Groundwater

Groundwater Flow Cycling Between a Submarine Spring and an Inland Fresh Water Spring

by J. Hal Davis[1] and Richard Verdi[2]

Abstract

Spring Creek Springs and Wakulla Springs are large first magnitude springs that derive water from the Upper Floridan Aquifer. The submarine Spring Creek Springs are located in a marine estuary and Wakulla Springs are located 18 km inland. Wakulla Springs has had a consistent increase in flow from the 1930s to the present. This increase is probably due to the rising sea level, which puts additional pressure head on the submarine Spring Creek Springs, reducing its fresh water flow and increasing flows in Wakulla Springs. To improve understanding of the complex relations between these springs, flow and salinity data were collected from June 25, 2007 to June 30, 2010. The flow in Spring Creek Springs was most sensitive to rainfall and salt water intrusion, and the flow in Wakulla Springs was most sensitive to rainfall and the flow in Spring Creek Springs. Flows from the springs were found to be connected, and composed of three repeating phases in a karst spring flow cycle: Phase 1 occurred during low rainfall periods and was characterized by salt water backflow into the Spring Creek Springs caves. The higher density salt water blocked fresh water flow and resulted in a higher equivalent fresh water head in Spring Creek Springs than in Wakulla Springs. The blocked fresh water was diverted to Wakulla Springs, approximately doubling its flow. Phase 2 occurred when heavy rainfall resulted in temporarily high creek flows to nearby sinkholes that purged the salt water from the Spring Creek Springs caves. Phase 3 occurred after streams returned to base flow. The Spring Creek Springs caves retained a lower equivalent fresh water head than Wakulla Springs, causing them to flow large amounts of fresh water while Wakulla Springs flow was reduced by about half.

Introduction

Salt water intrusion in fresh water aquifers has long been recognized as a serious threat to potable water supplies and can occur by several different processes, one of which is the direct flow of sea water into submarine springs during backflow conditions. Submarine springs are common around the world and are usually associated with outcrops of carbonate rocks (Fleury et al. 2007). The Floridan Aquifer system, which is carbonate, underlies parts of Florida, Georgia, Alabama, and South Carolina (Miller 1986), and submarine springs occur in some areas where the aquifer system extends offshore (Bush and Johnston 1988). More than 700 springs discharging water from the Floridan Aquifer system in Florida have been identified, and 33 of these springs are first magnitude (Scott et al. 2004). A first magnitude spring is defined as having an average flow rate of at least 2.83 m^3/s using the classification system of Meinzer (1927). Thirty submarine springs or spring groups have been identified in Florida, most of which are near shore (Scott et al. 2004).

The evolution of the Upper Floridan Aquifer (UFA) has resulted in the development of large conduits that are present both inland and at the present coastline. In the past, large parts of the Florida Platform were exposed to karst formation processes during periods of lowered sea level, resulting in deep conduits that are now part of submarine spring systems (Fleury et al. 2007). The presence of submarine springs and conduits can allow salt water to move inland toward fresh water supplies. However, the investigation of salt water intrusion, which leads to brackish groundwater along the coast, rarely addresses the groundwater flow inside the karst aquifers (Fleury et al. 2007).

Fresh water flows from and sea water intrusion into submarine springs have rarely been quantified due to the difficulty of measurement, leading to a lack of understanding of the interaction of submarine springs with the marine environment. This interaction is affected by the rising sea level, which can increase the pressure head on submarine springs, changing flow patterns and groundwater movement in the aquifer.

The purpose of this study is to describe how the short-term dynamic hydrologic conditions occurring from June 2007 to June 2010 caused the flow in a group of coastal first-magnitude submarine springs to cycle from

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outflowing large quantities of fresh water to backflowing large quantities of sea water. During periods when the submarine springs were outflowing fresh water, another first-magnitude spring located 18 km inland from the coast showed a reduction in outflow of approximately 50%; when the submarine springs were backflowing sea water, the inland spring outflow approximately doubled. A long-term increase in outflow of the inland spring from the 1930s to present can be explained by rising sea level, which caused fresh water outflow to shift from the submarine springs to the inland spring.

Study Area

Spring Creek Springs and Wakulla Springs (Figure 1) are both regional groundwater discharge points in northern Florida with a combined springshed covering about 3000 km^2 (Davis and Katz 2007). Both are first magnitude springs (Rosenau et al. 1977; Scott et al. 2002, 2004) that derive water from the UFA, which is the primary source of potable water supply for Leon and Wakulla Counties, Florida (Water Supply 2008), and other surrounding counties that are upgradient of the springs. The occurrence of the Spring Creek Springs in a tidal estuary facilitated the measurement of sea water intrusion into and fresh water flow out of the UFA. These measurements were possible because flow between the springs and the Gulf of Mexico (Gulf) is funneled through the relatively narrow Spring Creek channel. The following measurements were made: flow rate and salinity in Spring Creek, flow rate in the Wakulla River, and flow rate in Lost Creek—a small creek that flows into Lost Creek Sink and is a source of water to both springs.

Spring Creek Springs

Spring Creek Springs consists of 14 individual springs in the tidally affected Spring Creek (Rosenau et al. 1977); however, Rosenau et al. (1977) reported the location of only eight of the springs and the present study was able to verify the location of only springs no. 1 to no. 11 (Figure 1). The location of springs no. 12 and no. 13 could not be determined, but they are reported to occur seaward of the U.S. Geological Survey (USGS) Spring Creek gauge (Lane 2001). Only two flow measurements of Spring Creek Springs were reported prior to 2002 (Scott et al. 2002, 2004): 56.6 m^3/s, measured on May 30, 1974 (Rosenau et al. 1977), and 8.69 m^3/s, measured on November 1, 1991 (Davis 1996). So the flow from these springs was poorly characterized.

Spring Creek Springs is a type 2 submarine spring (Fleury et al. 2007). Type 2 submarine springs are characterized by (1) a well-developed extensive karstic network joined by deep vertical conduits; (2) conduits that are large compared to the volume of fresh water being conveyed resulting in a hydraulic head that is often too weak to prevent sea water from entering; (3) well-developed internal conduit networks that drain vast recharge areas and have large storage capacities; and (4) springs that have high mean groundwater discharge rates with strong seasonal variability; the salinity of the water is often low during high flow, but rises as the flow rate decreases.

Spring Creek, wherein the Spring Creek Springs occur, is relatively short, extending only about 3.2 km inland from the Gulf. The stage in Spring Creek rises and falls with the tides and there is little or no inflow of water occurring at the headwaters. During a typical tidal cycle, the rising tide causes sea water to flow upstream in Spring Creek. During the higher part of the high tide, water commonly backflows through the spring caves and into the UFA; this is especially common during periods of low rainfall. At times, whirlpools can be observed above the spring vents due to backflows. All the Spring Creek Springs have been observed to occasionally reverse flow at high tide (Lane 2001; Scott et al. 2004). During lower tidal stages, water typically flows out of the UFA and into Spring Creek. During some high rainfall periods (when aquifer water levels are high) Spring Creek Springs may discharge fresh water during entire tidal cycles. Dimova et al. (2011) found that the discharge of the Spring Creek Springs responded very quickly to large rainfall events, requiring only 1 or 2 d for the salinity to decrease from 27 to 2 ppm in one case.

Several of the caves at Spring Creek Springs have been explored and described by Kincaid and Werner (2008). They described the cave associated with Spring Creek Spring 1 (Figure 1) as trending approximately 45 m to the north of the spring vent, where it reached a depth of about 50 m below water surface (bws) and was observed to continue trending deeper. This vent was the largest of the conduits explored, and measured approximately 15 m in diameter. The cave associated with Spring Creek Spring 2 was the longest of the surveyed caves (more than 300 m in length) and trended to the southwest at an average depth of 45 m bws. The cave associated with the Spring Creek Spring 10 was mapped for approximately 230 m, and it trended to the west-northwest where it connected to the cave associated with Spring Creek Spring 8; these two caves averaged between 4.5 and 9 m in diameter.

Wakulla Springs

Wakulla Springs is located about 23 river km upstream from the Gulf (Figure 1) and is the headwaters of the Wakulla River; the straight line distance to the Gulf is 18 km. Almost all of the flow in the river comes from a single large spring vent (Rosenau et al. 1977). Wakulla Springs does not reverse flow and sea water does not move upstream in the Wakulla River to the spring. Groundwater travels to Wakulla Springs through an extensive submerged cave system (Loper et al. 2005). The Wakulla Springs cave system was first extensively explored by cave divers in the late 1980s, and the caves were penetrated to a distance of several hundred meters (Stone 1989). The Wakulla Springs cave has a depth of about 60 m bws near the origin, and depths throughout the cave generally range between 75 and 90 m, with some depths as great as 110 m (Stone 1989). More than 50 km of submerged conduits that connect to at least 27 named sinkholes and to Wakulla Springs have been mapped

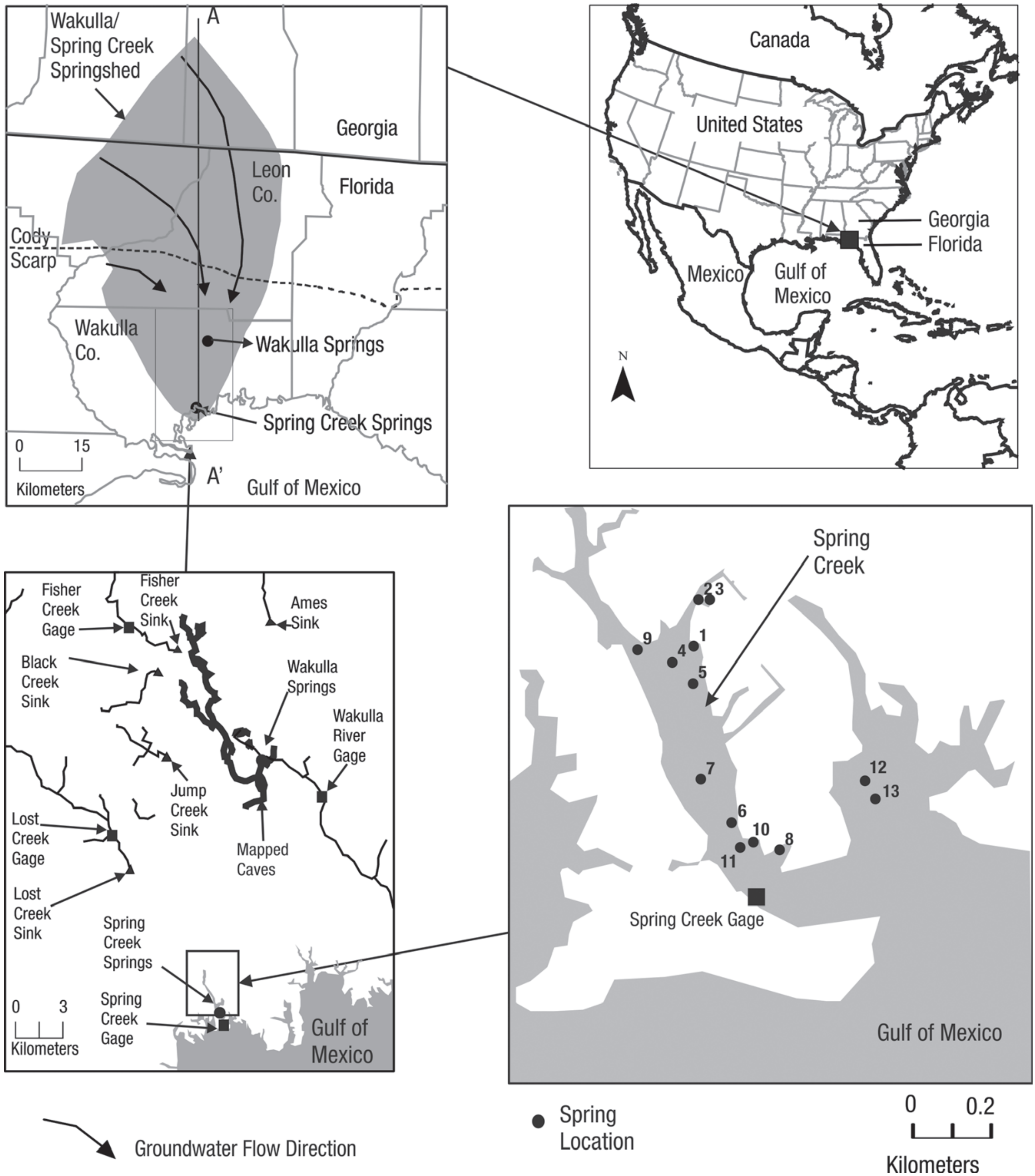

Figure 1. Location of study area, Spring Creek Springs, Wakulla Springs, and Lost Creek Sink (cross section A-A′ shown in Figure 3).

(Woodville Karst Plain Project 2012); it is the longest mapped underwater cave system in the United States and the fourth longest mapped underwater cave system in the world (Kincaid and Werner 2008).

The flow at Wakulla Springs has had a long-term increase between 1929 and 2010 (Figure 2) based on intermittent measurements from 1929 through 2003 and continuous gauging from October 2004 through October 2010, and October 2011 to present. The increased flow does not appear to have resulted from increased head in the aquifer because no long-term changes in the potentiometric surface have been observed in the UFA in the Wakulla/Spring Creek springshed (Bush and Johnston 1988; Davis and Katz 2007). Davis and Katz (2007) suggested two possible reasons for the long-term increase in flow: (1) a small rise in sea level along the Gulf

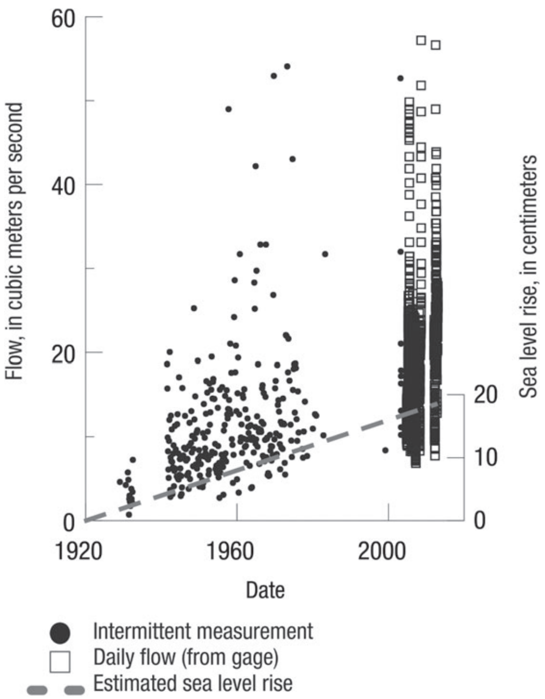

Figure 2. Flow from Wakulla Springs from 1930 to 2010 and estimated sea level rise from 1920 to 2020.

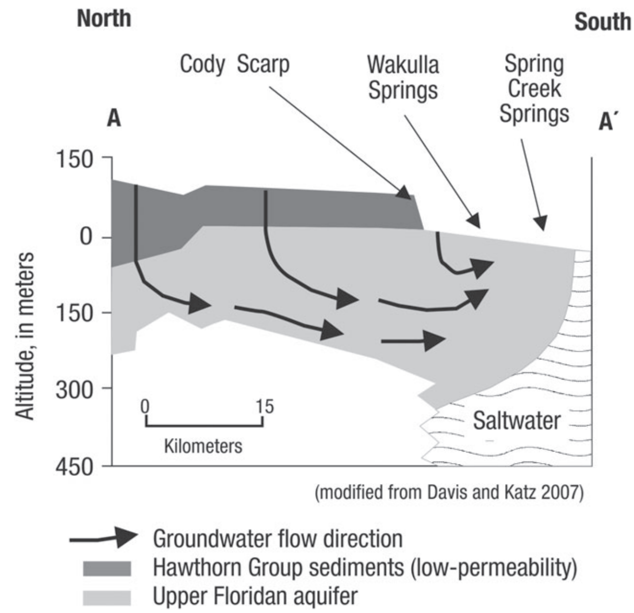

Figure 3. Generalized cross section through Upper Floridan aquifer (location shown in Figure 1).

coast of Florida from 1932 to 2007 may have contributed additional head on the Spring Creek Springs causing a reduction in flow and a corresponding increase in Wakulla Springs flow; or (2) the evolution of the submerged cave passages at Wakulla Springs may have allowed for greater groundwater capture in the same way that one river can capture flow from another river through erosional processes.

Hydrology of the UFA

The ultimate source of water to the UFA in the study area is from precipitation, which recharges the aquifer through three different processes. The first process occurs in the area north of the Cody Scarp where the UFA is overlain by the low-permeability Hawthorn Group sediments (Figures 1 and 3). Davis and Katz (2007) estimated that the recharge rate in this area ranged from about 2.5 to 20.3 cm/year with the highest recharge rates occurring where the Hawthorn Group sediments were thin or breached.

The second recharge process occurs south of the Cody Scarp, where the UFA is covered by a thin veneer of sands, silts, and clays, and the land surface topography consists mostly of closed basins with extensive sinkhole development typical of karst terrains. Precipitation can move rapidly through the overlying sediments and into the UFA. Davis and Katz (2007) estimated that the recharge rate in this area was about 46 cm/year; the estimated travel time of water through these sediments to the UFA is hours to weeks.

The third recharge process is from streams discharging directly into sinkholes (also referred to as sinks; Figure 1). The five largest streams are (1) Fisher Creek, discharging into Fisher Creek Sink; (2) Munson Slough, discharging into Ames Sink; (3) Lost Creek, discharging into Lost Creek Sink; (4) the relatively small Jump Creek, discharging into Jump Creek Sink; and (5) Black Creek, discharging into Black Creek Sink. Surface water flow in these five streams is highly variable: flows peak shortly after heavy rainfall events, base flow is low, and most cease flowing entirely during dry periods.

Groundwater flow velocity measurements indicate that groundwater can move rapidly for long distances. Dyes injected into Fisher Creek Sink (straight line distance to Wakulla Spring is 9.2 km) and Ames Sink (straight line distance is 9.0 km) were detected in Wakulla Springs at periods ranging from 10 to 21 d (Kincaid and Werner 2008). Dye also was injected into Lost Creek Sink and was detected at Spring Creek Spring 10 after less than 7 d; the same dye was also detected later at Wakulla Springs (Kincaid and Werner 2008). Based on these results, Kincaid and Werner (2008) speculated that the Wakulla Springs cave system must extend and connect to the Spring Creek Springs cave system.

Sea Level Rise

The location of Spring Creek Springs in a tidally affected zone makes these springs particularly sensitive to rises in sea level. Zervas (2001) examined tidal data collected on the west coast of Florida and determined that mean sea level was rising at the following locations and rates: Key West at 2.27 mm/year (from 1913 to 1999); St. Petersburg at 2.40 mm/year (1947 to 1999); Clearwater Beach at 2.76 mm/year (1973 to 1999); Cedar Key at 1.87 mm/year (1914 to 1999); Apalachicola at 1.53 mm/year (1967 to 1999); Panama City at 0.30 mm/year (1973 to 1999); and Pensacola at

2.14 mm/year (1923 to 1999). Douglas (1991) also examined the tidal data at Key West and determined an annual increase of 2.3 mm/year (1930 to 1980). The average rate for these sites is 1.95 mm/year; the rates were averaged to help remove any bias that may occur at an individual site. For the period 1930 to 2010, this would correspond to a cumulative sea level rise of 15.5 cm (Figure 2).

Data Collection

The goal of the data collection effort was to collect continuous flow and water-quality measurements in Spring Creek and Wakulla River (gage locations shown on Figure 1). A data collection platform was maintained on Spring Creek from June 2007 through June 2010 and used to collect (1) water velocity across the Spring Creek channel; (2) tidal stage; (3) water temperature; (4) specific conductance; (5) wind speed; (6) wind direction; and (7) precipitation. Data were collected at 15-min intervals. Water velocity was measured using an ultrasonic (or Doppler) type flow meter whereby an ultrasonic beam is transmitted across the channel and water velocity is calculated from the transit return time. As a check, approximately every 6 weeks, the water velocity was measured using a boat moving across the channel equipped with an ultrasonic type flow meter. In Spring Creek, the direction of flow can be outward toward the Gulf or landward toward the springs, depending on the tide; the variable direction of flow required the development of an index-velocity rating and a stage-area rating to accurately compute direction and magnitude of flows. Flow was computed by multiplying the velocity in the cross section by the area of the submerged channel at the cross section. The quality of the flow data ranged from good (less than ±5% of the true value) to poor (greater than ±15%), with most measurements in the fair (±8%) range.

The specific conductance measurement was converted to a salinity value by placing the conductance probe into solutions of known salinity during routine servicing of the gauge. The specific conductance was measured across the channel using a handheld conductance meter before the gage was installed and sporadically after for the duration of the study. The water conductance was vertically uniform, most likely because (1) the bay leading to Spring Creek is shallow, reducing the likelihood of salinity stratification; and (2) Spring Creek is shallow (generally <2 m) and has a rocky limestone bottom, increasing the likelihood of turbulent flow in the channel. The vertical salinity distribution was not measured routinely, and stratification could have occurred.

The USGS has maintained a stream gage on the Wakulla River from October 2004 through October 2010 and October 2011 to present. The Wakulla River gage was located about 4.8 river km downstream from the spring or about 18 river km upstream from the Gulf. Almost all the flow at the gage is from Wakulla Springs, with only a few smaller springs adding negligible flow. Although located about 18 km inland from the coast, the Wakulla River exhibits some tidal fluctuations and required the use of a velocity meter to develop an index-velocity rating. Prior to the installation of this gage, the Wakulla River flow had only been measured intermittently since the 1930s (Figure 2).

The USGS maintained a stream gage on Lost Creek (Figure 1) from October 1998 to September 2005, and from January 2007 to July 2010; stage data were collected at 15-min intervals. The computation of flow at Lost Creek required a typical stage-flow logarithmic relation whereby an increase in stage equaled an increase in flow. Prior to the installation of the stream gage, Lost Creek flow had only been measured intermittently since 1928.

Spring Creek Springs Fresh Water and Salt Water Flow

The tidal stage at the Spring Creek gage typically ranged from about -0.6 to $+0.6$ m (North American Vertical Datum of 1988, NAVD88). Flow moving upstream from the Gulf toward the springs is referred to herein as negative flow and flow moving out toward the Gulf is referred to herein as positive flow; an instantaneous measurement is defined as a single value determined at the gage at a 15-min interval. A typical tidal cycle follows this progression: (1) at the lowest point of the low tide the flow in Spring Creek is near zero as the tide shifts from falling to rising; (2) as the tide rises, sea water flows from the Gulf and reaches a peak negative flow just before the maximum high tide; and (3) as the tide falls, the flow upstream in the creek decreases and eventually stops, whereupon the creek resumes flowing downstream to the Gulf.

The analysis of instantaneous 15-min flow data involved calculating a net average flow during a period of two tidal cycles. This period was chosen because it lasted approximately 1 d and was considered the minimum period in which a useful net flow could be determined. For each individual two-tidal-cycle period, all of the flows were summed to give a total flow. These sums always consisted of both positive and negative flows; if the summation was a positive number then there was net outflow to the Gulf, and if it was negative then there was a net inflow to the UFA. All reported flow values were rounded to the nearest whole number.

The instantaneous flow measurements were summed using the following method. Each summation always began at a mean tide height of 0.0 on a rising tide and ended on the falling tide at 0.0 m. The tide height of 0.0 was used as the beginning and ending point so that the volume of surface water in the creek channel would be the same; thus, the net average flow calculated would be limited to water that flowed from (or backflowed into) the UFA through the springs. In some cases, the tide height did not cross the 0.0 tide mark at the end of the second tidal cycle; for these cases, the summation was extended to include the next two-tidal-cycles. In some rare cases it was necessary to sum during three or more two-tide-cycle periods before the tide height recrossed the 0.0 tide height mark.

The UFA near Spring Creek Springs, Spring Creek Springs caves, Spring Creek, and the estuary can be viewed as a mixing zone where water from the UFA comes into contact with the sea water from the Gulf. Consequently, the water in Spring Creek ranged from nearly pure sea water when the springs were backflowing, to nearly pure fresh water during high fresh water outflow (Figure 4a). To improve understanding of the data, these flows were subdivided into fresh water and salt water components using the salinity and the assumption that the water in Spring Creek is a simple mixture of sea water and fresh water. The salinity ranged from less than 2 ppt to about 35 ppt. Thirty-five parts per thousand is the expected value for sea water (Zhen-Gang 2008). For example, an instantaneous flow measurement of 10 m^3/s with a salinity of 26.25 ppt (26.25 ppt/35 ppt = 0.75 or 75% salt water and 25% fresh water) was interpreted to indicate that the flow is a mixture of 7.5 m^3/s salt water and 2.5 m^3/s fresh water. The calculated salt water and fresh water flows were summed using the same two-tidal-cycle method as previously discussed. The flow of fresh water from Spring Creek Springs is highly variable, ranging from near zero (or slightly negative at times) to large outflows (Figure 4f). The flow of salt water is less variable and of lower magnitude and shifts also from inflows to outflows (Figure 4e).

Conceptual Model

The data collected in this study were used to develop a conceptual model to explain the cycling of fresh water and salt water flows in Spring Creek Springs, and to explain how this cycling causes changes in Wakulla Springs. The flow from Spring Creek and Wakulla Springs are connected in a repeating karst spring flow cycle that is composed of three distinct phases.

Phase 1 of the conceptual flow model occurs during an extended period of low rainfall that persists for several weeks or more. The key characteristic of this phase is that surface water flow into local sinkholes decreases to base flow conditions. The reduced recharge allows sea water to move upstream in Spring Creek and backflow into the springs, thus filling the caves with salt water and blocking fresh water outflow (Figure 5a). Once the caves are filled with salt water, the density difference between fresh water and salt water becomes an important mechanism in preventing fresh water flow from resuming. With the fresh water flow blocked, groundwater levels in the UFA around Spring Creek rise. For the salt water to be pushed out of the caves, the fresh water head in the UFA must exceed the equivalent fresh water head in the caves. If it is assumed that the Spring Creek Springs caves are 90 m deep and filled with pure salt water, then the head in the UFA would need to exceed 2.3 m to allow fresh water flow to resume (the actual maximum depth of the Spring Creek caves is unknown but for this calculation it was assumed that they were similar to the Wakulla caves). As the groundwater levels rise, the flow in Wakulla Springs increases so that groundwater that had been going to Spring Creek Springs is now intercepted by Wakulla Springs. Because Wakulla Springs has a pool elevation of about 1.5 m and the UFA is very transmissive, the groundwater levels are prevented from reaching a height 2.3 m and cannot push the salt water out of the Spring Creek Springs caves. Under these conditions, Wakulla Springs will discharge at rates near the higher end of its range and Spring Creek Springs will have no fresh water discharge. This set of phase 1 conditions can persist for a period of weeks to months and will change only when a period of high rainfall occurs.

A high rainfall period marks the end of phase 1 and the beginning of phase 2 (Figure 5b). A large rainfall event generates runoff to Lost Creek, which in turn, causes the stage and flows into Lost Creek Sink to rise. Similar conditions would also occur at Fisher, Black, Jump, and Ames Sinks. The influx of fresh surface water and associated head rise at the sinks is sufficient to push the salt water out of the Spring Creek Springs caves and cause fresh water flow to begin. The flow from Spring Creek Springs is a mixture of fresh water and salt water; however, during these high-flow periods the majority of the mixture will be fresh water (after the initial saltwater in the caves has been flushed out). The blockage of fresh water flow by salt water in Spring Creek Springs caves during phase 1 had caused groundwater levels around the springs to rise. When the salt water is pushed out and replaced with fresh water, the equivalent fresh water head at the springs decreases from about 2.3 m to sea level. The decrease in fresh water head creates a sharp gradient between the head in the caves and the head in the surrounding UFA, resulting in additional groundwater flow into the caves. Thus the groundwater flowing from Spring Creek Springs is a combination of the flow due to recharge into Lost Creek Sink and flow from storage in the UFA. Phase 2 of the cycle usually lasts only a few weeks, but can be extended by additional rainfall.

A period of little or no rainfall marks the end of phase 2 and the initiation of phase 3 (Figure 5c). Lost Creek and other streams return to base flow conditions. During phase 3, the Spring Creek Springs caves continue to discharge large quantities of fresh water, and the equivalent fresh water head is still at or near the actual spring pool elevation. While conditions remain dry, the amount of flow in Spring Creek that originated as surface water flow into Lost Creek Sink decreases rapidly. At this point, most of the flow in Spring Creek Springs (and Wakulla Springs) is derived from a reduction in storage in the UFA, which in turn causes groundwater levels to decrease. The Spring Creek Springs caves typically will contain mostly fresh water and the equivalent fresh water head is roughly equal to the tidal stage, whereas Wakulla Springs has a pool elevation of about 1.5 m, and a large part of the groundwater flow is captured by Spring Creek Springs. The groundwater levels will slowly decrease as storage in the UFA is reduced due to spring flows. Phase 3 conditions can last for months. As dry conditions return and persist, the lower water levels in the UFA make it susceptible to saltwater intrusion. Eventually, sea water will move upstream in Spring Creek in sufficient quantities to reenter the cave system, marking the end of phase 3 and the beginning of phase 1.

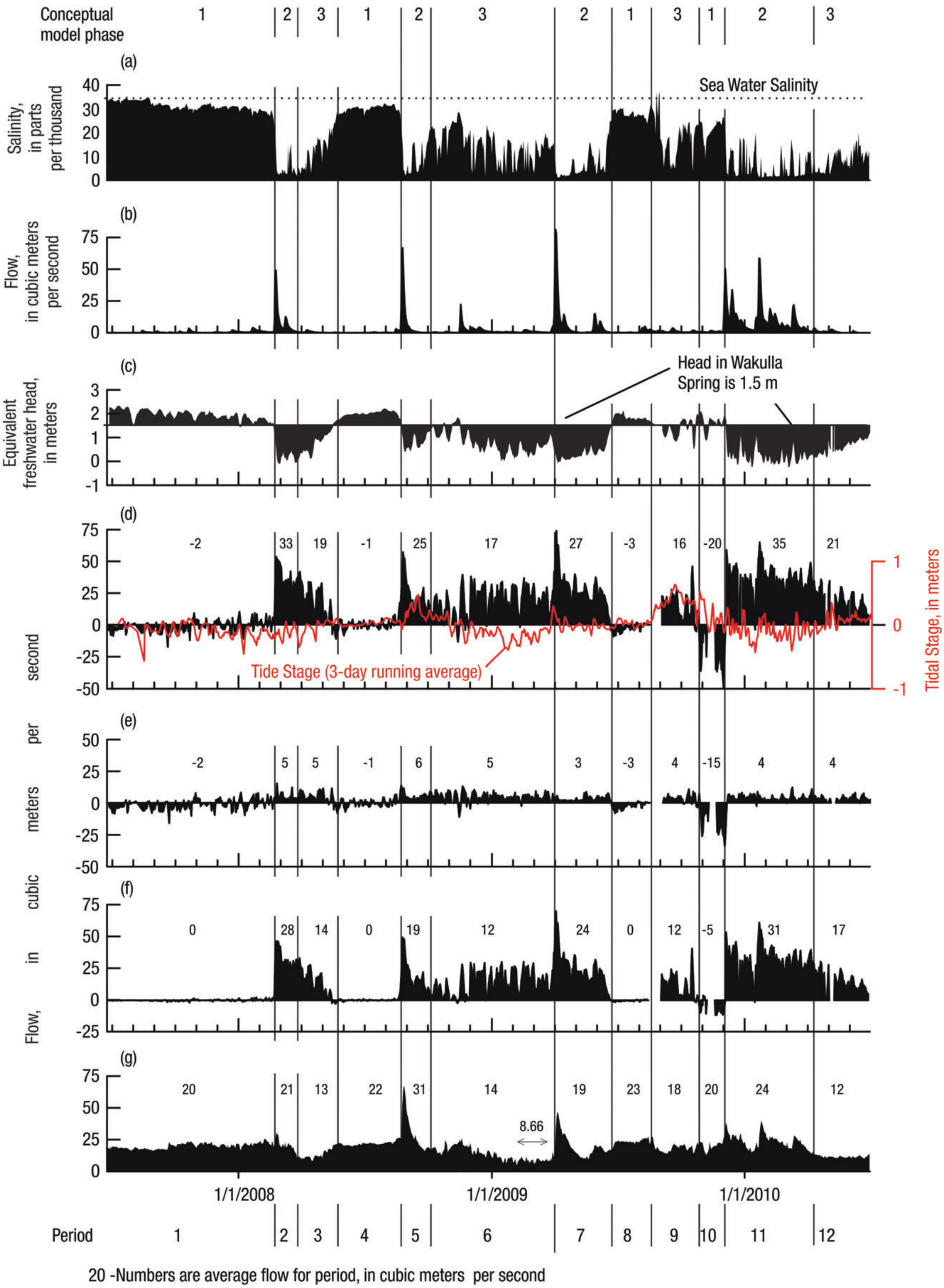

Figure 4. Spring Creek salinity (a), Lost Creek flow (b), equivalent fresh water head in Spring Creek Springs caves (assumes caves are 90 m deep) (c), Spring Creek total flow and tidal stage (includes both fresh and salt water components) (d), Spring Creek salt water flow (calculated) (e), Spring Creek fresh water flow (calculated) (f), and Wakulla Springs flow (g).

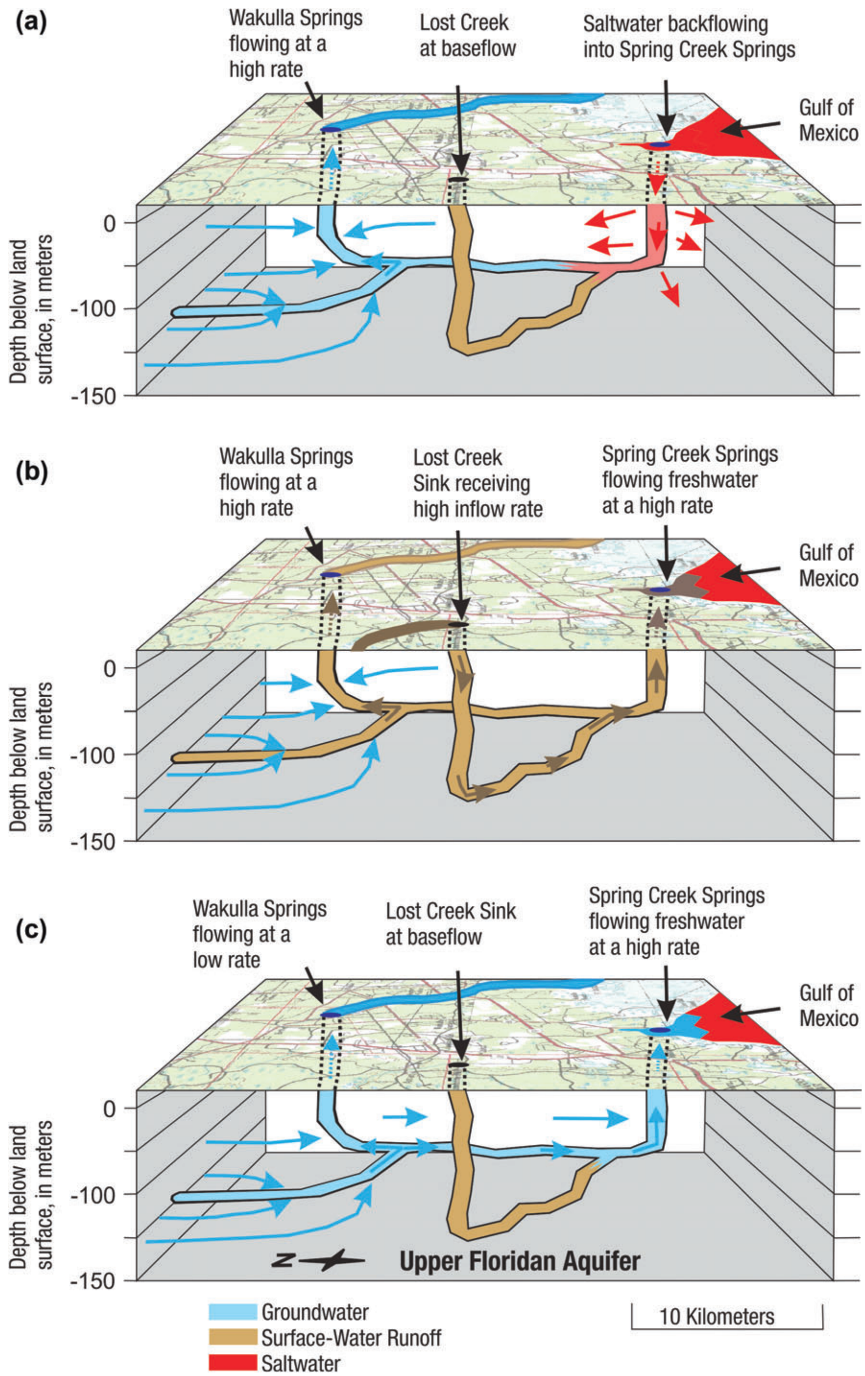

Figure 5. Conceptual model of groundwater flow. (a) Phase 1: Sea water backflow; (b) Phase 2: Surface water inflow; (c) Phase 3: Groundwater outflow.

Data Interpretation

The Spring Creek Springs flows were classified into 12 periods; in each period the hydrologic conditions were relatively stable and a new period began when the conditions changed (Figure 4 and Table 1). The prevailing conditions for each period are discussed in the following sections.

Salinity in Spring Creek Springs

A key component of the conceptual model is the salinity variation in Spring Creek Springs. High salinity periods, which persist for months, rapidly transit into low salinity periods, and last for months. The transitions from high to low salinity were caused by large rainfall events, which resulted in high creek flows and thus high recharge rates into sinkholes. Sudden decreases in salinity occurred at the transitions from periods 1 to 2, 4 to 5, 6 to 7, and 10 to 11 (Figure 4a and 4b). In each of these examples a high flow rate into Lost Creek Sink resulted in the salinity in Spring Creek decreasing from near sea water concentrations of 35 ppt to nearer fresh water concentrations of 2 to 4 ppt.

Table 1
Classification of Flow Periods and Average Flow Rates

Flow Period	Start Date	End Date	Spring Creek Total Flow (m^3/s)	Spring Creek Fresh Water Flow (m^3/s)	Spring Creek Salt Water Flow (m^3/s)	Percent Fresh Water	Percent Salt Water	Flow in Wakulla Springs (m^3/s)	Conceptual Model Phase
1	6/25/2007	2/19/2008	−2	0	−2	0	100	20	1
2	2/20/2008	3/25/2008	33	28	5	85	15	21	2
3	3/26/2008	5/19/2008	19	14	5	74	26	13	3
4	5/20/2008	8/19/2008	−1	0	−1	0	100	22	1
5	8/20/2008	9/30/2008	25	19	6	76	24	31	2
6	10/1/2008	3/26/2009	17	12	5	71	29	14	3
7	3/27/2009	6/21/2009	27	24	3	89	11	19	2
8	6/22/2009	8/26/2009	−3	0	−3	0	100	23	1
9	8/27/2009	10/23/2009	16	12	4	75	25	18	3
10	10/24/2009	12/2/2009	−20	−5	−15	25	75	20	1
11	12/3/2009	4/6/2010	35	31	4	89	11	24	2
12	4/7/2010	6/30/2010	21	17	4	81	19	12	3
Average flow rate during study[1]			14	12	2			19	
Average flow rate for conceptual model phase									
Phase 1 (periods 1, 4, 8, 10)			−6	−1	−5			21	
Phase 2 (periods 2, 5, 7, 11)			30	26	4			24	
Phase 3 (periods 3, 6, 9, 12)			18	14	4			14	

[1] Average flows for the entire study period may be different than averaging the period flows because the individual periods are of different lengths.

Effect of Water Density on Spring Flows

Spring Creek and Wakulla Springs are located about 17 km apart and they compete for groundwater. In this competition, the potentiometric head of the springs is important because the lower the head the greater the groundwater gradient toward an individual spring. The head at Wakulla Springs is consistently about 1.5 m and emits only fresh water. For Spring Creek Springs, the head determination is more variable and complicated. The spring pool elevation is equal to the tide height. If the Spring Creek Springs caves contained only fresh water, then the head would also be equal to the tide height. However, if the Spring Creek Springs caves are filled with higher density salt water, a direct head comparison with Wakulla Springs is misleading. To provide a valid head comparison, an equivalent fresh water head must be calculated for Spring Creek Springs. The equivalent fresh water head was calculated using the Ghyben-Herzberg equation:

$$z = \frac{\rho_f}{\rho_s - \rho_f}\ h_f$$

where z is the height of the vertical column of salt water, ρ_f the density of fresh water, ρ_s the density of salt water, h_f the height the fresh water will rise above the top of the salt water in a static condition. The equation was solved for h_f and applied using the following conditions: (1) the Spring Creek Caves were assumed to be 90 m deep (z); (2) ρ_s was the density calculated from the measured salinity; and (3) h_f was added to the tide height to give the equivalent fresh water head. Using this method, the equivalent fresh water head would be 2.3 m if the caves were filled with pure sea water (and assuming the tide height is 0). The equivalent fresh water head would be proportionally less if the caves were filled with a mixture of fresh water and sea water; for example, if the mixture were 50-50 then the equivalent fresh water head would be 2.3 m/(2) which equals 1.15 m. When the salinity levels are high, the equivalent fresh water head in Spring Creek Springs exceeds the head in Wakulla Springs (Figure 4c), a condition that occurred in periods 1, 4, and 8. Spring Creek Springs had no fresh water outflow during these periods. When the salinity was low, the equivalent fresh water head in Spring Creek Springs was lower than the head in Wakulla Springs, which occurred during periods 2, 3, 5, 6, 7, 11, and 12. During these periods Spring Creek Springs discharged large volumes of fresh water. In periods 9 and 10 the equivalent fresh water head remained similar to the head in Wakulla Springs.

Comparison of Spring Flows

The average fresh water flows for Wakulla Springs and Spring Creek Springs for the period of data collection were 19 and 12 m^3/s, respectively. During phase 1 conditions of the conceptual model (periods 1, 4, 8 and 10; Figure 4 and Table 1) Wakulla Springs flow averaged 21 m^3/s and Spring Creek Springs fresh water flow averaged -1 m^3/s. The flow in Wakulla Springs is derived from recharge that occurred throughout the springshed during periods 1, 4, 8, and 10, corresponding to low periods of rainfall and streams experienced base flow conditions or were dry. During phase 2 conditions (periods 2, 5, 7, and 11), the average Wakulla Springs flow increased to 24 m^3/s and Spring Creek Springs fresh water flow increased to 26 m^3/s. These four periods are relatively short and occur when stream flows into sinkholes are highest due to heavy rainfall. During phase 3 conditions (periods 3, 6, 9, and 12) the average flows in Wakulla Springs and Spring Creek Springs are 14 m^3/s, and streams are once again at base flow conditions or dry.

Discussions and Conclusions

The submarine Spring Creek Springs fresh water flow rate is sensitive to rainfall. During dry conditions, which prevail during phase 1 of the conceptual model, the springs cease to flow fresh water because salt water flows into the Spring Creek Springs caves completely blocking fresh water flow. This pattern occurred four times during the period June 2007 to June 2010, and during these times Wakulla Springs flow averaged 21 m^3/s. During heavy rainfall periods, in phase 2 of the conceptual model, both springs discharged fresh water at their highest average rates (26 m^3/s and 24 m^3/s for Spring Creek Springs and Wakulla Springs, respectively). The high discharge rates were partially due to nearby streams flowing into sinkholes. After streams returned to base flow or became dry, in phase 3 of the conceptual model, fresh water flow at Spring Creek Springs continued at an average rate of 14 m^3/s for weeks to months, and Wakulla Springs flow diminished to its lowest average rate of 14 m^3/s. Wakulla Springs flow is also sensitive to rainfall and to the fresh water flow rate in Spring Creek Springs.

A long-term increase in Wakulla Springs flow from 1930 to present has occurred. The increase in flow is probably a consequence of an estimated 15.5-cm rise in sea level (Figure 2) and the sensitivity of Spring Creek and Wakulla Springs to sea level changes. In the past, when sea level was lower, sea water intrusion into the Spring Creek Springs likely would have occurred less frequently and shorter in duration, resulting in more fresh water flow from Spring Creek Springs and lower flows from Wakulla Springs.

Inland spring flows are easier to measure than submarine spring flows, which are often difficult, expensive, and sometimes impossible to measure. For Wakulla Springs, prior to the data collected for this study, the flow had been intermittingly measured 304 times from 1928 to 2003, and continuously monitored after that; Spring Creek Springs flow had been measured only twice. The quantification of groundwater flow that focuses primarily on inland spring flows could lead to errors if submarine spring flows are not carefully considered in the analysis.

There was a net 2 m^3/s salt water flow from Spring Creek Springs during the period of data collection. If the intrusion of sea water represented the only source of the salt water within the aquifer, net salt water flow would be zero. Three possible explanations for the higher than expected net salt water outflow are (1) the data collection period was simply too short to represent all important conditions; (2) the aquifer is still purging salt water that was trapped during deposition or entered in earlier times; (3) there was a systemic error in the salt balance. The highest backflow rate of sea water occurred during period 10 when it averaged a negative 15 m^3/s. This flow rate occurred during and was probably caused by unusually high tides (Figure 4d). If this interpretation is correct then it indicates just how sensitive Spring Creek Springs flow is to sea level.

The accuracy of the flow data is difficult to access. Most of the data were classified as fair, indicating that measured values should be within $\pm 8\%$ of the actual values. Data were collected every 15 min and averaged during two-tidal-cycles. If measurement error was random then the averaging should improve the accuracy, but averaging would not improve accuracy if errors are systemic.

The equivalent fresh water head in Spring Creek Springs was calculated using the Ghyben-Herzberg equation which assumes static conditions. Since there was flow in the Spring Creek Springs caves, static conditions did not occur. How much error this assumption introduced into the calculations is difficult to determine. If the caves reach an assumed depth of 90 m relatively close to their origin then the error would be minimized because the fresh water-salt water interface would probably be in the lateral part of the cave system and not the vertical part.

In three cases the data do not show a sequential transition through each phase of the conceptual model. From period 6 to 7 there was a transition from phase 3 to 2. This transition occurred because of heavy rainfall that prevented phase 1 from developing. From period 7 to 8 there was a transition from phase 2 to 1. This transition probably occurred because the springs had been discharging fresh water for approximately 10 months prior to period 8. The extended period of fresh water discharge may have resulted in low aquifer levels that allowed salt water to more easily backflow into the springs, which is the primary characteristic of phase 1. From period 8 to 9 there was a transition from phase 1 to 3. The unique characteristic of this transition is that the salinity in Spring Creek decreased in the absence of a heavy rainfall or inflows into Lost Creek Sink. During period 9 the equivalent fresh water head in Spring Creek Springs moved above and below the head in Wakulla Springs, which may have allowed fresh water to move past Wakulla Springs and into Spring Creek Springs, having the same effect as an influx from Lost Creek. Since this kind of transition only happened once during the study period, it is presumed to be rare. If future data collection indicates that it is more common, then it may represent a new phase in the conceptual model.

Werner and Simmons (2009) investigated several scenarios concerning how sea water intrusion could occur in a coastal aquifer. They found that sea water intrusion would be greatest where a constant head existed inland; the constant head prevented groundwater levels from rising, and thus sea water would have a lower fresh water head gradient to overcome. The combination of the inland location of Wakulla Springs (with an extensive submerged cave system) and the very high transmissivity of the UFA may allow Wakulla Springs to maintain a constant head similar to conditions prevailing at sites investigated by Werner and Simmons (2009). These two factors would allow sea water that backflows into Spring Creek Springs to move farther inland than it would if Wakulla Springs was not present.

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