Case Study

Streamflow and Nutrients from a Karst Watershed with a Downstream Embayment: Chapel Branch Creek

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Abstract: Understanding sources of streamflow and nutrient concentrations are fundamental for the assessment of pollutant loadings that can lead to water quality impairments. The objective of this study was to evaluate the discharge of three main tributaries, draining different land uses with karst features, as well as their combined influences on total nitrogen (TN) and total phosphorus (TP) levels in reservoir-like embayment (R-E) on a stream entering Lake Marion, South Carolina. From 2007–2009, hydrology, TN, and TP data were collected from the 1,555-ha Chapel Branch Creek (CBC) watershed. In general, monthly streamflow in all tributaries was found to be −10% of rainfall, and as little as 0.1% in the smallest tributary. The third tributary flowed into a cave system and discharged via a cave spring (CS) into the embayment while gaining a sustained groundwater flow from a second cave (GW) system. The CS flow was substantially larger than the flow measured in the other tributaries. The small amount of rainfall that became surface flow and the large flow at the cave spring indicated a significant water loss from the surface watershed to subsurface flow or a groundwater source area substantially larger than the surface watershed. Nutrient concentrations in flows from tributaries draining various land uses were not significantly different ($\alpha = 0.05$) for most of the locations. A simple water balance was developed to estimate the R-E outflow to Lake Marion using measured discharges from three tributaries, change in storage computed using a bathymetric survey, daily lake level changes, rainfall, and computed evaporation. Mean monthly TN and TP concentrations in the embayment were substantially lower than the observed means from the two tributary outlets and the CS into the embayment, indicating a loss in the embayment. The second cave system at CS, representing an unknown subsurface drainage area, was the source of nearly 50% of TP loading, over 50% of flow, and over 70% of TN loading to CBC. These results may have implications in water quality management of the CBC watershed. **DOI: 10.1061/(ASCE)HE.1943-5584.0000794.** *© 2014 American Society of Civil Engineers.*

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Introduction

Understanding watershed hydrology is critical to management decisions such as total maximum daily load (TMDL) development, as hydrology is often a primary driving force for nutrient cycling and loading dynamics and subsequent downstream water quality effects (Amatya et al. 2011a). Karst watersheds have complex hydrologic and transport processes by which groundwater can variably influence surface water flow, both in magnitude and duration. The presence of karst features such as sinkholes, caves, depressions, voids, conduits, and sinking streams act as rapid pathways for flows and subsequently for potential pollutant loads into streams and groundwater. Therefore, karst watersheds are prone to considerable monitoring, modeling, and management challenges. In addition, hydrologic and water quality studies on watersheds affected by karst features are limited.

Karst topography and geology is defined as a type of landscape formed from the dissolution of soluble rocks including limestone, dolomite, and gypsum. Nearly all surface karst features are formed by internal drainage, subsidence, and collapse caused by the development of underlying caves as cited by White (1988) and Ford and Williams (2007). In the United States, karst ecosystems cover approximately 20% of the country, and karst aquifers provide 40% of the water used for drinking (Yachtao 2009). Human activities (agriculture, urban, and residential) on karst landscapes may make them vulnerable to water quality impairment (Pasquarell and Boyer 1995; Boyer and Pasquarell 1996; Ryan and Meiman 1996; Baffaut and Benson 2009).

For flow into sinkholes and sinking streams to occur, there must be sufficient rainfall to cause surface runoff (Felton 1994). Rather than occurring as overland and channel flow via streams, karst water flows below ground through systems of conduits and fractures until it typically emerges as a spring (White 1988). The geology of karst-influenced watersheds has been generally characterized by very high infiltration rates perhaps because of some direct linkage between the surface and subsurface conduits (Felton 1994; Pasquarell and Boyer 1995; Boyer and Pasquarell 1996; Baffaut and Benson 2009; Amatya et al. 2011a). Pasquarell and Boyer (1995) reported fecal bacteria can travel in karst aquifers over distances of several kilometers and that karst resurgence springs of the most intensively agricultural basin were contaminated with these bacteria. All et al. (2009) emphasized that land use controls and planning, combined with required sewer and septic controls of homes and businesses, as well as the identification of cave and sinkhole locations, could protect the major conduit of subsurface water flow from polluting activities. Similar observations

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were recently made by Edwards et al. (2011) for Chapel Branch Creek (CBC), a karst watershed located adjacent to Lake Marion in South Carolina that is listed as a 303(d) impaired water body and is the focal watershed for this study.

The primary objective of this study was to determine flows and nutrient (N and P) loading from the various land uses found on the CBC watershed, to support development of a total daily maximum load (TMDL). Initially, mean N and P levels in surface waters draining from subwatersheds with various land uses were tested to examine source area contributions to TN and TP load to the CBC at Lake Marion. While conducting the study, the sampling and monitoring design protocol was revised as initial data revealed the influence of the karst features on water quantity and chemistry at the lake edge in a region known for sinkholes and cave systems (Siple 1975; Spigner 1978). Sampling design was modified to include a cave spring outlet, and sampling intensity was increased significantly between the initial study plan and the final conclusion of the study. Results from estimates of flow and nutrient levels in the surface waters, as well as at the groundwater input to the cave spring, were used with a water balance approach to estimate hydrologic and water quality discharges from the CBC through the downstream reservoir-like embayment (R-E). This article not only outlines the influence of karst features on the hydrology and nutrient loads of the CBC watershed where those features were not easily discernable, but also identifies challenges and potential solutions used for hydrologic evaluation of karst watersheds with a downstream embayment.

Materials and Methods

Site Description

The CBC watershed is located within the upper coastal plain region of Orangeburg County, South Carolina, USA, adjacent to Lake Marion and near the town of Santee and Interstate I-95 (33°30.6′ N, 80°27.9′W). The watershed encompasses a small tributary of the former Santee River that now flows directly into Lake Marion and is a portion of the 11-digit HUC 03050111-010, located in southeastern Orangeburg County (Fig. 1) (SCDHEC 2005). Lake Marion is a hydroelectric reservoir operated by the South Carolina Public Service Authority—Santee Cooper (Moncks Corner, SC). The watershed drains an area of approximately 1,555 ha (3,760 acres) with mixed land uses. Headwater sections of the watershed are relatively flat lands at about 36.6 m (120 ft) above mean sea level (amsl) with somewhat steeper topography [25.9 to 30.0 m (85 to 100 ft) amsl] near the edge of Lake Marion. The surface soils in the watershed are dominated by moderately to somewhat poorly drained Goldsboro-Lynchburg series sandy clay loam on most of the agricultural areas in the west and southwest and somewhat well-drained Neeses series sandy clay and clay loam to the east (USDA NRCS 2011).

Chapel Branch Creek was listed on the 2004 South Carolina 303(d) list for impaired surface waters due to elevated nitrogen (N), phosphorus (P) chlorophyll a, and pH [SCDHEC (2004)]. This impairment occurred at sample station SC-014, located in the flooded R-E embayment about 3 km west of Lake Marion (Fig. 1). The CBC watershed incorporates complex land use patterns with residential, commercial, and industrial areas interspersed among agricultural and forested lands that are located within Santee State Park on the left bank of CBC. There are also two golf courses and a wastewater treatment plant maintained by the town of Santee located along the eastern boundary of the drainage area. Embayment TN and TP loading via export from these upstream source areas to Lake Marion were the main concern in the CBC watershed.

The coastal plain is covered by several horizontal beds of sedimentary rocks striking northeast-southwest and dipping southeast or south in this region (Heron 1962; Siple 1975). Santee Limestone, a carbonate formation from the middle Eocene, approximately

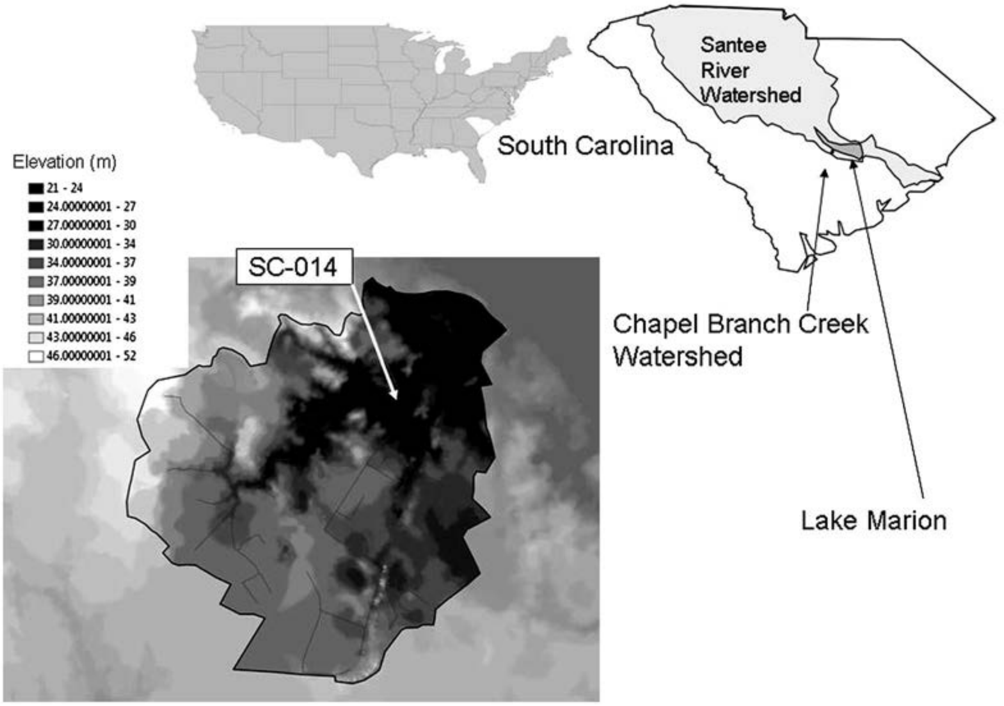

Fig. 1. Location map of Chapel Branch Creek (CBC) watershed at Lake Marion in South Carolina, USA; also included is the topography of the CBC watershed as a digital elevation model in which SC DHEC monitoring station (SC-014) is also shown (Used by permission. Copyright © Esri. All rights reserved.)

40 million years ago (Willoughby 2002), is a major such sedimentary rock as a part of the Floridan aquifer extending to the South Carolina upper coastal plain. The Santee Limestone is overlain by more recent sediment, but outcrops particularly on the south shore of Lake Marion near Santee, along the flooded section of CBC. The rise and fall of sea levels in the geologic past led to the development of solution voids at different elevations in this region (Siple 1975), thus creating subsurface flow connections both horizontally and vertically throughout the limestone. The result is mantled karst geology and topography with small sinkholes, disappearing streams, small caves, and springs.

Hydrologic and Water Quality Monitoring between 2007 and 2009

Monitoring included rainfall recording, seasonal grab sampling of water quality, continuous flow measurements, and automated sampling throughout the CBC watershed.

Rainfall

Three automatic tipping bucket rain gauges connected with HOBO dataloggers (Onset Inc., Bourne, MA) were installed across the watershed (Fig. 2) to measure rainfall and analyze the spatial variability: one located at the town of Santee Administrative Park (TOWN), the second at the Wastewater Treatment Plant (PLANT), and a third at Santee State Park (PARK), located north of the CBC watershed. Gauge data were monitored weekly and depth in a standard rain gauge was measured to calibrate tipping bucket data (Amatya et al. 2011b). Data collected for varying periods from August 2006 to October 2009 at these three gauges were processed to obtain the monthly and annual totals used in the hydrologic analysis. Long-term (1971–2000) rainfall data from Holly Hill, South Carolina—U.S. Weather Bureau Station 384197 was also used to assess and compare the rainfall pattern at the site during the 2007–2009 study period. When data was bad or missing at a rain gauge, the data were adjusted using data from the closest rain gauge. Details of the instrumentation and installation of rain gauges are given in Amatya et al. (2010).

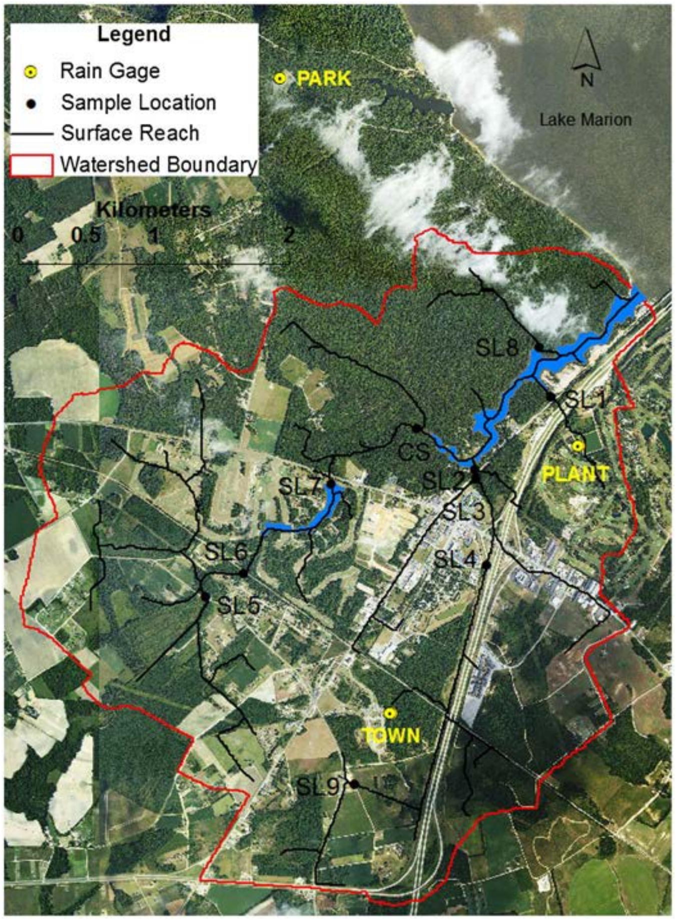

Fig. 2. Chapel Branch Creek (CBC) watershed at Lake Marion in Town of Santee, South Carolina; note: the locations of continuous [SL1, SL2, SL4, SL5, SL7, and cave spring (CS)], grab (SL3, SL6, and SL9) monitoring stations, and three rain gauges (PARK, TOWN, and PLANT) are also shown over the photo imagery (USDA 2005 NAIP)

Manual (Grab) Sampling

The entire CBC watershed and then nine subwatersheds within it were delineated using contour lines of USGS Quadrangles. Aerial photographs and ground checking were used to evaluate land use across the watershed. Subwatersheds were delineated based on nine sampling locations (SL1-SL9) to isolate water quality of each of the major land uses on the watershed (Fig. 2). Each location (except SL8, a forested subwatershed on sandy soils which did not produce runoff during the study) was sampled for one storm event in each of the four seasons (winter: February 2008; spring: April 2009; summer; July 2009; fall: October 2009). A total of five grab samples, based on hydrograph stage at each location, were taken for each event: two samples were taken during the rising limb of the hydrograph prior to peak stage, the third during the falling limb of the hydrograph immediately following peak stage, the fourth on the falling limb of the hydrograph at a stage approximately halfway between peak and low flow, and the fifth near the low flow. A staff gauge was used at each location to determine hydrograph stage prior to sampling. One field duplicate was taken at random for a total of six samples from each point. Samples were immediately preserved on ice and taken to the Santee Cooper Analytical and Biological Laboratory (Moncks Corner, SC, USA) for all analyses. The preparation and analytical methods performed include using ION CHROMATOGRAPHY for inorganic anions, EPA method 300.0, and colorimetric, semi-automated digester, atomic absorption II (AAII) methods for ammonia-nitrogen (EPA method 350.1), total Kjeldahl nitrogen (TKN) (EPA method 351.2), and total phosphorus (TP) (EPA method 365.4) (Eaton et al. 2005). Nitrogen analyzed as nitrate, ammonium, and total Kjeldahl nitrogen (TKN) allowed computation of total nitrogen (TN), which was the impairment parameter at this location based on SC water quality standards and resulted in the 303(d) listing.

Nutrient data for TN and TP were analyzed for testing significances between the means for the automatic weekly and grab storm samples using analysis of variance (ANOVA) with an uneven sample numbers from all sampling stations (Chambers 1977). Differences in TN and TP for various source areas with different land uses were also tested with Duncan's multiple range tests (Chambers 1977).

Flow Monitoring and Automated Sampling

A continuous Doppler-based flow logger (ISCO 4150, Lincoln, NE) was installed in March 2007 at the outlet of a 0.90-m-diameter concrete culvert at sampling location SL7. The flow logger monitored water level and average velocity in 15-min intervals to obtain flow rates. An ISCO 3700 discrete water quality sampler (Lincoln, NE) was connected to the ISCO 4150 flow logger at the pond outlet at sampling location SL7, just upstream of a location where regulatory water quality monitoring has been performed on a monthly basis since 1996 (Larry McCord, Laboratory Manager, Santee Cooper Analytical and Biological Laboratory, personal communication, 2004). The ISCO flow logger was programmed to trigger the sampler on flow-proportional basis during the storm events. The 1-L bottles, preserved with sulfuric acid, were serviced every week or after storm events and transported on ice to the laboratory. Based on rainfall events observed at the nearest TOWN gage, discrete baseflow samples were combined into weekly composite samples. On one selected storm event per month, discrete concentrations were measured throughout the storm hydrograph. Laboratory analyses were performed using the same techniques as previously described for grab samples.

During 2007 and early 2008, central South Carolina experienced a prolonged drought and there was little flow in Chapel Branch Creek or in its various subwatersheds. Collecting event grab samples and automated weekly samples from SL7 station alone could not meet quality control standards with too many missing samples during this period. Therefore, additional sampling stations were installed for collecting additional data.

The subwatershed drained by SL2 contained the catchments of SL3, SL4, and SL9, so an additional continuous Doppler-based flow logger (Greyline Instruments, Model OCF_IV, Massena, NY) and an ISCO 3700 discrete water quality sampler (24 one-L bottles) were installed at the outlet of the approximately 1.5-m-diameter concrete right culvert at sampling location SL2 with a dual culvert in June 2007. A malfunctioning Greyline flowmeter was replaced with a new ISCO 4150 flow logger in June 2008 at this location. The total flow rate of the dual culvert was estimated by combining the measured flow rate at one of the culverts and estimated rates for the second culvert using the stage height at the adjacent culvert and Manning's formula (McCuen 1989). An ISCO 4150 flow logger connected to an ISCO 3700 discrete water quality sampler with 24 one-L bottles was deployed in May 2008 in a dual box culvert at SL4. Since these culverts were identical in cross-section and bottom height, flow rate measured at one culvert was doubled to obtain total flow rate for this dual culvert. An identical flow logger and a sampler were installed in an approximately 0.75-m-diameter concrete circular culvert at SL5 in May 2008. A third logger and sampler were deployed in an approximately 1.2 × 0.75-m size concrete box culvert in June 2008 at SL1 (Fig. 2). Stage and flow data processing from these new flow loggers and sample protocols for these added automated samplers were as described above for SL7 and detailed in Amatya et al. (2010).

The presence of a spring emerging from a cave in the lower CBC on the west side of the watershed downstream of the Santee National Golf Course pond has been the object of study for a number of years. The CBC enters an cave about 1.5 km below SL7 as surface water and emerges at a cave spring about 500 m further down the valley (Holler 2000) (Fig. 2). The CBC channel was surveyed from SL7 to where the stream enters the ground in winter of 2007. At that time, flow rates entering the ground and emerging at CS were similar, so the connection mapped by Holler (2000) was assumed to convey water from SL7 to CS and from that point into the embayment. Near the end of the drought in 2008, visual observations confirmed that, although flow at SL7 had ceased, there was a continuous flow at the cave spring. Dye tests revealed that the CS received water from a second cave through a series of sinkholes in a southwesterly direction from the spring. Subsequently, LIDAR data was obtained and analyzed for the CBC watershed, by which the existence of multiple sinkholes and closed depressions that were not evident on the USGS contour maps or aerial photography was verified (Edwards et al. 2011). The second cave was in line with several small sinkholes and depressions that crossed the entire CBC watershed (Edwards et al. 2011).

Because the CS received flow from a second source, the flow data from SL7 did not represent the entire input to the creek at the cave spring (CS) outlet. Another automated sampling station was added at the CS outlet in November 2008. An Infinities data logger (Port Orange, FL) measured stream stage, and an ISCO 2700 automated water sampler took daily time-based water quality samples. Flow was calculated from a rating curve developed by repeated manual stream cross-sectional flow measurements (Amatya et al. 2010, 2011a, b). This instrument collected valid measurements from January to October 2009. Sample handling and laboratory analyses were performed as previously described. Automated sampling was conducted at all stations from July 2008 to June 2009 with two baseflow samples and one storm flow sample collected each month. Concentration data from automated samples were tested by ANOVA and Duncan's multiple range tests in the same manner as the storm grab samples discussed above.

Streamflow was measured for differing time periods at each of the different sampling locations at SL1 (June 2008 to October 2009), SL2 (July 2007 to October 2009), SL4 (June 2008 to mid-July 2009), SL 7 (March 2007 to mid-July 2009), and CS (December 2008 to October 2009). Measured 15-min streamflow rates were converted into depth-based flows in millimeters with respect to each subwatershed area. Runoff coefficients (ROC) defined as a ratio of streamflow and corresponding rainfall were calculated for the monthly as well as the whole measurement periods at all sampling locations. Rainfall measured at the TOWN gauge was allocated to the SL2, SL4, SL7, and CS sampling locations, whereas the gauge at PLANT was assigned to the SL1 location.

For analyses of surface and subsurface flows in this karst-dominated watershed, all flows were summed from the surface stream tributaries draining SL1, SL2, and SL7 to compare with the flow from the cave spring (CS), which included both the surface flow from SL7 as well as the subsurface flow from an unknown subsurface area. Since SL7 is within the subwatershed that drains to the CS outlet, the subsurface flow component at the CS outlet was calculated as the difference of the flow at CS and SL7 outlets.

Input flow from all sources to the embayment as well as nutrients (TN and TP) was continuously measured only from January until June of 2009 as flow monitoring was discontinued from July 2009 at SL4 and SL7.

In related efforts, a distributed, watershed-scale hydrology and nutrient model based on the SWAT (soil and water assessment tool) model (Arnold et al. 1998) was developed for the CBC watershed (Amatya et al. 2011a). Originally, the model was to be parameterized based on the continuous flow and nutrient data recorded at SL7. Model calibration and verification was altered over the course of the project based on modifications to our original sampling and hydrologic monitoring plans. A complete description of the model calibration, verification, and modeling results for hydrology are available in Amatya et al. (2011a).

Reservoir-Like Embayment Water Budget

Due to the previously described drought conditions, lake levels in Lake Marion became very low and the water volume in the embayment (R-E) section of CBC was depleted. The drought led to further investigation into the possible effects of low downstream lake and embayment levels on surface loads mostly from SL1 near the South Carolina Department of Health and Environmental Control (DHEC) sampling station at SC-014 in the CBC watershed (Fig. 1). Specifically, these investigations were used to determine whether flow into the embayment occurred entirely downstream or if the embayment allowed instantaneous mixing (distribution) of discharges from SL1, SL2, and CS without stratification at SC-014. In order to examine the role of various inputs and embayment volume, daily outflow (discharge) was calculated using a daily water balance based on daily rain, inflows, and evaporation rates as potential evapotranspiration (PET) by the Turc (1961) method using the daily measured weather data at a station located across the lake (Amatya et al. 2011a). Watson et al. (2001) also used a water balance approach [Eq. (1)] to estimate vertical leakage as a residual component for Magnolia Lake, typical of many karst lakes on deep permeable Floridan aquifer in north-central Florida:

$$Q_{\text{out}} = Q\text{SL1} + Q\text{SL2} + \text{QCS} + R - \text{ET} \pm \Delta V \tag{1}$$

where Q_{out} = monthly averaged daily discharge to Lake Marion, QSL1 = monthly averaged daily discharge at sample location SL1, QSL2 = monthly averaged daily discharge at sample location SL2, QCS = monthly averaged daily discharge at the cave spring, R = daily rainfall, ET = daily estimated evaporation as PET, and ΔV = change in volume of flooded section for the daily change in Lake Marion elevation.

Monthly average daily discharge values were obtained from both measured and SWAT-modeled outputs (Amatya et al. 2011a). The SWAT outputs were used as inputs for the periods when measured values were not available. Monthly water budgets were used because the SWAT calibration parameters produced better results over a monthly period than for the daily at SL1 and SL2 (Amatya et al. 2011a). Also, the use of monthly averages was additionally justified because residence time was calculated to be between 20 to 30 days for the measured flows.

All the parameters in Eq. (1), except for ΔV, were determined from measured data or calibrated model output as previously discussed. To determine ΔV, water levels in flooded CBC and a derived hypsometric curve (equation of volume vs. depth) were used. The water level and thus volume in flooded CBC was controlled by the level of Lake Marion, which is a result of hydrologic inputs of the entire Santee River watershed and releases for hydroelectric generation and spillway operation on Wilson Dam at the lower end of Lake Marion 15 km southeast of CBC (Fig. 1). Lake Marion elevation is monitored at three stations by USGS: Trezesvants Landing (USGS_02169810, 33°43′52″ N, 80°37′43″ W), Elloree (USGS _02169921, 33°33′07″ N, 80°30′16″ W), and Lake Marion at Pineville (USGS_02171000, 33°27′00″ N, 80°09′50″ N). Elloree is only 9 km from CBC and the examination of the record at Elloree and Wilson Dam (Pineville) showed less than 0.05 m difference in lake level between the stations. By this justification, the lake level at Elloree was used to estimate level within the flooded section of CBC.

The hypsometric curve was developed from three sources: LIDAR elevations of Orangeburg County obtained from SC Department of Natural Resources (DNR), National Agricultural Imagery Program (NAIP) orthophotograph from February 2005 (Mihalik et al. 2008), and a sonar survey conducted in September 2009. GIS was used to convert all data to uniform units and datum (NAD1983 UTM m horizontally, NAVD 1988 m vertically). The lake level when the 2005 orthophoto was taken was 22.57 m. The outline of the flooded section of CBC was digitized as a hard breakline on a triangulated irregular network (TIN) GIS layer made from the LIDAR ground data points. This TIN included data to a level of 20.31 m, the level of Lake Marion when the LIDAR data was collected.

On September 29, 2009, the bottom of the flooded portion of CBC was surveyed with a real-time kinematic (RTK) controlled sonar (Williams 2008). The lake level as measured by the USGS gauge was 21.882 m and by the RTK survey was 21.948 m, a difference of 0.066 m, which was within the error recorded by the RTK control. An elevation of 21.882 m was used as the water level and approximately 150,000 bottom points were recorded. These points were then used as mass points to modify the TIN within the breakline of the 2005 lake elevation. This modified TIN was used to create a relationship between water level and flooded volume for the range of water level over the 2006–2009 period. This relationship, along with the measured or calculated average daily flow at SL1, SL2, CS, and the volume-based rainfall and PET were entered into a spreadsheet model to calculate daily embayment discharge or flows. Daily flows were then summed by month to produce monthly averaged daily outflow.

Results

Rainfall

Table 1 shows the comparison of annual rainfall measured at three gauges used in this study, as well as the long-term average (normal) measured at Holly Hill, South Carolina. The gauge at TOWN consistently measured somewhat higher rainfall than that at the PLANT gauge, which recorded the lowest rainfall in 2008, the only year with data for all months at all three gauges. Results demonstrate a spatially variable pattern in precipitation within the watershed that is characteristic to this region, especially during the summer thunderstorms and depressions. The three gauges had consistently lower rainfall than the long-term average for 2007, 2008, and 2009, indicating drier conditions than normal for these three years. The maximum monthly rainfall exceeding 250 mm, 100 mm higher than the long-term average, was observed in July 2009 at the TOWN gauge. Lowest values of rain (<10 mm) occurred at PARK gauge in November 2007 and at TOWN and PLANT gauges in September 2009. Monthly rain was below normal for 8 out of 12 months in 2007. That pattern of drought continued until June 2008 as discussed above. The potential drought, demonstrated by lower than average rainfall in 2007, was further supported by the highest estimated PET of 1218 mm estimated for 2007 compared to 2008 (1190 mm) and 2009 (1121 mm until November after which the study was terminated) (Table 1).

Table 1. Measured Annual Rainfall at Three Gauges Compared to Long-Term Average at Holly Hill Station, South Carolina; Shown Are also the Mean Annual Air Temperature from the U.S. Fish and Wildlife Weather Station across the Lake and Estimated Annual Turc's PET

	Rainfall (mm)						
Year	PARK	TOWN	PLANT	Average	Long-term	Turc PET (mm)	Air temperature (°C)
2007	N/A	1,002	936	969	1,261	1,218	19
2008	1,015	1,164	1,111	1,097	1,261	1,190	18
2009	N/A	1,097	1,100	1,099	1,261	1,121	19
Average	N/A	1,088	1,049	1,055	1,261	1,176	18.7

The average annual rainfall from the three gauges at the site was lower than both the long-term normal and annual estimated PET in all the three years. Year 2007 showed a larger difference (−249 mm) between average rainfall and PET, assumed as the soil water deficit, than in 2008 (−93 mm), indicating the effects of drought in 2007 followed by 2008. The difference was the smallest with only −22 mm of soil water deficit in 2009, indicating an overall deficit of −121 mm, on average for the 3-year period. Since the weather, e.g., rainfall and PET, is a driving force in hydrology (streamflow or runoff), this recent drying trend might have affected runoff amount, nutrient dynamics and loading and flow movement by both surface and groundwater within the CBC watershed.

Streamflow

Streamflow at all monitoring stations was generally less than 10% of incoming rainfall from July 2007 to June 2009 (Fig. 3). Runoff coefficients (ROC) for SL1 and SL4 had the lowest values at 4.9% and 5.1%, respectively, while SL2 and SL7 yielded higher ROC values of 6.6% and 6.0%, respectively (Fig. 4). These percentages were below typical ROCs (20–30%) measured from the forested watersheds both in South Carolina and North Carolina, USA (Amatya et al. 2006; Amatya and Skaggs 2011; La Torre Torres et al. 2011). Based on these previous studies, and although a drought occurred in 2007–2008, the ROC values at CBC were much lower than would be expected.

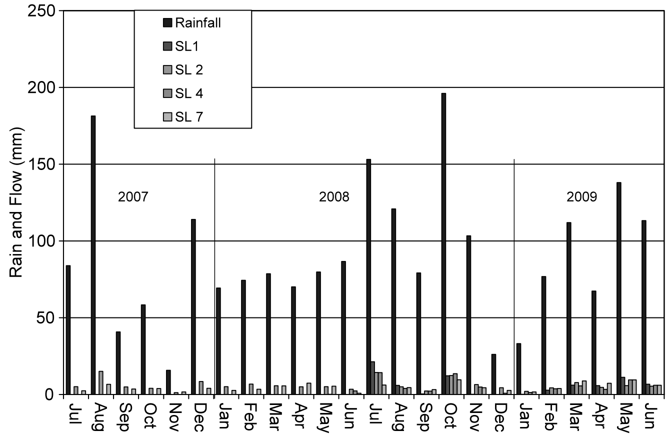

Fig. 3. Monthly rainfall and flow from tributaries (SL1, SL2, SL4, and SL7) of Chapel Branch Creek; each represented as mm depth over each subwatershed

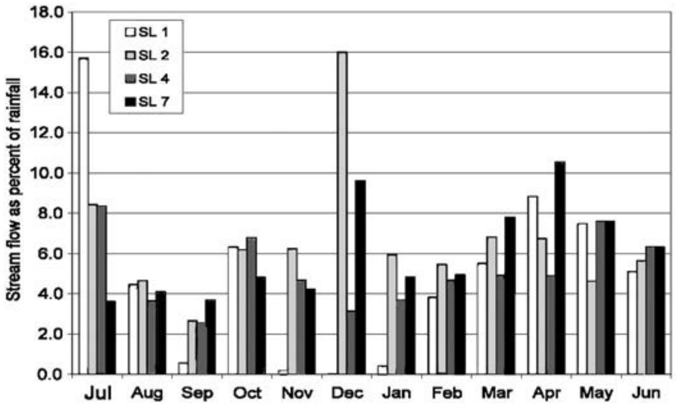

Fig. 4. Runoff coefficients (streamflow as percent of rainfall) for the year (July 2008–June 2009); based on data collected when all four ISCO flow recorders were present, expressed as a percentage of rainfall

Monitoring of the CS revealed a baseflow of approximately 0.1 m^3/s, with peak flows observed following the rain events. Comparing the flows at the CS and SL7 revealed that the peak flows following rain events were due to inflow of surface water from SL7 [Fig. 5(a)]. In addition, the subsurface underground channel behaved somewhat as a storage reservoir with a dampening and broadening of the storm peak. A regression of the data in Fig. 5(a) shows that 90% of the variation of the measured flow at the CS can be explained by a linear regression with an intercept of 0.12 m^3/s and a slope of 0.84 [Fig. 5(b)]. The intercept is very similar to the mean flow difference between downstream and upstream stations (CS-SL7) of 0.1048 ± 0.017 m^3/s measured over the six-month period. Inspection of the scatter plot [Fig. 5(b)] also indicated a nonlinear response for SL7 flows of 1.2 m^3/s. In Figs. 5(a and b), the points marked A in the plot are the initial rise of the first large peak, while the points marked B are the recession showing a continued flow of nearly 0.23 m^3/s at the cave spring for a few hours after SL7 had dropped to near 0. Most of the nonlinearity in Fig. 5(b) is due to that single large flow at SL7 in late March. The presence of a nonlinearity in the first large peak flow (0.25 m^3/s) but not in the second smaller peak flow (0.20 m^3/s) suggests the cave may have a maximum flow capacity on the order of 0.12 m^3/s. When the SL7 flow rate exceeds 0.12 m^3/s, a portion of the flow either bypasses the cave or is stored for a short period.

Flow at the cave spring was clearly much larger than that of any of the surface watersheds for January to June 2009 period [Fig. 6(a)]. SL4 is a subwatershed within SL2, and SL7 is an upstream contributing source to the CS flow, and SL7 seldom produced monthly runoff of more than 10% of the rainfall compared to the much larger value observed at the CS outlet, so it was assumed that watershed discharges could be summed based on these specific outlets. Therefore, a comparison of surface to subsurface flow results was made using the sum of SL1, SL2, and SL7 as the surface flow total, and the difference between the cave spring and SL7 as the subsurface flow total [Fig. 6(b)]. The total flow from three surface tributaries varied between only 16% and 25% of the subsurface flow. Total flow, with subsurface included, yielded a ROC of 33.8% for the determined CBC watershed area of 1,555 ha (Amatya et al. 2011b). These results suggest that runoff *missing* in surface flow is returned to CBC as subsurface flow to the cave spring. This large ROC during a drought period may also indicate the subsurface system that feeds the second cave may be larger than the overall CBC surface watershed.

Phosphorus

The original seasonal storm sampling was carried out on February 22, 2008 (winter); April 2, 2009 (spring); July 29, 2009 (summer); and November 11, 2009 (fall). Winter event grab sampling revealed that our original hydrologic monitoring plan was inadequate to capture the vastly different flow patterns of subwatersheds that fed SL1, SL2, SL3, and SL4 and lack of surface flow at SL8. The undeveloped forest, represented by SL8, did not produce surface runoff throughout the study and was therefore removed from the sampling and monitoring plan. SL1, SL2, SL3, and SL4 produced rapid peaks and short duration hydrographs that contrasted greatly to the flow at SL7 due to an effect of a reservoir at this location. These results were consistent with observations made by Ryan and Meiman (1996), who reported that accurately recording transient variations at karst springs requires more rigorous sampling strategies than traditional methods.

J. Hydrol. Eng. 2014.19:428-438.

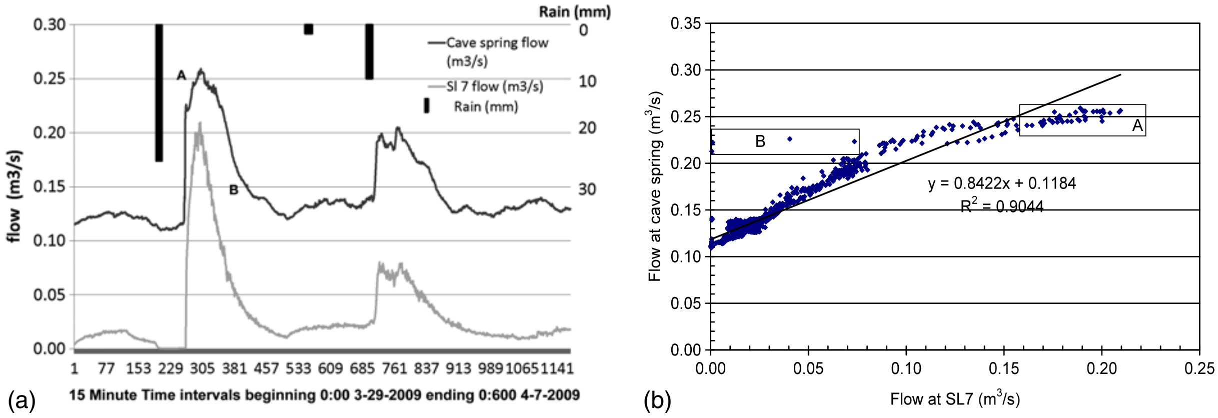

Fig. 5. (a) Hydrographs of cave spring and SL7 in March 29 to April 7, 2009 indicating flow near 0.1 m^3/s at the CS; the large storm event shows storage (A) and release of stored waters (B); (b) scatter plot of 15-min interval flow data for the cave spring and SL7 with best-fit intercept of 0.118 m^3/s as the constant discharge from the second cave; points in boxes A and B correspond to the data at those positions in the hydrograph in Fig. 5(a)

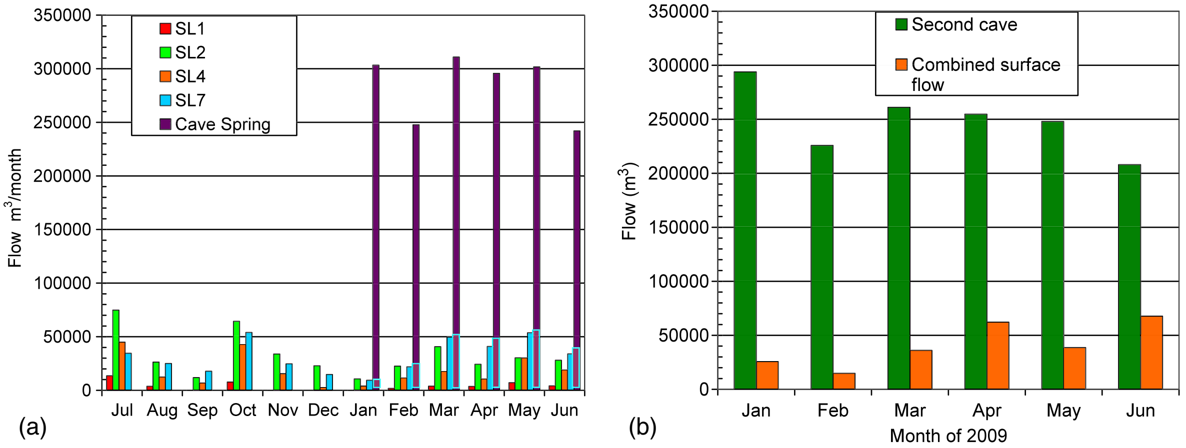

Fig. 6. (a) Monthly flow of the four surface subwatersheds (SL1, SL2, SL4, and SL7) and the cave spring; outlines on cave spring indicate portion of cave spring flow due to input from SL7; (b) comparison of all surface flows and the subsurface flow from the second cave feeding the cave spring

One advantage of the delays caused by drought was that the cave spring location was included in all 2009 storm sampling. Data analyzed by ANOVA for uneven sample numbers indicated that neither the hydrograph position nor season produced significant differences in the means of total P concentrations, while sample location was highly significant ($\alpha = 0.01$). Location differences in data from storm grab sampling [Fig. 7(a)] tested with Duncan's multiple range tests showed that mean TP concentration only at SL1 was significantly higher ($\alpha = 0.05$) than any other sampling location (for a specific land use).

Mean TP concentrations from automated samplers were somewhat higher for SL1 and somewhat lower for SL7 [Fig. 7(b)] than for the other sampling sites. Statistical significance was the same with only SL1 significantly higher ($\alpha = 0.05$) than the other sampling sites.

Nitrogen

Total nitrogen concentrations in storm samples [Fig. 8(a)] did show differences, but high variability led to no significant differences in the means. The high TN values at SL1 were due primarily to high ammonium concentrations. Ammonium concentrations at SL1 were an order of magnitude higher in the winter sampling period. It was suspected that a leak in the line delivering effluent to the golf course may have been the source and values were much lower after the line was repaired. Concentration of nitrate was consistently higher at the cave spring (CS), but high standard errors limited the sensitivity of the ANOVA.

Mean TN concentrations measured from automated samplers were unreasonably high due to extremely high nitrate concentrations at SL1 and SL2 locations during the summer of 2008. Concentrations as high as 3,000 mg/L were found in several samples from these two stations. Similarly, concentrations of 300–400 mg/L were also found in water samples at SL4 and SL5 stations. However, similar high values were not found in grab samples during that period, but all attempts to isolate a source of contamination were unsuccessful. For this article, data from automated samplers for the period from only November 2008 through July 2009 have been used [Fig. 8(b)]. With this limited data set, ANOVA tests resulted in highly significant ($\alpha = 0.01$) location effect due to land uses (source areas) and a Duncan's multiple range test showed significant differences ($\alpha = 0.05$) in TN between CS and SL1 as well as results from these two locations being significantly higher ($\alpha = 0.05$) than the other four sampling sites (SL2, SL4, SL5, and SL7).

J. Hydrol. Eng. 2014.19:428-438.

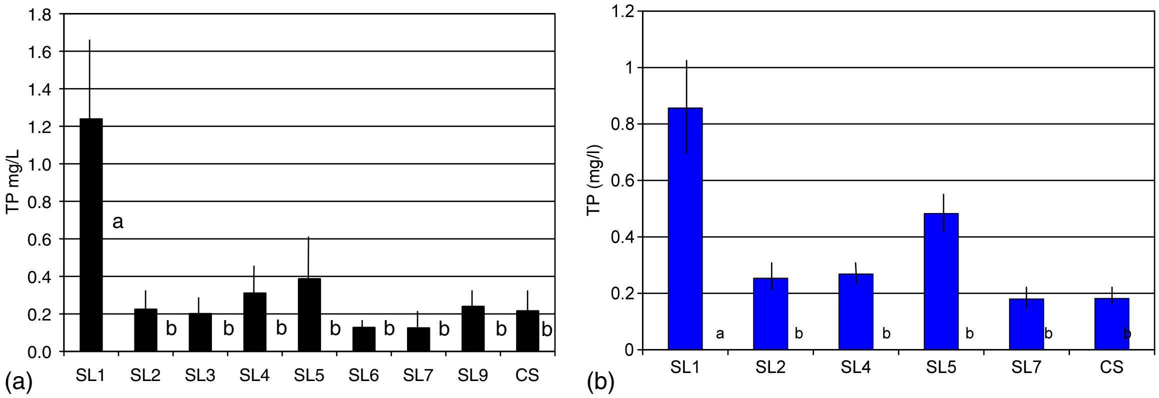

Fig. 7. (a) Overall mean total phosphorus concentrations in storm grab samples ± one standard error of the mean; (b) overall mean total phosphorus concentrations in weekly and storm samples collected by automated samplers; means with same lowercase letter are not significantly different ($\alpha = 0.05$)

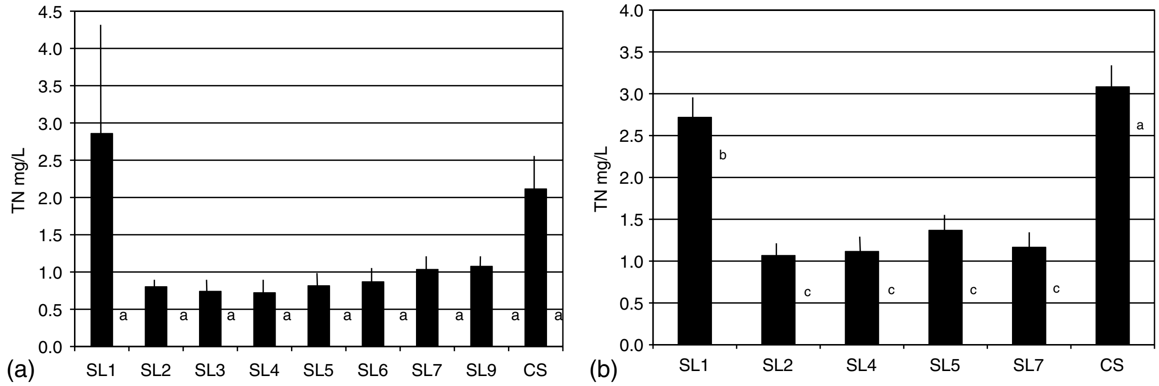

Fig. 8. (a) Overall mean total nitrogen concentrations in storm grab samples ± one standard error of the mean; (b) overall mean total nitrogen concentrations in weekly and storm samples collected by automated samplers; means with same lowercase letter are not significantly different ($\alpha = 0.05$)

Embayment (R-E) Input-Output and Nutrient Loading

The CBC embayment (R-E) contained as little as 60,000 m^3 during the drought of 2007 but can hold $823,000$ m^3 when the lake level is at the emergency spillway elevation (Amatya et al. 2011a). Between January and June of 2009, the embayment volume varied from 481,000 to 745,000 m^3 (Fig. 9). Given the size of embayment storage, lake level changes affected by inputs of Santee River and operation of Wilson dam downstream (Fig. 1) can make outflow somewhat independent of inflow. Note that the R-E outflow continued to decline in March and April despite an increase in inflow for those two months and only increased in May after the lake had stabilized at a higher level. Also, the high rate of outflow from R-E continued in June as Lake Marion was drawn down for hydroelectric generation.

Volume changes within the R-E embayment were found to be generally much less than the monthly inputs of flow from three major input tributaries of the watershed and a constant outflow was maintained. However, monthly input volume as a portion of R-E embayment volume varied from 63% in January to 43% in June, implying a residence time ranging from 6–9 weeks within the embayment.

Inflow and outflow data for the R-E embayment were available for all stations during the January to June 2009 period (Fig. 10). Most of the flow from the CBC was derived from the second cave (GW) that feeds the cave spring (CS) as was shown by the data earlier. High concentrations of nitrate in the second cave (GW) and its high flow volumes [Fig. 6(b)] resulted in it being the predominant source of total nitrogen to the embayment. However, nitrogen delivery to Lake Marion was at consistently lower rates than that of the input to the embayment.

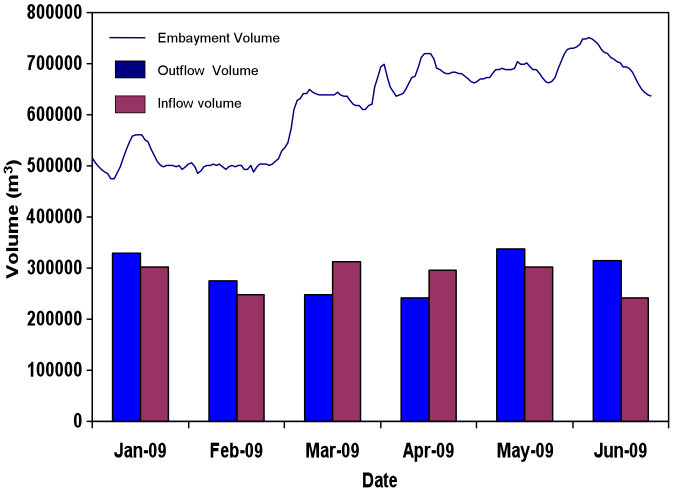

Fig. 9. Volumes of inputs, outputs, and stored water in embayment for January to June 2009; direct rainfall and evaporation are not shown at this scale

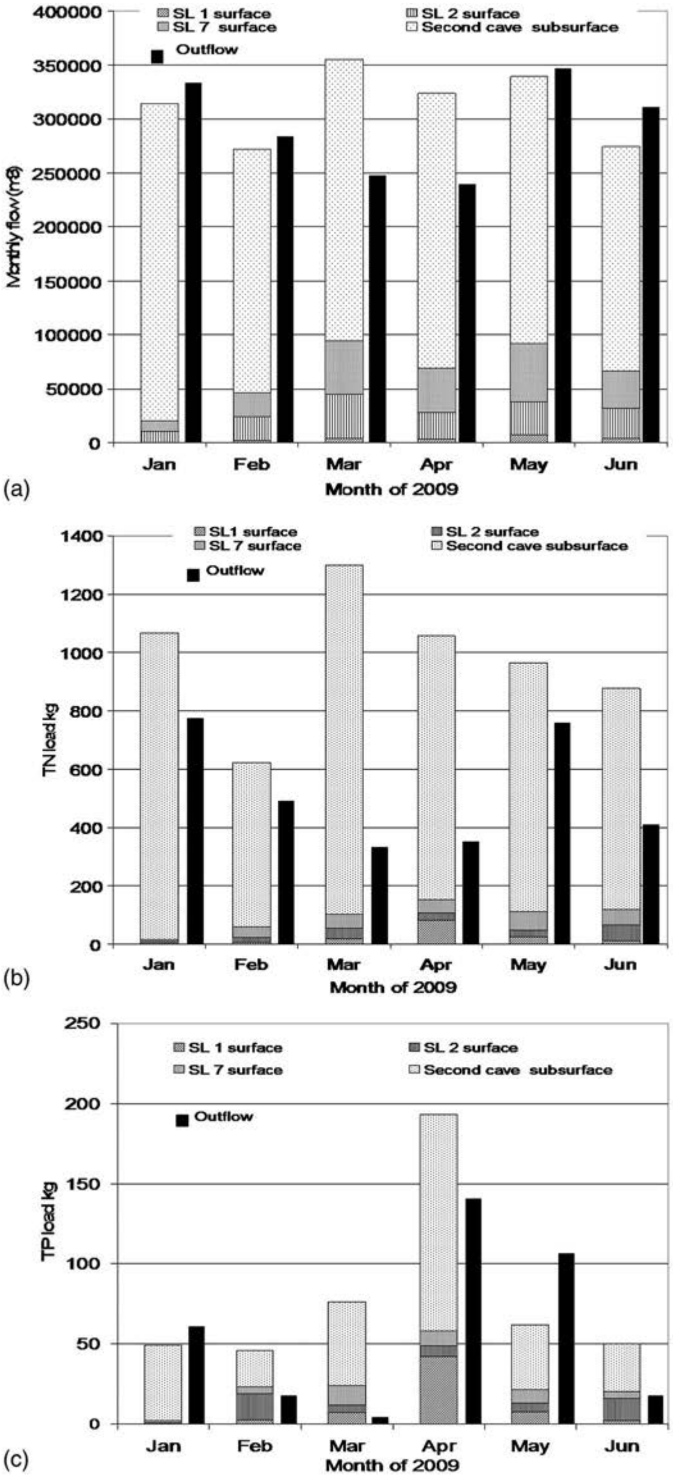

Fig. 10. (a) Inputs and outputs of water; (b) total nitrogen; (c) total phosphorus from Chapel Branch Creek watershed to the embayment and outflow from the embayment to Lake Marion; outflow was calculated from flow data and a single concentration estimate for each month at SC-014

Phosphorus export (TP) differed slightly from that of nitrogen in that phosphorus concentrations measured at the cave spring (CS) were not significantly ($\alpha = 0.05$) different from those at the surface sites. The concentration of TP in the second cave (GW) must also have been relatively similar to that of SL7, although the load calculation suggested it may have been somewhat smaller. Total phosphorus export from the R-E embayment to Lake Marion also generally showed a reduction within the embayment. However, the high input load in April 2009 did not leave the system until the end of May as would be expected from average residence times.

Discussion

In this study, it was determined that CBC watershed was not only a very complex system with many potential pollutant sources from urban and suburban land use areas, but also complicated by karst features (Edwards et al. 2011). Both the storm and continuous sampling at stations draining each of the land use types within the watershed revealed that surface water quality was not different under various land uses. The only exception was the small subwatershed (SL1) where sewage effluent was used for golf course irrigation. During the study, a leak in an effluent line was repaired in this watershed. Despite high TN and TP concentrations in flow from this subwatershed, SL1 contributed relatively little to the overall nutrient loading of the embayment due to relatively small flow as shown in Fig. 4.

The drought of 2007–2008 delayed the study implementation and resulted in installation of continuous monitoring of the tributaries draining SL1, SL2, SL4, and SL5 subwatersheds in addition to the original one at SL7, as previously described. Continuous flow measurements revealed that less than 10% of the rainfall (ROC) was being produced as surface runoff at all locations (Fig. 3). The drought of 2007 might have also led to small ROC values in that year. However, the ROC values calculated for the months after June 2008 are also much lower for this type of land use containing 56% developed areas (e.g., highways, roads, town) and agricultural lands, leading to a speculation that the water lost to groundwater might have been conveyed through underground conduits toward the CS outlet [Fig. 1(b)]. The smaller subwatersheds (SL1 and SL4) produced even less runoff than the two larger ones (SL7 and SL2) (Fig. 4). As an example, the SL4 station upstream of SL2 yielded the ROC values less than 5% in 10 out of 14 months during the June 2008 to July 2009 measurement period (Fig. 4). The possible drought effect is not likely, since after October 2008 the drought conditions had ended and ROC values were also small during that period. The two subwatersheds (SL2 and SL7) produced nearly the same ROC values despite the fact that land use upstream of SL7 was primarily agriculture and forest, while that land use upstream of SL2 contained the developed areas of the town of Santee in addition to substantial highway infrastructure. When a LIDAR-based elevation model of the watershed became available in 2009, it was revealed that both subwatersheds (SL2 and SL7) have a number of sinkholes and closed depressions, suggesting that water was being lost to the subsurface at both locations. Furthermore, a coincidental sinkhole collapse on August 13, 2009, reinforced the indication of water loss through underground conduits, as the location of that sinkhole was in line with the proposed direction of groundwater flow from SL4 toward the CS outlet (Fig. 1) (Edwards and Amatya 2010). It was also determined that the bottom of the ditch connecting SL9 to SL4 was nearly 0.3 m higher than two depressions upstream of the ditch. The elevation difference suggested that flow from SL9 to SL4 occurred only when runoff was relatively high; otherwise, that area of the watershed may have contributed only to the groundwater system.

The drought also revealed the presence of a second cave (GW) producing flow at the CS location. The golf course pond located immediately upstream of SL7 resulted in more prolonged discharge. Measurements at CS revealed that a nearly continuous flow of 0.08 m^3/s occurred at the GW location, which produced a much greater volume of water on a monthly basis, demonstrating that this subsurface source was the dominant input to the flooded embayment in the lower section of CBC. Water supplied to the CS by GW resulted in high TN concentrations but moderate TP concentrations. As a result, subsurface flow from GW contributed about 50% of the phosphorus, 60% of the flow, and over 70% of the nitrogen entering the lower embayment.

The karst features in the study watershed, such as sinkholes, depressions, and caves, may have provided connectivity of the surface water with the underground water (Edwards et al. 2011). This connectivity might have occurred during conditions of small flows according to the ROCs observed at the areas draining SL1, SL2, SL4, and SL7 as previously discussed. The total outflow measured at the CS outlet indicated that groundwater provided more than double the input flow compared to the combined surface inputs from SL1, SL2, and SL7 within the CBC watershed (Fig. 5). This gives an indication that the contribution of groundwater at the CS outlet could account for all of the water lost at SL2 and SL7, and possibly an even larger area than the surface watershed. Furthermore, the fact that the ROC value of 33.8% for the CBC watershed was higher than a value of 29.1%, obtained by Felton (1994) for a watershed with similar size and land use in central Kentucky additionally supports this hypothesis.

Results indicated that the reservoir hydrodynamics in the R-E embayment led to a nutrient reduction and thus improvement in water quality delivered to Lake Marion. Residence time varied from 4 to 9 weeks with differences in water level. Calculated total nitrogen output from the embayment was always less than the input from the upstream watershed. Calculated total phosphorus export was generally also lower than the inputs, although the high inputs did result in a delayed peak of phosphorus export to Lake Marion.

The role of subsurface flow in this study altered our initial understanding of this relatively small karst watershed. Sources of N and P in the embayment were dominated by flow from a second cave (GW) that had a subsurface source of water. This source appeared to have a large storage capacity and exhibited near constant outflow. Several significant geological processes, including a sinkhole collapse (Edwards and Amatya 2010) and dye trace and LiDAR data (Edwards et al. 2011) during the study period, confirmed direct surface and subsurface hydrologic interactions in this watershed. These interactions suggest that a primary nitrogen source area may be located to the southwest of the cave spring. The topographical orientation also agreed with the apparent general low percentage of rainfall-based flow that occurred in surface streams. Loss of water within streams and closed depressions in the surface watershed was likely a part of the source of groundwater flow in the cave spring location.

Conclusions

The results from this study demonstrate the need for understanding the karst nature of CBC watershed, especially with respect to TMDL development. The existing unique karst geology must be considered for water quality management for the CBC watershed and will aid in defining mechanisms for reducing the nutrient loads from the watershed. For example, measured flow rates in various tributaries suggest that subsurface sources may represent a flow contribution from an area larger than the entire surface watershed. Water balance analysis indicated a residence time ranging from 6–9 weeks in the embayment that interacts with incoming flows and lake water levels. Nutrient concentrations in flows from tributaries draining various land uses (source areas) were not significantly different ($\alpha = 0.05$, at 95% confidence level) for most of the locations. The most notable aspects for consideration include (1) the importance of constant subsurface discharge from the cave spring in the water, nitrogen and to a lesser extent phosphorus budgets of the watershed and (2) the role of lake level interaction with the embayment that reduced watershed discharges to Lake Marion.

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