Title

Numerical study of groundwater flow cycling controlled by seawater/freshwater interaction in a coastal karst aquifer through conduit network using CFPv2

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Numerical study of groundwater flow cycling controlled by seawater/freshwater interaction in a coastal karst aquifer through conduit network using CFPv2

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Highlights

- Groundwater flow cycling is quantitatively represented by a numerical model.
- Seawater/freshwater interface position significantly affects groundwater interaction.
- Discrete-continuum CFPv2 model is applied for non-laminar flow in conduits.
- Understanding the hydrological process is important to seawater intrusion.
- The effect of sea level rise on groundwater flow in a karst aquifer is evaluated.

Abstract

In this study, a groundwater flow cycling in a karst springshed and an interaction between two springs, Spring Creek Springs and Wakulla Springs, through a subground conduit network are numerically simulated using CFPv2, the latest research version of MODFLOW-CFP (Conduit Flow Process). The Spring Creek Springs and Wakulla Springs, located in a marine estuary and 11 miles inland, respectively, are two major groundwater discharge spots in the Woodville Karst Plain (WKP), North Florida, USA. A three-phase conceptual model of groundwater flow cycling between the two springs and surface water recharge from a major surface creek (Lost Creek) was proposed in various rainfall conditions. A high permeable subground karst conduit network connecting the two springs was found by tracer tests and cave diving. Flow rate of discharge, salinity, sea level and tide height at Spring Creek Springs could significantly affect groundwater discharge and water stage at Wakulla Springs simultaneously. Based on the conceptual model, a numerical hybrid discrete-continuum groundwater flow model is developed using CFPv2 and calibrated by field measurements. Non-laminar flows in conduits and flow exchange between conduits and porous medium are implemented in the hybrid coupling numerical model. Time-variable salinity and equivalent freshwater head boundary conditions at the submarine spring as well as changing recharges have significant impacts on seawater/freshwater interaction and springs' discharges. The developed numerical model is used to simulate the dynamic hydrological process and quantitatively represent the three-phase conceptual model from June 2007 to June 2010. Simulated results of two springs' discharges match reasonably well to measurements with correlation coefficients 0.891 and 0.866 at Spring Creeks Springs and Wakulla Springs, respectively. The impacts of sea level rise on regional groundwater flow field and relationship between the inland springs and submarine springs are evaluated as well in this study.

- **Previous** article
- **Next** article

Keywords

CFPv2

Coastal karst aquifer

Non-laminar conduit flow

Groundwater flow cycling

Sea level rise

1. Introduction

Karst carbonate rock has relatively large void spaces and loose porous medium structure that contains large amount of groundwater resource, usually becomes a regional aquifer, such as the Floridan aquifer in Florida and south parts of Georgia, Alabama and South Carolina (Bush and Johnston, 1988). Ford and Williams (1989) reported that karst bedrocksencompass about 10-20% of the Earth's landmass, supply drinking water for nearly 25% of the world's population. Complex subground conduit systems usually can be found in a karst aquifer due to long-term carbonate dissolution in joints and fractures (Davis, 1996). Hydraulic characteristics of a rapid non-laminar even turbulent flow in conduit networks could be significant different from those of a slow darcian flow in a porous medium. As a result, dual permeability or even triple permeability characteristics including porous medium, fractures and conduits, control groundwater flow patterns in a well-developed heterogeneous karst aquifer (Ritter et al., 2002, Scanlon et al., 2003). Although most groundwater resource in a karst aquifer is stored in carbonate matrix pores, groundwater flow is mainly through the conduit system (Kincaid et al., 2005, Davis et al., 2010). Rapid water flows in conduits and dynamic water exchanges between conduits and surrounding rocks accelerate the groundwater residence time, which is important to groundwater contamination as well as seawater intrusion in coastal area (Kuniansky, 2008). Contaminants contained in conduits can be pushed into the carbonate matrix when water pressure in a conduit is higher than that in its surrounding matrix during high-flow events. During low-flow events, contaminants flow from matrix back into the conduit when pressure difference reverses (Martin and Dean, 2001). Groundwater contamination as well as seawater intrusion in a karst aquifer can persist for a long time because of matrix retention and dynamic exchange (Green et al., 2006, Katz et al., 2004).

Sea level rise has been recognized as one of the most threatened environmental issues world-widely because of global warming and climate changes (Voss and Souza, 1987, Bear et al., 1999, IPCC, 2007, FitzGerald et al., 2008). The rising sea level not only inundates cities and farmlands on the shore, but also contaminates fresh groundwater resource through seawater intrusion in a coastal aquifer. According to the Ghyben-Herzburg relationship, a slight sea level rise would move the mixing interface significantly further landward in an aquifer (Werner and Simmons, 2009). In a karst coastal aquifer with well-developed conduits, seawater could fill in the submarine caves and intrude much further through the high permeable conduits. Davis and Verdi (2014) reported the flow discharge rate at an inland karst spring (Wakulla Springs) significantly increased in the last century. A historical data of rising sea level at the Gulf of Mexico is believed to be an important reason that affects the inland spring's discharge through submarine caves and extended conduit networks. The effects of sea level rise on the groundwater flow cycling and regional flow field in the aquifer was predicted and quantitatively evaluated in this study.

Many numerical dual-permeability models have been developed to study groundwater flow and solute transport in karst aquifers with well-developed conduits (Bakalowicz, 2005, Reimann et al., 2014, Xu et al., 2015). Dreybrodt (1998)developed a limestone dissolution continuum model coupled with conduit flow to simulate karst evolution and groundwater flow in a karst aquifer. Palmer (1991) also developed a numerical model for groundwater flow in a karst aquifer by coupling three-dimensional laminar groundwater flow in porous medium with turbulent flow in a karst conduit. Groves and Howard (1994) used two-dimensional pipe networks to simulate the processes of conduit development under laminar flow conditions at field scales. Later on, the simulation method was extended to turbulent flow by Howard and Groves (1995). Simulations of conduit evolution were conducted from random, two-dimensional fractures in a karst aquifer by Siemers and Dreybrodt (1998). Kaufmann and Braun (2000) coupled a pipe network with a continuum system to study karst development processes. Their study results indicate the early karstificationmight be enhanced by the presence of a diffuse flow system.

Hybrid discrete-continuum model coupled discrete pipe flowwith continuum porous medium flow has been verified to be an appropriate approach to simulate groundwater in a karst aquifer (Kiraly, 1998, Kaufmann, 2009). Clemson et al. (1996)developed the CAVE (Carbonate Aquifer Void Evolution) code, which is a discrete-continuum model to simulate non-laminar pipe flow coupled with darcian flow in continuum matrix domain. The model was and further extended by Liedl et al. (2003). Shoemaker et al. (2008) developed the CFP (Conduit Flow Process) packages for MODFLOW-2005 based on the previous works, which has been applied and evaluated in a number of studies (e.g., Reimann and Hill, 2009, Hill et al., 2010, Gallegos et al., 2013). Recently, Reimann et al. (2011)enabled MODFLOW-CFP to simulate unsaturated flow in conduits and water exchange between matrix and partial filled conduits. Furthermore, conduit associated drainable storage (CADS) and time-variable boundary condition was added in MODFLOW-CFPM1 by Reimann et al. (2014). Based on these studies, a research version of CFPv2 has been developed by Reimann et al., 2013, Reimann et al., 2014 and used in this study.

Based on the springs' discharges, surface water recharges, salinity at Spring Creek Springs and precipitation data in the WKP from June 2007 to June 2010, Davis and Verdi (2014)proposed a conceptual model of three repeating phases for the groundwater interactions among Spring Creek Springs, Wakulla Springs and Lost Creek. In phase 1, seawater backflows into the conduits at Spring Creek Springs (seawater siphoning) with high salinity and very low freshwater discharge during an extended low rainfall period. Freshwater discharge is blocked at Spring Creek Springs by higher-density seawater and diverted to Wakulla Springs. Phase 1 switches to phase 2 after a heavy rainfall event resulting from temporarily high inflows from sinkholes to groundwater that purge seawater out of the Spring Creek Springs submarine conduits. Discharges of both springs increase dramatically in this phase, especially at the submarine springs. Phase 2 transforms to phase 3 when a low rainfall period returns.

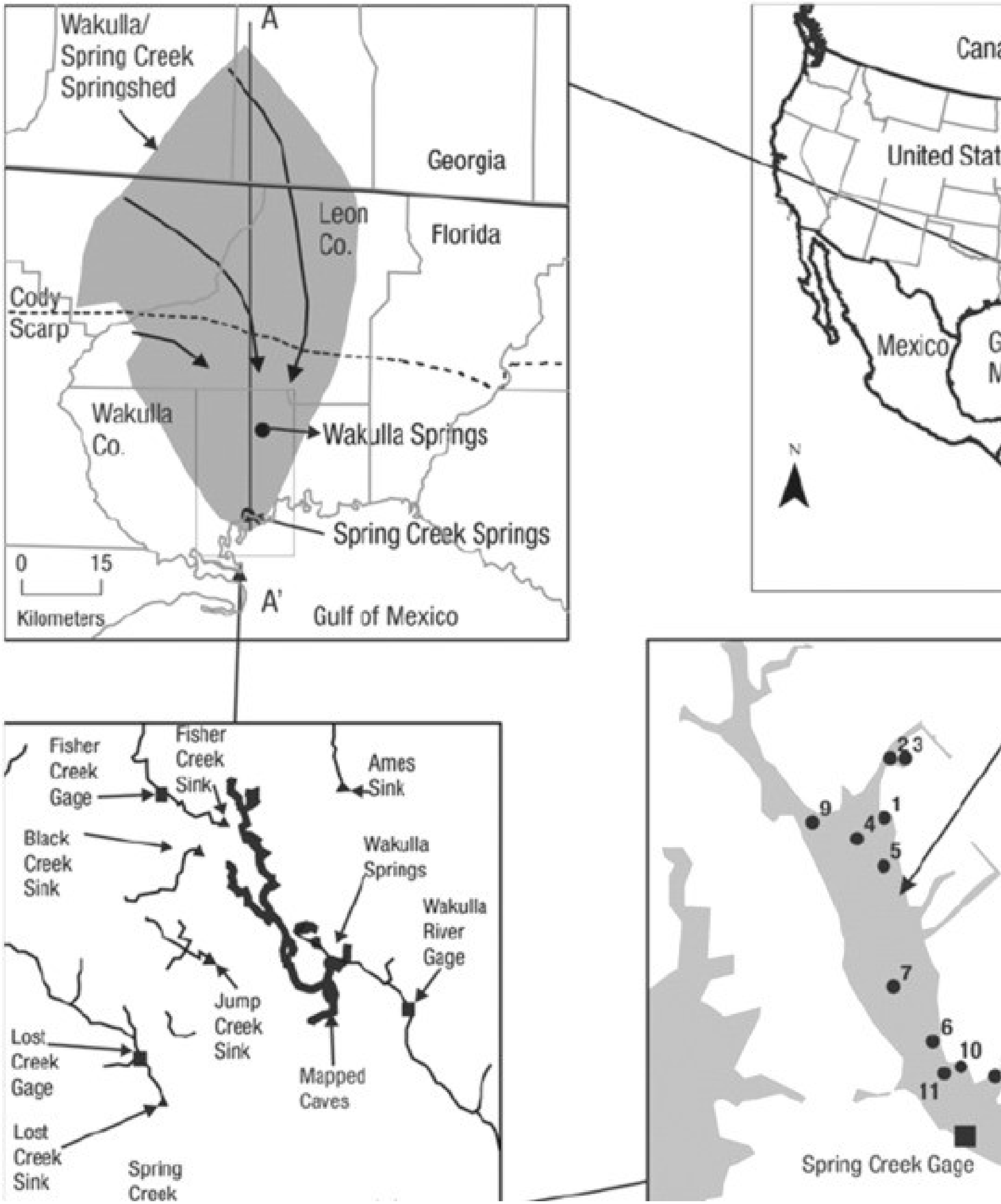
Surface water recharge returns to baseflow condition, but the submarine springs remain large quantity of freshwater discharge coming from groundwater storage; therefore, salinity is still low at the submarine spring.

In this study, CFPv2 was applied instead of MODFLOW-CFP to simulate the seawater and groundwater interaction processes since MODFLOW-CFP is not applicable to a time dependent boundary condition in the numerical model. The CFPv2 model is setup to numerically represent the conceptual model of the groundwater flow cycling in the Upper Floridan Aquifer (UPA) of Woodville Karst Plain (WKP), north Florida, USA. The modeling study focuses on the impacts of precipitation, surface water recharges and hydraulic headvariation caused by seawater intrusion at Spring Creek Springs on springs' discharge and groundwater flow cycling. The rest of the paper is arranged as: the hydrological characteristics of the Woodville Karst Plain (WKP), the Upper Floridan Aquifer (UPA), and the springs including Wakulla Springs and Spring Creek Springs are introduced in part 2. The governing equations, numerical methods, data collections are presented in part 3. The model implementations, numerical simulation results and prediction of sea level rise are provided in part 4. The discussion and conclusion including the uncertainties and impacts on seawater intrusion are made in part 5.

2. Study site

2.1. The Woodville Karst Plain and Upper Floridan Aquifer

The study site is located at the Woodville Karst Plain (WKP), north Florida, USA, which extends north to the Cody Scarp and the City of Tallahassee, and south to the Gulf of Mexico (Fig. 1). Apalachicola National Forest is the natural west boundary of WKP, however, the exact location of east boundary of WKP is still unknown. The rolling hill surface of WKP is covered by thin veneer of sands, silts and clays with sinkholes. The land-surface altitudes range from 100 to 200 ft above sea level (ASL) at the north of Cody Scarp covering by a low permeable Hawthorn layer on the surface. However, the land-surface altitudes are generally less than 50 ft ASL at south of Cody Scarp and characterized by closed basins, typical of karst terrains without Hawthorn layer (Smajstrla et al., 1984). The average annual temperature in Tallahassee is 67 °F and the average annual precipitation is about 61.3 inches per year (in/yr) during the study period (FCC, 2014). The average potential evapotranspiration in the WKP ranged from 51.91 to 54.23 in/yr from 2007 to 2010, which was calculated by USGS Florida Water Science Center (USGS, 2013).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Spring Creek Gage

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Fig. 1. Location of the study area, Woodville Karst Plain (WKP) and two springs, Wakulla Spring and Spring Creek Springs, modified from Davis and Verdi (2014).

The major hydrogeological setting in the WKP is the Floridan Aquifer, which is one of the world's most productive aquifers (Miller, 1986). In the conceptual model by Davis and Verdi (2014) as well as this study, only the Upper Floridan Aquifer (UFA) is considered and simulated, which is separated by the Paleocene low-permeable Clayton Formation with the Lower Floridan Aquifer (Fig. 2). Highly permeable limestone in the WKP can be over 1300 ft in thickness of the UFA. At the top of the UFA, the less permeable Hawthorn group is the confining unit between water table aquifer and the Upper Floridan Aquifer. The Hawthorn Group occurs in the north of Cody Scarp, but is absent in most parts of the study region at the south of the Cody Scarp (Miller, 1986). The very shallow water table aquifer, thin veneer of sands, silts, and clays present on land surface are not included in either the conceptual or numerical model.

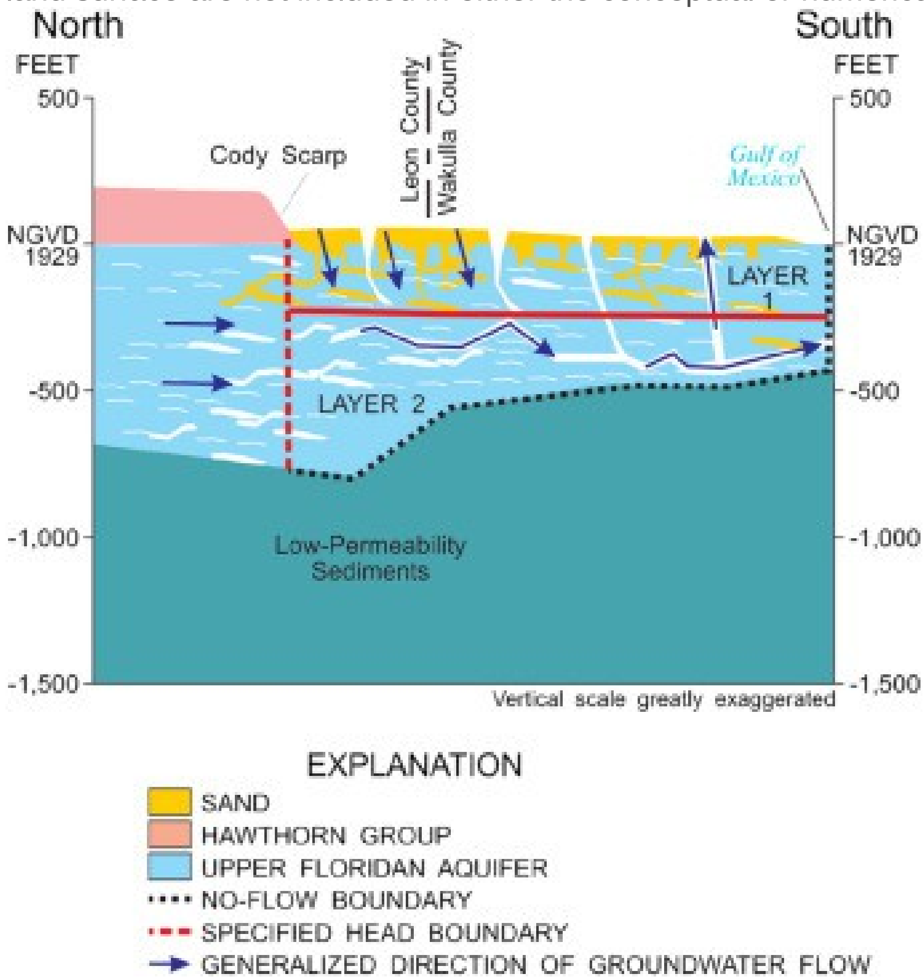

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Fig. 2. Generalized geological cross section in Woodville Karst Plain and model layers, modified from Davis et al. (2010).

Carbonate limestone is the major porous medium in the study area, which is characterized by an uneven distribution of heterogeneous permeability due to extremely high permeable subground fractures and conduits (Bush and Johnston, 1988). Openings in loosely cemented limestone and mosaics of many fractures and solution-widened joints can be found in the study region (Davis, 1996). Many fractures, cavities and conduits with sizes ranged from less than one foot to larger than 50 ft in diameter are observed in the study area. Tracer tests were conducted to verify the possible conduit network distribution and connection with Wakulla Springs, Spring Creek Springs and Lost Creek Sink (Kincaid and Werner, 2008, Kincaid et al., 2011). High permeability characteristics were also observed between the Southeast Sprayfield, St. Mark Spring and some sinkholes such as Black Sink and Fisher Sink connected with Wakulla Springs by tracer tests (Kincaid and Werner, 2008). Regional transmissivity distribution in the UFA is heterogeneous, ranging from 1.3×10^3 to 1.3×10^4 ft squared per day (ft^2/d), and can be as large as 1.3×10^6 ft^2/d due to highly permeable karst conduit texture (Davis, 1996).

2.2. Wakulla Springs

The group of Wakulla Springs is located 11 miles from the shoreline, 14.3 miles upstream from the Gulf along the Wakulla River, which is one of the largest springs in the Floridan Aquifer, even in the entire southeastern of United States (Davis, 1996, Florida Springs Task Force, 2000). The elevation at Wakulla Springs is about 5.0 ft above sea level, which is important to determine groundwater discharge and conduit flow direction in the entire study area. Discharge at Wakulla Springs remains nearly 400 ft^3/s even in the dry season, and seawater cannot move upstream through Wakulla River to the inland spring. However, salinity and equivalent freshwater head at Spring Creek Springs significantly affect groundwater discharge at Wakulla Springs through subsurface conduits, which has been discussed in the groundwater flow cycling conceptual model by Davis and Verdi (2014), and will be quantitatively simulated and represented in this study.

Wakulla River comes from the extensive submerged cave system and flows out through Wakulla Springs, which is a single giant vent with several small vents nearby. The depth of Wakulla Springs cave is estimated to be about 200 ft near the origin, extended horizontally to 300 ft and could be 360 ft deep at some locations (Florida Springs Task Force, 2000). Diameter of the major vent at Wakulla Springs can be as large as 100 ft, which allows it to discharge huge quantity of groundwater. Kincaid et al. (2005) investigated the recharge sources to Wakulla Springshed by tracer tests, and Kulakowski (2010) reported the water balance of recharges coming from the creeks and sinkholes including Black Creek (Black Sink), Monson Slough (Ames Sink) and Fisher Creek (Fisher Sink) to Wakulla Springs. In addition, Lost Creek could recharge Wakulla Springs as well through a subground conduit network, which has been verified by Kincaid et al. (2005).

There are 37 miles of mapped conduits explored by cave divers who are able to enter the submerged cave system through Wakulla Springs or nearby sinkholes (Fig. 3) (Davis et al., 2010). Most of the conduit systems are located right beneath Wakulla Springshed, and extended northward to Fisher Creek and Black Creek and southward to the Spring Creek Springs. Cave explorers identified cave passages as tunnels with alphabetic letter designations. This cave system, for orientation and description purposes as shown in Fig. 3, is assumed to start at the spring vent and initially heads southward where it branches into the A- and K-tunnels. The A- and K-tunnels eventually merge to form the O-tunnel, which connects to the Q-tunnel. The Q-tunnel continues heading toward the Spring Creek Springs, at least to the point where a diving exploration team had to turn around. The B-tunnel initially trends eastward, then turns northward in the general direction of the SEF sprayfield of the City of Tallahassee, Turf Sink and St. Marks Spring in northeast parts of the WKP. The C-tunnel is located close to the B-tunnel and trends toward south, and the relatively short D-tunnel heads northward. The extensive R-tunnel connects near the A-K-O tunnel junction, also connects with other tunnels that extend several miles northwestward passing through several sinkholes to Fisher Sink and Turner Sink. In general, groundwater flow characteristics in these complicated subground tunnel systems are quite different from that in a porous medium.

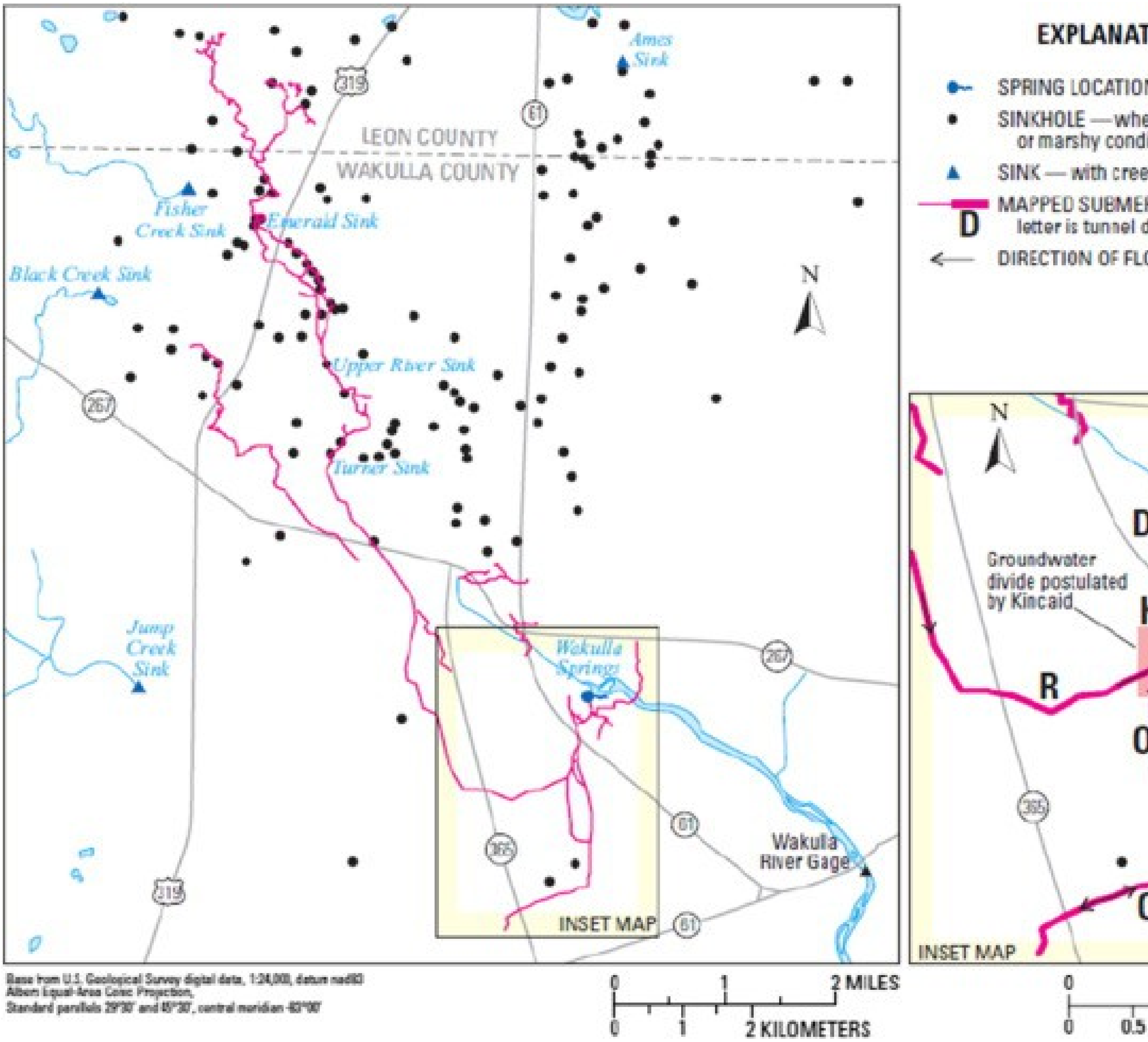

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Fig. 3. Locations of subground conduit network systems in the area of Wakulla Spring, modified from Davis et al. (2010).

2.3. Spring Creek Springs

Spring Creek Springs are a group of 14 individual submarine spring vents near the shoreline, and vents no. 1 and no. 10 are two major discharge spots (Florida Springs Task Force, 2000) (Fig. 1). However, the exact locations and discharges of the vents are difficult to accurately explore and measure because they are under sea level in the bay. Cave divers in Spring Creek Springs found an extensive karstic network joined by deep vertical conduits. Freshwater discharge is negligible in some periods comparing with its cave diameter as large as 50 ft. Meanwhile, the pressure of freshwater discharge is too weak to prevent seawater intruding into the conduits. The giant internal conduits system has a large storage capacity that keeps tons of seawater during drought seasons when rainfall and surface water recharge are low. However, there is no evidence on how far seawater intrudes through the submarine springs, and the exact location of seawater/freshwater interface is unknown. On the other hand, freshwater discharge at Spring Creek Springs dramatically increases after a high rainfall event, sometimes a tropical storm or a hurricane. Meanwhile, seawater can be pushed out at the submarine caves. Time-dependent groundwater discharge significantly affects salinity at Spring Creek Springs and controls the condition of seawater intrusion simultaneously. The submarine caves of Spring Creek Springs were seldom explored by cave divers due to complicated flow conditions especially when seawater is siphoning. Cave divers explored the submarine caves trended approximately 150 ft to the north of the spring vent, and reached a depth of about 160 ft below sea level (Kincaid and Werner, 2008). The depths of Spring Creek Springs are believed to be approximate 300 ft, especially at no. 1 and no. 10 vents, which are the biggest and major conduit outlets. However, divers were not able to reach the cave bottom. Therefore, the estimated depth is only available by assuming the submarine spring has the same depth as Wakulla Springs (Davis and Verdi, 2014). The conduit systems at Spring Creek Springs are believed to separate as two tunnels, in which one tunnel is northeastward to Wakulla Springs, and the other is northwestward to Lost Creek. The existence of high permeable conduit networks connecting Spring Creek Springs, Wakulla Springs and Lost Creek in the WKP were confirmed by a series of tracer tests as well (Kincaid and Werner, 2008, Kincaid et al., 2011).

2.4. Data collection

Prior to 2002, very few data at Spring Creek Springs were collected because of the measurement difficulty. Total discharge of Spring Creek Springs was measured at the mouth of the estuary by a USGS gage, which is a continuous data collection platform maintained from June 2007 through June 2010. The USGS gage also collects the hydrological data including total discharge, calculated flow velocity, tidal stage, electrical conductivity (salinity) and precipitation. Flow direction at Spring Creek Springs can be outward to the Gulf or landward to the caves, which means freshwater could discharge to the Gulf or seawater could intrude into the aquifer through subground caves. Salinity is diluted during the period of freshwater discharging at Spring Creek Springs. On the other hand, intermittent records of hydrological data at Wakulla Springs started from 1960s or even earlier by several government agencies. The USGS stream gage at Wakulla River has been used to collect stream data continuously since October 2004, which provides the spring discharge and water stage data for this study. In additional, flow rate at Lost Creek is also an important source of surface water recharge in this study, which is one of the largest creeks recharging sinkholes and conduit networks in the study area, and was also monitored by a USGS gage.

Precipitation data were collected from the weather stations at Florida State University, Tallahassee Regional Airport, the City of Crawfordville (St. Marks 9.2 W FL US) and Spring Creek Springs (St. Marks 8.2 FL US) maintained by Florida Climate Center, NOAA and USGS (FCC, 2014). Evapotranspiration was calculated by USGS Florida Water Science Center (USGS, 2013). However, precipitation and evapotranspiration calibrations are necessary to obtain recharge rates for the numerical groundwater model. In addition to Lost Sink, surface water recharge data including stream flow rates at Fisher Sink, Black Sink and Ames Sink provided by NWFWMD (Northwest Florida Water Management District) and Kulakowski (2010)were applied in this study as direct conduits recharges to Wakulla Springs.

3. Methods

MODFLOW is one of the most commonly used finite-difference computer codes for groundwater flow simulation in a porous medium (Harbaugh et al., 2000, Harbaugh 2005). A hybrid discrete-continuum numerical model, MODFLOW-CFP, as the Conduit Flow Process (CFP) package coupled with MODFLOW-2005, has been developed by the USGS (Shoemaker et al., 2008) and further extended to the latest research version of CFPv2 (Reimann et al., 2011, Reimann et al., 2014), which is applied in this study. Darcy’s Law is generally used to simulate laminar flow in a porous medium; however, it is not appropriate to describe non-laminar flow, which is common in a karst aquifer (Bear, 1972). Therefore, non-laminar conduit flow is simulated by Darcy-Weisbach and other auxiliary equations in MODFLOW-CFP and CFPv2. MODFLOW-CFP and CFPv2 were developed to simulate groundwater flow in a karst aquifer with well-developed conduits by coupling darcian flow in porous medium by traditional MODFLOW with a discrete network of cylindrical pipe flow implemented by CFP packages. Advective exchange between conduits and surrounding porous matrix is also considered in MODFLOW-CFP and CFPv2. The governing equations are introduced below.

3.1. Hybrid discrete-continuum flow modeling

According to Darcy's Law and mass conservation, three-dimensional continuum equation for groundwater flow in a porous medium including source/sink term is described as follows:

$$(1)\quad \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s\frac{\partial h}{\partial t}$$

Where K_{xx}, K_{yy} and K_{zz} are values for hydraulic conductivity[LT^{-1}] along the x, y, z axis, respectively. h is the hydraulic head [L], W is the volumetric flux per unit volume [T^{-1}] as sink/source term, and S_s is the specific storage [L^{-1}].

Since Darcy's Law is only appropriate for laminar flow with Reynold number less than 10 (Bear, 1972), Darcy-Weisbach equation, which is suitable for either non-laminar or laminar flow, is used to simulate groundwater flow in high permeable karst conduit networks in which a conduit is conceptualized as a pipe,

$$(2)\quad \Delta h=h_L=f\frac{\Delta l}{d}\frac{V^2}{2g}$$

Where Δh or h_L is the head loss [L] measured along the pipe length Δl [L], f is the friction factor [dimensionless], d is the pipe diameter [L], V is the mean velocity [LT^{-1}], and g is the gravitational acceleration constant [LT^{-2}].

Darcy-Weisbach equation can be reformulated to solve for volumetric flow rate in Shoemaker et al. (2008). MODFLOW-CFP and CFPv2 are able to solve non-saturated pipe flow but not applied in this study because all layers are assumed as confined aquifers and conduits are fully saturated. Caves and conduits are defined as a discrete pipe network consisting of cylindrical tubes and nodes within the cells of grid defined in the model. The advective exchanges between porous media and conduit nodes are assumed to be linear with head difference as follow,

$$(3)\quad Q_{ex}=\alpha_{j,i,k}\left(h_n-h_{j,i,k}\right)$$

Where Q_{ex} is the volumetric flow exchange rate [L^3T^{-1}], $\alpha_{j,i,k}$ is the pipe conductance at MODFLOW cell j, i, k [L^2T^{-1}], h_n is the head [L] at pipe node n located at the center of the MODFLOW cell, and $h_{j,i,k}$ is the head [L] in the encompassing MODFLOW cell j, i, k.

3.2. Equivalent freshwater head at Spring Creek Springs

A schematic diagram of the submarine caves system at Spring Creek Spring is presented in Fig. 4. In the transition zone of freshwater and seawater in a coastal aquifer, hydraulic head and seawater pressure are dependent on density and salinity. To calculate spatial hydraulic gradient and flow field, the concept of equivalent freshwater head is used in this study to represent seawater pressure in the submarine caves at Spring Creek Springs. The equivalent freshwater head at Spring Creek Springs is calculated using the measured salinity data in each stress period, which is important to determine whether the submarine cave is flowing or siphoning. A small change of seawater pressure at Spring Creek Springs would significantly affect groundwater discharge at Wakulla Springs because the topography is extremely flat and hydraulic gradient is very small in the study area. If the submarine caves contain only freshwater while Spring Creek Springs are discharging freshwater such as phase 2 and 3 of the conceptual model, the equivalent freshwater head would be equal to the tide height or sea level. On the other hand, a direct use of spring altitude as equivalent freshwater head would be incorrect if the submarine caves are filled with higher density salt water while Spring Creek Springs are siphoning. The equivalent freshwater head is calculated by Ghyben-Herzberg equation,

(4) $h_f = \frac{\rho_s - \rho_f}{\rho_f} z$

Where *z* [L] is the height of the vertical column of salt water, or the depth of mixing interface below sea level in the conduits, ρ_f[ML^{-3}] is the density of freshwater, ρ_s [ML^{-3}] is the density of salt water, and h_f [L] is the equivalent freshwater head, which is also the height of freshwater rise above the top of the salt water in a static condition.

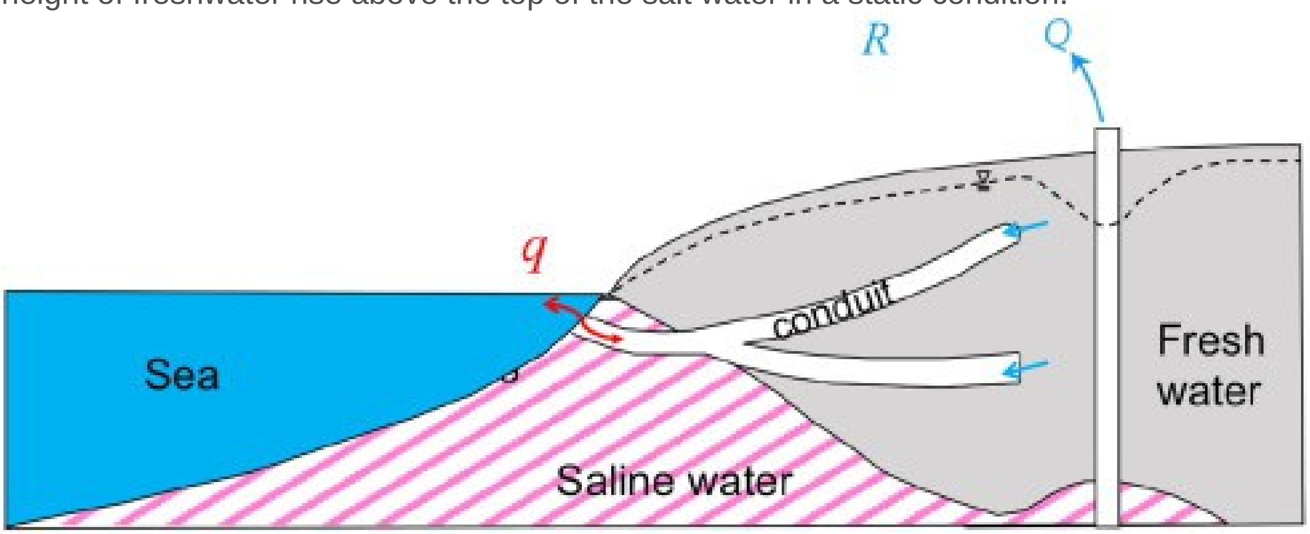

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Fig. 4. Schematic cross-section of a coastal karst aquifer with conduit networks and submarine spring (Spring Creek Springs). Flow direction q would be seaward when precipitation recharge R is large; however, reversal occurs when sea level rises, pumping rate Q is high or precipitation recharge R is small.

Seawater density ρ_s is calculated by the measured salinity using the equation that correlates fluid density and solute concentration (Langevin et al., 2003):

$$\rho_s = \rho_f + \alpha \times s \quad (5)$$

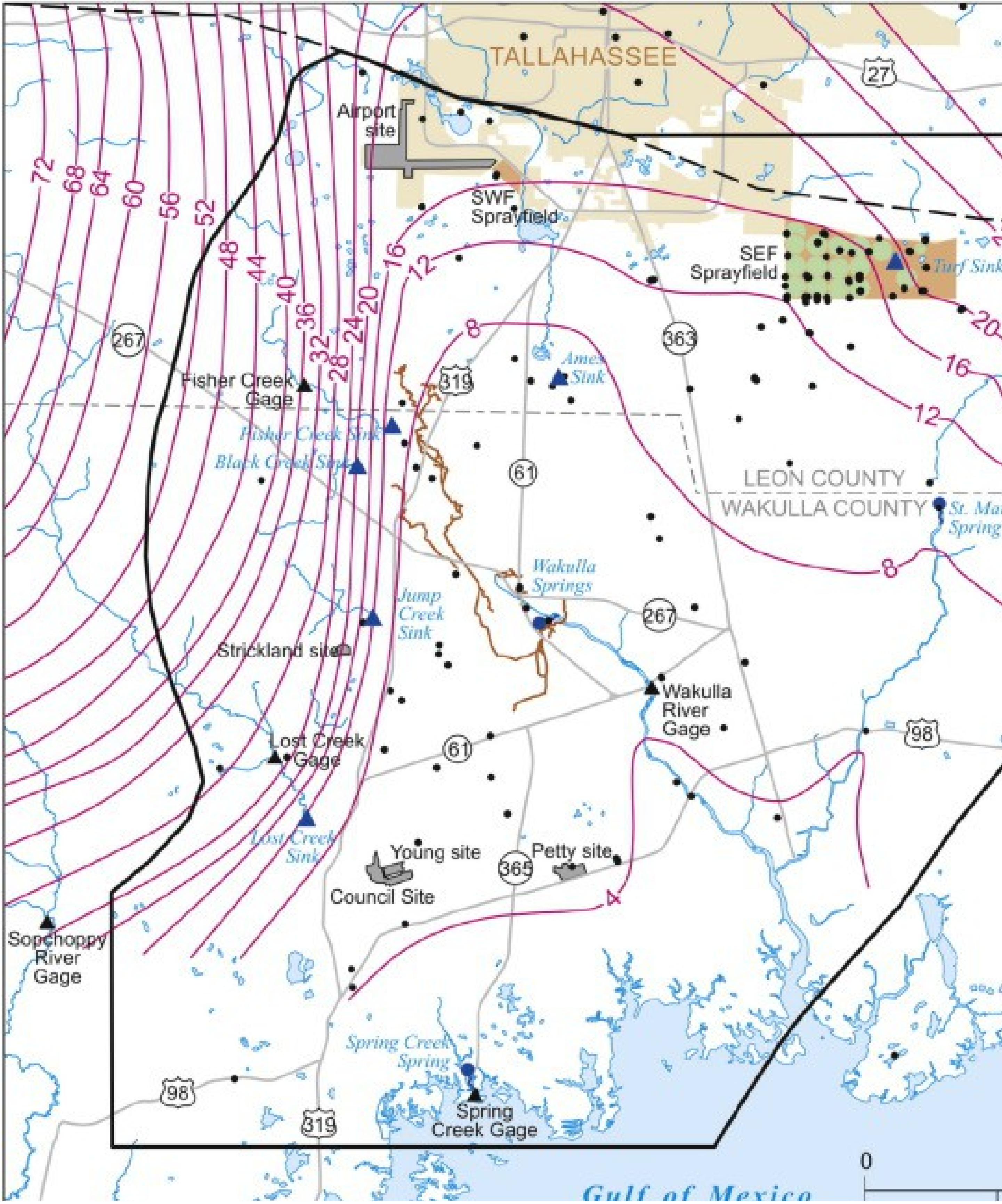
where α ($\partial\rho/\partial s$) [dimensionless] is the change rate of density with salinity, or slope of the linear equation that relates solute concentration to fluid density, s [ML^{-3}] is the salinity of salt water.

In this study, salinity is converted from the measured electrical conductivities. The height of the vertical column of seawater is assumed as nearly 300 ft deep during phase 1 in the conduit connecting Spring Creek Springs, based on the assumption that the depth of Spring Creek Springs cave is almost same as Wakulla Springs conduit networks, where has been explored by cave divers. Meanwhile, the depth of seawater/freshwater interface is also 300 ft in the conduit at the Spring Creek Springs in phase 1. Equivalent freshwater head at Spring Creek Springs in phase 1 is calculated as 7.5 ft above sea level by the Ghyben-Herzberg equation. The equivalent fresh water head proportionally decreases if the caves are filled with a mixture of freshwater and seawater. For example, if the freshwater and seawater mixture were half-half, then the equivalent fresh water head would be 3.75 ft; if the freshwater is dominated in the cave as in phase 2 and 3 conditions, the equivalent freshwater head should be equal to sea level or tide height.

4. Model implementation and calibration

4.1. Spatial and temporal numerical discretization

In previous studies, a long-term (1968–2018) MODFLOW model was developed for groundwater flow in the Woodville Karst Plain by Davis et al. (2010), later it was modified to a MODFLOW-CFP model by Gallegos et al. (2013). The CFPv2 model in this study was based on the previous long-term MODFLOW and MODFLOW-CFP models with the same spatial domain, but the temporal period of simulation is reduced to three years from June 2007 to June 2010. The numerical models in Davis et al. (2010) and Gallegos et al. (2013) have 58 stress periods with a time discretization of nearly one year for each period. In this study, however, there are 156 stress periods within the three years in the numerical model setup, and the length of each stress period is 7 days (1 week). The time discretization is much shorter than previous models, which generates simulation results with higher resolution. The spatial discretization of grid cells, boundary conditions and hydraulic parameters are almost the same as previous MODFLOW-CFP model by Gallegos et al. (2013) in Fig. 5. For the study region, the southeastern side is a no-flow boundary because it follows approximately a groundwater flow line as delineated by the model. Constant head boundary conditions are assigned to other boundary sides, which are determined by the regional groundwater flow model (Davis and Katz, 2007). The initial and boundary conditions on the shoreline is based on time-variable equivalent freshwater head at Spring Creek Springs, which has been explained in part 3.2.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Airport site
SWF Sprayfield
SEF Sprayfield
Turf Sink
Ames Sink
Fisher Creek Gage
Fisher Creek Sink
Black Creek Sink
LEON COUNTY
WAKULLA COUNTY
Wakulla Springs
Jump Creek Sink
Strickland site
Wakulla River Gage
Lost Creek Gage
Lost Creek Sink
Young site
Petty site
Council Site
Sopchoppy River Gage
Spring Creek Spring
Spring Creek Gage
Gulf of Mexico
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Fig. 5. Sub-regional model boundary of the Woodville Karst Plain, modified from Davis et al. (2010).

4.2. Tide stage calibration

The long-term variation of tide level is used to calibrate the simulated and measured discharges at two major springs, Wakulla Springs and Spring Creek Springs. The difference of daily low and high tide heights ranges from 1.8 to 3.0 ft, however, which is not considered in this study because the length of each stress period is one week, and daily tidal changes are internal variation within each stress period. According to the long-term variation of tide height observed by USGS tidal gage at Spring Creek Springs, average daily tide height level in summer is 0.8 ~ 1.2 ft above NAVD88 (North American Vertical Datum), but could be approximate − 0.3 to 0.1 ft in winter time. Time-variable tide levels as well as measured sea levels from June 2007 to June 2010 are applied in the numerical modeling to calculate equivalent freshwater heads at Spring Creek Springs. Simulated discharge would be underestimated at Wakulla Springs and overestimated measurements at Spring Creek Springs if sea level is assumed constant as 0.0 ft all year around in the numerical model, because the actual tide level is slightly higher than 0.0 ft above NAVD88 at Spring Creek Springs, especially in summer time. Calibrated model matched better with the field observations than original simulation without adjustment of tide level variation.

4.3. Recharges and evapotranspiration calibration

The net recharges coming from creeks and rainfall are used to calibrate the simulated and measured discharges at two major springs, Wakulla Springs and Spring Creek Springs. The consecutive precipitation data from Florida State University and Tallahassee Regional Airport are used to calculate recharges in the north part of WKP, and the data from the other two stations at Crawfordville (St. Marks 9.2 W FL US) and Spring Creek Springs (St. Marks 8.2 SW FL US) are used for the middle and south parts of the study area, respectively.

Generally speaking, net surface water recharge to aquifer is equal to the difference of precipitation and evapotranspiration. The potential evapotranspiration data are available from USGS Florida Water Science Center (USGS, 2013), which were transformed to the real evapotranspiration values by an empirical correction factor of 0.7 (Farnsworth and Thompson, 1982). The time discretization of each stress period in the numerical model was as long as one week; therefore, net recharge would be underestimated during a hurricane or tropical storm, because great amount of rainfall in a short period of time would be averaged and reduced by evapotranspiration. For example, the net recharge of an instant rainstorm should be higher than that of a light rain last for a long time with the same total precipitations.

Surface water recharge at Lost Creek is a direct recharge flow to subground conduit networks, which can divert to either Wakulla Springs or Spring Creek Springs, depending on the equivalent freshwater head at Spring Creek Springs. In addition, Fisher Sink, Black Sink and Ames Sink are conduit recharge source locations as well, but most of which flow to Wakulla Springs through D, AK and K tunnels especially during drought season. Some surface creeks including Fisher Creek and Lost Creek have large areas of runoff catchments that beyond the spatial domain of the numerical model. Since the soils and sands on the surface of study area are extremely loose, most rainfall could directly infiltrate into aquifer and become groundwater very quickly, especially at the south of the Cody Scarp without Hawthorn clay formation on the surface. In other words, point source recharges to conduit systems from surface creeks at sinkholes are only small part of total recharges in this study. Regional recharge from the northern boundary is more significant and simulated as constant head boundary conditions in the numerical model.

5. Simulation results

Davis and Verdi (2014) proposed a conceptual model that describes a groundwater flow cycling and interaction between Spring Creek Springs and Wakulla Springs. The effects of precipitation and flow rate at Lost Creek Sink were also introduced and analyzed in Davis and Verdi (2014). The results of numerical model in this study represent a quantitative description of the hydrological interaction between the springs as well as the three-phase transition of groundwater flow cycling. Time-variable recharges and seawater pressure in terms of equivalent freshwater head at Spring Creek Springs are decisive factors to groundwater interaction. Generally speaking, the numerical simulation matches reasonably well with the discharge measurements at two springs. The correlation coefficients between simulations and measurements are 0.891 and 0.866 at Spring Creeks Springs and Wakulla Springs, respectively.

The three-year groundwater flow cycling was divided as 12 periods basically according to salinity at Spring Creek Springs and groundwater discharges at the two springs. The dates and periods of each phase in the conceptual model were documented in Table 1 (Davis and Verdi, 2014), as well as the averaged measured and simulated discharges at two major springs in each period. Hydrologic conditions such as groundwater discharge, salinity, precipitation and surface water recharges were relatively stable in one period. A new period began when conditions changed.

Table 1. Classification of flow periods, phases in the conceptual model, measured and simulated flow rates (SC: Spring Creek Springs; WK: Wakulla Springs; flow rates are in cubic feet per second (ft^3/s), negative values at Spring Creeks Springs indicate reverse flow).

Period	Start date	End date	Measured flow rate (SC)	Simulated flow rate (SC)	Measured flow rate (WK)	Simulated flow rate (WK)	Conceptual model phase
1	06/25/2007	02/19/2008	− 2	184	707	602	1
2	02/20/2008	03/25/2008	951	925	693	532	2
3	03/26/2008	05/19/2008	468	336	466	393	3
4	05/20/2008	08/19/2008	− 2	131	760	575	1
5	08/20/2008	09/30/2008	644	1023	934	704	2
6	10/01/2008	03/26/2009	443	395	483	412	3
7	03/27/2009	06/21/2009	875	861	691	533	2
8	06/22/2009	08/26/2009	− 10	115	830	680	1
9	08/27/2009	10/23/2009	445	413	636	420	3
10	10/24/2009	12/02/2009	− 224	100	698	546	1
11	12/03/2009	04/06/2010	1072	979	832	521	2
12	04/07/2010	06/22/2010	642	483	406	393	3

5.1. Phase 1

Phase 1 proposed in Davis and Verdi (2014) occurs during an extended low rainfall condition for several weeks or even longer. Surface water recharges decrease to baseflowconditions due to low precipitation in the study area during this phase. Seawater moves landward and backflows into the aquifer through the Spring Creek Springs caves, blocking most freshwater discharge due to higher equivalent freshwater head. A slight rise of groundwater level is found in the sinkholes when freshwater flow is blocked at the submarine caves during phase 1, because the equivalent freshwater head at Spring Creek Springs is 7.5 ft since the submarine caves are filled with pure seawater. In the modeling simulation, equivalent freshwater head was calculated by the measured salinity at Spring Creek Springs. The river stage or hydraulic head at Wakulla Springs is only 5.0 ft, which means groundwater would prefer to discharge at inland Wakulla Springs rather than Spring Creek Springs due to higher pressure on the shore in this phase. Wakulla Springs is the major discharge spring in the entire WKP aquifer;

on the other hand, very low freshwater discharge is incapable to purge seawater out of the submarine caves and dilute salinity at Spring Creek Springs.

Phase 1 includes the periods 1, 4, 8 and 10 of the 12 periods in the three-year study and occupies the longest time periods. The first period lasts almost eight months from June 2007 to February 2008, which is also the longest period of the conceptual model due to extended drought condition. Measured freshwater discharge of Spring Creek Springs was nearly zero or even negative in phase 1, which means Spring Creek Springs stopped flowing and began siphoning while seawater is filled and intruded into the submarine conduits (Fig. 6). Wakulla Springs was the major groundwater discharge spot of the entire WKP aquifer with an average flow rate of 700–800 ft^3/s in measurement as well as modeling simulation during phase 1. Surface water recharge at Lost Creek remains baseflow condition, while its contribution to aquifer and groundwater flow cycling is very small. Generally speaking, simulated results of groundwater discharge are overestimated at Spring Creek Springs but underestimated at Wakulla Springs, which will be demonstrated in the discussion part. Discharge at Wakulla Springs is nearly 20% underestimated by simulation at the beginning of period 1 due to the inaccurate initial conditions, however, does not affect the simulation results in later periods. Simulated discharges at Spring Creek Springs have relatively larger oscillations than measurements, but remained a very low level comparing with other phases in the model.

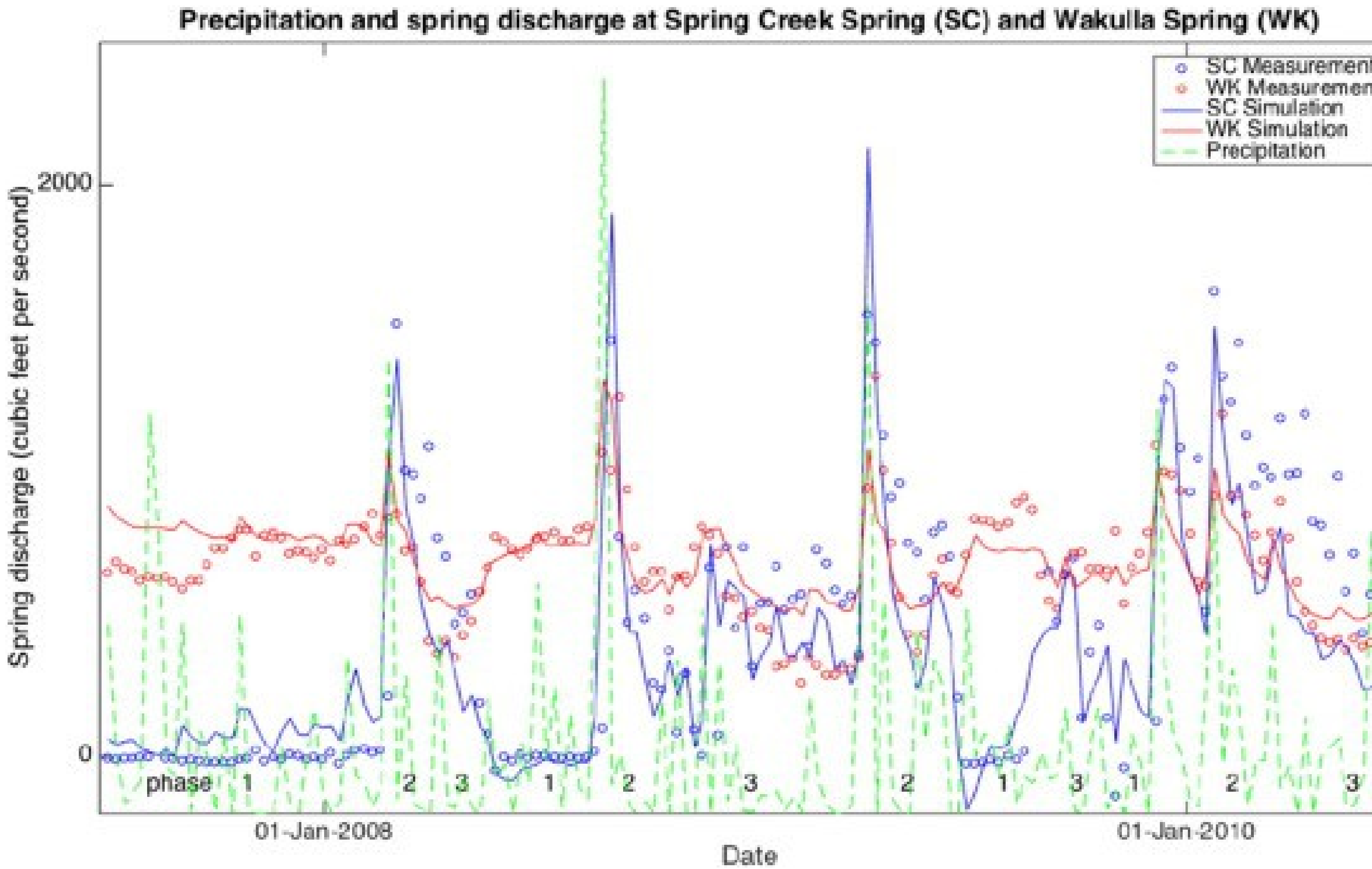

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Fig. 6. Measured and simulated results of discharges at Wakulla Springs and Spring Creek Springs, from June 2007 to June 2010, as well as precipitation.

5.2. Phase 2

A high precipitation event with large amount of rainfall is expected at the end of phase 1 or the beginning of phase 2, sometimes a tropical storm or hurricane. Phase 2 is the shortest phase in the conceptual model of groundwater flow cycling, which only lasts a few weeks but can be extended if there is an additional rainfall. The abundant rainfall in short period of time lead to high surface runoffs in creeks, then recharges into local sinkholes and becomes groundwater in the UFA. Lost Creek is the largest and most important creek in the study area that affects groundwater flow cycling, while its water flows and discharges through subground conduits north to Wakulla Springs and/or south to Spring Creek Springs. Fisher, Black, Jump and Ames Sinks of Wakulla Springshed also receive large amount of runoff from the north part of the WKP. Rainfall and surface water recharges raise water levels at sinkholes with significant groundwater flow into

subground conduit networks, push seawater out of submarine caves and dilute salinity at Spring Creek Springs. Freshwater is filled in the caves of the Spring Creek Springs during this phase, in which great portion of freshwater discharge comes from Lost Creek. The equivalent freshwater head is no longer 7.5 ft as phase 1, which needs to be re-calculated by the measured low salinity. When the entire caves are filled with freshwater, the equivalent freshwater head at Spring Creek Springs should be the altitude of sea level or tide level. Therefore, groundwater in the aquifer would prefer to discharge at Spring Creek Springs with lower hydraulic head and higher gradient comparing with inland Wakulla Springs. As a result, freshwater discharge at Spring Creek Spring increased more dramatically than Wakulla Springs in phase 2.
Periods 2, 5, 7 and 11 belong to phase 2 in the conceptual model proposed by Davis and Verdi (2014). Discharges at both Wakulla Springs and Spring Creek Springs increase dramatically and reach the highest rates during this phase. The average measured discharges during this period were 910 ft^3/s and 850 ft^3/s at Spring Creek Springs and Wakulla Springs, respectively. The peaks of Spring Creek Springs discharges are more significant than Wakulla Springs, could be 1500 ft^3/s in period 2 and 11, and even higher than 2000 ft^3/s in period 5 and 7, which are the most remarkable characteristics in the groundwater flow cycling conceptual model as well as numerical simulation. On the other hand, discharge at Wakulla Springs only slightly increased at the beginnings of period 2 and 11, but significantly increased at periods 5 and 7 due to higher rainfall recharges. Simulated results at Spring Creek Springs and Wakulla Springs match very well with measurements, except the peaks of discharge at Spring Creek Springs overestimated slightly at period 5 and 7. In general, rainfall water and surface runoff dominates the entire aquifer and discharge at both two springs during this phase.

5.3. Phase 3

After a high rainfall event in phase 2, the water cycling process moves to phase 3 when low rainfall conditions return. Lost Creek and other surface creeks also return to baseflow condition. However, the caves in the Spring Creek Springs are still containing and discharging large quantity of freshwater. As a result, equivalent freshwater head remains at or near the actual spring pool elevation of sea level because salinity is still very low at the submarine spring. In this scenario, discharges at both Spring Creek Springs and Wakulla Springs come from abundant groundwater storage in the UFA. Meanwhile, the groundwater level slowly drops with the reduction of storage. Phase 3 can last for as long as months, depending on groundwater storage, previous total precipitation and additional recharges. Extended low rainfall condition allows seawater once again flow into the Spring Creek Springs caves when freshwater discharge is significantly decreased, then phase 3 terminates and return to phase 1.

The duration of phase 3 varies from six weeks as in periods 3 and 9, or can be as long as three months in period 6. Discharge at Spring Creek Springs decreased to almost half of phase 2, but still much higher than that in phase 1. Discharge at Wakulla Springs decreased about 30% from phase 2 and can be even lower than that in phase 1. At this phase, the discharges at two springs are relatively similar. After streams return to baseflow conditions and become dry in phase 3, freshwater discharge at Spring Creek Springs remains a high flow rate of 500 ft^3/s in averaged for weeks to months, however, discharge at Wakulla Springs decreases to the lowest rate of 500 ft^3/s. Numerical simulation results match very well with the measurements of discharge at Spring Creek Spring, except for a nearly 15-20% underestimation of discharge in the last period of phase 3. Simulated discharge at Wakulla Springs is generally slightly lower but still reasonably matches with measurements, which may be due to missing sources of recharge or underestimation of surface creek baseflows. In general, simulated results reasonably match with field measurements.

5.4. Prediction of sea level rise effect on groundwater flow cycling

Rising sea level in the past 100 years has been verified by IPCC (2007) in global scale, and also observed in local monitoring gages by Davis and Katz (2007) and Davis and Verdi (2014). IPCC (2007) estimated the global sea level is going to keep rising nearly 3 ft if half of the ice sheet on Antarctic and Greenland is melted at the end of this century. As a prediction, the effects of rising sea level on the groundwater flow cycling and springs' discharges in the WKP aquifer are quantitatively simulated in this study. The discharges at Wakulla Springs and Spring Creek Springs are evaluated under the condition of 3.0 ft sea level rise by increasing the equivalent freshwater head at the submarine spring on the shore, but all other conditions remain the same as previous model. It should be pointed out this approach is only a simplified prediction because other conditions and assumptions may also change with rising sea level.

The simulation results are presented in Fig. 7. As shown in the figure, discharge will significantly increase at Wakulla Springs and decrease at Spring Creek Springs correspondingly when sea level rises 3.0 ft. Because of rising sea level, seawater pressure and equivalent freshwater head at the caves of submarine springs rises to block freshwater discharge from the Spring Creek springs groundwater will prefer to discharge at Wakulla Springs. The 3.0 ft rising sea level results in nearly 200 ft^3/s

increase of freshwater discharge at Wakulla Springs, as well as 200 ft^3/s decrease at Spring Creek Springs by assuming the rainfall and recharges do not change in phases 1 and 3 of the conceptual model. The effects of rising sea level on the peaks of discharges at both springs in phase 2 are not as significant as those in phases 1 and 3. Water levels in sinkholes and the entire groundwater level in the aquifer rise significantly after a high rainfall event. At the same time, hydraulic gradient increases dramatically along the conduit networks. As a result, the differences of hydraulic gradient and discharges at both springs are small compared with the calibrated model. On the other hand, tide level could rise as high as 4.0 ft if the high precipitation event in phase 2 is a tropical storm or hurricane. Higher tide level in terms of higher equivalent freshwater head would significantly reduce the discharge at Spring Creek Springs. Zervas (2001) and Davis and Verdi (2014) reported the increasing discharge at Wakulla Springs from 1930 to 2010 along with the rising sea level in the Gulf of Mexico (Fig. 8), also verified the prediction results by the numerical model.

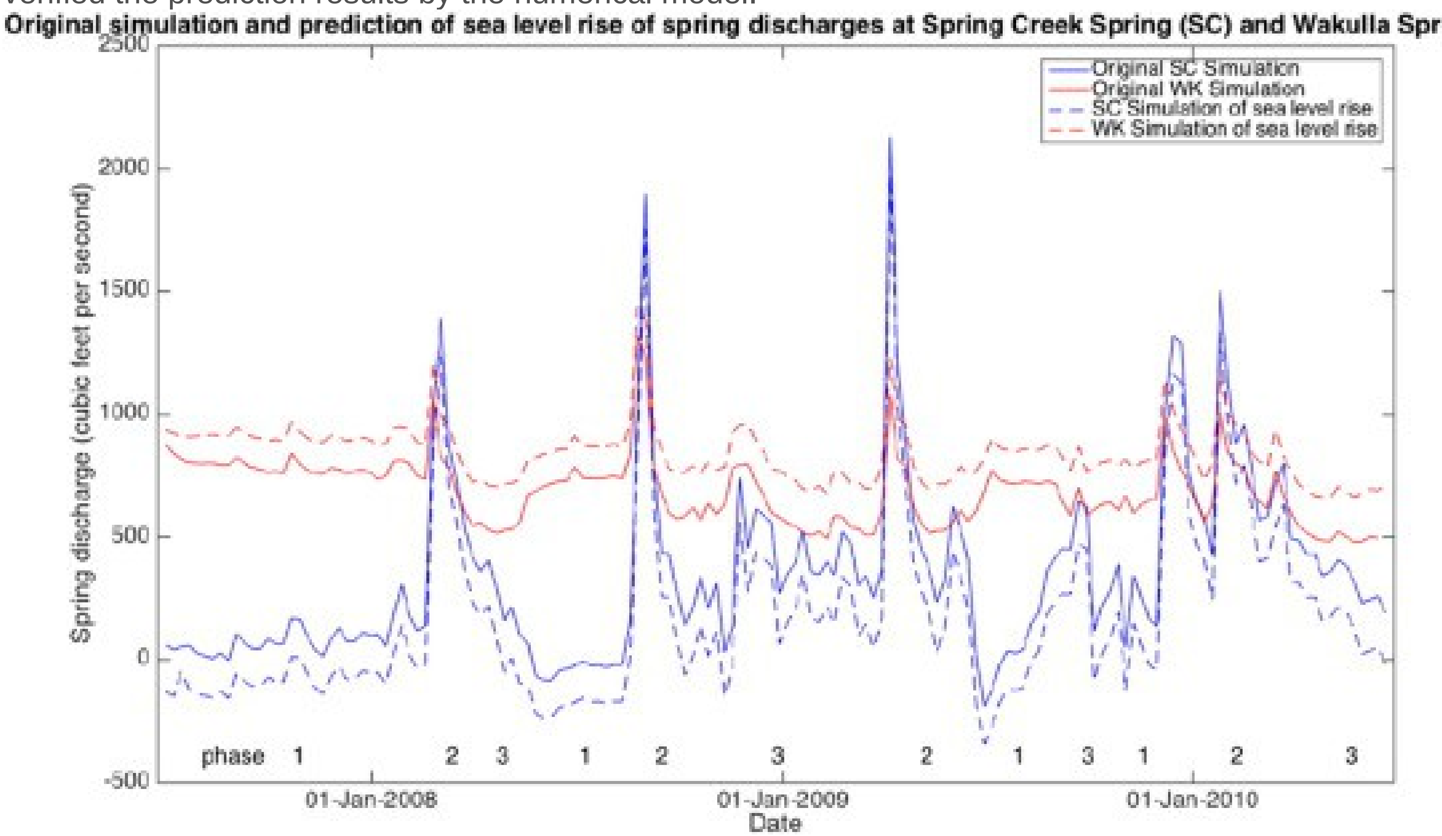

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Fig. 7. Original (calibrated) simulation results and the prediction of rising sea level of the discharges at Wakulla Springs and Spring Creek Springs, from June 2007 to June 2010.

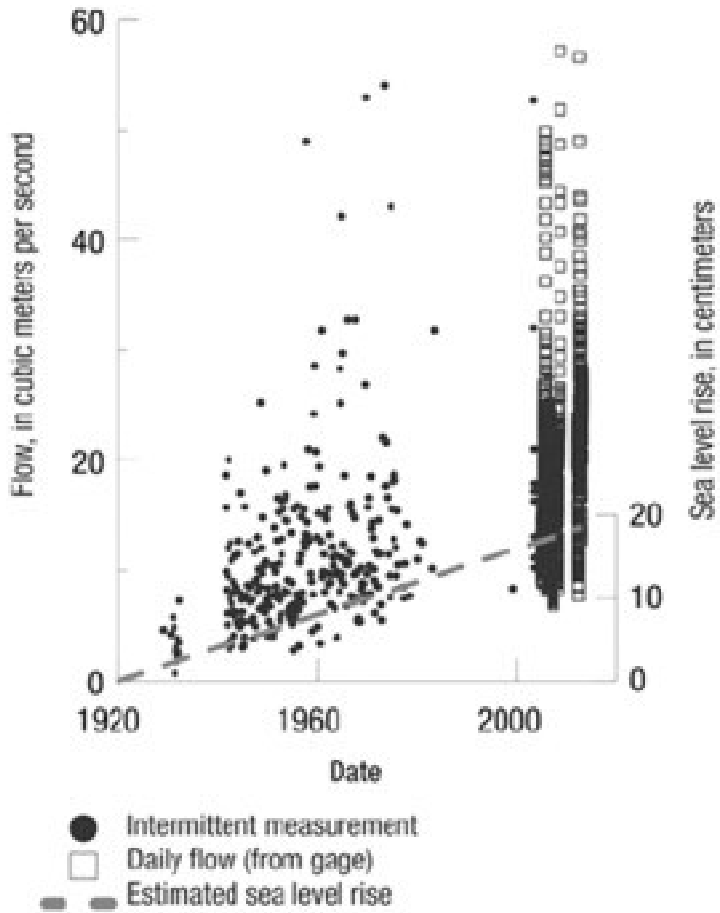

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Fig. 8. Flow at Wakulla Springs from 1930 to 2010 and estimated sea level rise from 1920 to 2020, modified from Davis and Verdi (2014).

6. Discussion

Numerical CFPv2 groundwater modeling in this study provides a quantitative description of groundwater flow cycling and discharges at Spring Creek Springs and Wakulla Springs from June 2007 to June 2010, based on the three-phase conceptual model for groundwater interaction in the WKP (Davis and Verdi, 2014). Conduit flow could be non-laminar even turbulent, so Darcy's Law as well as the MODFLOW code for groundwater flow in porous medium are no longer appropriate to describe groundwater flow in a karst aquifer with conduits. Discrete-continuum models MODFLOW-CFP and CFPv2 coupled non-laminar flow in conduits and darcian flow in porous medium, allows us to accurately estimate the effect of conduit networks on groundwater flow field in a karst aquifer. The calculation of equivalent freshwater head at Spring Creek Springs provides an approach to quantitatively represent the seawater pressure at the submarine spring.

The difference between simulations and measurements of discharge at Wakulla Springs is larger than that at Spring Creek Springs, especially in phase 3 in which simulation results are generally underestimated comparing with measurements. There are several uncertain factors for the simulation error. Firstly, it is difficult to guarantee the data quality and accuracy for all measurements. Most field measurements including springs' discharges and water level are classified as fair quality, which means the error can be ± 8% of the real values. Therefore, the measurement errors could lead to significant simulation error. Secondly, the temporal discretization of numerical model is set as seven days (one week) in each stress period, which is much shorter than one-year stress period used in the previous long-term models (Gallegos et al., 2013, Davis and Verdi, 2014), but still too long to directly compare with the daily or hourly measurements of spring discharges, rainfall and surface recharges. However, it is not realistic to apply daily stress period in the numerical model due to the limit of computational capacity. The average of measurements in each stress period could cause significant error in the numerical simulation. For example, an instant heavy rainfall event is averaged in the seven-day stress period, the peaks of springs' discharges could be underestimated and actual evapotranspiration could be overestimated. In addition, the uniform empirical correction factor is used to obtain the real evapotranspiration from potential evapotranspiration in this study, which could be another error source for surface recharges. Thirdly, the estimation of equivalent freshwater head at Spring Creek Springs is another possible error, which is calculated by Ghyben-Herzberg equation based on the assumption that the depths of Spring Creek Springs' caves are nearly 300 ft. However, the exact cave depths are unknown and also hardly explored. The assumed depth is based on the assumption the cave depth in the Spring Creek springs is the same as that in Wakulla Springs, which has been well explored by cave divers. The equivalent freshwater head would be even higher if the caves of Spring Creek Springs are deeper than 300 ft, which means the interface of seawater and freshwater would be deeper than 300 ft as well. Last but not least, some precipitation data in the middle and south part of the WKP are missing in this study, which bring in some error for the estimation of rainfall recharge because the precipitation in Tallahassee Regional Airport could be different from those in Crawfordville and Spring Creek Springs.

Generally speaking, simulation results of discharge match well with measurements, especially for the discharge peaks at Spring Creek Springs in phase 2. The correlation coefficients between measurements and simulation results at Spring Creek Springs and Wakulla Springs are 0.891 and 0.866, respectively. Most simulation results match well with measurements in phase 2 and phase 3, except some specific periods.

Groundwater discharge is generally overestimated at Spring Creek Springs but underestimated at Wakulla Springs in phase 1, with larger variances as well (Table 1; Fig. 6). The calculation of equivalent freshwater head at Spring Creek Springs may be a reason for the mismatch, since the submarine caves might be deeper than the assumed 300 ft. Another possible reason would be the data quality for discharge flow rate measurements at Spring Creek Springs, because it is very difficult to accurately measure the total flow rate for a group of submarine springs. Tracer tests by Kincaid et al. (2005) pointed out those vents and caves could have different hydrological characteristics, for example, tracer was strongly detected at Spring Creek Spring vent no. 10 but not detected at vents no. 1 and no. 11. The USGS gage is located at the mouth of the bay, which means the measured flow speed could be different from those in the vents. In other words, our knowledge of the submarine springs is still insufficient. The numerical simulation results indicate that discharges at both Spring Creek Springs and Wakulla Springs are very sensitive to precipitation, especially for the discharge at Spring Creek Springs after a high rainfall event. Freshwater discharge and/or seawater intrusion vary under different rainfall conditions. Generally speaking, freshwater would discharge into bay after an instant storm, and seawater would flow reversely into the conduit during a long drought season. On the other hand, groundwater discharge at Wakulla Springs is not only affected by precipitation recharge but also freshwater discharge and salinity variation at Spring Creek Springs. During drought season such as phase 1 of the conceptual model, freshwater discharge at Spring Creek Springs is almost ceased or even reversed because of low rainfall recharge, while seawater blocks the freshwater discharge and intrudes into the cave. In the meantime, groundwater discharge at Wakulla Springs could be relatively high. Both discharges at Wakulla Springs and Spring Creek Springs significantly increase at phase 2 with a heavy rainfall event. Freshwater discharge remains high level as well as low salinity at Spring Creek Springs in phase 3, but discharge at Wakulla Springs could be even lower than that in phase 1.

The phase change is complicated in some cases. Periods of 7–9 did not show a sequential transition through each phase of the conceptual model (Davis and Verdi, 2014). Period 6–7 was a transition from phase 3 to 2 due to a heavy rainfall event that prevented phase 1 occurred. Period 7 to 8 was a transition from phase 2 to 1, because the springs had been discharging freshwater for approximately 10 months prior to period 8, and groundwater level of the UFA was low due to extended period of freshwater discharge. As a result, caves at Spring Creek Springs are filled with siphoning seawater, which is the primary characteristic of phase 1. Period 8–9 was a transition from phase 1 to 3, and the salinity at Spring Creek Springs slightly decreased at this transition due to medium rainfall or surface recharges, which allows freshwater discharges at both Wakulla Springs and Spring Creek Springs. Davis and Verdi (2014)believed it is rare since the transition only happened once during the study period. However, a new description of the conceptual model may be needed if future data indicate that it is more common.

Both conceptual model and numerical model are very important to understand and evaluate the interaction of seawater and freshwater within conduit networks in the study area. High-density seawater and the interface of freshwater/seawater could significantly affect groundwater flow field in terms of equivalent freshwater head. Currently, MODFLOW-CFP and CFPv2 are only able to simulate constant-density flow but not for variable-density flow. As a result, the concept of equivalent freshwater head is introduced to represent seawater pressure and simulate the entire hydrological processes. Equivalent freshwater head is calculated using the salinity measurements at Spring Creek Springs as time-variable boundary conditions in the numerical model.

Understanding the groundwater flow cycling processes plays a basic role in the study of seawater intrusion in a coastal karst aquifer, especially in the Woodville Karst Plain. Seawater is able to intrude into conduit networks when groundwater level is constant and low in the entire aquifer during phase 1 of the conceptual model. Salinity is high at Spring Creek Springs with little freshwater discharge. Spring Creek Springs discharge freshwater during phase 2 and 3; therefore, seawater is purged out from the submarine caves. However, these two phases are generally shorter than phase 1, which means seawater intrusion through submarine caves occurs in most of the time. Seawater is expected to intrude further through the caves of Spring Creek Springs under sea level rise condition because of the higher seawater pressure at the mouths of caves. The exact intrusion distance is still unknown in this study because the flow model with equivalent freshwater head is not able to determine how far seawater could intrude through the conduits without a transport modeling simulation of salinity distribution. More studies are still needed to gain a better understanding of variable-density seawater intrusion process. It is obvious that seawater intrusion is an important issue in a coastal karst aquifer through submarine conduit networks, which depends on the hydrological conditions and groundwater flow cycling, especially in the Woodville Karst Plain.

7. Conclusions

A modeling method for density-dependent flow in a karst aquifer with conduits is developed and used to simulate groundwater flow cycling in the Woodville Karst Plain in this study. Complex interactions between seawater, freshwater and recharges in a dual permeability karst aquifer are numerically simulated by a discrete-continuum CFPv2 model. In general, the simulation results reasonably match the field observations and verify the relationship between the discharges at submarine springs and inland springs under various precipitation and hydrological conditions. The study results indicate that Spring Creek Springs and Wakulla Springs compete with each other for freshwater discharges, and high-density seawater intrusion plays an important role in the competition, and also regional groundwater flow. The numerical modeling results indicate that sea level rise in the future would affect the hydrological conditions in the entire coastal aquifer, block freshwater discharge at the submarine springs and increase the flow rate at the inland springs. Overall, the numerical study significantly improve our understanding on groundwater flow system in the springshed and pave our way for future research on seawater intrusion to groundwater.

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$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s\left(\frac{\partial h}{\partial t}\right) \quad (1)$$

Where K_{xx}, K_{yy} and K_{zz} are values for hydraulic conductivity [LT^{-1}] along the *x*, *y*, *z* axis, respectively. *h* is the hydraulic head [L], *W* is the volumetric flux per unit volume [T^{-1}] as sink/source term, and S_s is the specific storage [L^{-1}].

Since Darcy's Law is only appropriate for laminar flow with Reynold number less than 10 (Bear, 1972), Darcy-Weisbach equation, which is suitable for either non-laminar or laminar flow, is used to simulate groundwater flow in high permeable karst conduit networks in which a conduit is conceptualized as a pipe,

$$\Delta h = h_L = f\frac{\Delta l}{d}\frac{V^2}{2g} \quad (2)$$

Where Δh or h_L is the head loss [L] measured along the pipe length Δl [L], *f* is the friction factor [dimensionless], *d* is the pipe diameter [L], *V* is the mean velocity [LT^{-1}], and *g* is the gravitational acceleration constant [LT^{-2}].

Darcy-Weisbach equation can be reformulated to solve for volumetric flow rate in Shoemaker et al. (2008). MODFLOW-CFP and CFPv2 are able to solve non-saturated pipe flow but not applied in this study because all layers are assumed as confined aquifers and conduits are fully saturated. Caves and conduits are defined as a discrete pipe network consisting of cylindrical tubes and nodes within the cells of grid defined in the model. The advective exchanges between porous media and conduit nodes are assumed to be linear with head difference as follow,

$$h_f = \frac{\rho_s - \rho_f}{\rho_f} z \tag{4}$$

Where z [L] is the height of the vertical column of salt water, or the depth of mixing interface below sea level in the conduits, ρ_f [ML^{-3}] is the density of freshwater, ρ_s [ML^{-3}] is the density of salt water, and h_f [L] is the equivalent freshwater head, which is also the height of freshwater rise above the top of the salt water in a static condition.

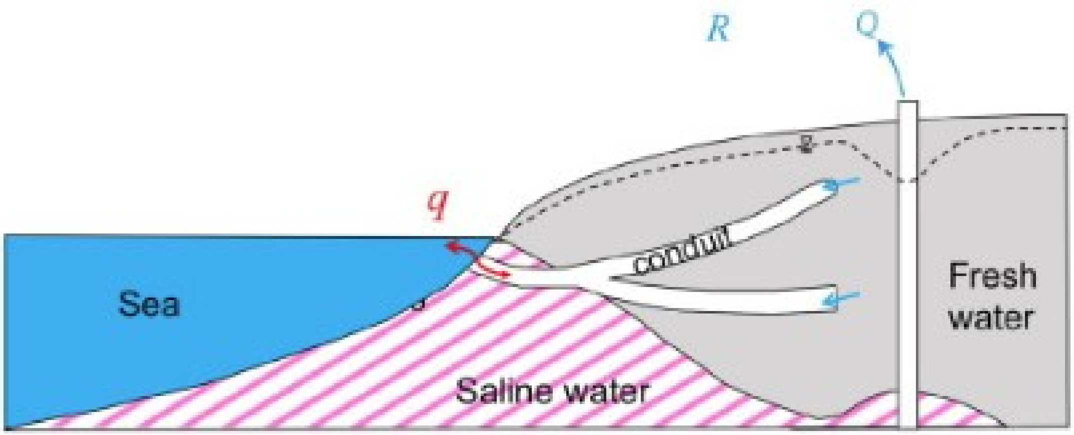

Fig. 4. Schematic cross-section of a coastal karst aquifer with conduit networks and submarine spring (Spring Creek Springs). Flow direction q would be seaward when precipitation recharge R is large; however, reversal occurs when sea level rises, pumping rate Q is high or precipitation recharge R is small.

Seawater density ρ_s is calculated by the measured salinity using the equation that correlates fluid density and solute concentration (Langevin et al., 2003):

$$\rho_s = \rho_f + \alpha \times s \tag{5}$$