SWAT-BASED STREAMFLOW AND EMBAYMENT MODELING OF KARST-AFFECTED CHAPEL BRANCH WATERSHED, SOUTH CAROLINA

D. M. Amatya, M. Jha, A. E. Edwards, T. M. Williams, D. R. Hitchcock

ABSTRACT. *SWAT is a GIS-based basin-scale model widely used for the characterization of hydrology and water quality of large, complex watersheds; however, SWAT has not been fully tested in watersheds with karst geomorphology and downstream reservoir-like embayment. In this study, SWAT was applied to test its ability to predict monthly streamflow dynamics for a 1,555 ha karst watershed, Chapel Branch Creek, which drains to a large embayment and is comprised of highly diverse land uses. SWAT was able to accurately simulate the monthly streamflow at a cave spring (CS) outlet draining mostly agricultural and forested lands and a golf course plus an unknown groundwater discharging area, only after adding known monthly subsurface inputs as a point source at that location. Monthly streamflows at two other locations, both with multiple land uses, were overpredicted when lower lake levels were prevalent as a result of surface water flow to groundwater (losing streams). The model underpredicted the flows during rising lake levels, likely due to high conductivity and also a deep percolation coefficient representing flow lost to shallow and deep groundwater. At the main watershed outlet, a wide section performing as a reservoir embayment (R-E), the model was able to more accurately simulate the measured mean monthly outflows. The R-E storage was estimated by using a daily water balance approach with upstream inflows, rainfall, and PET as inputs and using parameters obtained by bathymetric survey, LiDAR, and downstream lake level data. Results demonstrated the substantial influence of the karst features in the water balance, with conduit and diffuse flow as an explanation for the missing upstream flows appearing via subsurface conveyance to the downstream cave spring, thus providing a more accurate simulation at the embayment outlet. Results also highlighted the influences of downstream lake levels and karst voids/conduits on the watershed hydrologic balance. Simulation performance of hydrology could be improved with more accurate DEMs obtained from LiDAR for karst feature identification and related modification of SWAT parameters. This SWAT modeling effort may have implications on nutrient and sediment loading estimates for TMDL development and implementation in karst watersheds with large downstream embayments that have significant changes in water level due to adjoining lakes.*

Keywords. *Deep percolation, Groundwater (baseflow), Hydrologic models, Lake Marion, Losing streams, Runoff, Saturated conductivity, TMDL, Upper coastal plain.*

Understanding watershed hydrology is critical, as it is often a primary driving force for nutrient cycling and loading dynamics and subsequent downstream water quality impacts as a result of rapid urbanization and other land use changes. For this purpose, many monitoring studies, both in upland and lowland watersheds with various land use types, have been conducted in recent decades to better understand hydrologic as well as nutrient cycling and transport processes. Due to the limited and competing resources for long-term monitoring, researchers are increasingly inclined toward the development and application of process-based, lumped, empirical, or even conceptual models to better understand complex watershed processes and their interactions with climate, topography, soils, and land use and management. Furthermore, validated models are useful for providing reliable assessments of water quantity and quality impacts to land managers, planners, and decision-makers.

A distributed, watershed-scale hydrology and nutrient model using the SWAT (Soil and Water Assessment Tool) hydrology and water quality model (Arnold et al., 1998) was developed for the 1,555 ha Chapel Branch Creek (CBC) watershed. SWAT was selected for the CBC watershed to better understand its hydrologic processes (streamflow pathways and dynamics) that drive nutrient and sediment loading (Amatya et al., 2008). The CBC watershed drains a small tributary to the Santee River near Lake Marion in the upper coastal plain of central South Carolina. It has been listed by the South Carolina Department of Health and Environmental Control (SCDHEC) under U.S. EPA approved SC 2004 303(d) list of water bodies for impairment of aquatic life (AL) due to elevated chlorophyll *a*, TN, TP, and pH (Williams et

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al., 2007). At the onset of this study, the CBC watershed had no historical hydrologic or water quality data other than the grab sample data measured by the state utility and lake management agency, Santee Cooper, at SC-014 and SC-045 (fig. 1). The study watershed is small (1,555 ha) in comparison to others where SWAT has been applied (Gassman et al., 2007), but the wide diversity of land uses in the area (e.g., agriculture, forest, golf courses, interstate highways and local roads, and urban and suburban areas) and the karst terrain typical of the region (Spigner, 1978) provide a complex watershed hydrology and water quality assessment scenario.

Chapel Branch Creek is in the upper coastal plain of South Carolina, which is underlain by Santee limestone, a carbonate formation from the middle Eocene (40 mya) (Willoughby, 2002). The rise and fall of sea levels in the geologic past in this region led to the development of solutional voids at different elevations (Siple, 1975), thus creating subsurface flow connections not just horizontally, but vertically throughout the limestone. The water table for the main conduits and voids (C&V) within the limestone aquifer depend on proximity to Lake Marion (Siple, 1975). Where the limestone meets the lake, water levels have decreased to meet the lake's water level, with C&V discharging their water at springs along the limestone-lake interface, such as the spring at Santee Cave. In another companion study, dye trace results at the site showed a connection between the karst aquifer and surface water level of Chapel Branch Creek, controlled by Lake Marion (Edwards et al., 2011a). These data also indicated a relationship between fluctuating base level of the lake with vertical storage in the watershed karst and surface flow.

Although in recent years the SWAT model has been widely and successfully tested for various geographical regions with multiple management practices, studies on watersheds affected by karst features (e.g., sink holes, losing streams, springs, and caves that potentially provide for significant groundwater linkages) are limited due to the complex processes by which groundwater can variably influence surface water flow, both in magnitude and duration. As a result, to date, commonly used hydrologic models such as SWAT for more typical basins do not provide satisfactory estimates of runoff in karst regions (Ghanbarpour et al., 2010). Ghanbarpour et al. (2010) proposed stochastic, time series autoregressive models using historic streamflow data for simulating weekly and monthly streamflow in karst systems. Schomberg et al. (2005), as cited by those authors, concluded that karst watersheds are more complex and more poorly understood than non-karst systems (Felton, 1994) and have been shown to require more specialized calibration to obtain accurate results (Spruill et al., 2000). Similarly, Jourde et al. (2007) and Salerno and Tartari (2009) showed that surface runoff hydrologic models cannot simulate the flow in the karst part of watersheds due to the additional and perhaps delayed contribution of karst groundwater to surface flow. These researchers suggested the use of a fully coupled surface-subsurface hydrologic model to characterize the dynamics of the karst groundwater contribution to the surface drainage network. Salerno and Tartari (2009) presented a potential application of wavelet analysis (WA) to help define the nature and behavior of the karst contribution to river flows, thereby improving the performance of surface hydrological modeling, including those processes utilized by SWAT.

Recently, Baffaut and Benson (2009) modified the SWAT 2005 code to simulate faster aquifer recharge in karst environments (SWAT-B&B) by modifying subroutines for deep groundwater recharge and maximizing the hydraulic conductivity for sink holes simulated as ponds and for losing streams and tributaries. Although the authors reported improvement in the partitioning of streamflow between surface and return flows, they also highlighted the possibilities and limitations in modeling flow and water pollutant movement in a karst watershed. Yachtao (2009) further modified the works of Baffaut and Benson (2009) (SWAT-B&B) in SWAT-Karst to represent karst environments at the hydrologic response unit (HRU) scale. In the Opequon Creek watershed study, Yachtao (2009) found that SWAT-Karst using HRUs to represent sinkholes had a more notable impact in the watershed hydrology than SWAT-B&B using ponds to represent sinkholes. The author reported that the SWAT-karst and the SWAT-B&B versions performed better than SWAT in predicting streamflow in a karst-influenced watershed.

The main objective of this study is to test the capability of the SWAT model to predict monthly and annual outflows at various locations of the CBC watershed affected by karst features as well as at the reservoir-embayment (R-E) watershed outlet at the lake edge. The uniqueness of the SWAT model testing is two-fold: (1) the ability to predict outflows at one individual subwatershed and two other locations draining multiple subwatersheds within this karst watershed, a property typical of distributed watershed models such as SWAT, as opposed to calibration with measured data only at the watershed outlet; and (2) the ability to predict watershed outflow at the wide flooded R-E downstream as affected by the lake level changes as a boundary condition for model validation.

Methods

Site Description

Chapel Branch Creek (CBC) is a small tributary of the former Santee River that now flows directly into Lake Marion, a dam reservoir, near the town of Santee, South Carolina (a portion of the 11-digit HUC 03050111-010) (fig. 1). The watershed with its main outlet at the lake (33° 30′ 7.5″ N and 80° 27′ 37.1″ W) drains approximately 1,555 ha of land through two main drainage areas (fig. 1). The northwestern area draining to the cave spring (CS) outlet is the valley of CBC, with a natural creek that has been modified by drainage ditches near the watershed boundary along with a dam and a pond within the valley (ERC, 1999). The southeastern section is composed primarily of ditches, culverts, and storm drains associated with the development along the highways and roads.

Topography of the watershed is flat and approximately 37 m a.m.s.l. (above mean sea level) in the upstream areas, with somewhat steeper topography (25 to 30 m a.m.s.l.) on the downstream section near Lake Marion (Mihalik et al., 2008). The CBC watershed incorporates complex land use patterns, with residential, commercial, and industrial areas interspersed among agricultural and forested lands (fig. 1). The watershed also has some karst features, with depressions, sinkholes, losing stream tributaries, springs, and caves (Edwards et al., 2011b). Soils reflect somewhat poorly and poorly drained paleudults with relatively heavy subsoil on the flat

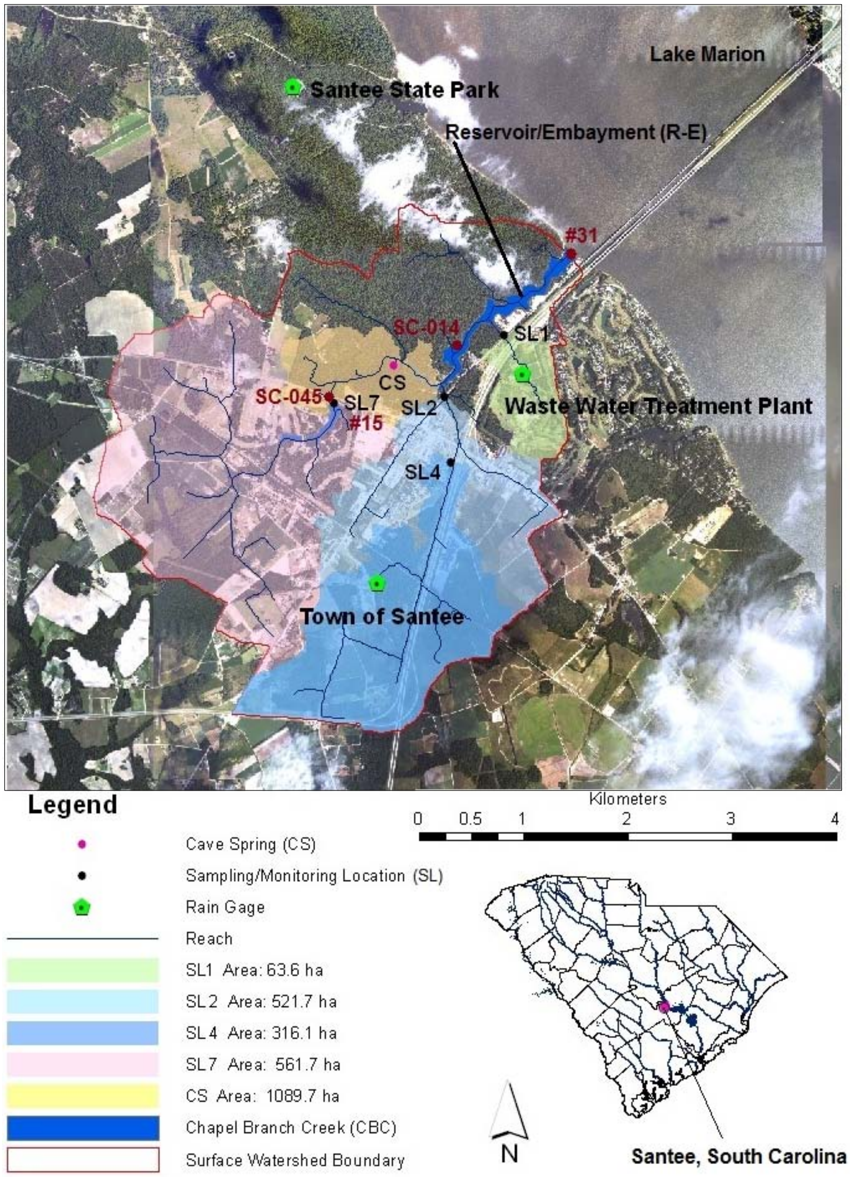

Figure 1. Location map, boundary, and tributaries of Chapel Branch Creek watershed draining to Lake Marion, South Carolina. Rain gauges and flow monitoring stations are also shown. SC-014 and SC-045 are sampling stations maintained by SCDHEC.

terrace surface. The lower watershed has excessively well drained soils with heavy subsoils as well as dune soils with sand throughout the profile (Mihalik et al., 2008). The entire watershed contains portions of two golf courses, a small urban center in the town of Santee, a fringe of suburban housing, and a sewage treatment plant for the town and a highway rest area (fig. 1). Agriculture, as the primary land use in the watershed, is primarily small grain and vegetable produce. Most of the forested lands are located within Santee State Park on the northwest left bank of the CBC (Mihalik et al., 2008). Out of two primary locations draining multiple subwatersheds used for flow calibration, a cave spring (CS) outlet drains about 1,090 ha of land comprised of agricultural and forested lands and also a golf course (fig. 1). The second location (SL2) drains 522 ha of land comprised of an urban municipal area along with major highways and roads, and some agricultural and forested lands. A third individual subwatershed (SL1) (63 ha) contains another golf course that receives wastewater treatment plant effluent via land application as well as the highway rest area (fig. 1).

Hydrologic Monitoring

Rainfall

Rainfall was continuously measured from August 2006 to October 2009 with varying periods at three installed automatic and manual gauges at the town of Santee (TS) (from August 2006 to October 2009), the wastewater treatment plant (WWTP) (from March 2007 to October 2009), and Santee State Park (SSP) (from May 2007 to October 2009) (fig. 1). For any missing data, temporal data from the nearby gauge were used while calibrating the total rain with the adjacent manual gauge for obtaining the adjusted rainfall and its distribution.

A large spatial variability in rainfall measurements at different gauge locations was observed in some months, which is characteristic of this region, especially during summer storm events and tropical depressions (Amatya et al., 2006, 2008). The maximum monthly rainfall exceeding 250 mm, which is 100 mm higher than the long-term average, was observed in July 2009 at the TS gauge. The lowest values of monthly rainfall (<10 mm) occurred in November 2007 and September 2009. Monthly rainfall was below normal for eight out of 12 months in 2007, and this pattern of drought continued until June 2008. The annual total in 2008 for the SSP gauge was 1015 mm, while the long-term average was 266 mm higher at 1281 mm. All three gauges had consistently lower annual rainfall than the long-term average, indicating drier conditions than normal for these four years. Details of rainfall measurements and analysis are discussed by Amatya et al. (2010). Daily rainfall data from these three rain gauges from 2006 to 2009 were used in SWAT model simulations.

Weather

Data on air temperature, relative humidity, solar radiation, and wind speed were obtained from the nearby U.S. Fish and Wildlife Service (U.S. FWS) weather station (http://fam.nwcg.gov/fam-web/) at Santee National Wildlife Refuge across Lake Marion to the northeast. Hourly weather data were processed to obtain daily average values for calculating the daily potential evapotranspiration (PET) using Turc's method (Turc, 1961) as described by Amatya et al. (1995). The potential drought shown by lower than average rainfall in 2007 is further supported by the highest estimated PET of 1218 mm estimated for 2007 compared to 2008 and 2009. Weather data from this station from 2006 to 2009 were used in SWAT model simulations.

Stream Flows

An ISCO flowmeter at SL2 (fig. 1) was installed to measure flow rate only in the right culvert of a dual 1.5 m (5 ft) diameter circular concrete culvert draining most of the developed areas in the town of Santee, including roads and highways in the southeastern section. The total flow rate of the dual culvert at SL2 was estimated by combining the ISCO-based flow rate with the flow rate estimated for the left culvert using the stage height at the right culvert and Manning's formula (McCuen, 1989).

Flowmeters were later installed at the box culvert outlet of subwatershed SL1 and the cave spring (CS) outlet (fig. 1) receiving surface flow from SL7, about 2 km downstream of it and also a sustained underground water discharge from an unknown subsurface area (west and southwest of it). In this study, data measured from August 2008 to October 2009 at SL1, from July 2007 to October 2009 at SL2, and from December 2008 to October 2009 at CS were used for analysis. Measured flow rates (in $m^3 s^{-1}$) at 10 to 15 min intervals were further processed to obtain daily, monthly, and annual totals (in mm depth) for water balance and model calibration (Amatya et al., 2010). Flow data at the CS outlet were estimated using a stage-discharge relationship developed by the measurements of velocity and stage at a fixed cross-section on a weekly basis. Details of quality control on all flow data are presented by Amatya et al. (2010).

SWAT Model

The SWAT model (Arnold et al., 1998) was chosen for this study because it is a public domain model that has been successfully applied to assess the hydrologic and water quality impacts of land management practices on water, sediment, and agricultural chemicals in complex watersheds such as Chapel Branch with its varying soils, land uses, and management conditions. Details of all the hydrologic processes (e.g., surface runoff, baseflow, water yield, ET, etc.) including the flow and nutrient routing simulated by SWAT and the output variables (water, sediment, nutrients, and pesticides) can be found in Neitsch et al. (2002).

SWAT Model Setup

Since SWAT is a watershed-scale distributed model, the first step in the model setup is watershed delineation into subwatersheds, each connected through a stream channel and further subdivided into HRUs with unique combination of soils, land uses, and management practices (Borah et al., 2006). This study used multiple HRUs, with land use 5% over subbasin area and soil class 5% over land use area, resulting in 452 HRUs within the 31 delineated subwatersheds. The watershed was delineated using the ArcView SWAT2003 model with spatial data on digital elevation model (DEM), land use, soils, and other field observations. The GIS spatial data on the USGS 1:24,000 scale DEM, land use in the SWAT code (table 1) built by digitizing digital USGS topographic maps and 2005 National Agricultural Imagery Program (NAIP) aerial photography with 1 m resolution, and the SSURGO shapefile and database for the SC-075 soil map of Orangeburg County, South Carolina, obtained from the USDA-NRCS website, were analyzed and processed to obtain the necessary spatial layers for the SWAT-CBC model setup (Mihalik et al., 2008; Amatya et al., 2008; Williams et al., 2007). The missing hydraulic conductivity (K) values from the NRCS database for soils were updated with data from the Orangeburg County Soil District (NRCS, 2007).

Although the default watershed delineation in the SWAT interface is available for creating subwatersheds and stream reaches using the DEMs and hydrography (Jha et al., 2004), 31 outlets were manually chosen based on the enhanced hydrography layer, resulting in an average subwatershed area of 50.3 ha, or 3.2% of the total watershed, consistent with suggestions by Arabi et al. (2006) for representing the BMPs in the SWAT model. The final outlet (subwatershed 31) for Chapel Branch Creek was at the downstream boundary of the reservoir-embayment (R-E) at Lake Marion (fig. 1). A point source was then added in subwatershed 16 containing the cave spring (CS), which contributes a sustained groundwater flow, possibly from an estimated area of 1,090 ha or more, including subwatersheds SL2 and SL7, to the CBC headwaters. The baseflow was estimated by using the measured daily streamflow at the CS outlet with the autofilter program (Arnold and Allen, 1999) recommended in the SWAT model. The measured data showed a sustained baseflow rate of 0.08 $m^3 s^{-1}$, yielding about 90% of the total streamflow (Amatya et al., 2010). Two reservoirs including the down-

Table 1. SWAT land use codes, descriptions, and percent of watershed area for CBC watershed.

SWAT Code	Description	% of Watershed Area
FSRD	Mixed forest	44.09
RNGE	Range	26.65
AGRL	Agriculture	16.39
UTRN	Transportation	7.75
UCOM	Commercial	3.06
WATR	Open water	1.96
URML	Urban medium density	0.10
PAST	Pasture	0.01

Table 2. SWAT model parameters used in the hydrologic calibration

Parameter	Notation	Range	Final Value
Soil evaporation compensation factor	ESCO	0.75 to 0.95	0.80
Surface runoff lag coefficient	SURLAG	1 to 10	4
Soil available water capacity	SOL_AWC	0 to 1	0.08 to 0.21
Hydraulic conductivity of main channel	CH_K1	0.01 to 150	150 mm h^{-1}
Hydraulic conductivity of tributary channel	CH_K2	0.01 to 150	150 mm h^{-1}
Groundwater delay coefficient	GW_DELAY	0 to 100	15 days
Baseflow recession coefficient	ALPHA_BF	0 to 1	0.7
Groundwater movement coefficient to root zone	GW_REVAP	0.02 to 2.0	0.2
Curve number	CN	--	--
Rangeland, RNGE	--	35 to 84	80 to 81
Mixed forest, FRSD	--	36 to 79	50
Agriculture land, AGRL	--	51 to 94	70
Commercial urban, UCOM	--	46 to 95	80 to 82
Transportation, UTRN	--	83 to 98	95
Deep aquifer percolation coefficient	RCHRG_DP	0 to 1	0.73 to 0.95

stream embayment (R-E) and a golf course pond (an impounded upstream section of CBC at SL7) were added to subwatersheds 31 and 15, respectively (fig. 1).

Model Parameterization

SWAT offers numerous default values and their possible ranges for parameters such as curve number, soil available water capacity, soil evaporation loss, and groundwater parameters for calibration of hydrology (Manguerra and Engel, 1998; Neitsch et al., 2002; Bosch et al., 2004; Neitsch et al., 2004; Feyereisen et al., 2007). The values of these parameters need to vary within the given ranges first for the calibration of watershed hydrology and streamflow, and then to water quality parameters.

Calibration of the SWAT model constructed for the CBC watershed was more than a standard calibration due to complex karst watershed characteristics, including depressions and sinkholes, that trap surface water from the streams and tributaries to the underground system through interconnected conduits. As indicated earlier, only a few studies had attempted to model karst hydrology. Measured flow data at SL2 and CS (fig. 1) suggested that a substantial portion of surface water might have been lost before discharging at the outlet of SL2 and that potentially reappeared at CS (Amatya et al., 2010). To capture this process in the SWAT model, first the effective hydraulic conductivity values for the main and lateral channels were set high at 150 mm h^{-1} (table 2) to lose surface water to the shallow aquifer, as suggested by Baffaut and Benson (2009). Secondly, a deep aquifer percolation coefficient, a parameter in SWAT that explains the fraction of baseflow out of the drainage area and lost from the watershed system, was used in further calibration.

After sensitivity analysis, specific values in the upper range for the SL1, SL2, and CS locations were chosen for this deep percolation coefficient (table 2) to provide a reasonable estimate of water loss to groundwater from this karst system for flow calibration. The values of this parameter in addition to those for other standard parameters (CN, ESCO, SOL_AWC, and GW_REVAP) were used in the calibration at all three locations (SL1, SL2, and CS) to closely match measured streamflow. For example, the curve numbers ranges verified by SCS (1986) according to land use (table 1) were calibrated to match the surface runoff. Missing and incomplete available water capacity values of the soil layer values were derived from Dunne and Leopold (1978). Manning's "n" values for overland flow and for main and tributary channels were based on land use values using SCS (1986) and McCuen (1989), respectively. The most sensitive hydrologic parameters in flow calibration for this karst watershed included curve number, effective hydraulic conductivity in the main and tributary alluvium, and the deep aquifer percolation coefficient. Table 2 lists the parameters used in the hydrologic calibration of the SWAT-CBC model with their final calibrated values.

Reservoir Parameterization

Two reservoirs are represented in the SWAT model for the CBC watershed (fig. 1). The SWAT input parameters for a small reservoir, such as a pond in subwatershed 15 at the SL7 outlet, were extracted from the report by ERC (1999). In this article, only the reservoir-embayment (R-E) in subwatershed 31, which represents the lower flooded wide section (outlet) of the CBC watershed, is discussed. Such a wide and shallow (about 200 m wide and 3 m deep on average) water body is generally modeled using more complex 2-D or 3-D hydrodynamic models, such as the U.S. EPA's WASP (Ambrose et al., 1991) or the U.S. Army Corp of Engineers' BATHTUB (Kennedy, 1995). For example, Tufford and McKellar (1999) applied the WASP model to evaluate the water outflow and eutrophication dynamics of Lake Marion, which receives outflows from the CBC watershed among many others. To test SWAT's ability to predict the R-E outflows, this water body was modeled as a reservoir with assumed spillway elevations aligned with those of the Lake Marion dam, which is located about 16 km downstream of the CBC outlet (Amatya et al., 2010). The principal spillway and emergency spillway levels were estimated from the Lake Marion water levels (USGS, 2009).

The area and elevation data for this reservoir, obtained by bathymetric survey results (fig. 2a), were combined with recent LiDAR data (fig. 2b) (SCDNR, 2009) to develop a complete bottom map of the embayment. A hypsometric curve was created from the bottom map to express R-E volume as a function of Lake Marion level. Daily lake level data for 2007 to 2009 (fig. 2c) were used to determine the volume of the embayment using the hypsometric curve (fig. 2d). These estimates of bay volume were then combined with monthly mean inflow data (lateral flows from SL1, SL2, and CS expressed as a daily value) to calculate daily R-E discharge (flow), a mass balance including inputs of rainfall and in-

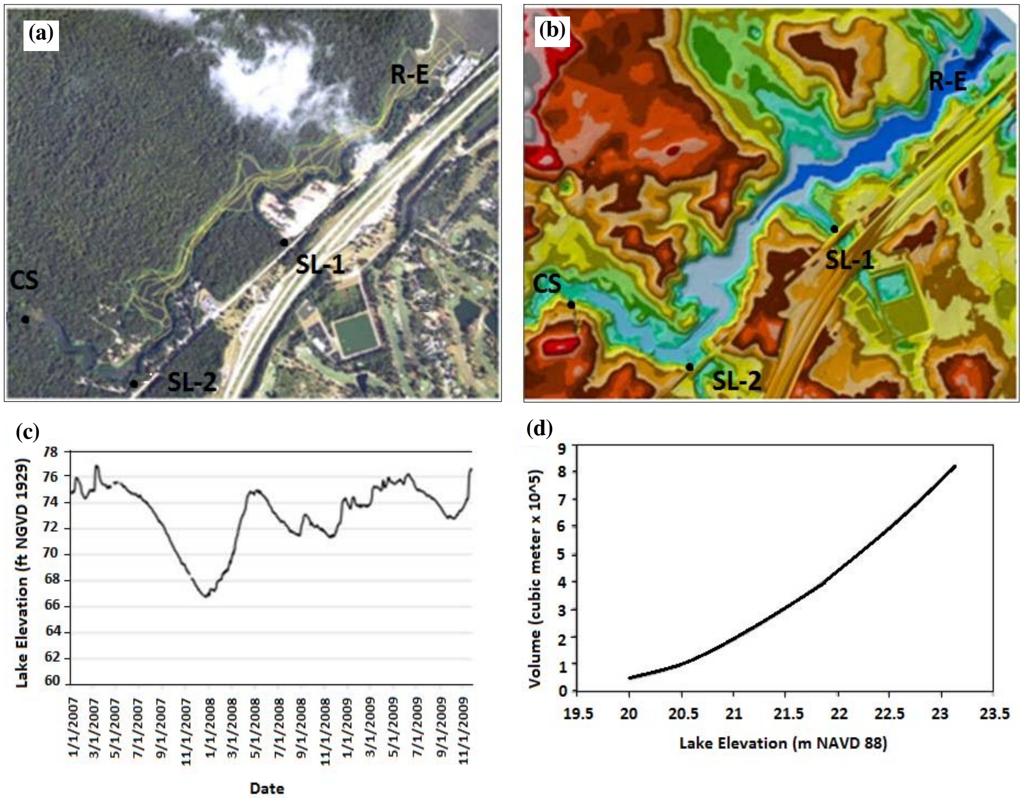

Figure 2. Reservoir-embayment (R-E) bathymetric data: (a) locations of cross-sections of the R-E, (b) LIDAR map of the R-E, (c) lake water levels for 2007-2009, and (d) volume versus lake elevation.

flows (fig. 2), and outputs of Turc method-based PET, as described in detail by Amatya et al. (2010).

The bathymetric survey and resulting hypsometric curve (fig. 2) allow evaluation of the model output by two comparisons. For the period from January to October 2009, all inputs were measured and PET was estimated by Turc's method. The calculated flow for this period represents a true measured flow rate from the embayment for the first comparison with the SWAT model output. In the second comparison, SWAT-simulated inflows for SL1, SL2, and CS were used as inflows (fig. 2) for calculating the reservoir-embayment discharge in the water balance method. Furthermore, measured monthly flows at SL1 (August 2008 to October 2009), SL2 (July 2007 to October 2009), and CS (only from January to October 2009) and SWAT-simulated outflows for the remaining months at SL1, SL2, and CS were used to find the monthly estimated outflows of the reservoir-embayment as affected by the lake level changes for the 34-month (2007-2009) period.

Model Evaluation Criteria

The statistics used for the model performance evaluation in this study were the coefficient of determination (R^2), the Nash-Sutcliffe (N-S) coefficient (or model efficiency, E), and the mean bias or mean absolute error (MAE %) between the measured and simulated values for a given period, as described in current literature (Moriasi et al., 2007; Coffey et al., 2004; Feyereisen et al., 2007; Bosch et al., 2004; Santhi et al., 2001; Majid, 2009). Means and standard deviations were also used to compare the long-term averages and their distribution between monthly measured and predicted flow.

The model was simulated for 2006 to 2009, with 2006 as a "warm-up" period not used for analysis. Unlike in other modeling studies, due to unavailability of flow data at the main watershed outlet, calibration of streamflow was performed with the limited data mentioned above from one individual subwatershed (SL1) and two other locations (SL2 and CS) draining multiple subwatersheds within the watershed. However, the validation was performed by comparing the SWAT-predicted flow from the watershed outlet (subwatershed 31) (fig. 1) simulated as a reservoir-like embayment (R-E) (figs. 2a and 2b) with that of the estimated monthly outflows at the outlet.

Results

Watershed Water Balance

The final calibration resulted in a predicted average annual basin water yield of 65 mm at the watershed outlet for average annual rainfall of 1048 mm. This is equivalent to a runoff coefficient (ROC) (outflow as a percentage of rainfall) of 6.2%, similar to the values observed at the SL2 (7%) and SL7 (5.6%) locations (fig. 1) (Amatya et al., 2010). The average annual ET loss was 638 mm, or 61% of the total rainfall. Feyereisen et al. (2007) found average annual (1995-2004) ET of 807 mm (~71% of the average annual rainfall) for a coastal plain watershed in the Georgia piedmont containing 65% forest with the remaining land use primarily agricultural. The simulated average annual ET for the period 2006-2009 in this study may be reasonable for a watershed containing only 44% forest land with the remaining 43% being agricultural and range, and nearly 10% impervious lands

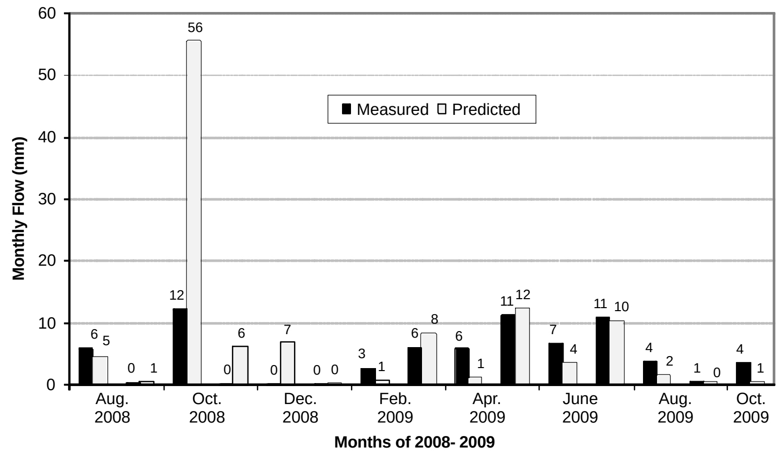

Figure 3. Measured and predicted monthly flows for August 2008 to October 2009 period at SL1 subwatershed.

(table 1). Furthermore, the drought of 2007 to mid-2008 may also have reduced the ET. Thus, the water balance of 345 mm was assumed to leave through deep seepage or groundwater recharge that is completely lost from the system (Amatya et al., 2010). With these simulated water balance results accepted for the watershed average condition, the model was tested to predict the streamflows at SL1, SL2, and CS locations (fig. 1).

SL1 Outlet

Figure 3 shows a comparison between the measured and predicted monthly flows for SL1. The model overpredicted for the months of October to December 2008 (severely for October) compared to the measured data. The mean monthly measured and predicted flows for SL1 for the same 15-month period are presented in figure 4a. Without the October 2008 data with two large events (fig. 4b), the mean monthly prediction of 4.1 mm was in good agreement with the measured data (4.2 mm) with a bias of only 0.1 mm (or 2.4%) underprediction and R^2 and N-S model efficiency (E) of 0.43 and 0.26, respectively. The simulated annual and seasonal runoff coefficients (ROC) varying between 0.04 to 0.14 were consistently higher than the measured data varying between 0.04 to 0.06, indicating overprediction by the model for all cases with inclusion of the October 2008 data.

SL2 Outlet

The measured and predicted monthly outflows at the SL2 outlet draining the CBC watershed from the eastern main tributary are presented in figure 5. Out of the 28 months of data, flow was underpredicted for 50% of the time (14 months). The model overpredicted the flows in the wet months of January and October 2008 by more than triple, although rainfall variability was ruled out. Severe underpredictions were noted in July 2008, June 2009, and August 2009.

Although the mean monthly bias (average of difference between monthly measured and predicted) was just 2 mm overprediction (fig. 4a), the R^2 and E statistics were very poor, (0.37 and -2.55, respectively). These results indicate that using a measured mean value is as accurate as using the model predictions for the monthly flow. However, when the very wet month of October 2008 was removed (fig. 4b), the mean monthly bias was 0.7 mm overprediction, and the predicted mean monthly flow of 7.1 mm for the 27-month period

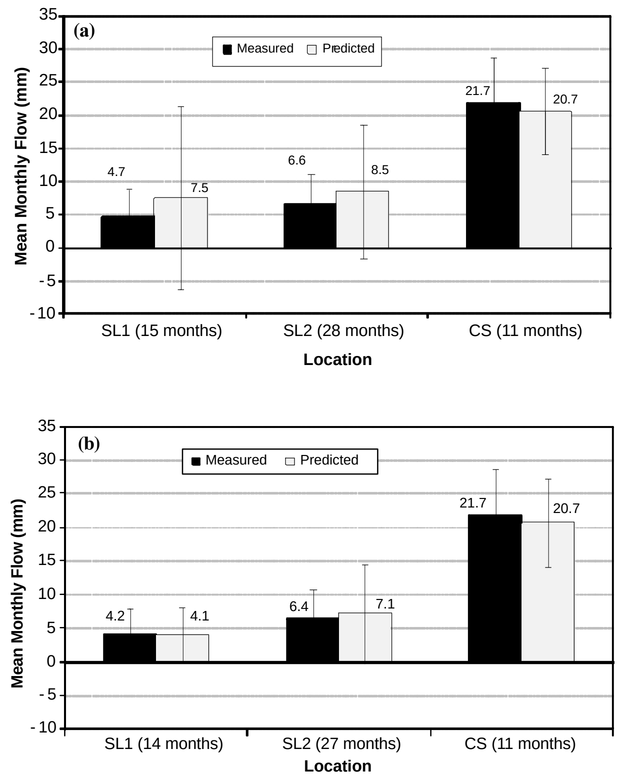

Figure 4. Measured and predicted mean monthly flows for SL1, SL2, and CS (a) with all data included and (b) with exclusion of October 2008 data with high flow events.

(without October 2008) was 10.9% higher than the measured data of 6.4 mm. Although the new R^2 of 0.39 and E statistics of -0.74 were improved compared to the previous simulations, these statistics indicate a poor calibration. The runoff coefficient (ROC) values for SL2 (not shown) indicate that the predictions in 2009 followed by 2007 were better compared with other periods that included the October 2008 data collected during extremely wet weather conditions. The predicted ROCs varied between 0.07 and 0.10 compared to the measured range of 0.06 to 0.07 at this location.

Cave Spring (CS) Outlet

The data in figure 6 show the monthly predicted flows compared with the measured data for a limited 11-month

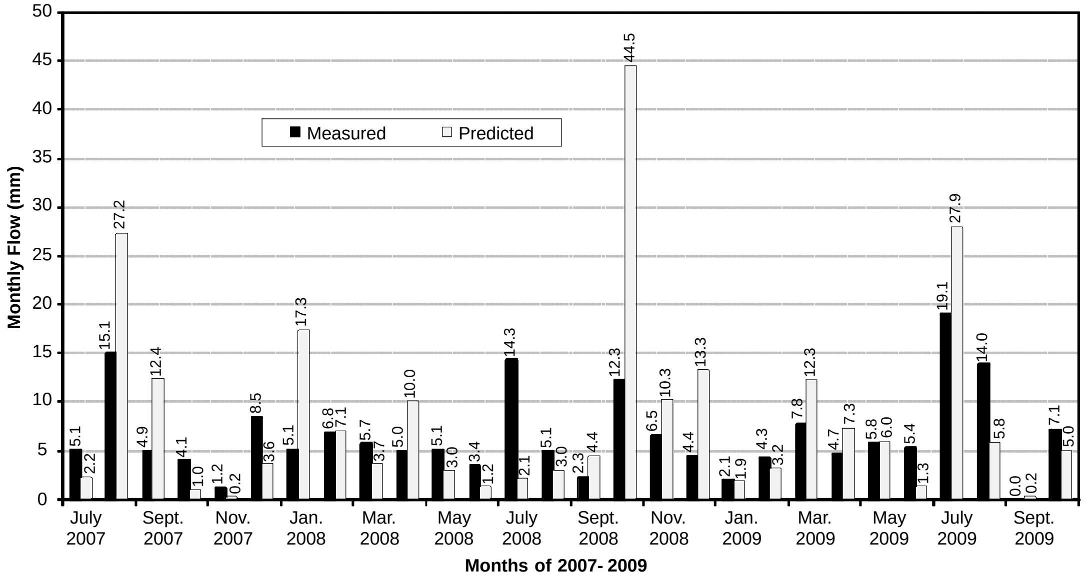

Figure 5. Measured and predicted monthly flows for July 2007 to October 2009 at location SL2 with all data.

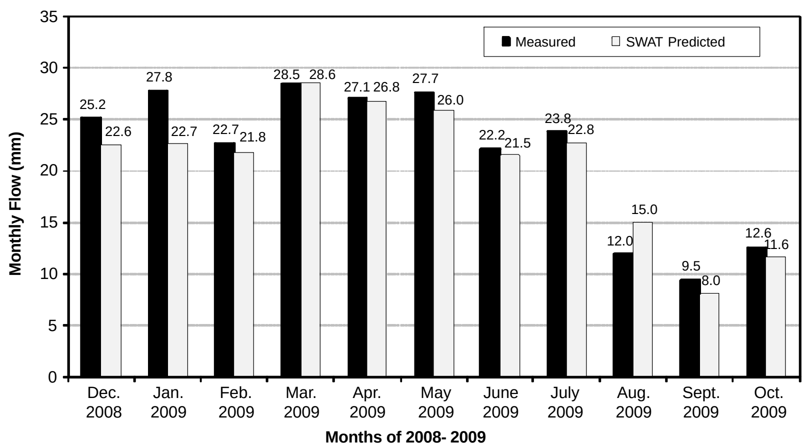

Figure 6. Measured and predicted monthly flows at the cave spring (CS) outlet.

(December 2008 to October 2009) period when measurements were available. Visual observation shows that the predictions were in very good agreement with the measured data for most of the months, except for an overprediction in August 2009. This is expected because the majority (~90%) of the flow at this location is due to groundwater flow, as estimated using the Arnold and Allen (1999) method, that was directly input as a point source of flow in the model for this location. The remainder of the error is due to predictions in the surface streamflow contributed by SL7 and its downstream portion draining to the cave inlet (fig. 1).

In addition to prediction-related error, small errors in December 2008 and part of January 2009 might be due to extrapolated data when the stream was obstructed by a downstream beaver dam. Furthermore, calculated flows obtained by using the rating-curve method itself may have some errors due to some stability problems caused by sediment in the stream bed (Harmel et al., 2006). This is the best calibration of flow at this location based on the calculated mean absolute error (MAE) of 0.2 mm, R^2 of 0.86, and E of 0.86 (Moriasi et al., 2007). The month-to-month variation was within 16% , as expected due to some measurement uncertainty. On a mean monthly basis, the mean absolute error (MAE) was within 5% (fig. 4), which is considered to be very good (Moraisi et al., 2007). The measured and predicted ROC varying between 0.22 and 0.25 (not shown) also indicate a closer agreement of predictions with the measured data. These ROC values are three to four times higher than those observed for subwatersheds SL1 and SL2, discussed earlier.

Validation at the Watershed Outlet (Reservoir Embayment, R-E)

The SWAT-predicted outputs at subwatershed 31 (R-E) for the 34-month simulation period, compared to the water balance outputs, are presented in figure 7a. The model under- and overpredicted the outflow in some months, and good agreements were found only in a few months, resulting in a poor performance with an R^2 value of only 0.19 and E value of -0.34. However, the model was able to capture the rising and falling outflow dynamics of June to November 2008 and May to September 2009, including the peaks in October 2008 and July 2009.

When measurements were available for all three stations in 2009 (fig. 7b), the R^2 and E statistics improved to 0.55 and

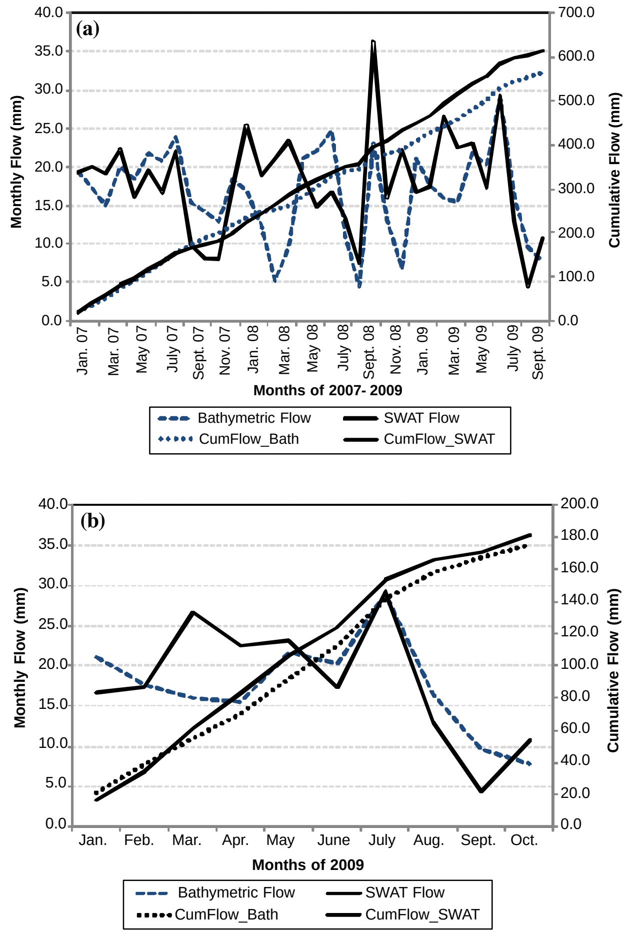

Figure 7. Bathymetric-estimated and SWAT-simulated monthly and cumulative monthly reservoir-embayment (R-E) outflow for (a) the 34-month (2007-2009) period and (b) ten months of 2009.

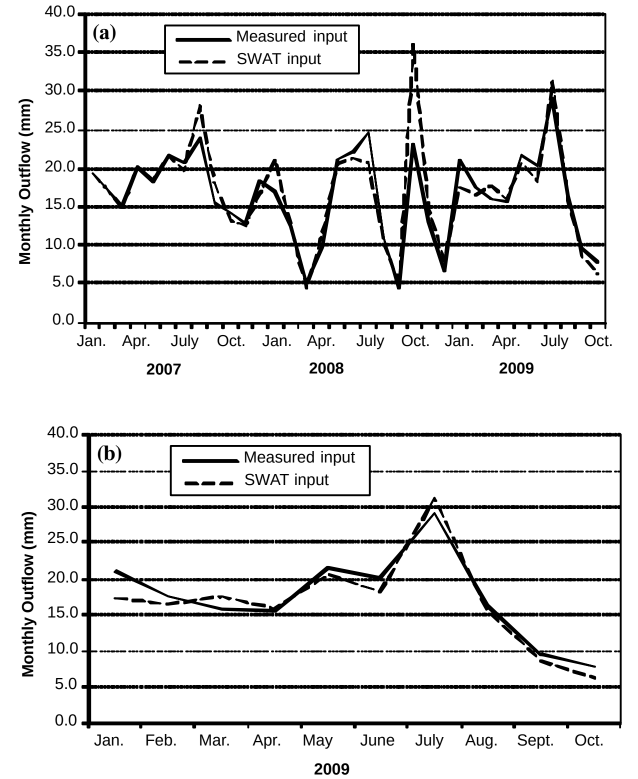

Figure 9. Estimated monthly R-E outflows for (a) the 34-month period using measured (solid line) and SWAT estimated (broken line) data and (b) the ten-month period in 2009 when data for all three stations were available.

0.29, respectively. The severe overprediction of the monthly incoming flow of SL1 and SL2 in the wet month of October 2008 (and also some overpredictions in the following months; figs. 3 and 5) with lower lake level also resulted in about 55% overprediction of R-E estimated outflow.

The cumulative monthly bathymetry-based and SWAT-simulated reservoir-embayment outflows for the 34-month period are also shown in figure 7a. The SWAT-simulated cumulative outflows closely followed the bathymetry-based estimates until November 2008, after which SWAT began overpredicting discharges, resulting in an overall cumulative outflow overprediction of 9.1% by the end of the 34-month period. However, SWAT's monthly and cumulative flow predictions for the January to October 2009 period (fig. 7b), when measured flow data were available for all three locations (SL1, SL2 and CS), were shown to perform better (R^2 = 0.54, E =0.28) than the 34-month period. The ten-month cumulative monthly flow was overpredicted just by 3.5%.

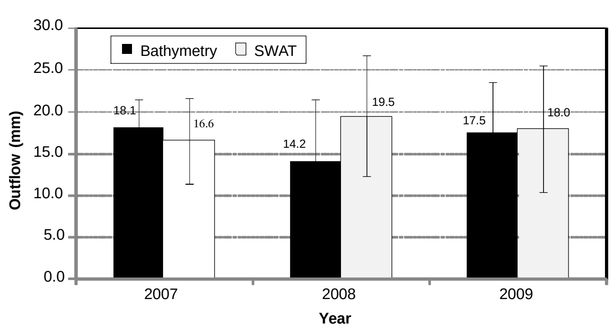

Figure 8. Measured (bathymetry) and SWAT-predicted mean monthly outflow from the reservoir-embayment (R-E) for each of the three years (2007-2009). Vertical bars are standard deviations.

The mean difference between the monthly predicted and measured outflows was only 1.5 mm overprediction, with the largest value of 15.9 mm in March 2008, followed by December and April of 2008 when the lake level was also low. Similarly, the predicted mean (18.1 mm) and standard deviation (6.6 mm) were close (<10% error) to the measured mean (16.6 mm) and standard deviation (5.9). The results in figure 8 show the mean monthly reservoir outflows predicted by SWAT compared with the bathymetry-based estimates for the years 2007 to 2009. The plot also shows the standard deviations for both the predicted and estimated mean monthly outflow for each of the years. Clearly, there was no substantial difference (as shown by the standard deviations) between the predicted and estimated values, except that in 2008 the difference was somewhat larger than in 2007 and 2009.

The model underpredicted the annual outflow by only 9.8% in 2007 (the year became drier toward the winter, with decreasing lake water levels) and overpredicted by only 6.5% in 2009 with increasing lake water levels (fig. 8). The largest difference of 37% overprediction was observed in 2008, with very dry months and low lake levels until September, which followed the wettest month (October 2008) of the study period.

An alternative examination of SWAT's ability to estimate flow can be made by using all SWAT values for input to SL1, SL2, and CS in the water balance estimation of outflow to the lake. Figure 9a shows a comparison of the water balance estimated outflow using SWAT-generated inflow for the 34-month period (2007-2009) in which SWAT-simulated values were used when measured data were not available (January 2007 to July 2008 for SL1, January 2007 to June 2007 for SL2, and January 2007 to December 2008 for CS).

Figure 9b represents data for the ten-month period when measured flow data for all three locations (SL1, SL2, and CS) were available. Clearly, the water balance based monthly outflows of the reservoir-embayment (R-E) using the SWAT model inputs (broken line) matched closely (R^2 = 0.94; E = 0.91) with the estimates using all the measured inflows (solid line) for the ten-month period in 2009 (fig. 9b) when measured data were available for all three locations. Although there were larger discrepancies between measured and SWAT-predicted monthly outflows at SL1 and SL2 individually (figs. 3 and 5), this closer agreement in the embayment outflow is most likely due to the bias by including CS outflow, which was at least three times higher than that of SL1 or SL2 and which had a large amount of measured baseflow added as a point source in the model (R^2 = 0.86 and E = 0.86 for CS in fig. 6). The largest error occurred for the wet month of October 2008, when SWAT overpredicted the flows for both SL1 and SL2 and CS had no measurement.

Discussion

SWAT Flow Predictions at SL1, SL2, and CS

The karst features, such as sink holes, depressions, and caves, in the study watershed have resulted from and continue to create the conduits and voids (C&V) due to dissolution of carbonate in the underground (subsurface) areas of the watershed that are potentially linked to the sides and bottom of the lake (Edwards et al., 2011a). This may have provided a rapid connectivity of the surface water with the underground water from subsurface C&V that do not correspond with surface watershed boundaries in such karst systems (White, 1988), yielding subsurface flow from unknown source areas. Furthermore, when the lake levels are lower (fig. 2c), a larger volume of underground C&V become empty, creating storage for more surface water to sink and disappear from various land areas connected to these sink holes, depressions, etc. (Edwards et al., 2011a). This would result in reduced flows appearing at the monitoring stations where the model is being tested for its ability to predict the flows. The very large overprediction in October 2008 at SL1 may be such an example, as the effect of rainfall variability was ruled out for this small (63 ha) subwatershed with its own rain gauge. Loss to subsurface flow may also have been responsible for the large overprediction at SL2, where the rain gauge is located near the center of the subwatershed. Loss of surface water was especially evident near SL4 upstream from the SL2 catchment outlet (fig. 1). The deep seepage coefficient was adjusted to capture these dynamics for flow calibration. However, when the lake levels were high in July 2009, with all C&V of the karst features full of water, there were only 50% overprediction at SL2 (fig. 5) and only a slight underprediction at SL1 (fig. 3) and CS (fig. 6). This indicates that the water lost via shallow groundwater in upstream areas may have been conveyed to the flooded embayment, and SWAT's slight overprediction at SL2 may have been justified when the lake level was high.

The current SWAT model would also not be able to capture seepage (subsurface) flow coming from an unknown area in this karst watershed, resulting in model underpredictions such as those in December 2007, June-July 2008, and August 2009 at SL2 (fig. 5). Similarly, the underprediction may also be due to the fact that the model might be losing water due to the high conductivity used for the streams and tributaries on this karst system when actually the lake levels were high, with underground voids full of water and potentially preventing loss of surface water. Thus, the method of Baffaut and Benson (2009) adopted in this system did not improve the simulation much, probably due to variations in karst characteristics in terms of size, location, and hydraulic connectivity compared to those used by Baffaut and Benson (2009). This may suggest a need of coupling a process-based subsurface hydrology submodel in SWAT to more accurately characterize the dynamics of karst groundwater contribution to a surface drainage network consistent with Jourde at al. (2007).

Some of the other discrepancies may be attributed to the use of extrapolated data for the missing periods or periods with submergence and also effects of rainfall variability across the watershed (Tuppad et al., 2010; Chaubey et al., 1999), especially during the summer to fall seasons typical to the region. For example, the variability of 35 to 65 mm rainfall amounts observed among three gauges in July 2008, June 2009, and August of 2009 (Amatya et al., 2010) may have also contributed in underestimation of flows in those months.

The locations of various karst features, such as depressions and sink holes, were also not as obvious on the watershed with typical USGS quad maps nor on the NAIP imagery (fig. 1) used in the study until the Light Detection and Ranging (LiDAR) based DEMs were available most recently (fig. 2b) (Edwards et al., 2011b). The SL1 subwatershed (fig. 1) is near where we discovered several springs during the field investigation and may have significant subsurface leakage. Furthermore, the site investigation also revealed a series of beaver dams in the stream, potentially allowing water to be lost by percolation to groundwater and evaporation. Possibly because of all these reasons, the largest discrepancy between the predicted and measured flow was noted for SL1 for a five-month period in 2008 for which the predicted runoff coefficient (ROC) was four times higher than those measured when the lake levels were low. This indicates that SWAT model calibration in karst topography is rather an art of deciding on specific parameter values based on observation from the measured data and actual site inspection, consistent with the findings of Spruill et al. (2000). While the final calibration does not guarantee to replicate the original condition of the karst hydrology, we are confident that we were able to capture some uncertainties through modeling parameters.

Flow data from 2009, with rising lake levels (fig. 2c), yielded about 20% underprediction of ROC at SL1. On the other hand, SWAT predicted 1.6 times higher ROC at SL2 than measured in 2008 with lower lake levels, while the closest prediction was observed for the ten-month period in 2009 when the lake levels started to rise compared to 2007-2008. For the 2007-2009 period, the overprediction (0.09) of runoff (ROC) by about 30% compared to the measured value (0.07) at SL2 may be mostly explained by water lost due to the karst features that SWAT could not capture. Such measured values of ROC are lower for this type of land use containing 56% developed areas (highways, roads, town, etc.) and agricultural lands, leading to speculation that the water lost to groundwater (especially near the upstream SL4 monitoring area on the highway) might have made its way through underground conduits toward the CS outlet (fig. 1). Coincidentally, a sinkhole collapse on August 13, 2009, confirmed this speculation, as the location of that sinkhole seemed to lie in the direction of groundwater flow from SL4 toward the CS outlet (fig. 1) (Edwards and Amatya, 2010). The total outflow measured at CS was more than double the surface inputs from SL1, SL2, and SL7 combined within the CBC watershed. The fact that SL7, located upstream of CS outlet (fig. 1), never produced monthly runoff of more than 10% of the rainfall (Amatya et al., 2008) indicates that the contribution of baseflow at the CS outlet could account for all of the water lost at SL2 and SL7, and possibly an even larger area of the surface watershed. As expected, the best agreement between the predicted and measured flow was obtained for the CS outlet, where the measured baseflow was added to the model as an input point discharge. The model underpredicted the total measured flow by less than 5%, which is well within the measurement errors (Harmel et al., 2006). This interpretation generates two specific hypotheses: (1) some of the water lost from losing streams in SL2 could have been conveyed through underground conduits to the CS outlet and (2) groundwater from a larger subsurface area than estimated in this study as the surface area bounding SL2, SL7, and the area downstream of SL7 at the CS outlet may have been contributing (fig. 1).

One reason for poor model performance as shown by the model goodness-of-fit (R^2 and E) may also be due to limitations in the measured flow data for the SL2 and CS locations draining multiple subwatersheds. Recently, Harmel et al. (2010) demonstrated the need for a correction factor to incorporate both the measurement uncertainty and model uncertainty in evaluating goodness-of-fit statistics. Similarly, the calibration at all three stations and the validation at the reservoir-embayment, as shown below, were severely limited by available measured flow data.

SWAT Flow Validation at the R-E Outlet

The flow of the lower flooded reservoir-embayment (R-E) at subwatershed 31 of the CBC outlet (fig. 1) is affected by the water levels of Lake Marion (fig. 2d) (USGS, 2009). The R-E receives lateral inflows from SL1, SL2, and CS and a minimal flow from the forested area on the left bank (figs. 1, 2a, and 2b). The measured inflows at these stations are also dependent on the lake levels, as discussed above. The large overpredictions in October 2008 at SL1 and SL2 during low lake levels may have resulted in overestimation of R-E flow by 55% (fig. 7a). However, in July 2009 with high lake levels, the 50% overprediction at SL2 and a slight underprediction at SL1 and CS resulted in a very good match with the estimated flow at the R-E outlet (fig. 7b). These results indicate the ability of the model to perform well at the main watershed reservoir-embayment (R-E) outlet at certain lake levels and where all outflows were assumed to be discharged. Most of the larger discrepancies in 2007 and 2008 may have occurred because measured flow data were not available and thus were extrapolated for use in the bathymetry-based embayment outflow estimate, in contrast with much improved results in 2009 when all measured data were available.

On a longer-term basis, however, SWAT was able to capture the mean monthly outflows of the CBC watershed within 10% as affected by the losing streams of karst features and their interaction with month-to-month variation in lake level changes in at least two out of three years, potentially avoiding a need to apply more complex hydrodynamic models such as WASP (Ambrose et al., 1991) or BATHTUB (Kennedy, 1995) for these objectives.

The relatively poor performance of SWAT's monthly flow predictions (R^2 = 0.55 and E = 0.29) of the reservoir-embayment (R-E) in figure 7b compared to the water balance method's outputs (R^2 = 0.94; E = 0.91) with the SWAT inputs for SL1, SL2, and CS in figure 9b for the ten-month period of 2009 is also most likely due to the use of simple DEMs for generating embayment volume as well as the use of simulated spillway levels of the R-E in SWAT. The water balance approach used more accurate volume data based on bathymetry and LiDAR data for the R-E and also incorporated monthly lake water levels. However, the mean monthly SWAT predictions of outflow at the R-E outlet were acceptable given the various limitations discussed above. This clearly indicates future potential to enhance flow predictions with the SWAT model in similar embayments with the use of more accurate data on embayment volume as well as lake level changes as boundary condition at the outlet.

Summary and Conclusion

SWAT, a widely used watershed-scale distributed hydrologic model, was applied to test its ability to predict monthly streamflows of a karst-affected watershed in the upper coastal plain of South Carolina. The 1,555 ha mixed land use watershed with a flooded embayment outlet draining to Lake Marion was delineated into 31 subbasins using ArcView SWAT2003. Efforts were made to manually calibrate the model with limited monthly streamflows measured at two major locations (SL2 and the CS outlet) draining multiple subwatersheds and an individual subwatershed (SL1). After adding a limited seasonal measured baseflow as a point source input (assuming a 70% subsurface drainage area of the total watershed area at that location) into the model, SWAT's predictions of monthly streamflows at the CS outlet were in good agreement with the measurements, as expected. However, the poor model performance in predicting monthly flows at locations SL1 and SL2 was likely due to potential flow pathways through the karst features and interaction with downstream lake water levels. This indicates that the SWAT model, built primarily for predicting streamflows dominated by surface water hydrology, is unable to accurately predict the monthly in-stream outflows dominated by groundwater on this karst watershed.

However, despite the influence of karst features, their nature and extent of subsurface connectivity through voids and conduits, and their interaction with lake water levels, SWAT's monthly predictions at the watershed reservoir-like embayment (R-E) outlet were better than at the locations draining subwatersheds, especially during periods of rising lake levels. Furthermore, SWAT was able to more accurately capture the mean monthly streamflow for each year at the R-E outlet, where the in-stream flows discharge, indicating a satisfactory performance on a long-term basis on a watershed-scale. This indicates the potential application of

SWAT as a simplified hydrodynamic model for estimating mean monthly outflow when resources are limited for the additional use of complex models in an embayment outlet. Future studies should also consider using the LiDAR-based DEMs, not only for their finer resolution but also for detecting karst features such as depressions and sink holes, which could be modeled more precisely using the most recent enhancements in SWAT (Yactao, 2009; Baffaut and Benson, 2009). Even with such modifications, the uncertainty in subsurface conduits may pose challenges in predicting groundwater contribution to streamflow (Jourde et al., 2007; Salemo and Tartari, 2009). Since these factors that affect the hydrology may have large implications in the modeling of nutrient and sediment loadings downstream, including the development and implementation of total maximum daily loads (TMDLs), further research is needed to enhance the capability of SWAT subsurface hydrology modules for application on watersheds with karst features.

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