder, S. V., D. M. Amayta, T. J. Callahan, C. C. Trettin, and J. Hakkila. 2007. Hydrology and water budget for a forested Atlantic coastal plain watershed, South Carolina. *J American Water Resour. Assoc.* 43(3): 563-575.

Harmel, R. D., R. J. Cooper, R. M. Slade, R. L. Haney, and J. G. Arnold. 2006. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. *Trans. ASABE* 49(3): 689-701.

Hashemi, M., and E. O'Connell. 2010. Chapter 5: From hydrologic models to policy-relevant Decision Support Systems (DSSs): A historical perspective. In *Handbook of Research on Hydroinformatics: Technologies, Theories, and Applications.* T. M. Gasmelseid, ed. Hershey, Pa.: Information Resources Management Association.

Hook, D. D., M. A. Buford, and T. M. Williams. 1991. Impact of Hurricane Hugo on the South Carolina coastal pine forest. *J. Coastal Res.* SI(8): 291-300.

Hupp, C. R., A. R. Pierce, and G. B. Noe. 2009. Floodplain geomorphic processes and environmental impacts of human alterations of coastal plain rivers, U.S.A. *Wetlands* 29(2): 413-429.

Kannan, N., C. Santhi, J. R. Williams, and J. G. Arnold. 2007. Development of a continuous soil moisture accounting procedure for curve number methodology and its behaviour with different evapotranspiration methods. *Hydrol. Proc*. 22(13): 2114-2121.

Khanal, S., P. B. Parajuli, and J. Hatten. 2011. Evaluating hydrologic effect of forest harvesting at upper Pearl River watershed in Mississippi. ASABE Paper No. 1110895. St. Joseph, Mich.: ASABE.

Lam, Q. D., B. Schmalz, and N. Fohrer. 2010. Modeling point and diffuse source pollution of nitrate in a rural lowland catchment using the SWAT model. *Agric. Water Mgmt.* 97(2): 317-325.

La Torre Torres, I. B. 2008. Seasonal relationships between precipitation and streamflow patterns related to watershed characterization of two third-order coastal plain watersheds in South Carolina. 2008. MS thesis. Charleston, S.C.: College of Charleston.

La Torre Torres, I., D. M. Amatya, T. J. Callahan, and G. Sun. 2011. Seasonal rainfall-runoff relationships in a lowland forested watershed in the southeastern U.S.A. *Hydrol. Proc.* 25(13): 2032-2045.

Licciardello, F., C. G. Rossi, R. Srinivasan, S. M. Zimbone, and S. Barbagllo. 2011. Hydrologic evaluation of a Mediterranean watershed using the SWAT model with multiple PET estimation methods. *Trans. ASABE* 54(5): 1615-1625.

Luzio, M. D., R. Srinivasan, J. R. Arnold, and S. L. Neitsch. 2002. *ArcView Interface for SWAT2000: User's Guide*. College Station, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory, and Blackland Research and Extension Center. Available at: www.brc.tamus.edu/swat/downloads/doc/swatav2000.pdf.

McCuen, R. H. 1989. *Hydrologic Analysis and Design*. Englewood Cliffs, N.J.: Prentice-Hall.

Monteith, J. L. 1965. Evaporation and environment. In *Proc. 19th Symposium of the Society for Experimental Biology*, 205-233. New York, N.Y.: Cambridge University Press.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885-900.

Moriasi, D. N., J. G. Arnold, G. G. Vazquez-Amabile, and B. A. Engel. 2011. Shallow water table depth algorithm in SWAT: Recent developments. *Trans. ASABE* 54(5): 1705-1711.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, S. Srinivasan, and J. R. Williams. 2004. *Soil and Water Assessment Tool: Input/Output File Documentation, Version 2005*. College Station, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory, and Blackland Research Center. Available at: www.brc.tamus.edu/swat/downloads/doc/swat2005.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2005. *Soil and Water Assessment Tool: Theoretical Documentation, Version 2005*. College Station, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory, and Blackland Research Center. Available at: www.brc.tamus.edu/swat/downloads/doc/swat2005/SWAT%202005%20theory%20final.pdf.

Rao, M., G. Fan, J. Thomas, G. Cherian, V. Chudiwale, and M. Awawdeh. 2007. A web-based GIS decision support system for managing and planning USDA's Conservation Reserve Program (CRP). *Environ. Modeling and Software* 22(9): 1270-1280.

Sadeghi A., Y. Kwang, C. Graff, G. McCarty, L. McConnell, A. Shirmohammadi, D. Hively, and K. A. Sefton. 2007. Assessing the performance of SWAT and AnnAGNPS models in a coastal plain watershed, Choptank River, Maryland, U.S.A. ASABE Paper No. 072032. St. Joseph, Mich.: ASABE.

Santhi, C., N. Kannan, J. G. Arnold, and M. Di Luzio. 2008. Spatial calibration and temporal validation of flow for regional-scale hydrologic modeling. *J. American Water Resour. Assoc.* 44(4): 829-846.

Scavia, D., J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell, R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger, and J. G. Titus. 2002. Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries* 25(2). 149-164.

SCS. 1980. Soil survey of Berkeley County, South Carolina. Washington, D.C.: USDA Soil Conservation Service.

SCS. 1986. Technical release 55: Urban hydrology for small watersheds. NTIS No. PB87101580. Washington, D.C.: USDA Soil Conservation Service. Available at: www.cpesc.org/reference/tr55.pdf.

Skaggs, R. W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, N.C.: North Carolina State University, Water Resources Research Institute.

Stednick, J. D. 1996. Monitoring the effects of timber harvest on annual water yield. *J. Hydrol.* 176(1): 79-95.

Sun, G., S. G. McNulty, D. M. Amatya, R. W. Skaggs, L. W. Swift Jr., J. P. Shepard, and H. Riekerk. 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the southern U.S. *J. Hydrol.* 263(1-4): 92-104.

Sun, G., A. Noormets, M. Gavazzi, S. G. McNulty, J. Chen, J.-C. Domec, J. King, D. M. Amatya, and R. W. Skaggs. 2010. Energy and water balances of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA. *Forest Ecol. and Mgmt.* 259(7): 1299-1310.

Swindel, B. F., C. J. Lassiter, and H. Riekerk. 1983. Effects of clearcutting and site preparation on stormflow volumes of streams in *Pinus elliottii* flatwoods forests. *Forest Ecol. and Mgmt.* 5(4): 245-253.

Tian, S., M. A. Youssef, R. W. Skaggs, D. M. Amatya, and G. M. Chescheir. 2012. Modeling water, carbon, and nitrogen dynamics for two drained pine plantations under intensive management practices. *Forest Ecol. and Mgmt.* 264: 20-36.

Trettin, C. C., D. M. Amatya, C. Kaufman, N. Levine, and R. T. Morgan. 2008. Recognizing change in hydrologic functions and pathways due to historical agricultural use: Implications to hydrologic assessment and modeling. In *Proc. 3rd Interagency Conf. on Research on Watersheds.* Washington, D.C.: U.S. Geological Survey.

Tuppad, P., K. R. Douglas-Mankin, T. Lee, R. Srinivasan, and J. G. Arnold. 2011. Soil and Water Assessment Tool (SWAT) hydrologic/water quality model: Extended capability and wider adoption. *Trans. ASABE* 54(5): 1677-1684.

Vazquez-Amabile, G. G., and B. A. Engel. 2005. Use of SWAT to compute groundwater table depth and streamflow in the Muscatatuck River watershed. *Trans. ASABE* 48(3): 991-1003.

Veith, T. L., M. W. Van Liew, D. D. Bosh, and J. G. Arnold. 2010. Parameter sensitivity and uncertainty in SWAT: A comparison across five USDA-ARS watersheds. *Trans. ASABE* 53(5): 1477-1486.

Watson, B. M., R. A. McKeown, G. Putz, and J. D. MacDonald. 2009. Modification of SWAT for modelling streamflow from forested watersheds on Canadian boreal plain. *J. Environ. Eng. and Sci.* 7(S1): 145-159.

Wu, K., and Y. J. Xu. 2006. Evaluation of the applicability of the SWAT model for coastal watersheds in southeastern Louisiana. *J. American Water Resour. Assoc*. 42(5): 1247-1260.

Zhang, X., and M. Huang. 2004. ArcCN-Runoff: An ArcGIS tool for generating curve number and runoff maps. *Environ. Modeling and Software* 19(10): 875-879.