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Calibration and Validation of the SWAT Model for a Forested Watershed in Coastal South Carolina

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Abstract. *Modeling the hydrology of low-gradient coastal watersheds on shallow, poorly drained soils is a challenging task due to the complexities in watershed delineation, runoff generation processes and pathways, flooding, and submergence caused by tropical storms. The objective of the study is to calibrate and validate a GIS-based spatially-distributed hydrologic model, SWAT, for a low-gradient, third-order Turkey Creek watershed (7,260 ha) within the Francis Marion National Forest in South Carolina Coastal Plain. The model calibration used GIS spatial data and two years (2005 – wet and 2006 - dry) of stream flow and climate data, and was validated with one very dry year (2007) of data. Based on limited field measurements, results showed that the SWAT model*

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with an improved one-parameter "depletion coefficient" can predict the stream flow processes of this watershed reasonably well and better than the classical CN method. The model performed "Good (E = 0.74; RSR = 0.51)" to "Very Good (E = 0.98; RSR = 0.15)" for the monthly and only "Satisfactory (E = 0.65; RSR = 0.60)" to "Good (E = 0.67; RSR = 0.57)" for the daily calibration and validation periods, respectively. It was concluded that the refined SWAT model was still unable to accurately capture the flow dynamics of this forest ecosystem with high water table shallow soils for very wet saturated and very dry antecedent conditions which warrants further investigations on these forest systems. Finally, the three-year average annual runoff coefficient of 17% and ET of 900 mm predicted by the model were found reasonable compared to other published data for the region.

Keywords. *Water balance, Stream outflows, Subsurface drainage, Evapotranspiration, Poorly Drained Soils, Francis Marion National Forest.*

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Introduction

Understanding the hydrology of watersheds along the coastal plain is critical as hydrology is the primary driving force to better understand nutrient cycling and loading dynamics as well as to address water quality issues as a result of rapid urbanization near the coastal waters. At the watershed scale, the hydrology can be quite complex due to both the variability of and interactions between land use, soil, climate conditions, vegetation, and geology (Fernandez et al., 2007; Van Liew and Garbrecht, 2003). Although long-term monitoring of these watersheds can be used to better understand the hydrological processes and their dynamics, including effects of climate variability and disturbances, it can often be prohibited due to limited resources. This lack of resources has led to the development of watershed-scale hydrologic models. These models simultaneously analyze topographic, soil, vegetation, land use, and vegetation spatial data together with climatic data for not only understanding the watershed hydrologic processes but also for making decisions on alternative best management scenarios designed to reduce the negative impact of anthropogenic activities on water quantity and quality (Bosch et al., 2004; Vazquez-Amabile and Engel, 2005). Most recently, these models, after their calibration and validation, are being used for predicting the impacts of alternative scenarios like climate change on hydrology, water quality and nutrient fluxes (Amatya et al., 2004; Francos et al., 2001). Most of such models available in literature are either for uplands (Arnold et al., 1998; Donigian et al., 1995; Young et al., 1989) or for artificially drained low gradient systems (Amatya et al., 2004; Fernandez et al., 2007). Furthermore, most of these models were originally developed for agricultural systems.

In recent years a watershed-scale hydrology and water quality model, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) developed primarily for upland agricultural ecosystems, has found its wide application for various purposes in various geographic regions around the world (Gassman et al., 2007). However, there have been limited studies on its application on low-gradient coastal plain watersheds of the Southeastern U.S. In contrast to upland watersheds, the low-gradient Southeastern coastal plain watersheds are characterized by slow-moving streams, high annual precipitation, poorly drained high water table soils, low evapo-transpiration (ET) during winter and early spring, and high ET during summer-fall. Furthermore much of these lands in the Southeastern coastal plains are covered by forests. For the first time Wu and Xu (2006) applied the SWAT hydrologic model on three mixed land use but predominantly forested coastal watersheds in Louisiana. Based on the results of two-year calibration and 10 to 20 years of validation data for all these three watersheds the authors demonstrated that the SWAT is capable of simulating hydrologic processes for medium to large-scale coastal lowland watersheds. The authors also found Manning's roughness coefficient for the mail channel, SCS curve number, and soil evaporation compensation factor as the most sensitive parameters for these costal watersheds. These watersheds studied by Wu and Xu (2006) had no more than 67% of the forested area with the remaining percentages varying between 31 to 39% on agricultural lands and 1 to 5% on urban areas.

Understanding the hydrologic processes of undisturbed or less disturbed systems by monitoring and/or modeling approach is vital as they can provide a reference data base for evaluating impacts of similar other developing watersheds in the region. This is especially true for the Atlantic Coastal Plain where the ongoing rapid development poses a threat to the adjacent aquatic ecosystems. Therefore, there is a critical need to develop a reliable hydrology and water quality model for an undisturbed (or less developed) natural forest ecosystem for accurately assessing the baseline hydrologic information. There has been no attempt yet of testing this widely used SWAT model for such systems. Recently, with only a limited field measured data set, Haley (2007) tested the model's ability to predict daily stream outflows from

a 72 km^2 low-gradient forested watershed at US Forest Service Francis Marion National Forest in coastal South Carolina using only two years (2005-06) of precipitation and weather data. The author found curve number, available soil water content, and Manning 's roughness as the most sensitive parameters. Using them as the calibration parameters and given the limited other field data, the SWAT model produced satisfactory estimates of daily and monthly runoff with Nash-Sutcliffe model efficiencies (E), a model evaluation goodness of fit criteria, greater than 0.4 (Haley 2007). The model's prediction of annual outflows was within 5.1% and 13.1% of the measured data for 2005 and 2006, respectively. However, the author reported that the model apparently failed to accurately describe the low flow regimes as indicated by over estimation of stream flow especially during the summer months although these deviations are likely a result of both model and data deficiencies. This was consistent with the results of Feyereisen et al (2007) who reported that the SWAT's predictive capabilities are less suited for drier conditions. Haley (2007) had made several suggestions that may improve the model's stream flow predictions that include the field measured soil hydraulic properties e.g. hydraulic conductivity, refining the curve numbers that are not well defined for various forest types in the SWAT database, additional years of data for refining the calibration, and most importantly the flow (runoff) generation process for the poorly drained shallow water table soils with low storage, especially the riparian forest buffers. Haley (2007) cited works by Bosch et al (2004) who indicated deficiencies of SWAT in accurately predicting the stream flow rates for watersheds with large wetland areas, especially riparian buffers with saturated soils similar to the environment in her study.

Therefore, the main objective of this study is to extend the work of Haley (2007) to improve the SWAT model's ability to predict the stream flows of the 72 km^2 Turkey Creek watershed on the poorly drained high water table soils of the South Carolina lower coastal plain. The extension and improvement were made as follows. One additional year (2007) of weather and stream flow data is used herein as a validation year. Most importantly, an alternative runoff generation process in SWAT that was not tested by Haley (2007) was tested herein for all three years. This new method reported by Kannan et al (2007) is a one-parameter evapotranspiration and precipitation based continuous soil moisture accounting procedure for the use in the SCS CN method for continuous hydrologic simulation, which was shown to better describe the flow generation on shallow water table soils. Rainfall input in the year 2005 was also adjusted and improvements in parameters for surface runoff, base flow, and ET component were also made as described below in the model calibration section.

Methods

Site Description

The study site is the Turkey Creek watershed (WS 78), originally established by the USDA Forest Service in 1964 and monitored until 1984. Both the rainfall and stream outflow were measured on the watershed during that period. Recognizing the importance of data from the forested watershed as a reference in a rapidly changing coastal environment, in 2004 a large-scale eco-hydrological monitoring and modeling program was initiated and the gauging of WS-78 re-established (Amatya and Trettin, 2007a). The watershed was reactivated by the Forest Service, Center for Forested Wetlands Research ("Center" hereinafter) in Charleston, SC (http://www.srs.fs.usda.gov/charleston/) by installing a real-time stream flow gauging station including a rain gauge (http://waterdata.usgs.gov/sc/nwis/uv?site_no=02172035) approximately 800 m upstream of the previous gauging station in cooperation with the US Geological Survey (USGS) and the College of Charleston (www.cofc.edu). This paper, however, presents the data collected from 2005 since its revitalization to 2007 only.

The Turkey Creek watershed is a third-order stream system draining an approximate area of 7,260 ha located at 33° 08'N latitude and 79° 47'W longitude approximately 60 km north-west of City of Charleston near Huger, in Berkeley County of South Carolina (Fig. 1). Located 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 3.6 m at the stream gauging station to 14 m above mean sea level (amsl). The sub-tropical climate is characteristic of the coastal plain having 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. Annual rainfall at the site varied from 830 mm 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.

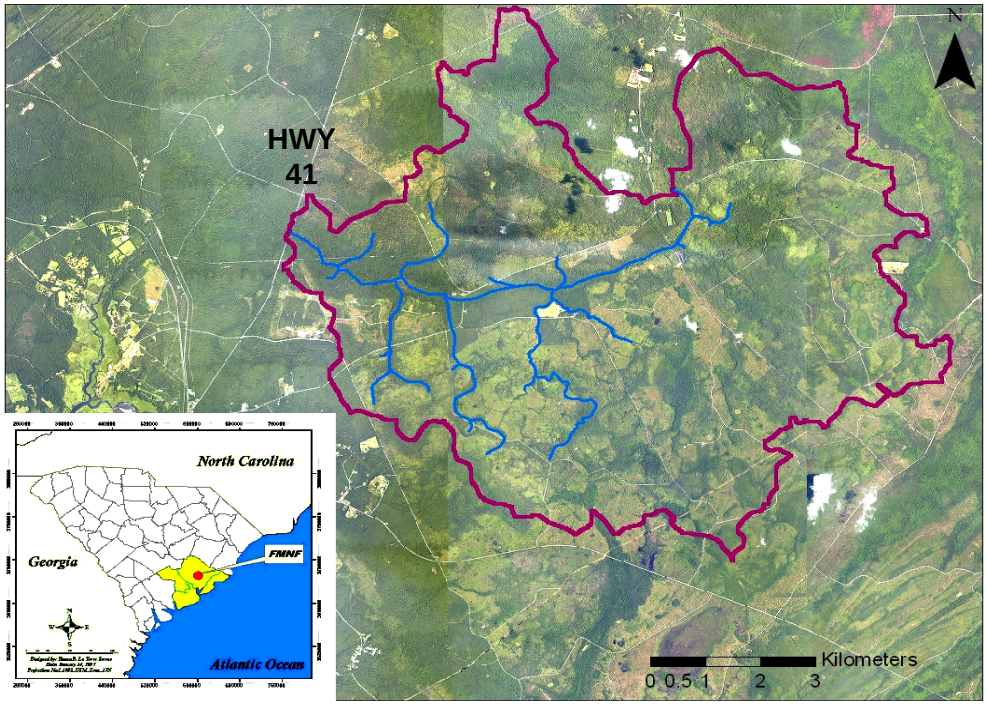

Figure 1. Location map of the Turkey Creek watershed at Francis Marion National Forest in Coastal South Carolina and the watershed boundary with stream hydrography.

Land use within the watershed is comprised of 88% pine forest (mostly regenerated loblolly (*Pinus taeda* L.) and long leaf pine (*Pinus palustris*)), 10% wetlands and water, and 2% agricultural lands, roads and open 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 17 years old. The watershed is dominated by poorly drained soils of Wahee (clayey, mixed, thermic *Aeric Ochraquults*) and Lenoir (clayey, mixed, thermic *Aeric Paleaquults*) series (SCS, 1980). The watershed also contains small areas of somewhat poorly and moderately well-drained sandy and loamy soils.

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. The watershed is also used for recreational purposes such as hunting, fishing, bird watching, hiking, canoeing, biking, historical tours, horse riding, all-terrain vehicle (ATV) use, and agriculture.

Hydro-meteorological Measurements

Rainfall

At present there are two automatic tipping bucket rain gauges in the study watershed. One gauge attached with a Campbell Scientific weather station is located near the middle of the Turkey Creek (TC) watershed and another gauge (USGS) established by the USGS in cooperation with the College of Charleston and Forest Service is linked with the stream flow monitoring station at the main outlet of the watershed. There are four more automated gauges around the watershed including one at the Santee Experimental Forest (SEF) Headquarters located about 5 km west of the watershed outlet (Fig. 1). In this study daily rainfall data from only two gauges (TC and USGS) on the watershed and one at the SEF site were used for the modeling analysis. Data from each of the automatic rain gauges were verified and calibrated using an adjacent manual rain gauge.

Stream Outflow

A new real time stream gauging station (about 800 m upstream of the old abandoned gauge) was established in 2004 by the USGS in cooperation with Forest Service and the College of Charleston at the main outlet of the watershed near the bridge on Hwy 41 (Figure 1) to collect stage heights in every 15-minutes using a Sutton data logger connected to the pressure transducer at the bottom of the stream (Amatya and Trettin, 2007a). Flow rates were calculated using a stage-discharge relationship developed by the USGS using frequent in-situ manual velocity measurements with a Marsh-McBirney meter at the stream cross section where the stage transducer is located. The 15-minute flow rates were integrated to obtain the daily outflow rates at the watershed outlet.

Weather Parameters

Climate data from two automated weather stations were available to estimate daily potential evapotranspiration (PET) needed to run the model (Haley 2007). One weather station is located 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, soil temperature, relative humidity, wind speed and direction, and solar and net radiation. This is a long-term weather station established in 1946 starting with just manual rainfall and temperature. The second one also a Campbell Scientific CR10X weather station was installed in the middle of the study site (Turkey Creek watershed) in October 2005 to measure precipitation, air temperature, relative humidity, wind speed and direction, and solar radiation on a half-hourly basis (Amatya and Trettin, 2007a).

SWAT Model

The Soil and Water Assessment Tool, SWAT, (Arnold et al., 1998) is a river basin scale model developed to quantify the impact of land management practices on the hydrology and water

quality in large, complex watersheds. This public domain model, actively supported by the USDA Agricultural Research Service, couples GIS spatial data characterizing a watershed with distributed parameter hydrological model to predict hydrologic processes including surface runoff, percolation, deep aquifer flow, evapotranspiration (ET), and channel routing (Wu and Xu, 2006). 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. In this study the 2005 version of the ArcView SWAT (AV-SWAT) (Neitsch et al., 2005) has been used for hydrologic modeling analysis.

The Natural Resources Conservation Service (NRCS), formally the Soil Conservation Services curve number (SCS-CN) method is used to calculate surface runoff and infiltration (USDA-SCS, 1972). The CN method is based on the soil type, land use and management practices in a particular area (Manguerra and Engel, 1998). Given a rain event, the CN determines the amount of infiltration and surface runoff in a given area. A larger the CN means higher amounts of surface runoff and less infiltration (Zhan and Huang, 2004). For current research conducted in coastal watersheds of Louisiana, the SCS curve numbers were found to be the most sensitive parameters used (Wu and Xu, 2006).

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-meter horizontal 1-meter vertical digital elevation model (DEM), geo-referenced stream layer, and aerial photos. 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 may help for an accurate stream flow routing in the SWAT model. Then the model was parameterized with both the GIS-based watershed spatial data such as DEMs, soils and land uses for hydrologic response units (HRUs) within each subwatershed and temporal input variables like precipitation and three-year (2005-07) weather data parameters.

The GIS based land use layers (La Torre Torres, 2008) were developed by digitizing a 2005 National Agriculture Imagery Program (NAIP) aerial photo at a 1:1500 scale (Haley, 2007). Based on these data, the total watershed area of 7260 ha was comprised of 98% forests and wetlands and only 2 % in crops, roads, and open area. Pine and pine-hardwood mixed forest covered more than 88% of the area. The soil data, provided by the NRCS, are also needed for the SWAT modeling. The SWAT model uses many of the soil characteristics provided by the NRCS 1:24,000 scale SSURGO data to determine factors such as runoff, soil water evaporation, percolation, and lateral movement of water through the soil layers. Soil porosity and hydraulic conductivity values of the soils in the watershed are also used by the model to calculate recharge to the aquifer, conditions creating a perched water table, and potential lag in lateral flow (Haley, 2007). These 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, lower weighted values (on average) of weighted CN's created using ESRI's Arc-CN Runoff Tool outside of the ArcView-SWAT were used for the final modeling analysis as the former with higher on average CNs were deemed more accurate based on the higher spatial resolution of polygons created in the former compared to only 213 HRUs created by the ArcView SWAT (Haley, 2007).

Precipitation Data

Precipitation data from three gauges mentioned earlier for 2005 to 2007 study periods were entered into the model. The precipitation data for 2005 came solely from the SEF site since the rain gauges were not yet in operation at the USGS site until February 2005 and the Turkey Creek weather station until October of 2005. Haley (2007) noted the variation that existed between the rainfall collected at the SEF and the two other gauges (TC and the USGS) based on the data for 2006. Overall, the cumulative rainfall was higher at the SEF site compared to the other gauges which were more consistent, as expected, and more accurately represented rainfall for Turkey Creek watershed. Somewhat larger differences in rainfall were generally observed for June to September, the months characterized by high intensity, short duration storms on the coastal plains. The model used data from all three gauges in 2006 and 2007 for accounting the spatial variability within the watershed.

Weather Data

The long-term Santee Experimental Forest (SEF) Headquarters temperature data was consistently higher than the temperatures observed in both 2005 (for last three months only) and 2006 at the TC site. Solar radiation was, in fact, higher for 2006 than in 2005 by 30% using the average annual value. The air temperature and solar radiation, as indicators for PET, varied between the two stations in 2006. The monthly average wind speed recorded at the TC weather station situated in the middle of a wide open field with no vegetation interfering with wind speed was also found to be higher than that recorded at SEF with a somewhat closer surrounding vegetation for both 2006 and 2007. The complete weather data measured at these stations were used to estimate Penman-Monteith based daily PET outside of the SWAT model (Haley 2007) for inputting into the model. However, data from only the SEF site was used for 2005 as the other station did not have a complete year of data.

Model Calibration and Validation

According to the SWAT model calibration guidelines (Luzio et al., 2002), simulations of the total water yield obtained from the SWAT output for the main outlet of Turkey Creek watershed were first calibrated based on average annual conditions. Once the model was calibrated for annual conditions, then the model was calibrated for monthly and eventually daily conditions. The guidelines also suggest using at least a year or more of “warm up” period to account for the instability in soil water balance computations caused by initial conditions. A two-year “warm up” period was used to simulate results for 2005-2006 period analyzed in this study. The weather parameters measured in these two years were replicated for simulations of the two previous years, 2003 and 2004 as the warming period. The simulations for 2003 and 2004 were then discarded, and only the results of predicted daily steam flows for 2005 -06 were used for the calibration analysis. Calibration processes involve repetitive analysis of simulated output files which includes precipitation, evapotranspiration, water yield, and contributions from surface and base flow that are compared with the measured data (primarily stream flows) for evaluating the performance of the model for the selected set of crucial input parameters. Based on published studies on SWAT calibration and sensitivity analyses (Arnold et al., 1998; Wu and Xu, 2006; Bosch et al., 2004), Haley (2007) conducted sensitivity analyses of 12 parameters chosen for model calibration to evaluate their effects on annual, monthly, and daily outflows.

In this study additional calibration was performed beyond what Haley (2007) reported using 2005-06 data to improve and further test the model predictions of stream outflows. First of all, the improved one-parameter model based on the CN procedure suggested by Kannan et al (2007) was used for refining the runoff prediction as mentioned earlier based on suggestions by

Haley (2007) in her earlier study for this watershed with poorly drained shallow soils where the model could not be calibrated using the evaporation soil compensation factor (ESCO) coefficient to reduce the runoff during the dry periods. The new parameter known as CNCOEF "depletion coefficient" (Table 1) theoretically varying from 0 to 2 in the method by Kannan et al (2007) was shown to be very sensitive to surface runoff and subsurface flow and less sensitive to ET. The model calibration involves the adjustment of this coefficient (CN calculation as a function of plant ET) until the predicted average basin/sub-basin surface runoff matches closely with that observed. The new calibrated input parameters are compared to those of Haley (2007) in Table 1. Secondly, rainfall data for 2005 used from the SEF site in the model was adjusted lowering all values by 15% based on the observations of Haley (2007) that the SEF data was consistently higher than that measured both at the USGS and TC gauges in 2006 and also based on similar observations in 2007. Furthermore, a quick comparison of the 2005 annual rainfall at the SEF site with data from another gauge on Lotti Road within 1 km from the study site (but not used) showed about 25% higher rain on the SEF than at the Lotti. Lastly, measured flow data for the months of June and July 2005 were totally excluded in this analysis as some high flow data measured during these months were questionable due to potential errors in stage created by bridge construction (December 2004 to August 2005) just below the flow sensor in the stream (Bodiford, 2008, personal communications). Haley (2007) also reported this potential error but analyzed both June and July, except for a two-day period in July with extremely high flows. However, some measured flow data that were intermittently not available for the periods of February 25 to March 09, March 17 to 29, October 01 to 06, October 18 to 24, and October 28 to November 03 in 2005 and January 19 to 25 in 2006 were excluded by Haley (2007) in her analysis. Since USGS had recently provided these data as estimated values this study has incorporated them in the analysis. Therefore, it may be unreasonable to directly compare our statistics of model evaluation results with that of Haley (2007).

Table 1. New calibration parameters input into the Turkey Creek SWAT model

Parameter	Description	Haley (2007) calibrated values	New Calibrated Values
CN	Curve Number	See Haley (2007)	See Haley (2007)
ICN	CN calculation as a function of plant ET	**0.0**	**1.0**
CNCOEF	Plant ET Curve Number coefficient	**0.00**	**0.30**
ESCO	Evaporation Soil Compensation Factor	**0.001**	**0.85**
EPCO	Evaporation Plant Compensation Factor	0.5	0.5
GW_REVAP	Groundwater "revap" coefficient	0.20	0.20
CH_N(1)	Manning's Roughness in main channel	**1.0**	**0.1**
CH_N(2)	Mannings roughness in tributaries	**0.2**	**0.15**
OV_N	Manning's roughness in overland flow	**1.0**	**0.5**
SOL_AWC	Soil available water content	0.4	0.4
ALPHA_BF	Alpha baseflow	0.0001	0.0001
SURLAG	Surface Runoff Lag Coefficient	**4.00**	**1.50**
CNMAX	Maximum Canopy Storage	N/A	0.50

After a satisfactory calibration of the model it was further validated with one year (2007) of data using the same set of input parameters used for the calibration. The validation process also included the evaluation of the model performance to predict the stream outflows on daily, monthly, and annual basis. The final parameters used both in the calibration and validation steps are presented in Table 1. 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 (subwatershed #39: Haley, 2007), the location of the stream gauging station, were used for the evaluation of the model performance. In this study, besides the graphical plots and tabular results, three standard statistical techniques, Nash-Sutcliffe coefficient (E), RMSE-observations standard deviation ratio (RSR), and Percent Bias (PBIAS), recommended by Moriasi et al. (2007) and also a widely used R^2 value (coefficient of determination) (Gassman et al., 2007) were used to test and evaluate the accuracy of the model simulations. In general, model simulation was judged satisfactory if E was > 0.50 and RSR <0.70, and if PBIAS was within ± 25% (Moriasi et al, 2007). These statistics were computed using monthly and daily observed stream flow values (in mm) and the monthly and daily water yields (in mm) predicted by SWAT at the main watershed outlet. Haley (2007) used Average Absolute Deviation (AAD) and Average Deviation (AD) between measured and predicted values as well as E and R^2 statistics.

Results and Discussion

Results of Av-SWAT (2005) based GIS spatial data development including field mapping of the stream tributaries and main channel for a detailed watershed characterization, watershed and subwatersheds delineation, and model parameterization, especially the runoff curve numbers (CN) for each HRUs based on the land use and soil types, for that matter the subwatersheds have been presented by Haley (2007) and La Torre Torres (2008). The Av-SWAT watershed delineation process produced altogether 39 subwatersheds within this 72.5 km^2 watershed. Similarly, results of hydrologic data analyses for 2005-06 were presented by Haley (2007).

Annual predicted outflows for the calibration years 2005 and 2006 are presented in Figure 2.

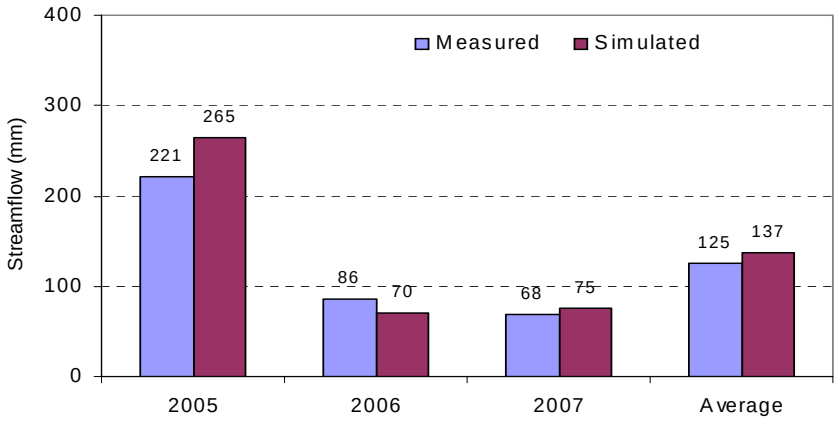

Figure 2. Measured and predicted annual stream outflows for three years (2005-07) and average annual stream flows for Turkey Creek watershed.

The comparison excludes data in 2005 for January (as the measured data were not yet

available) and June and July with very high stream flows as explained earlier. The model overpredicted (265 mm) the measured outflow (221 mm) by 20% in the wet year of 2005 (annual rainfall of 1579 mm at the SEF site) and underpredicted it (86 mm) by about 18.6% (70 mm) in dry year of 2006, indicating no systematic error. The overprediction here in 2005 was consistent with the results of Haley (2007) although an improved CN method (Kannan et al., 2007) was used herein and the data included in months February, March, June, July, October, and November were not exactly the same in both as mentioned earlier. However, it seems that the improved one-parameter based CN method resulted in lower flow predictions (only 70 mm) compared to 96 mm by Haley (2007) for the relatively drier year 2006. With the same parameters in the model, the annual predicted outflow of 75 mm for the validation year 2007 was about 10% higher than the measured (68 mm). The validation year 2007 was still relatively drier with annual rainfall of only 994 mm (at TC gauge) than 2006 with 1122 mm. The improved CN method seems to still hold the argument made by Haley (2007) and Feyereisen et al (2007) that the CN-based SWAT hydrology may not accurately simulate the flow dynamics of the poorly drained shallow soil ecosystems for drier conditions. On an average annual basis, the model overpredicted (137 mm) the measured average (125 mm) by about 10%. The differences observed will be discussed in the monthly and daily comparisons below.

For the average annual rainfall of 1147 mm for the 3-year of simulation the model predicted an average annual surface runoff of 178 mm (15.5% of the rainfall) and a base flow amount of 19 mm (1.7%) of the rainfall, which were 92% and 8% of the total stream flow (yield), respectively. This average base flow estimate of about 8% is much less than an estimate provided by La Torres (2008) using a hydrograph separation method of Swindel et al (1983) with the historic storm event data from the Turkey Creek watershed. A low base flow estimate in this study period may be attributed also to two years (2006 and 2007) with much reduced rainfall resulting in deeper water table depths as discussed above and low stream flows. As per other water balance components, the model predicted average annual evapotranspiration (ET) of 900 mm seems to be reasonable compared to a water balance study by Harder et al. (2007) in an adjacent first order watershed. The average annual water balance shows a soil water deficit of (1147 – 178-19 =) 50 mm, which may be consistent based on two relatively drier years. The average annual ET of 900 mm, as 81 % of the average annual PET of 1116 mm, and 78 % of the average annual rainfall is about 9% lower than the 13-year long-term historic data (983 mm) reported by Amatya and Trettin (2007b) for the study watershed.

Data in Figure 3 represent the monthly predicted outflows compared with the measured data for the two-year (2005-06) calibration and a one-year (2007) validation periods As mentioned earlier no measured data are plotted for January, June, and July in 2005. The model predictions generally followed the pattern of measured monthly outflows with some overpredictions in February, March, August, and September and underprediction in October and December. The discrepancies in February, March, and October may be also due to the fact that the measured data for most of the days in these months were estimated and Haley (2007) did not use them in the analysis. It was also the period when the bridge just downstream of the stage measuring sensor was under construction. Interestingly, the model was able to capture all monthly flows in relatively dry year of 2006 reasonably better than in 2005. Most importantly, the modified CN method in this study dramatically improved the predictions for the near zero flow months from April to August in 2006 compared to the results of Haley (2007) who found consistent flow overpredictions during these months. The model almost accurately predicted the outflows including the zero flows in the validation year of 2007, except for very dry months from August to September where a slight overprediction occurred. 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 (Haley, 2007), indicating that the period in 2007 was even drier than 2006. This was also supported by the data from ground water wells at the study site that had water table as deep as 2.5 m creating large soil storage in a well drained soil (not shown). This indicates that even the modified CN method in AV-SWAT may be still unable to capture the dynamics of this shallow soil with a varying soil storage as affected primarily by rainfall and ET.

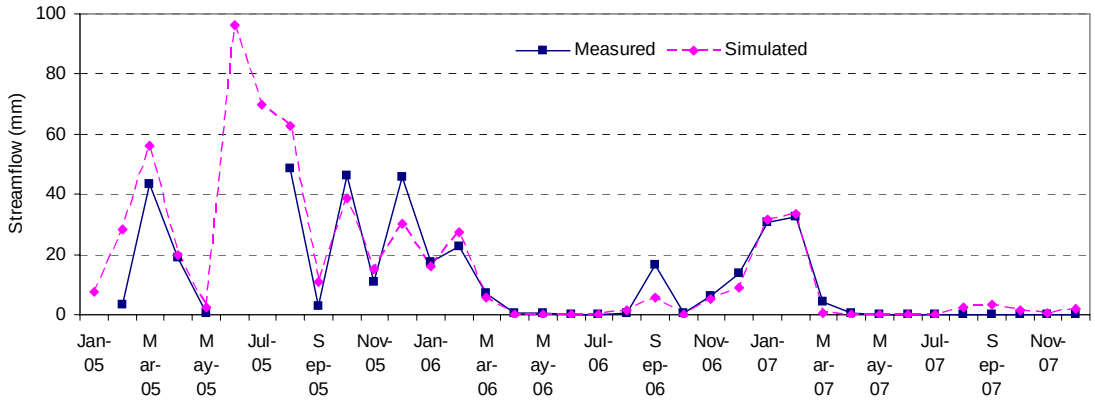

Figure 3. Measured and predicted monthly stream outflows for three years (2005-07) for Turkey Creek watershed.

Based on the Moriasi et al (2007), the model performance was "good" for the calibration period without the three months in question with measured stream flows. This is supported by the R^2-statistics of 0.78, Nash-Sutcliffe "E" of 0.74, the RSR value of 0.51 (< 0.70) and lower than 10% of PBIAS (Table 2). Similarly, the model performance was even better or "very good" for the validation year (2007) with R^2 and E values near unity, much lower RSR value and PBIAs of 10.6%. A negative PBIAS value for both the calibration and validation periods indicates an overestimation bias. The prediction results were also equally good based on the computed statistics taken for all three years together.

Table 2. Calculated model performance evaluation statistics for the monthly stream flows.

Monthly	R^2	E	RSR	PBIAS, %
2005-06 (Calib)	**0.78**	**0.74**	**0.51**	**-9.2**
2007 (Valid)	**0.98**	**0.98**	**0.15**	**--10.6**
2005, 2006 and 2007	**0.83**	**0.79**	**0.46**	**--9.5**

Simulation results using the daily flow data are presented in Figure 4, which again excludes the measured data for January, June and July in 2005. It is evident that the model was able to capture most of the daily flow events for both the calibration (2005-06) and validation (2007) years. The major discrepancies were observed in February-March of 2005 when the model

severely overpredicted the daily flows and in September 2006 when the model could not capture an event with a peak flow rate of near 4 mm day^{-1} that occurred after a long dry (near zero flow) period from May to August. The reason for overpredictions again is most likely due to a long dry period that occurred at the site from October 2004 to January 2005 based on the rainfall and flow data observed at nearby first-order watersheds (Amatya et al., 2006). Although the model was simulated with two years (2003-04) of "warm-up" period for initial moisture conditions the weather data from 2005 and 2006 were repeated for 2003-04. So it is likely that if the actual weather data observed at the nearby first-order watershed (WS77) was used for 2003 and 2004, the predictions in early 2005 may perhaps be improved. On the other hand, it is also likely that the calibrated improved one parameter CN-method has still not been able to capture the daily flow dynamics on this forest in shallow soil system. The model calibrated herein with the improved CN-method (Kannan et al., 2007), however, performed better during the dry months of April to August 2006 than reported earlier by Haley (2007).

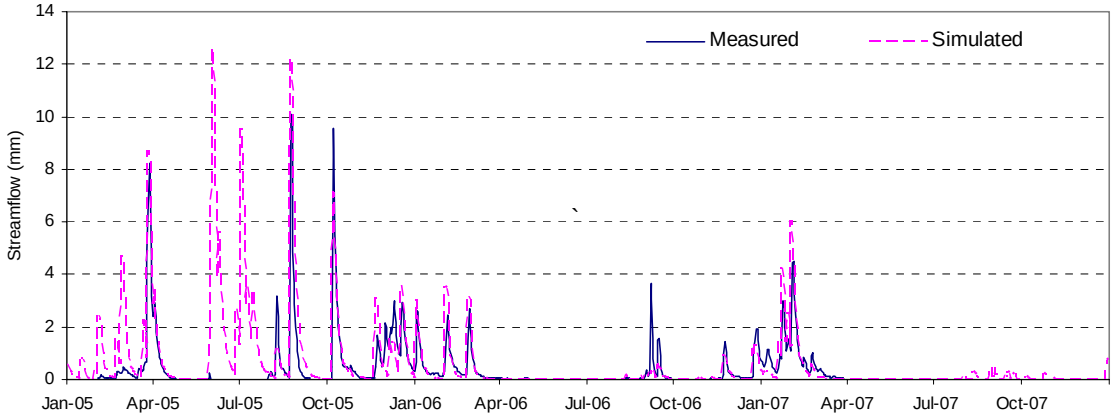

Figure 4. Measured and predicted daily stream outflows for three years (2005-07) for Turkey Creek watershed.

Interestingly, although the antecedent dry conditions for September 2006 were similar without flows to the early 2005 (as seen in the adjacent first-order watershed), the model substantially underpredicted the September 2006 flow event contrary to the February-March 2005 events. One possible reason is effect of aerially averaged rainfall during the summer-fall periods. For example, the total rainfall measured on two gauges on Turkey creek watershed was 40 to 50 mm less than the SEF gauge which may lower the average. Most importantly, the fact that the water table was at or near the surface in four out of the six ground water wells in early days of September 2006 due to repeated rain events in August on the study site (not shown) may have saturated these soils in which case the improved CN method might have failed to describe the runoff process for saturated conditions. Again the effect of long dry phenomenon observed in early 2005 seems to have repeated for August and September 2007 when the model somewhat overpredicted the flows. Overall, the daily flow predictions in Figure 3 were improved than the earlier results by Haley (2007), except for February-March 2005, during which she excluded analysis of several days of flows. The improved predictions are also supported by the calculated model evaluation statistics in Table 2.

Table 3. Calculated model performance evaluation statistics for the daily stream flows.

Daily	R^2	E	RSR	PBIAS, %
2005-06 (Calib)	0.70	0.65	0.60	-9.2
2007 (Valid)	0.74	0.67	0.57	-10.6
2005, 2006 and 2007	0.71	0.65	0.59	-9.5

As expected, the calculated statistics were somewhat poorer for the daily predictions than those obtained for the monthly periods (Table 1). However, the calculated R^2 and E-statistics of 0.70 and 0.65, respectively, obtained for predicting daily flows during the calibration period (Table 2) indicate that the model performed satisfactorily or just in the border of "Good" based on Moriasi et al (2007) rating. The PBIAS was similar to the one obtained for the monthly periods (Table 1). As for the monthly periods, the computed statistics for the validation period rated the model predictions of daily flows as "Good". Again the negative PBIAS for both periods is an indicative of overpredicting bias by the model. One reason for higher statistics is due to several days of zero and near-zero flows the model was able to predict The negative average deviation in both calibration and validation periods shows a slight tendency of the model to overpredict the monthly flows.

Conclusions and Recommendations

Based on a limited field measured data, results of this two-year (2005-06) refined calibration from the previous work by Haley (2007) and one-year (2007) validation analyses showed that the SWAT model with an improved one-parameter "depletion coefficient" for adjusting curve number (CN) based on plant ET can predict the stream flow processes of the low-gradient forested watershed reasonably well. The predictions were much improved over the classical CN method was used for runoff generation (Haley 2007). With the limited field calibration, the model performed "Good (E = 0.74; RSR = 0.51)" to "Very Good (E = 0.98; RSR = 0.15)" for the monthly calibration and validation periods and only "Satisfactory (E = 0.65; RSR = 0.60)" to "Good (E = 0.67; RSR = 0.57)" for the daily calibration and validation periods. It was also concluded that the refined SWAT model was still unable to accurately capture the flow dynamics of this forest ecosystem in high water table shallow soils for very wet saturated (September 2006) and very dry antecedent conditions (February 2005; Summer 2007) and warrant further investigations on these shallow soil systems, particularly in forests. On average, the annual water balance components estimated by the model were reasonable for the site.

The predictions of stream outflows may be further improved by some additional factors into consideration. First of all, inclusion of data from the rain gauge (on Lotti Road) just adjacent (west) of the study watershed instead of relying on rain data from the SEF site (which is 5 km southwest) may improve the predictions as seen by the consistently higher rainfall observed at the later site perhaps biasing the aerial average estimate. This will also eliminate the need for making an arbitrary assumption on rainfall amount from the SEF site to be applied on this watershed calibration as was done here. Additional testing with a wet to normal year of data would also be recommended as the only wet year (2005) in this study has flows estimated and/or extrapolated for several days in February, March, October, and November. Future modeling efforts with the SWAT model should consider multi-parameter calibration including the

water table depths being measured at various locations on the watershed. This should improve the parameter calibration, especially for the depletion coefficient for the curve number. Furthermore, it is suggested that the current curve number in this and previous study (Haley 2007) estimated based on land use and soil type be verified based on the findings of a recent CN optimization study using analysis of 51 observed historical storm events by La Torre Torres (2008). The author found the average CN based on the optimization analysis 8% lower than the one obtained by the literature-based values.

Improvements such as those outlined above for future works should improve the predictive capability of the model, thereby providing a better understanding of hydrologic dynamics and watershed response to land use change and climate variability on the Turkey Creek watershed and similar other low-gradient forested watersheds in the coastal plain.

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