QUANTIFYING WATER BUDGETS IN BEAUFORT COUNTY, SC

BY

SOUTHERN WATER RESOURCES

A.W. BADR, PH.D.

VIA

CLEMSON UNIVERSITY

AGREEMENT WITH

BEAUFORT COUNTY ENGINEERING DIVISION

2014

INTRODUCTION

Water budgets are needed primarily to determine the volume of fresh water that is being discharged into local tidal creeks and to determine how development is affecting components of the water budget. Areas of interest include the upper reaches of the Okatie River, which is part of a watershed that is fully developed and includes the retirement community of Sun City.

To address this issue, Southern Water Resources proposed to Beaufort County a network of surface- and ground-water monitoring stations strategically located within the watershed that will quantify precipitation, runoff, and changes in ground-water and surface-water storage. This network was installed in 2011 and 2012. Evapotranspiration was also estimated using a temperature-based approach. Data collected from the monitoring network was used as the basis for developing a water budget for a watershed within the Sun City development. Southern Water Resources also assisted the Beaufort County in the analysis and interpretation of this data.

Water Budgets

In its simplest terms, a water budget is an accounting of the volume of water entering a watershed (inputs), the volume of water leaving a watershed (outputs), and changes in the volume of water that is stored in the watershed (storage), over a fixed time interval. It is generally expressed by the equation:

$$Q_{in} - Q_{out} = \Delta S \text{ - - - - - - - - - - } (1)$$

where Q_{in} is the volume of water coming into the system (watershed) per unit of time, Q_{out} is the volume of water leaving the system per unit of time, and ΔS is the change in the volume of water in storage per unit of time. Three to four week time steps were used in the water budget analysis for this study.

Water enters a watershed primarily in the form of rainfall where it runs off to surface water bodies, evaporates and/or transpires from plants, or seeps into the ground. In this case, the water-budget equation above can be more accurately expressed as:

$$R - (Q_O + ET) = \Delta S \text{ - - - - - - - - } (2)$$

where P is precipitation, Q_O is runoff, and ET is evapotranspiration.

The above equation can be customized depending on the objectives and scale of a project, and depending on the complexity of the system that is being studied. Other inputs, for example, may include water that is transferred from other watersheds or pumped from confined aquifers and used for irrigation in the watershed (Q_{ir}). The water budget equation would then be expressed as:

$$(R + Q_{ir}) - (Q_O + ET) = \Delta S \text{ - - - - - - - - - - } (3)$$

Once calculated, a water budget is a valuable management tool that can be used to assess the availability and sustainability of water supplies within a watershed. Long-term (10 years or more) monitoring of the various components of a water budget can be used to assess the impacts that climate change and land-use modifications have on the water resources of an area.

OBJECTIVES

Watersheds commonly have different water budgets, reflecting differences in land cover, land use, soil characteristics, precipitation, geology, topography, and drainage patterns. Development can also alter the natural flow and distribution of water in a watershed and can change a water budget. Comparisons of water budgets between undeveloped and developed watersheds can be used to draw conclusions regarding the natural effects that soil characteristics, geology, or vegetation have on the water resources of the watershed. Comparisons of water budgets from undeveloped and developed watersheds can lend insights into the effects that human activities have on the water resources of the watershed.

The purpose of this project was to develop a water budget for the Sun City community in the Okatie River area, which is located in a part of a watershed that is fully developed. Runoff coefficients, or the ratio of runoff (Q_O) to rainfall (R), were also computed and compared to regional runoff coefficients determined from stream gaging stations monitored by the United States Geological Survey (USGS).

Specific objectives of this study were to:

1) quantify the amount of rainfall falling on the watershed (R),

2) quantify the amount of water imported into the watershed for irrigation purposes for both residences and golf courses (Q_{ir}),

3) quantify the amount of water discharging into the Okatie River as surface-water runoff (Q_O),

4) quantify the change in storage of the shallow water-table aquifer (ΔS_{wt}),

5) quantify the change in storage of the storm water ponds (ΔS_{rp}),

6) estimate the amount of water lost to the atmosphere by evapotranspiration (ET),

7) and compare runoff coefficients for the watershed with regional runoff coefficients.

The general water budget described above can be expressed in more detail for this study as:

$$(R + Q_{ir}) – (Q_O + ET) = \Delta S_{wt} + \Delta S_{rp}. \text{ - - - - - - - - - - } (4)$$

Scope of Work

Southern Water Resources was responsible for:

1) developing a plan to monitor the watershed with recommendations on which water budget components to monitor,
2) providing technical assistance on the siting of monitoring stations and the selection of appropriate equipment,
3) and evaluating data and developing a water budget for the watershed.

Beaufort County was responsible for:

1) purchasing the monitoring equipment,

2) installing the equipment,

3) maintaining the equipment,

4) installing monitoring wells,

5) collecting data from the monitoring stations,

6) collecting water use data for imported water and groundwater pumped from confined aquifers,

7) surveying elevations of monitoring wells and recorders in detention ponds,

8) and quality control.

Southern Water Resources’ first responsibility was to develop a monitoring plan for the watershed that would focus on the principal objective of quantifying the water budget. Fiscal budget constraints, however, limited the number of sites that could be monitored and the number of wells that could be drilled. Site visits were necessary to evaluate the outfall areas, to determine where weather stations could be installed without obstructions and where monitoring wells could be drilled without interfering with other construction projects in the study area. Details of the number and locations of monitoring stations including stream gages, weather stations, pond gages, and monitoring wells are presented in the Methods section. Monitoring wells were sited in each of the major hydrologic soil types that are represented in the watershed.

Southern Water Resources' second responsibility was to analyze the data that was collected from the various monitoring stations in order to generate the water budget for the study area. The water budget was computed for 3 to 4 week intervals and periods of analysis were limited by physical constraints at the weir outlet (see below).

METHODS

Water budget components for the study watershed located at Sun City are discussed below. Inputs to the watershed include rainfall (R) and the reuse of wastewater for irrigation purposes (Q_{ir}). Outputs from the watershed include surface water runoff (Q_O) and evapotranspiration (ET). Potential Evapotranspiration (PET) was computed to estimate the maximum amount of ET that could occur for the study watershed. Time periods for the water budget analysis were limited by periods when reliable surface runoff estimates were available (see below).

Rainfall (R)

Rainfall was measured by a manual rain gage located on the Palmetto Bluff watershed. Rainfall was typically recorded on a daily basis from Monday through Friday while rainfall totals during weekends were recorded on Monday mornings. To estimate daily rainfall on the weekends, totals recorded on Monday mornings were divided equally over Friday, Saturday and Sunday. Rainfall amounts were summed over the same 3 and 4-week periods for which flow was estimated as described below and presented in units of inches. Rainfall amounts for the selected time periods are presented in Table 1.

Water imported to watershed for irrigation (Q_{ir})

Wastewater from Sun City is reused for irrigation purposes within the study watershed, and thus, is treated as an additional inflow to the watershed. Wastewater reuse was estimated by prorating Sun City's total water use based on the percentage of houses located in the study watershed and assuming that this prorated amount is entirely returned to the watershed via irrigation. Water use data, in millions of gallons per month (MGM) were obtained from the applicable BJWSA treatment facility. Eighty percent of the water from this facility is used by Sun City. Average daily water use was estimated from the monthly water use data, and then total water use was summed over the time periods discussed below for the water budget based on the daily average values. The total water use for the selected time periods was then divided by the area of the watershed to determine the water use per unit area and converted to inches.

These values, included in Table 1, represent the amount of additional water added to the watershed from the reuse of wastewater for irrigation.

Runoff (Q_O)

Runoff or surface water outflow was estimated from a contracted rectangular weir located at the watershed outlet using the Francis equation (Gils, 1962). The form of the equation used computes outflow in cubic feet per second. The location of the weir is presented in Figure 1. The head or stage above the weir crest was measured with a pressure transducer at 5-minute intervals. Specifications for the weir allowed for outflow to be measured only when heads were equal to or less than 0.625 feet. During higher flow events, heads exceeded the 0.625 ft threshold at which the Francis equation is no longer valid for this weir. As a result of this limitation, outflow for high flow events could not be determined.

Figure 1. Groundwater and surface water monitoring sites on the study watershed.

Two periods of low to moderate flows were selected for analysis. The first period was from June 17, 2012 through August 4, 2012, and the second period was from September 16, 2012 through January 26, 2013. The second period included two flow events where heads above the weir crest briefly exceeded the 0.625 threshold limit and for each of these events the flow computed represents a minimum flow for the event. Flow volumes were determined by taking the average head over each 5-minute interval and computing the resulting flow rate over the 5-minute interval using the Francis equation. Flow volumes were computed for each 5 minute interval, normalized to the drainage area of the watershed (1000 acres) to compute outflows in units of feet and then converted to inches. Outflows were then summed over 4-week intervals for the time periods described above (each of the two time periods discussed above included one 3-week interval as well). Outflows for the selected periods are presented in Table 1.

Runoff-rainfall coefficients, the ratio of outflow to rainfall (Qo/R), was also computed and presented in Table 1. These coefficients were compared to regional basin coefficients determined for the Salkehatchie and Coosawhatchie basins (see below) by computing percent differences in the coefficients. Ratios of runoff to the sum of rainfall and wastewater reuse ($Q_O/(R+Q_{ir})$ were also computed and presented in Table 1.

Potential Evapotranspiration (PET)

Potential Evapotranspiration (PET) for the study watershed was estimated using the Hamon method (Hamon, 1963). The Hamon method utilizes average daily temperature and daylight length, which is determined from the latitude of the study site. Temperature data was taken from the Beaufort MCAS station (ID NBC), which was approximately 19 miles from the study watershed. Daily PET in inches was computed from the average daily temperature and daylight length and then summed over appropriate time periods (the same 4-week periods for which outflows were estimated) for inclusion in the water budget. PET estimates for the selected time periods are presented in Table 1. PET is the maximum amount of evapotranspiration (ET) that can occur if soil moisture conditions are not limited. During drier periods, actual ET will be less than the PET.

Pond Stages

Surface-water levels were measured at two ponds on the study watershed. The ponds are labeled SCW-1 and SCW-5 (the largest onsite pond) in Figure 1. Levels were measured on an hourly basis with an unvented pressure transducer. The unvented transducer measured total pressure in feet of water and the hourly readings were compensated by using an onsite barometric sensor to remove the effects of barometric pressure. After compensation, water levels were converted to elevations in feet above sea level.

Groundwater Levels

Groundwater levels were measured at three sites on the study watershed. These sites are labeled as SCW-2, SCW-3 and SCW-4 in Figure 1. Levels were measured on an hourly basis with a vented pressure transducer. The unvented transducer measured total pressure in feet of water and the hourly readings were compensated by using an onsite barometric sensor to remove the effects of barometric pressure. After compensation, groundwater levels were converted to elevations in feet above sea level.

Each monitoring station in the study was surveyed to determine its latitude and longitude coordinates using the North American Datum of 1983 (NAD83) as the horizontal control datum, and leveled to determine its elevation above mean sea level using the North American Vertical Datum of 1988 (NAVD88) as the vertical control datum. All of the measurements made during the course of the study were referenced to a common datum allowing for computations of horizontal and vertical hydraulic gradients and other parameters.

Runoff coefficients for regional, unregulated watershed

The undeveloped, Palmetto Bluff watershed was originally included in the scope of this project. The runoff from that watershed was to be used for a comparison against the developed, Sun City watershed. The data collected from the Palmetto Bluff watershed shows that infiltrating rainfall moves downward into the deep sand layers of the watershed, and very little, if any, moves out of the watershed as runoff. The South Carolina Department of Natural Resources (DNR) recently made a geologic map of the Pritchardville quadrangle in Beaufort and Jasper counties. This geologic map shows an abundance of sand deposits and silted streams in the area of the Palmetto Bluff watershed. All collected data from the Palmetto Bluff watershed are given in Appendix B.

Two alternative watersheds were used for the comparison against the Sun City watershed. The selected watersheds are similar to the Okatie watershed where they are subject to tides and weather patterns (Figure 2). USGS data from the Coosawhatchie River near Hampton (02176500) gage was selected because the flow is unregulated and the hydrologic unit is the same as the Okatie River unit near Bluffton (03050208). Flow data has been collected at this site since 1951. The drainage area at this station is 203 square miles and has an average annual runoff of 10.6 in. The second selected site of unregulated flow is the Salkehatchie River near Miley (02175500) gage where the flow has been measured since 1951. The drainage area of this site is 341 square miles and has an average annual runoff of 12.8 in. The hydrologic unit of this site is 03050207 and is adjacent to the 03050208 hydrological unit. Average rainfall in the Salkehatchie and Coosawhatchie basins is approximately 48 in based on the review of several rainfall gaging stations located in these basins. Average runoff coefficients for the

Coosawhatchie and Salkehatchie basins for the period 1951 – 2012 are 0.22 and 0.26, respectively. The coefficient that was used in this study was an average of the two watersheds (0.24).

The state average runoff-rainfall coefficient was established from the State water budget (Figure 3) discussed in the State Water Plan. The state average coefficient is:

(21 in – 8 in)/48 in = 0.27.

The average is higher in the Upstate and Piedmont region because of the bedrocks and lack of coastal, shallow soil aquifers. The average is lower in the Coastal area because of the presence of the shallow soil aquifer system and the high storage ability in the soil profile.

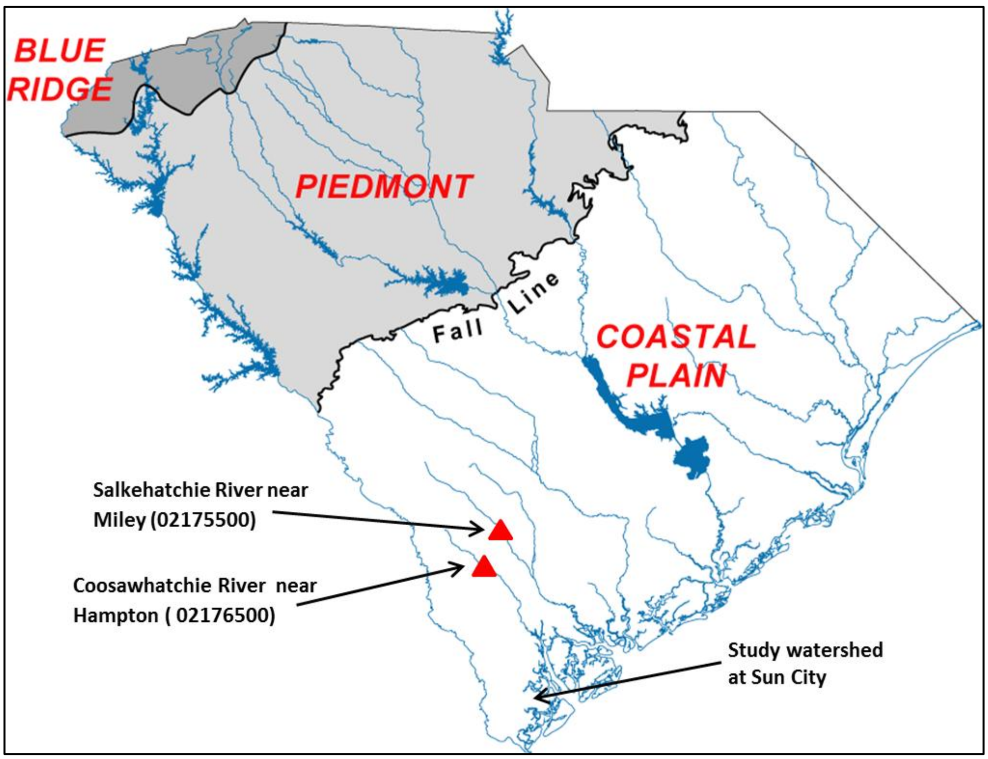

Figure 2. Location of unregulated gaging sites used to compute regional runoff-rainfall coefficients.

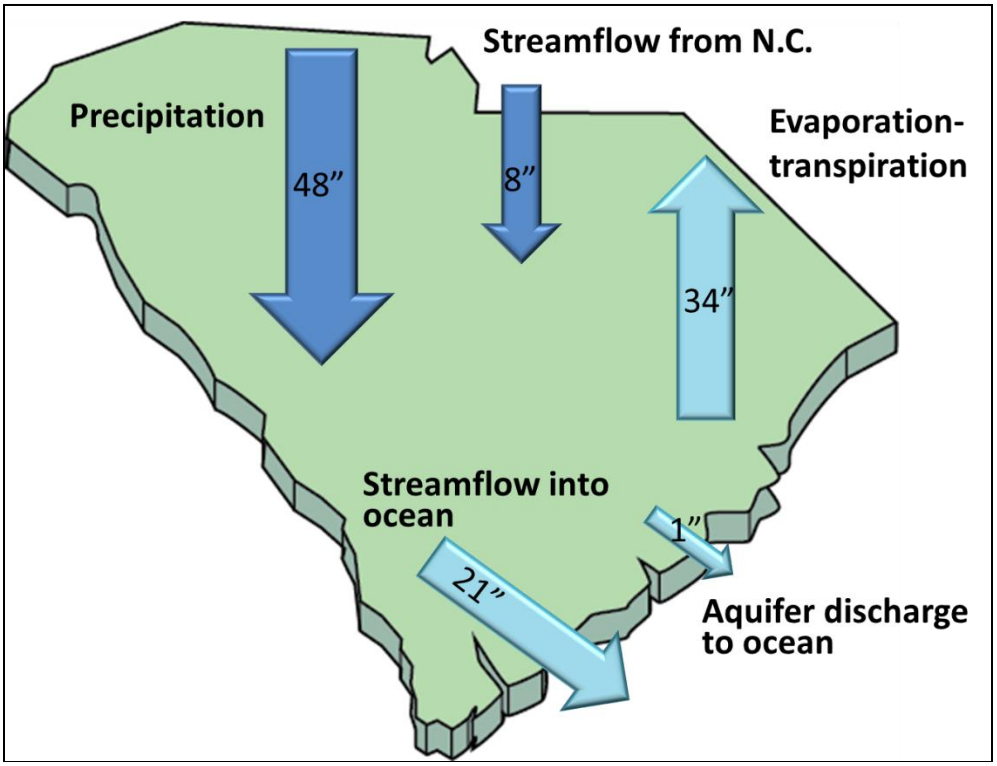

Figure 3. South Carolina’s water budget.

DISCUSSION

Water Budget Results

Precipitation and runoff are major components of the water budget in the study area. Therefore, it is critical that these two parameters be measured as accurately as possible using the best instrumentation available. Evapotranspiration is also a significant component of the water budget. Actual evapotranspiration will vary depending upon temperature and other meteorological variables. If an evaporation pan can be properly maintained or if an automated evaporation pan can be installed, it would greatly benefit any future studies on the watershed. For this study, potential evapotranspiration (PET) was used as a surrogate for actual evapotranspiration (ET).

Pond 5(SCW-5) is the largest pond in the Sun City development. While groundwater levels fluctuate due to rainfall and location, it is assumed that the groundwater levels in the watershed and SCW-5’s surface water elevations are trying to reach equilibrium at all times. Therefore, SCW-5 water levels were used to approximate the change in storage on the watershed.

Equation (3) was used to calculate the change of storage for each time unit in Table 1. For example, the total change in storage for the second period was:

$$(P + Q_{ir}) - (Q_O + ET) = (5.17 + 1.02) - (2.28 + 10.92) = -7.0 \text{ in.}$$

The measured change in storage was -7.7 in. Therefore, the percent error is:

$$[(7.7 - 7.0) / 7.7] \times 100\% = 9.2\%$$

The water budget results for the period from September 2012 through January 2013 in Table 1 gives a calculated change in storage within 10% of the observed changes in storage at pond SCW-5. However, measurement errors of runoff can be up to ± 15% for USGS streamflow gaging stations and compounded errors in the water budget can rise up to ± 45% according to the USGS.

The runoff-rainfall coefficients were calculated and included in Table 1 for each period. A coefficient was also calculated by dividing the runoff by the sum of the rainfall and additional water added to the system. The totals for the second period of analysis shows a significant increase in runoff where the coefficient measured in the Sun City watershed was more than 50% greater than the average annual runoff coefficient determined from the Coosawhatchie and Salkehatchie river basins.

Groundwater Well Data and Pond Stage Data Review

The observed water levels in groundwater wells and ponds are given the Figures 4 – 8 along with daily rainfall measured for the study period. Overall, water levels in the ponds and the wells were at their highest during August of 2012 when total monthly rainfall exceeded 13 inches and in February 2013, when monthly rainfall totals were approximately 9.5 inches. Levels were generally at their lowest during July 2012 owing to lack of rainfall and increased ET rates; however, SCW-3, SCW-4 and SCW-5 also experienced low level conditions in the fall of 2012.

Surface water levels in pond SCW-1 responded rapidly to rainfall events and increased as much as 2.5 ft during a large event in August 2012 (Figure 4). Levels in the pond also returned rapidly to pre - event levels. Levels in the pond typically showed little to no variation between rainfall events.

Q_{ir} (in)	[1] ΔS_{obs} (in)	ΔS_{calc} (in)	[2] % Diff. for ΔS	Q_O/R
			69.1	0.23
			71.4	0.04
			67.4	0.07

[1] ΔS is the change in storage observed at SCW-5.
[2] Percent difference between the observed and calculated ΔSC5 values.
[3] Average annual Q/R for the Salkehatchie and Coosewhatchie basins.
[4] Percent difference between the study watershed's runoff coefficients and the average annual runoff coefficient for the Salkehatchie and Coosewhatchie basins.

Table 1. Water budget results for the Sun City watershed for select periods.

(in)	[1] ΔS_{obs} (in)	ΔS_{calc} (in)	[2] % Diff. for ΔS	Q_O/R
).28	-3.28	-2.40	26.7	0.47
0.26	-6.91	-1.92	72.3	0.17
0.22	-0.77	-1.39	-80.7	0.45
0.16	4.96	0.25	94.9	0.34
0.10	-1.70	-1.55	9.3	9.26
1.02	-7.70	-7.00	9.2	0.44

Groundwater levels at SCW-2 also responc ... ;, but levels at the site also experienced drawdowns on the order of several fee ... nmer of 2012 (Figure 5). In the fall of 2012 and winter of 2012-2013, water ... 1, owing to lack of significant rainfall, until two large rainfall events ii ... ceable increases in water levels. Groundwater levels observed at SCW-3 resp ... all events, but also receded very rapidly. Significant drawdowns are observed i ... f the fall and early winter of 2012.

Groundwater levels at SCW-4 also responc ... iinfall events and receded to baseline, conditions after 3 to 4 weeks (Figure 7). Levels exl ... e variation between large storm events and never receded much below 10 ft, amsl, which r ... e for the influence of the large pond (SCW-5), which held water from 11 to 12 ft, amsl ... study period. Levels in the pond rarely dipped below 11 ft, amsl. SCW-5 (Figure 8) also r ... ly to rainfall events, increasing above 13 ft, amsl on several occasions, but also receded a ... han observed at SCW-1.

The weekly change in water levels for all r ... and ponds are found in Appendix A (Figures 9 – 13).

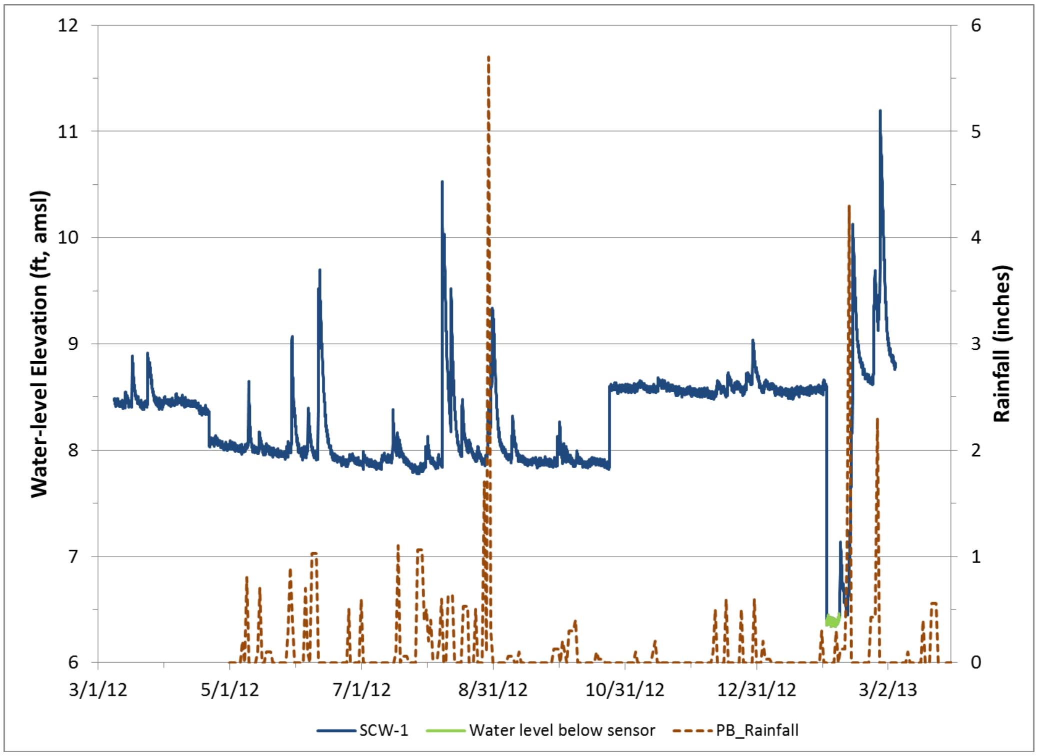

Figure 4. Water-level elevations for Pond 1 (SCW-1).

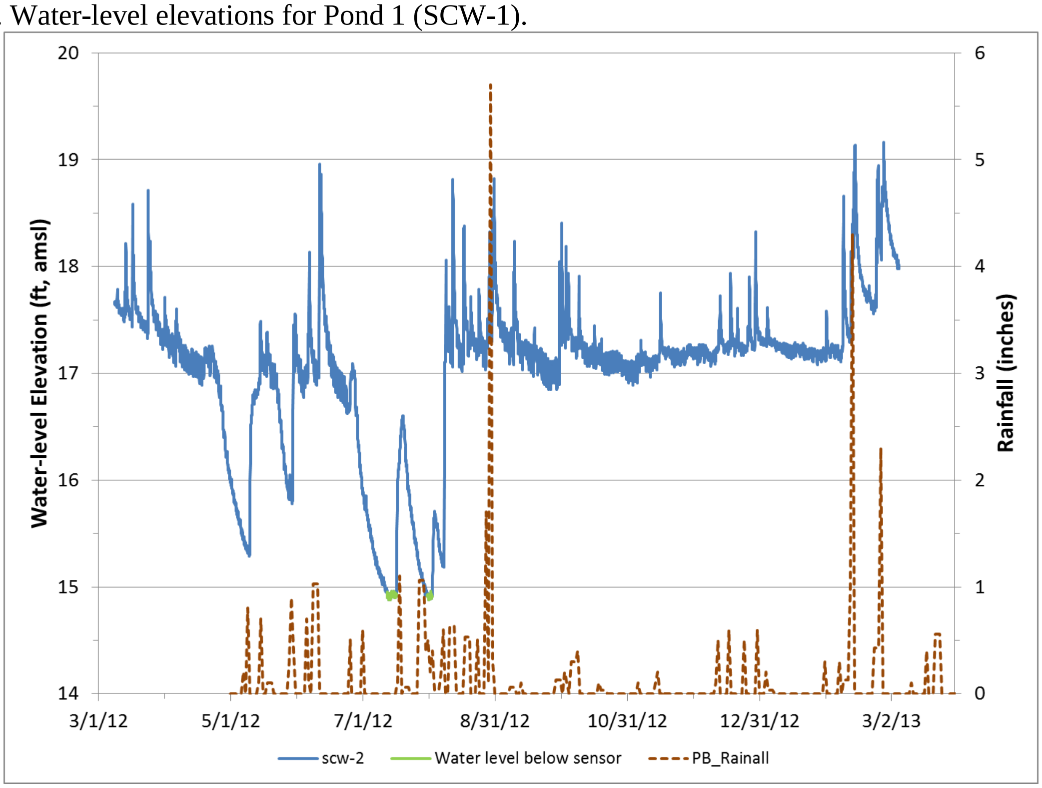

Figure 5. Groundwater-level elevations for SCW-2.

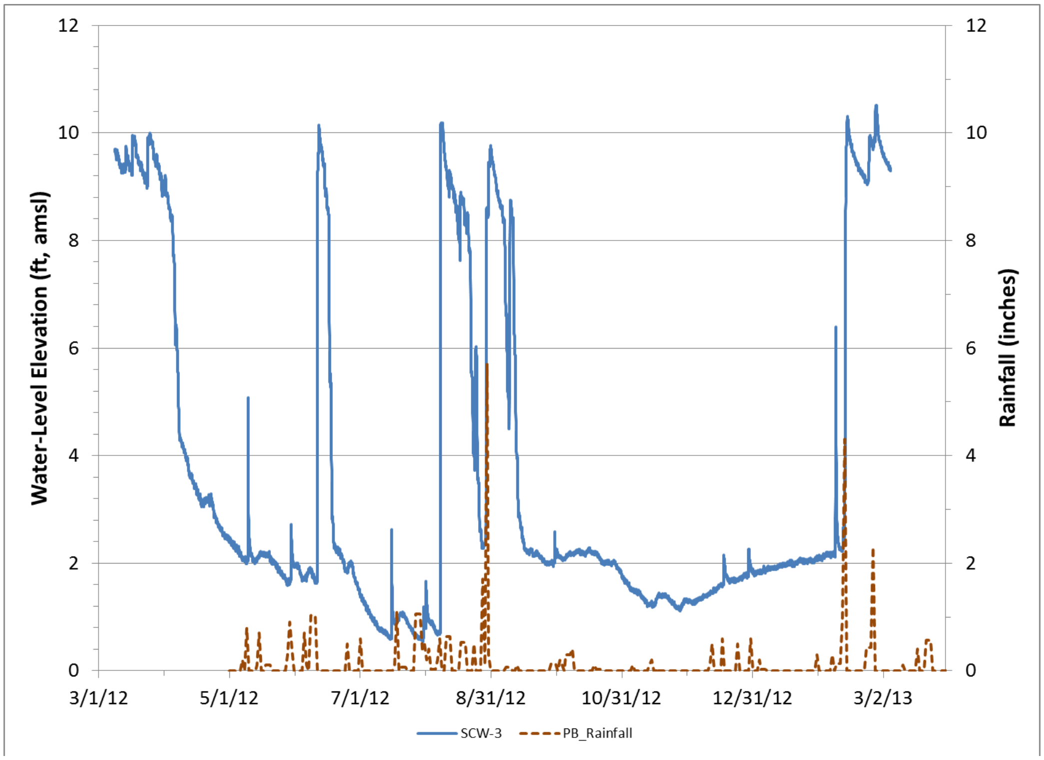

Figure 6. Groundwater-level elevations for SCW-3.

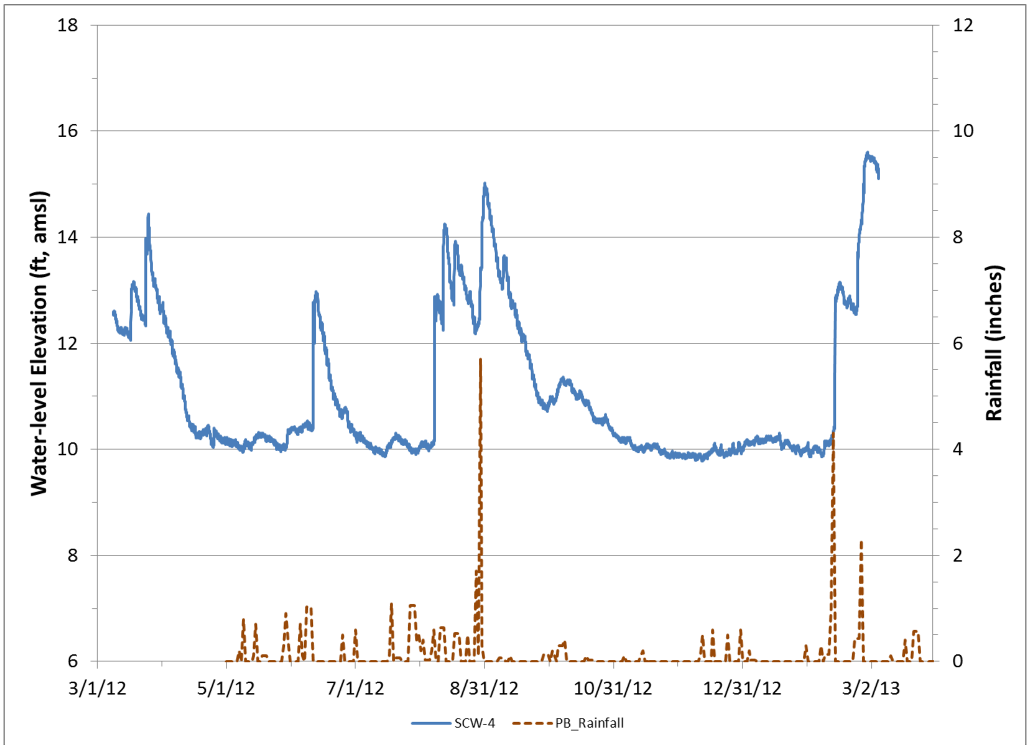

Figure 7. Groundwater-level elevations for SCW-4.

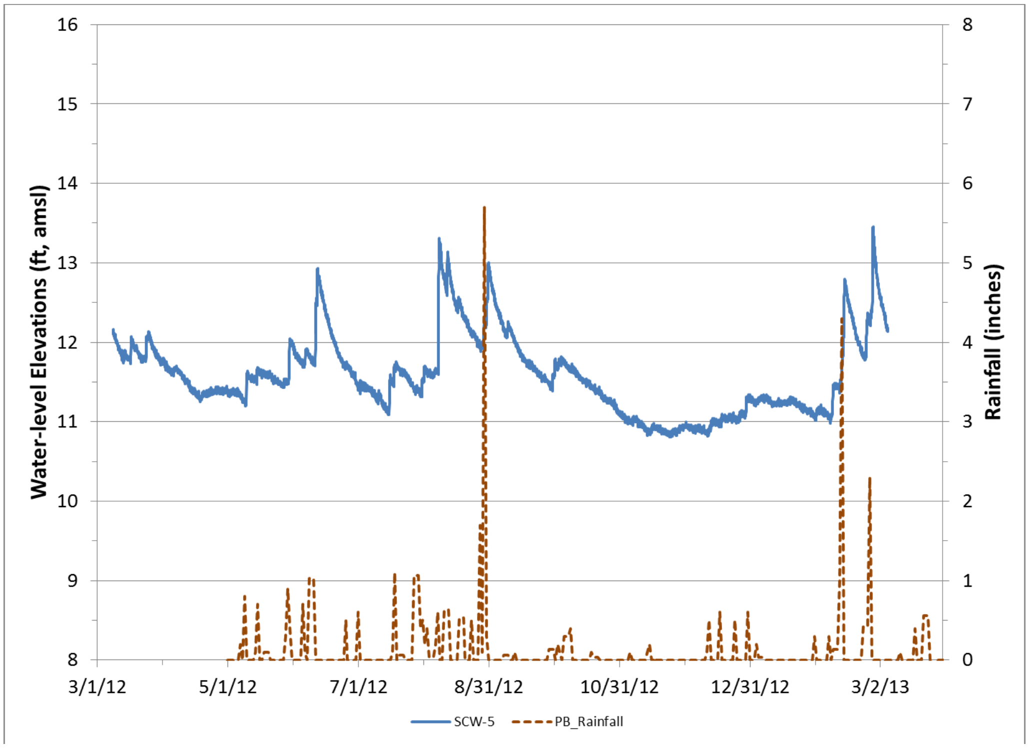

Figure 8. Water-level elevations for Pond 5 (SCW-5).

RECOMMENDATIONS

Data analysis on the Sun City watershed and the Coosawatchie and Salkewhatchie basins indicates an increase of more than 50 percent in the volume of water entering the headwaters of the May River as a result of land development.

Irrigated water added to the watershed was more than 20% of the natural rainfall during the monitoring period. The amount of available storage in the soil matrix was reduced due to the rising of the water table and the higher pond levels. Both the additional water and the higher water tables have increased the volumes and peak flows of runoff.

Surface runoff was not measured during high to very high rainfall events due to the physical limitation of the weir. Such volumes should be measured in future studies to quantify flows into the headwaters of the May River during these events.

Longer monitoring periods as well as additional monitoring stations are needed to measure more accurate runoff and rainfall during flood and drought events.

There was little to no stress on water availability in the developed area during the study period. During drier periods, the runoff was significantly less and the evapotranspiration was high, but stored water in the ponds was used to supplement the available effluent for golf course irrigation. Groundwater was available via two groundwater wells in the developed area; however, groundwater was not used during this monitoring period for irrigation.

To control the developed watershed's runoff and mimic the natural runoff, the following can be applied:

Aquifer Storage and recovery (ASR)

Aquifer storage and recovery (ASR) systems involve the injection and storage of potable water into an aquifer and the recovery of this water at a later time, usually to supplement water supplies. Most ASR projects in South Carolina are employed in coastal areas to meet high seasonal demands and to provide emergency supplies as needed. Treated surface water is injected into an aquifer during the off-peak season when demands are low and later recovered by pumping the treated water out of the aquifer to meet peak seasonal demands. Water injected into the aquifer must meet state and federal water-quality standards and ASR wells must be permitted by the S.C. Department of Health and Environmental Control (DHEC) in accordance with the S.C. Underground Injection Control Regulation (R. 61-87).

Currently four water suppliers operate ASR systems in the State: Grand Stand Water and Sewer Authority in Horry County; Mount Pleasant Waterworks in Charleston County; Kiawah Island Utility, Inc. in Charleston County; and Beaufort-Jasper Water and Sewer Authority in Beaufort and Jasper Counties.

The Orangeburg Department of Public Utilities, which uses the North Fork Edisto River as its drinking-water source, is in the process of installing two ASR wells, one in the Black Creek aquifer and the other in the Middendorf aquifer. The primary reason for developing this ASR system is not to have additional capacity during droughts when stream flows are low, but to improve the efficiency of their water treatment operations. During periods of low stream flow, when treatment of water from the North Fork Edisto is least expensive, treated water will be injected into the aquifers; during periods of high stream flow, when treatment of surface water is more expensive, the already-treated water stored underground will be recovered and made available for use with minimal additional treatment.

This suggested application of ASR is very unique in that extra runoff during normal and high flow periods will be harvested, treated and injected in a deep aquifer at the development site. The injection well will be used to supplement water supply demands during water shortages and drought periods. Adding water to the deep aquifers in the Coastal area can significantly help control salt water intrusion into the State's aquifers. State environmental agencies like DNR and DHEC as well as local governments should have a special interest in this application.

Normal Storm Water Management

Storm water ponds should be kept drained at all times to receive the extra runoff during normal and high flow periods. The stored water should be released slowly as non-flood flows downstream. This application controls the peak of the flow downstream and does not reduce the volume of extra runoff.

REFERENCES

Badr, A.W., Wachob A., and Gellici, J.A., 2004, South Carolina Water Plan - Second Edition.

Gils, Ranald V., 1962 *Fluid Mechanics and Hydraulics*, Schaum McGraw-Hill, page 135.

Hamon, W.R., 1963. Computation of Direct Runoff Amounts From Storm Rainfall. Int. Assoc. Sci. Hydrol. Pub. 63:52-62.

APPENDIX A

Weekly Change in Water Levels for

Groundwater Wells and Ponds in the Sun City Watershed

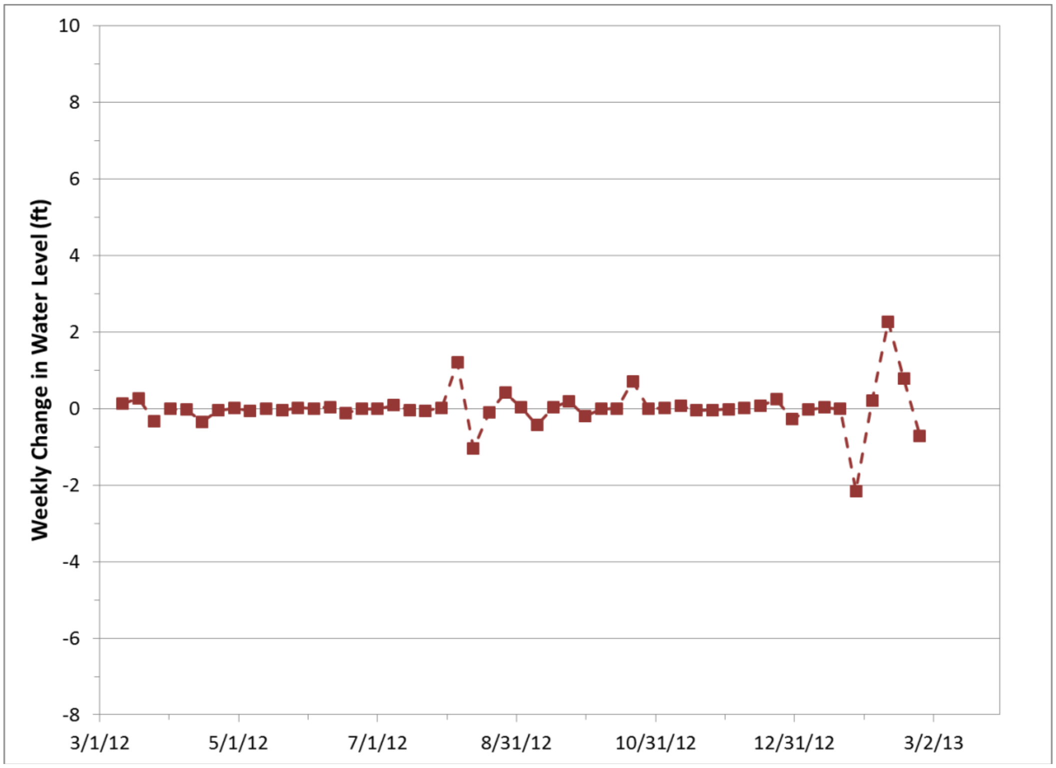

Figure 9. Weekly changes in water level at SCW-1.

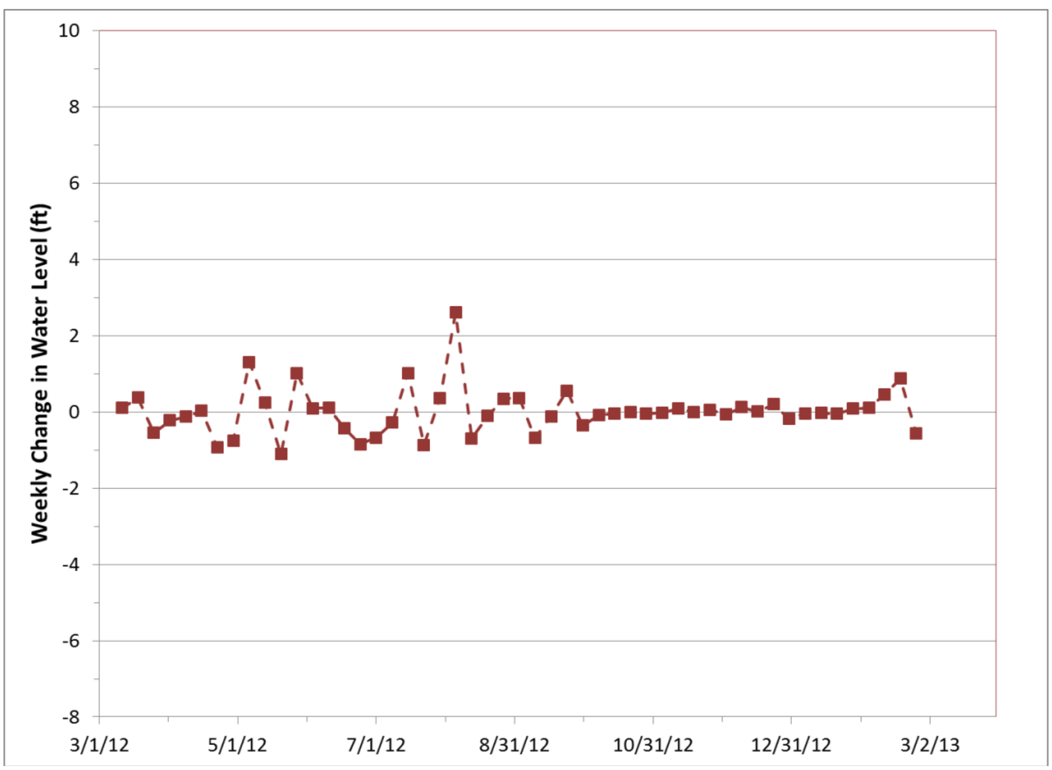

Figure 10. Weekly changes in water level at SCW-2.

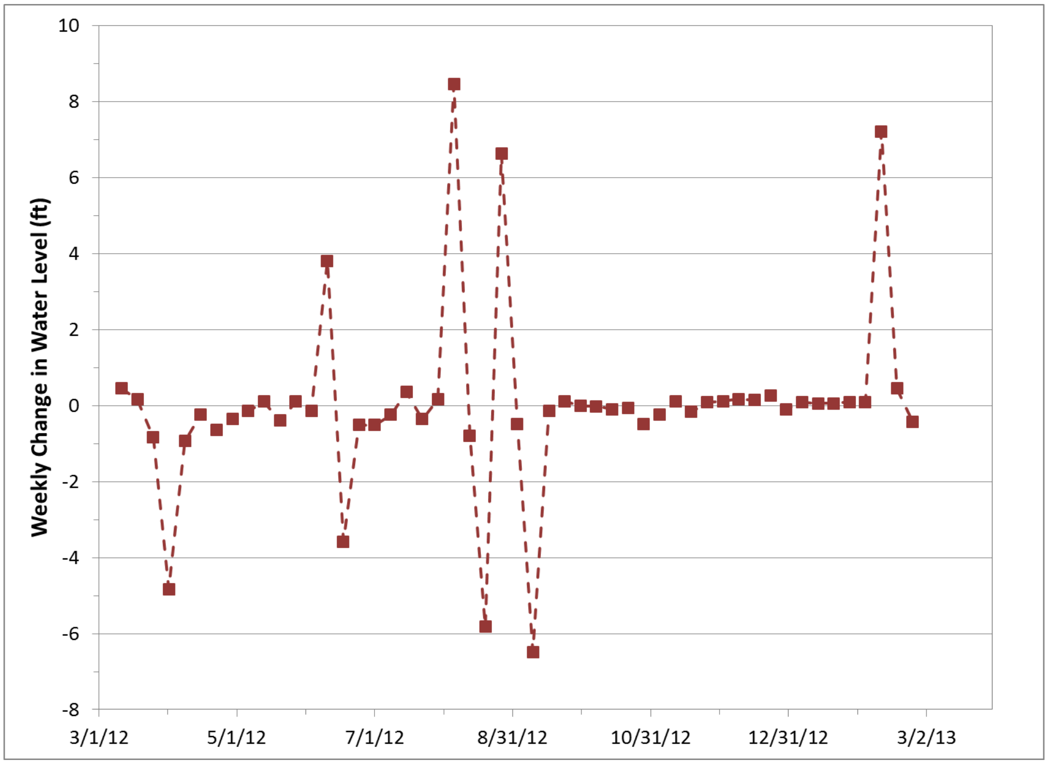

Figure 11. Weekly changes in water level at SCW-3.

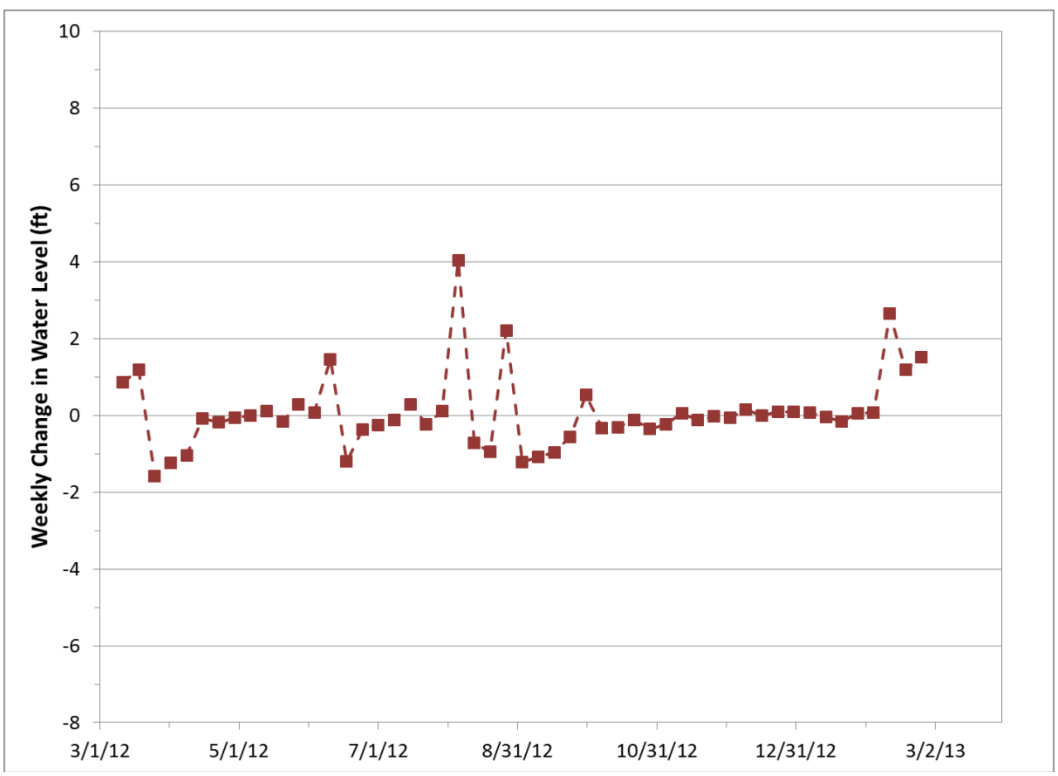

Figure 12. Weekly changes in water level at SCW-4.

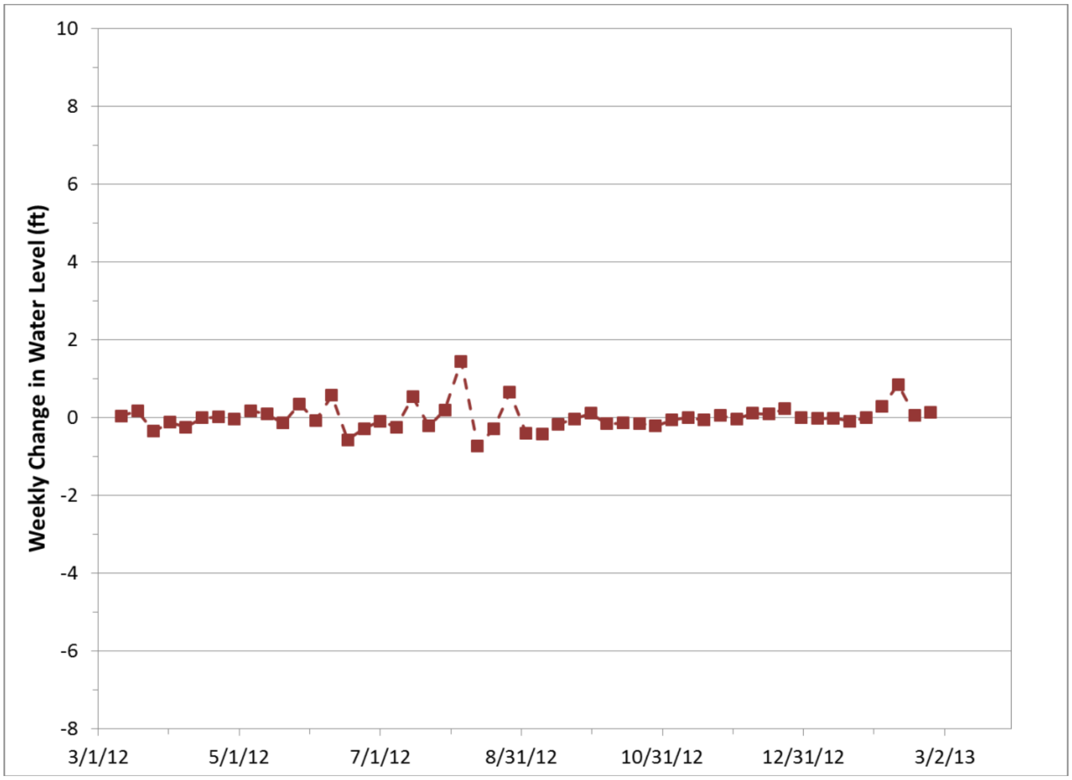

Figure 13. Weekly changes in water level at SCW-5.

APPENDIX B

Outlet Stage and Groundwater-level Elevations

in the Palmetto Bluff Watershed

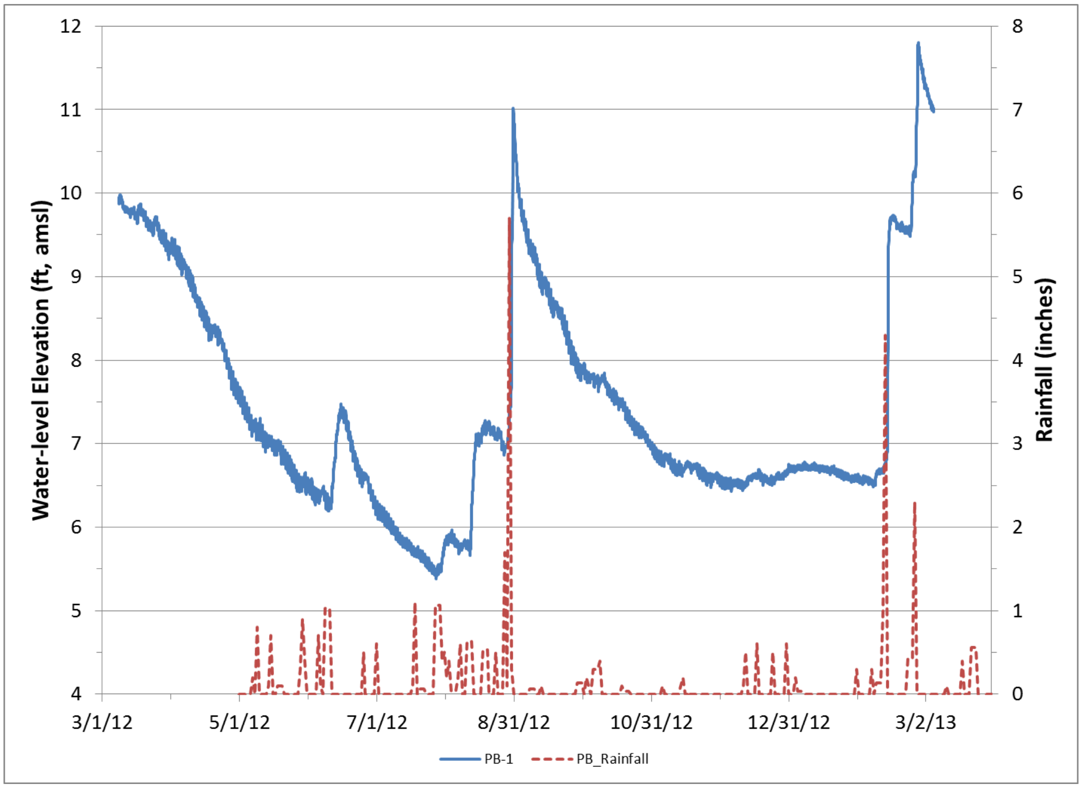

Figure 14. Groundwater-level elevations at PB-1.

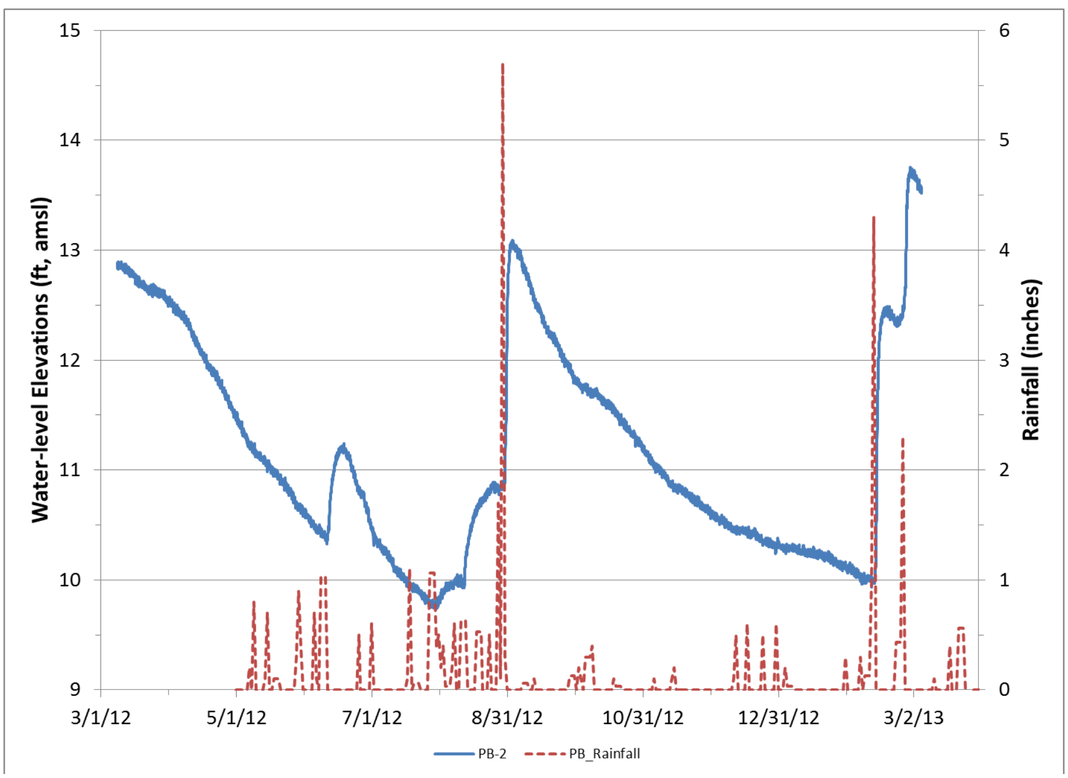

Figure 15. Groundwater-level elevations at PB-2.

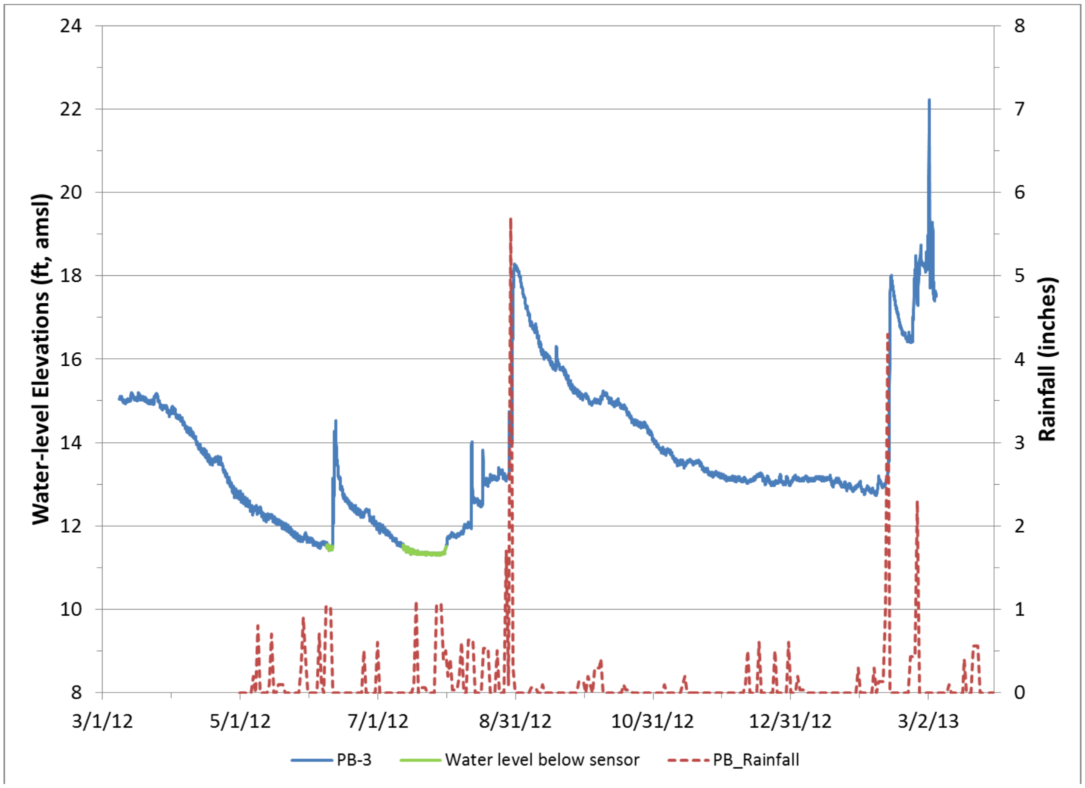

Figure 16. Groundwater-level elevations at PB-3.

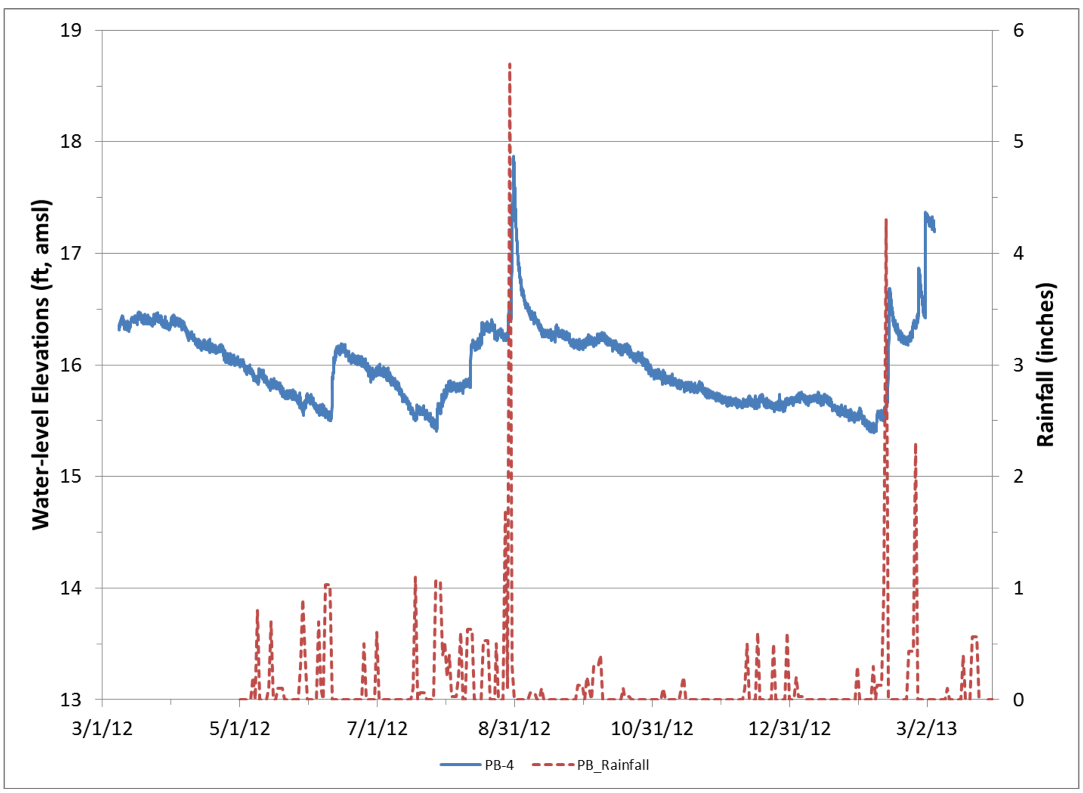

Figure 17. Groundwater-level elevations at PB-4.

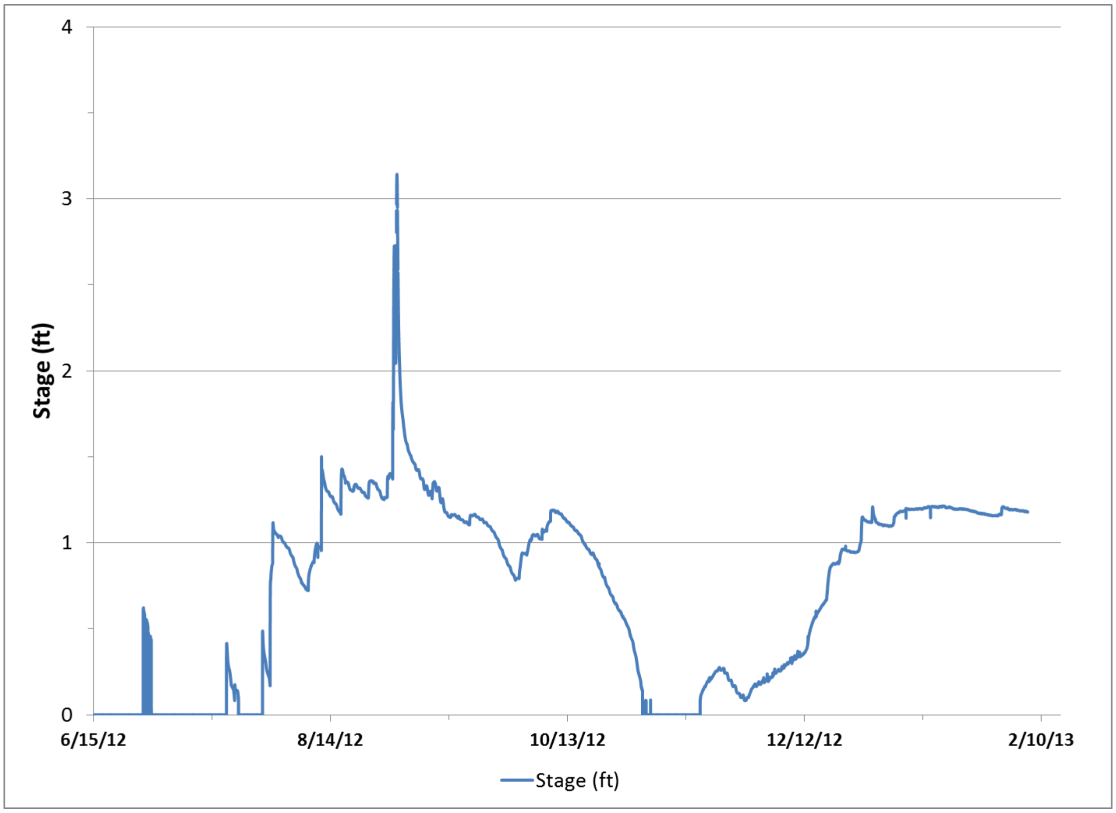

Figure 18. Outlet stage at the Palmetto Bluff watershed.