Numerical study of groundwater flow cycling controlled by seawater/ freshwater interaction in Woodville Karst Plain

Zhongyuan Xu[a,d], Bill X. Hu[b]*, Zexuan Xu[c]*, Xiujie Wu[d]

[a] College of Earth, Ocean, and Environment, University of Delaware, Newark, DE 19716, USA [b] Institute of Groundwater and Earth Sciences, The Jinan University, Guangzhou 510632, Guangdong Province, PR China [c] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley 94720, USA [d] College of Environment & Civil Engineering, Chengdu University of Technology, Chengdu 610059, China

*Corresponding authors. E-mail addresses: billhu@jnu.edu.cn (B.X. Hu), zexuanxu@lbl.gov (Z. Xu).

Abstract

Seawater intrusion due to sea level rise and climate change could significantly contaminate coastal groundwater resources, particularly in Florida, the flat low-land state in the United States. Based on the field investigation and hydrological measurements, a three-dimensional SEAWAT model is developed to evaluate the groundwater flow cycling and seawater intrusion to freshwater system in the Woodville Karst Plain (WKP), a typical karst groundwater system in the Floridan aquifer. The karst conduit network in the aquifer acts as fast flow pathway for groundwater flow and solute transport, so seawater could deeply intrude into the aquifer. Wakulla Spring, an inland spring 17 km from the coast and a coastal submarine spring, Spring Creek Spring Complex are connected through the conduit network. The flow direction between the two springs switches under various rainfall conditions in this region, thus the discharges at two karst springs are used to estimate the location of seawater/ freshwater mixing interface. The SEAWAT modeling results indicate that the mixing interface, defined as 2 PSU (Practical Salinity Unit), intrudes 3 to 5 km through the subsurface karst conduit during the dry season and severely contaminates nearly 1 km width of groundwater around the conduit. The salinity distribution and the distance of seawater intrusion through the conduit system are very sensitive to precipitation variation and the sea level boundary condition. Furthermore, predictions are made for seawater intrusion to the aquifer under various sea level rise, precipitation scenarios and water pumping. The results show that the seawater intrusion could reach and contaminate inland freshwater systems if sea level rises 1.0 m or during a long-term no-precipitation season. This study provides insights for modeling and predicting the vulnerability of a coastal karst aquifer through the simulation of variable-density flow.

Keywords: Seawater intrusion, Karst aquifer, Conduit system, Density dependent flow, Sea level rise

1. Introduction

Seawater intrusion management is important for local water resource protection in coastal regions. Due to the increasing consumption of freshwater resource in coastal areas, seawater intrusion problem deteriorates globally with sea level rise and groundwater over-pumping in coastal regions (Werner et al., 2013; Chang et al., 2018). Many studies have been conducted to understand and predict seawater intrusion, using analytical methods (Bakker, 1998; Reilly and Goodman, 1985; Dagan and Zeitoun, 1998), numerical models (Langevin et al., 2010;Voss, 1984; Sanford and Konikow, 1985; Kipp, 1997; Boufadel et al., 1999; Li et al., 2009; Li and Boufadel, 2010), field hydrologic measurements(Paster et al., 2006; Shalev et al., 2009), geophysical methods (Fretwell and Stewart, 1981; Ginsberg and Levanon, 1976) and laboratory experiments (Faulkner et al., 2009; Abdollahi-Nasab et al., 2010). Climate change and human activities would significantly influence the future seawater intrusion. Sea level rise has been widely recognized as a global environmental threat that moves the fresh-salt mixing zone landward, contaminates the freshwater system and reduces the usable freshwater resources (Bear et al., 1999; IPCC, 2007). In addition, freshwater and seawater cycling process can be significantly impacted by precipitation variation, especially extreme events (Greaver and Sternberg, 2010). Furthermore, water pumping may cause groundwater depletion if the pumping rate is greater than the natural replenishment, especially in the center of a city (Famiglietti, 2014; Varis et al., 2006). Lowering groundwater pressure may change the surrounding head distribution and enhance the seawater intrusion from seaside (Wada et al., 2010).

Compared to the aquifer with other geological media, karst aquifers are more vulnerable to contamination and difficult to remediate, including seawater intrusion (Xu et al., 2018b). Different from a porous medium aquifer, seawater intrudes rapidly and extensively through karst conduits in a coastal karst aquifer. In some cases, people who do not live at the shoreline are also threatened by the potential groundwater contamination because of the long distance seawater intrusion to the aquifer through the karst conduit system (Xu et al., 2016). The distance of seawater intrusion through a karst conduit is controlled by the hydraulic link between a submarine spring vent in the sea, and affected by sea level variation, precipitation intensity and human activities (Arfib et al., 2006; Fleury et al., 2007; Davis and Verdi, 2014). The study area in this paper, the Woodville Karst Plain (WKP), is a typical coastal karst aquifer that threatened by seawater intrusion and will be briefly introduce in Section 2.

Several numerical models have been developed in the WKP in the last decade, based on the hydrogeological investigation of subsurface conduit networks. Davis et al. (2010) established the darcian flow MODFLOW (Harbaugh, 2005) and MT3DMS (Zheng and Wang, 1999) models to simulate groundwater and nitrate movement in the WKP through highly permeable conduit networks. Later, the discrete-continuum numerical models are used for simulating groundwater in this karst aquifer. Gallegos et al. (2013)

simulated the groundwater flow in the WKP using MODFLOW-CFP, which solves the non-laminar flow in discrete conduit system by Darcy–Weisbach equation and couples with Darcy flow in the continuum porous medium(Shoemaker et al., 2008). The study results showed MODFLOW-CFP performed better than MODFLOW in the simulation of groundwater flow in the WKP. Reimann et al. (2011, 2013, 2014) enhanced MODFLOW-CFP to CFPv2 by adding mass and heat transport in the karst conduit. Xu et al. (2015a) applied this model to simulate groundwater flow and nitrate transport in the WKP, in which non-laminar flow and solute transport in conduits were simulated. Xu et al. (2015b) developed a CFPv2 model to simulate the seawater and freshwater interaction, the calculated equivalent freshwater head was applied on the boundaries prior to the simulation. However, none of those methods considers density-dependent flow, the salinity distribution in the aquifer could not be investigated. Recently, some new methods were developed for modeling the seawater intrusion in a karst aquifer, such as Q_{mer}-C_T (seawater discharge-salinity) hysteresis (Arfib et al., 2006), and 2D discrete-continuum variable-density flow and transport model VDFST-CFP (Xu and Hu, 2017). However, these methods are not applicable to the large 3D groundwater aquifer due to the limit of grid resolution and computation burden. In this study, we used SEAWAT (Guo and Langevin, 2002; Langevin et al., 2003, 2008) to simulate the seawater intrusion process in the WKP, which captures the effect of density variation in the groundwater.

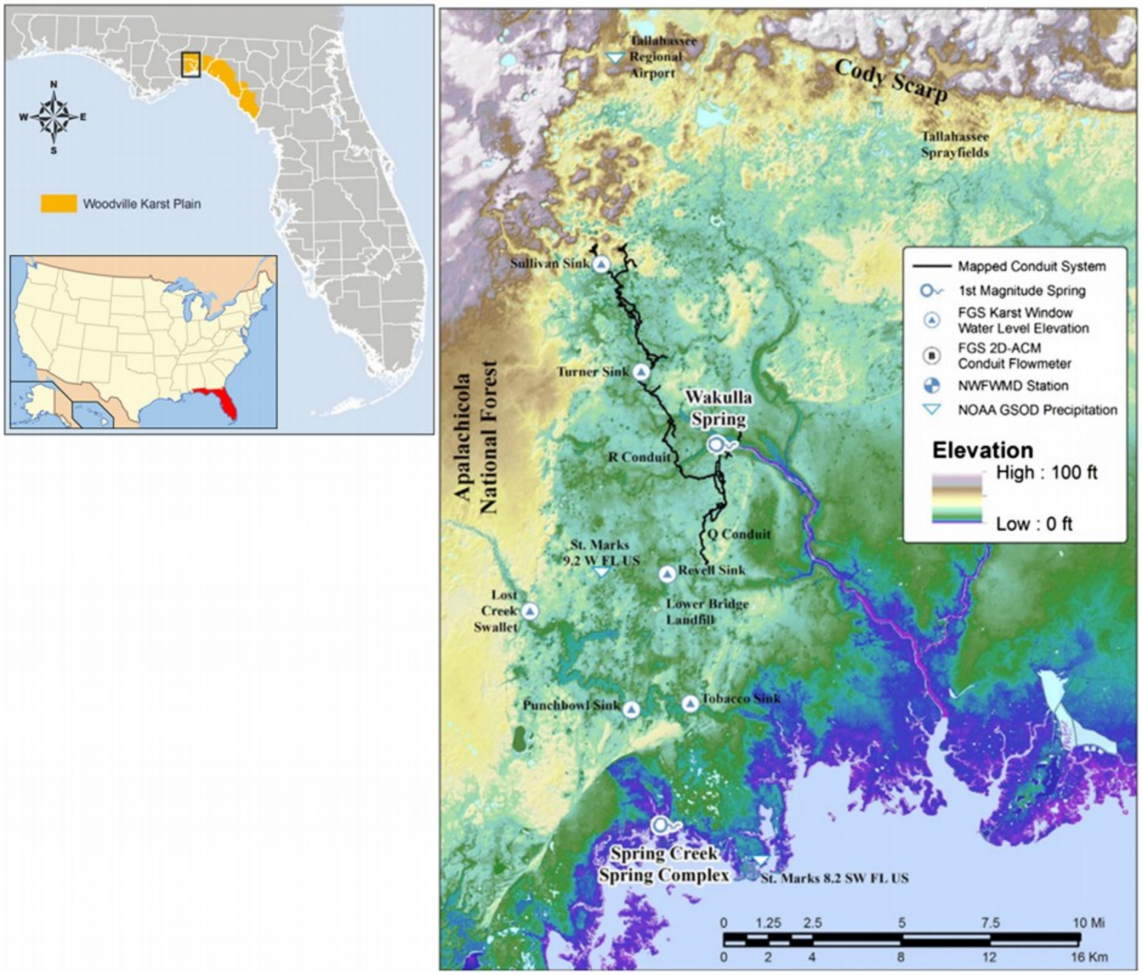

Fig 1. Left is the location of Woodville Karst Plain and study area, right is the map of study area including explored conduit system (Xu et al., 2016).

SEAWAT is one of the most popular numerical codes for simulating variable-density groundwater flow and solute transport that couples MODFLOW and MT3DMS with density dependent terms in the governing equations. By using SEAWAT, the physical processes of the seawater/freshwater interaction and salinity distribution can be studied under different environmental conditions. Due to the limitation on solving non-laminar flow, the non-laminar flow in karst conduits is simplified as preferential laminar flow calculated by Darcy’s Law, this method has been tested in the previous 2D cases (Xu et al., 2018a, 2019). Although most SEAWAT models are designed as two-dimensional due to the computational constraint, a three-dimensional SEAWAT model is developed in this study to simulate seawater intrusion and groundwater contamination to the coastal karst aquifer in the WKP. For addressing the objective of this study, the model is used a to quantitatively estimate the seawater intrusion distance and to predict seawater intrusion due to sea level rise, precipitation variations and groundwater pumping in the entire study region.

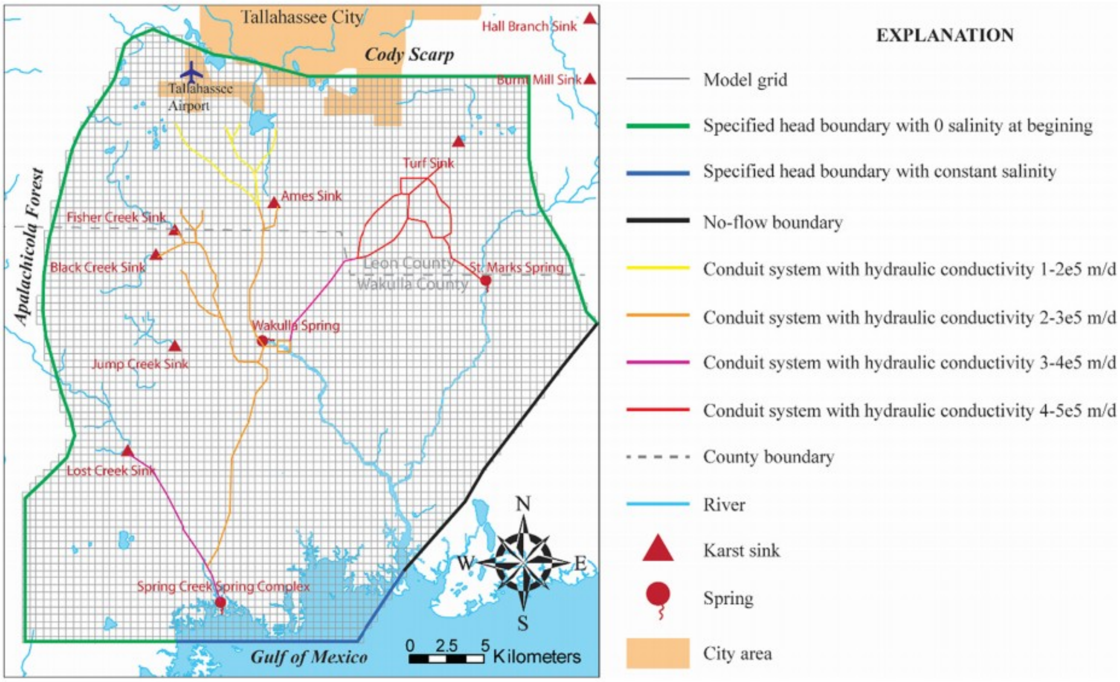

Fig 2. The discretization, boundary conditions, calibrated conduit conductivities of study area.

The rest parts of the paper are organized as: the study area is introduced in Section 2; the numerical model implementation and calibration are conducted in Section 3; simulation results are provided in Section 4; the scenario studies for sea level rise, precipitation variation and ground water pumping effect are conducted in Section 5; the discussion and conclusion are made in Sections 6 and 7, respectively.

2. Study area

The study area is located at the Woodville Karst Plain in north Florida, covered about 1300 km^2, bounded by the Cody Scarp at north, Gulf of Mexico at south, and Apalachicola forest at west (Fig. 1). The WKP porous media consist of a thin veneer of unconsolidated and undifferentiated Pleistocene quartz sand and shell beds overlaying a thick sequence of relatively horizontal carbonate rocks that comprise the Upper Floridan Aquifer (UFA) (Kincaid et al., 2005). The elevation in the WKP generally ranges from 0.0 to 10.5 m above mean sea level, with a trending slope of less than 0.75 m per km southward to Gulf (Bush and Johnston, 1988). The precipitation is relatively high with a humid climate, the average annual temperature and precipitation are about 19 °C and 1670 mm per year, respectively.

There are numerous springs, sinkholes and karst windows distributed in WKP. More than 400 sinkholes have been mapped in the northwestern quarter of the WKP (FLDEP, 2008; Benoit, 1992), and the major four sinkholes are Ames Sink, Black Sink, Fisher Sink and Lost Creek Sink. On the other hand, discharge from Woodville Karst Plain is primarily through Wakulla Spring, a surficial karst spring in land, and through Spring Creek Spring Complex (SCSC), a group of submarine springs at the southernmost of study site. A large and complex conduit system in the aquifer makes a connection between the freshwater system and seawater, distributes from Gulf of Mexico to the Wakulla Spring, then extended northward to the major sinkholes (Fig. 1). Many studies have been conducted to investigate the hydraulic connection, karst conduit distribution and discharge-recharge interaction in the WKP (Dyer, 2015; Kincaid et al., 2012; Lane, 2001; Li, 2012; Kincaid et al., 2005).

Wakulla Spring is the largest discharge surficial spring in the WKP with an average annual discharge of 9.7 m^3/s from year 2004 to 2005 (USGS, 2019). Wakulla Spring, located 17 km inland away from the coastal shoreline of Mexico Gulf, is the headwater of the 23.0 km Wakulla River to the sea. The elevation at Wakulla Spring riverbed is about 1.5 m above sea level and used as the critical head for the modeling in this study. The depth of Wakulla conduit system is estimated to be 60.9 m near the origin, extended horizontally to 91.4 m and could be as deep as 109.7 m somewhere (Florida Springs Task Force, 2000). Groundwater flow to Wakulla Spring is through an extensive submerged cave system (Loper et al., 2005). Cave divers have explored the cave system from Wakulla Spring to other sinkholes and identified several interconnected tunnels southward to the Gulf at the Spring Creek Sprint Complex (SCSC). In addition, tracer tests were conducted and proved the connection between Wakulla Spring, several large streams and sinkholes on the northeastern part of study area (Kincaid et al., 2005; Dyer, 2015).

SCSC is the major submarine spring in the study area consisting of 14 submarine spring vents opening to the Gulf of Mexico. SCSC is a type 2 submarine spring as defined by Fleury et al. (2007), which has welldeveloped karst networks and possess valuable storage capacities. The flow rates and directions of these springs vary dramatically depending on seasonal variability. Salinity in the caves is often low during high flow rate of freshwater, but increases when discharge flow rate decreases. During a low rainfall season with small surface recharges, the pressure of freshwater in the aquifer is too weak to prevent seawater flow into conduits. Thus, seawater intrudes through the SCSC during the low rainfall season and extends further north through the conduit network. Dyer (2015) reported the subsurface hydrology connection between SCSC, Wakulla Spring and Lost Creek Sink, highlighted the seawater intrusion process in the WKP through the conduit system.

The water resource supply in this region mainly depends on groundwater. More than 26 deep wells were utilized near the City of Tallahassee, located at the north boundary of the study area (Fig. 2), to provide more than 95000 m^3 of water to the residents each day (Davis and Katz, 2007). According to Davis and Katz (2007), these wells are far from the karst conduit system. Thus, the influence of water pumping in the Tallahassee City may has a limited influence on the seawater intrusion. A simplified case is conducted in Section 5 to discuss the effect of groundwater pumping on seawater intrusion.

Davis and Verdi (2014) developed a conceptual model for seawater and freshwater interaction at Woodville Karst Plain, three phases were determined based on salinity and discharge data obtained at Spring Creek springs and Wakulla spring between 2007 and 2010. Phase 1 is an extended period of low rainfall, in which the gradual decrease of surface water recharge to groundwater allows seawater to move landward and backflow into the aquifer through the Spring Creek Spring Complex (SCSC). In Phase 2, a high rainfall event generates a large amount of surface water recharge into aquifer, the seawater in the conduits is pushed out and replaced with freshwater, the equivalent fresh water head at the Spring creek vent decrease to the altitude of sea level or tidal level. In Phase 3, the low rainfall returns after the high rainfall period, the SCSC continue to discharge fresh water but the groundwater level in the Upper Floridan Aquifer (UFA) gradually drops with the storage reduction, the decreasing water level in aquifer becomes more and more vulnerable to seawater intrusion. Phase 3 may extend for a long time until the seawater moves upstream into conduits again.

3. Numerical model development

3.1. Model setup

To investigate the seawater and freshwater interaction in the WKP, a three-dimensional numerical model for variable density groundwater flow and solute transport in the Woodville Karst Plain was developed using SEAWAT. This SEAWAT model setup is based on the previous MODFLOW model by Davis et al. (2010) and CFPv2 model by Xu et al. (2015b). To reduce the computational cost for the simulation of the density dependent flow, the study domain was re-discretized and hence parameters were re-calibrated in this study. The temporal resolution of the numerical model is consistent with Xu et al.’s (2015b), which used weekly (7 days) water discharge and precipitation data measured from 2007 to 2010 at monitoring stations for the parameter inputs.

3.1.1. Model domain and discretization

Davis et al. (2010) defined a sub-regional model of WKP in two major layers, the first layer is mainly Oligocene Formation and Miocene Formation, including the bottom of Hawthorn sand cover and nearly the top of UFA (Upper Floridan Aquifer), with a uniform thickness of 60 m. The second layer is mainly Eocene Formation that extends to lowpermeability Paleocene Clayton Formation on the bottom, with the thickness of second layer varying from more than 300 m at northwestern boundary to 60 m at central and coastal area. The high permeable karst conduit structures are located in the second layer.

As finer resolution vertical discretization is required for variabledensity flow and solute transport simulation (Guo and Langevin, 2002), the two major stratigraphic layers of WKP was divided into 12 numerical layers, which is different from the previous models (Gallegos et al., 2013; Xu et al., 2015a,b). It includes 6 numerical layers for the top layer in the previous model, and 6 numerical layers for the second layer in the previous model with the thickness of 10 m for each numerical layer. The model only extends to 120 m deep and the deepest part of second layer in the previous model was not included in this model discretization to save computational cost. The average depth of subsurface conduit network exist nearly 90 m below the surface, thus the conduit zone in numerical model was defined from 70 to 110 m. Previous studies (Loper et al., 2005; Kincaid et al., 2005; Davis et al., 2010; Dyer, 2015) identified the major conduit network and preferential flow layers in the WKP are located at nearly 90 m below surface. In this study, the conduit zone is assumed to locate from 70 to 110- meter deep below surface. The porous medium near the karst conduit is highly karstification with higher permeability and effective porosity, which are re-calibrated in this study and adjusted by the method in the supplemental material, respectively. The lateral grid discretization is 500 m × 500 m, thus there are 92 rows, 86 columns, with 94,944 cells in total (Fig. 2).

3.1.2. Boundary conditions

The lateral boundary conditions for the 12 layers are identical to those used in Davis et al. (2010) and Davis and Katz (2007). The southeastern corner sea boundary was determined with a constant salinity 35 PSU (Practical Salinity Unit) and constant head 0 m, while the time-variable boundary condition at SCSC was calculated based on the salinity from USGS gage recordings. The southeastern perimeter is no-flow boundary because it follows a groundwater divide as delineated by a large regional model (Davis and Katz, 2007). The head on the north boundary is around 6.5 m, and the remaining inland boundaries were specified as constant head boundary conditions determined by Davis and Katz (2007). No-flow boundary was assigned to the bottom and precipitation is treated as recharge source term on the surface. Precipitation data was recorded at NOAA GHCN station located at the Tallahassee Airport and USGS gages at SCSC, evapotranspiration data was computed by USGS Florida Water Science Center (USGS, 2013). In this model, the precipitation recharge rate (Fig. 3a) has been calibrated by field precipitation data. Other recharges are the creek flows discharging into sinkholes, four major water receiving sinkholes are Ames Sink, Black Creek Sink, Fisher Creek Sink and Lost Creek Sink. The sinkhole recharge amounts are based on USGS and NWFWMD (Northwest Florida Water Management District) field monitoring data (Dyer, 2015).

3.2. Parameter calibration

Most aquifer parameters have been investigated or calibrated in previous numerical modeling studies (Davis and Katz, 2007; Davis et al., 2010;

Gallegos et al., 2013; Xu et al., 2018a), porosity and hydraulic conductivity are re-calibrated in this study as the domain discretization is modified. The porous medium parameters are extrapolated from the previous studies in most of the study domain. The hydraulic conductivities of porous medium are ranged from 15 to 9000 m/d, the six underneath layers (Eocene Formation) are more permeable due to stronger karstification. The effective porosity of the porous media ranges from 0.003 to 0.01. The longitudinal dispersivity in porous media is 10 m, the transversal dispersivity is the 1/10 of longitudinal one.

The major modified parameters of the SEAWAT model from previous numerical models are those used to describe the submerged conduit system zones due to re-discretization. The detailed conduit system geometry near Wakulla Spring was mapped by cave divers, the connections and flow velocities of other unmapped conduits were investigated by tracer tests (Kincaid et al., 2005, 2012; Li, 2012; Dyer, 2015).These conduit networks are represented using extreme high conductivities and porosity in Davis et al. (2010), which is re-calibrated in this study.

The SEAWAT model was calibrated automatically by UCODE-2005 (Poeter et al., 2005). The sensitivity analysis in Xu et al. (2018a) concluded that head gradient, salinity in the submarine spring, hydraulic conductivity and effective porosity of conduit zones are the important parameters for the head and salinity distribution in the conduit system. The first two factors were determined by the nature of aquifer system, effective porosity was calculated by the size of conduit zone (see Text S1), only hydraulic conductivity values in the conduit zones were calibrated by the discharge measurements at two major springs using the trial and error method. The salinity at SCSC was calculated from electrical conductivity measurement, which is defined as a boundary condition in this numerical model. Based on the field measurement, the simulated discharges at the two springs were compared with field observations in each calculation cycle until best matches were achieved.

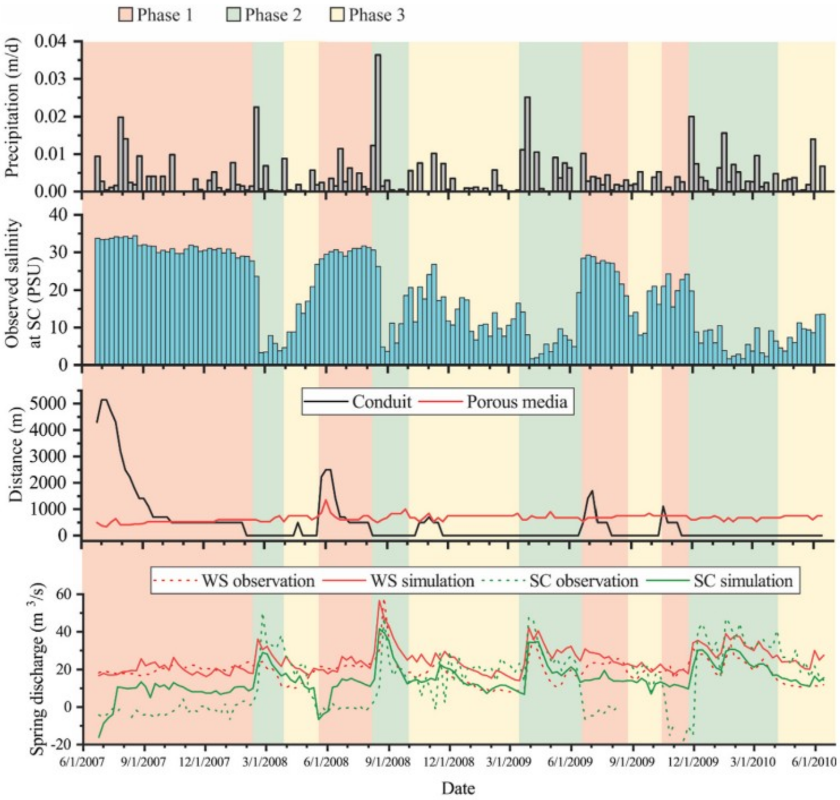

Fig 3. Results of numerical simulation from June 2007 to June 2010. From top to bottom: measured precipitation data on time scale; observed salinity variation at Spring Creek Spring Complex on time scale; simulated seawater intrusion distance in conduit system and average seawater intrusion distance in porous medium on time scale, the sea-fresh water profile is defined as 2 PSU; the comparison of observed discharge and simulated discharge at Wakulla Spring and Spring Creek Spring Complex on time scale, WS is Wakulla Spring, SC is Spring Creek Spring Complex. The time scale is divided into 12 periods with 3 phases.

The calibrated conductivity values for the karst conduit zones are showed in Fig. 2. The Nash–Sutcliffe model efficiency coefficient (NSE) of simulated discharges and observed discharges are 0.179 and 0.402 for Wakulla Spring and SCSC, respectively. The calibration results show that conductivity ranges from 1×10^5 to 5×10^5 m/d, which is smaller than the calibrated values in Davis et al. (2010) due to a coarser resolution.

4. Simulation results

According to the precipitation, salinity and discharge data, the simulated three-year period, from June 2007 to June 2010, is divided into 12 sub-periods and 3 phases based on the conceptual model by Davis and Verdi (2014) (Table 1). The precipitation, measured salinity at SCSC, modeled water discharge and distance of seawater intrusion along conduit network are shown in Fig. 3. In general, the observed salinity and modeled seawater intrusion distance are negatively correlated with precipitation and spring discharge. Three stress periods of the three flow regimes are selected to present the extend of seawater intrusion, which are June 2 to June 9, 2008, representing Phase 1; Aug 11 to Aug 18, 2008, representing Phase 2; Dec 1 to Dec 8, 2008, representing Phase 3. The salinity distribution and velocity fields are showed in Figs. 4 and 5. Precipitation variation determines the flow direction in the conduit system. More interpretation is illustrated below.

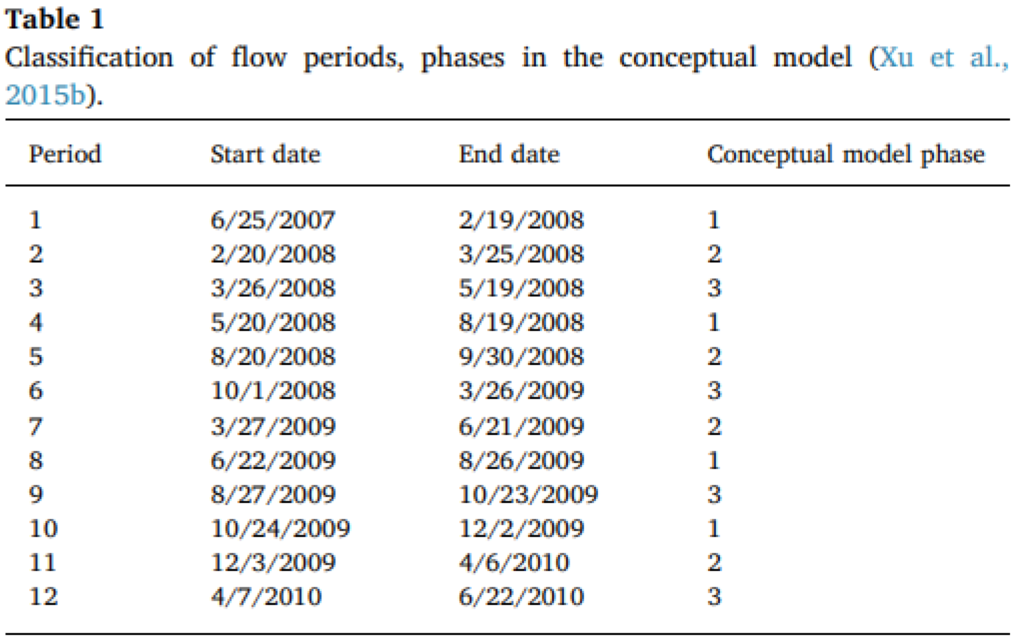

Table 1

Classification of flow periods, phases in the conceptual model (Xu et al., 2015b).

Period	Start date	End date	Conceptual model phase
1	6/25/2007	2/19/2008	1
2	2/20/2008	3/25/2008	2
3	3/26/2008	5/19/2008	3
4	5/20/2008	8/19/2008	1
5	8/20/2008	9/30/2008	2
6	10/1/2008	3/26/2009	3
7	3/27/2009	6/21/2009	2
8	6/22/2009	8/26/2009	1
9	8/27/2009	10/23/2009	3
10	10/24/2009	12/2/2009	1
11	12/3/2009	4/6/2010	2
12	4/7/2010	6/22/2010	3

Phase 1 represents the seawater intrusion condition during low precipitation period (red in Figs. 3; 4a and 5a). The salinity at SCSC is approximately 35 PSU (nearly seawater PSU) without freshwater mixing, and the observed groundwater discharge at SCSC is below zero, both indicates that seawater flows into the karst aquifer intrude through the subsurface conduit network. In Fig. 4a, the seawater-freshwater mixing zone, defining as 2 PSU salinity in this study, is much further landward in the conduit system than that in the non-conduit region. The longest seawater intrusion distance is nearly 5 km from coastline, while the average seawater intrusion in the non-conduit matrix is about 500 m from coastline. The conduit surrounding area (1–1.5 km) is also strongly contaminated by intruded seawater because of the solute exchange between conduit cells and matrix cells. The vertical profile (Fig. 4a) shows the seawater intrusion in the lower aquifer is much further than the upper aquifer due to the conduit zone (70–110 m) existed in the deeper aquifer. Fig. 5a shows flow direction at SCSC is landward, representing seawater intrusion at this karst vent. The seawater with higher hydraulic head blocks the freshwater discharge in the conduit system, thus the discharge at Lost Creek Sink is nearly zero and flow rate from Wakulla Spring to SCSC is very low or reversed.

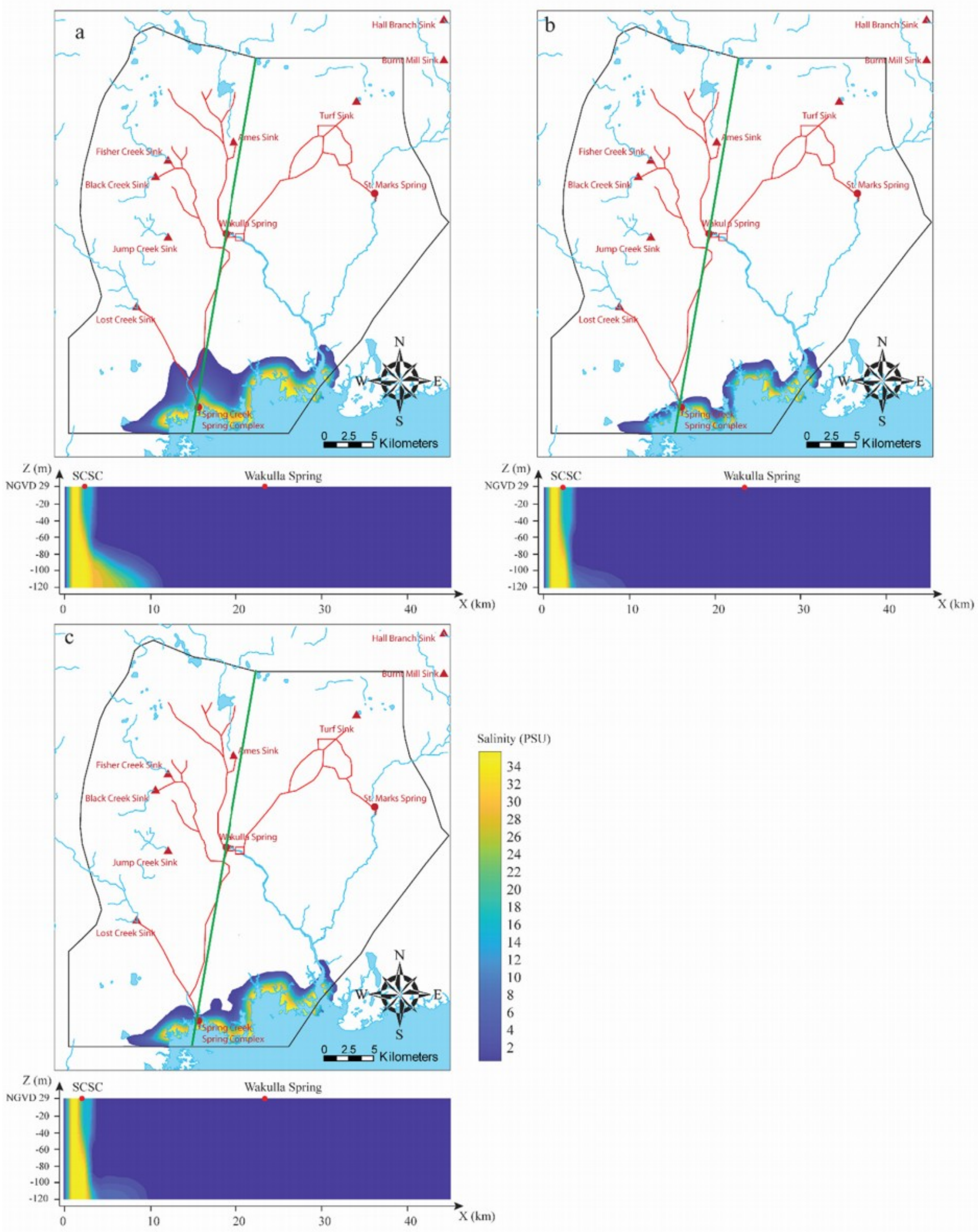

Fig 4. Salinity distribution on the horizontal plane at the depth of 80–90 m and vertical profile. The green line in the horizontal plane is the cross section of vertical profile, the green in the vertical plot indicates the depth of horizontal plane. (a) from June 2 to June 9, 2008 represents Phase 1; (b) from Aug 11 to Aug 18, 2008 represents Phase 2; (c) from Dec 1 to Dec 8, 2008 represents Phase 3. NGVD 29 is the National Geodetic Vertical Datum of 1929. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

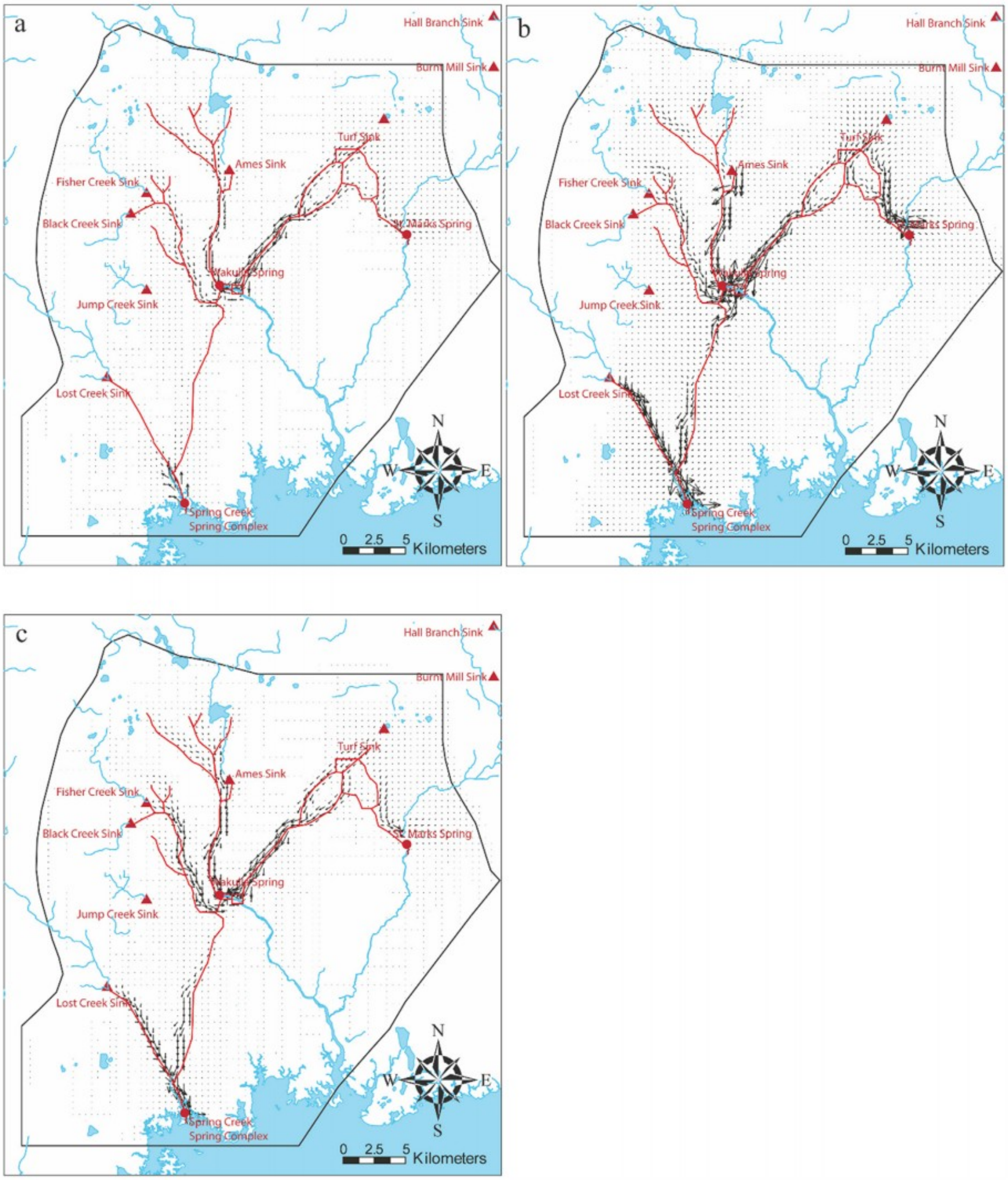

Fig 5. (a) Averaged groundwater velocity vector at the depth of 80–90 m from June 2 to June 9, 2008 represents Phase 1; (b) Groundwater velocity vector at Aug 11 to Aug 18, 2008 represents Phase 2; (c) Groundwater velocity vector at Dec 1 to Dec 8, 2008 represents Phase 3.

Phase 2 is the high precipitation and minimum seawater intrusion phase (green in Figs. 3; 4b, 5b), which usually happens after a storm or extreme rainfall event. Discharges increase at both Wakulla Spring and Spring Creek Spring, especially in September 2008 when a hurricane hit the region. The flow direction (Fig. 5b) and seawater intrusion condition in the conduit system reversed from the previous phase at SCSC, as fresh water with high pressure pushes the intruded seawater out of the SCSC and dilutes the salinity at conduit system to the minimum value (Fig. 4b). The width of seawater intrusion plume in porous media around conduit network decreases, at most 500 m, in Phase 2. One reason is that hydraulic head of freshwater system increases under a large precipitation, the salinity at coastal zone is diluted by recharged freshwater; another reason is that seawater is pushed out in conduit system, no salinity transport from conduit to surrounding media. In addition, the vertical profile (Fig. 4b) shows the salt is pushed out in the deeper aquifer (70–110 m). However, small amount of salt is still kept in the porous media that below the conduit zone, as the salt in the conduit zone is quickly pushed out, but the salt in the porous media remains for a longer time.

Phase 3 is the low precipitation and low seawater intrusion phase (yellow in Figs. 3, 4c and 5c). In this transition period after an extreme precipitation event and before the extended seawater intrusion, salinity is still low although groundwater discharge is decreasing at the SCSC, the conduit is still the major pathway for preferential flow water discharging to the ocean. While the seawater intrusion in porous media still occurs and increases due to decreasing freshwater discharge. Thus, the seawater intrusion in the regions without conduit network is more serious than in the conduit zone. The width of seawater intrusion plume in porous media around conduit network is 800 to 1000 m, while the intrusion distance in conduit system is less than 500 m. At the end of this phase, phase 1 returns when seawater intrudes extensively through the conduit.

5. Scenario predictions

Numerical modeling is an effective method for predicting seawater intrusion and managing water resources in the coastal region (Bear et al., 1992). Climate change and human activities have significant influences on the Woodville Karst Plain, where the extent of seawater intrusion is significantly determined by the sea level and precipitation recharge (Xu et al., 2016). The extreme weather conditions may have serious consequences over the coming decades, thus the numerical modeling prediction is important and necessary for water resource management in the future. After model coefficients were calibrated, predictions were conducted for three scenariosin this study: 1. Sea level rising; 2. Extreme high or low precipitation conditions; 3. Ground water pumping.

5.1. Sea level rising

Nearly one-meter sea level rise is predicted at the end of this century (IPCC, 2007). The effect of sea level variation on coastal seawater intrusion and groundwater cycling were investigated at a series of scenarios of sea level rises from 0.5 m to 2.0 m. These simulations were simplified as only sea level rise is modified, while other conditions remained the same as those used previously. The rising sea level may inundate a large portion of low-land coastal region. While, this scenario is assumed that a sea wall is constructed along the current coastline which is the usual case in the modeling of coastal regions, the coastal flooding is not considered.

Fig. 6 presents the spring discharges and seawater intrusion distances under various sea level rises, and Fig S1 shows the salinity distributions in the study area at different stages. Based on the conceptual model by Davis and Verdi (2014), sea level rise increases the hydraulic head at SCSC, blocks freshwater discharge and leads to further seawater flow into the submarine caves. As a result, a large portion of water diverts northward and discharges at Wakulla Spring significantly increase. Thus, the discharge decrease at SCSC would lead to discharge increase at Wakulla Spring with the sea level rise. Because the precipitation is assumed not changing, the three-phase division and discharge variation are same in different scenarios of sea level rising. The additional seawater intrusion distance increases non-linearly with the sea level rise and reaches the largest intrusion distance at about 17 km (Fig. 6b), which is the distance from SCSC to Wakulla Spring, indicating that Wakulla Spring is contaminated by seawater intrusion. This longest intrusion distance could be as long as 17 km from shoreline and reach Wakulla Spring during low rainfall seasons with just one-meter sea level rise. The porous media surrounded by the conduit system are also strongly affected by the seawater intrusion.

5.2. Extreme precipitation

Precipitation is a major controlling factor to groundwater system in the WKP, the above results (Section 4) have proved that the seawater intrusion and salinity distribution are strongly affected by precipitation. In this section, four precipitation scenarios, including no-precipitation, 0.5, 1.5 and 2.0 times of current precipitation, were studied using the SEAWAT model. The surface flow to the sinkholes is another recharge component to the aquifer, strongly correlates with local precipitation and affects the extent of seawater intrusion (Fig S2). Therefore, recharges from four sinkholes are required to be modified. The method for re-calculating sinkhole recharges under different precipitations is in the Text S2 and Fig S3. Other conditions remain the same as previously used.

Fig. 7 shows spring discharges at two major springs and seawater intrusion in the conduit system when precipitation varies from completely no rain to twice of the current rainfall. Fig S4 displays the corresponding salinity distribution at three phases. Both spring discharges at Wakulla Spring and SCSC increase with the precipitation increase, and inversely, the seawater intrusion distance decreases with precipitation increase. However, seawater intrusion from SCSC to inland freshwater system still happens in Phase 1 even the precipitation is doubled, indicating the season pattern of seawater intrusion determined by precipitation variation. The three-phase groundwater flow cycling is not presented in the case of no-precipitation. Under no-precipitation case, the seawater intrusion distance is much larger than other cases, reaching nearly 12 km from coastline at steady state condition. Unlike the extreme case of sea level rise, the salinity plume in the no-precipitation case is wider and shorter than the case of two-meter sea level rise, it means additional porous medium zones are contaminated, and the width of plume reaches about 10 km sometimes when seawater intrusion remains extensively in the conduit. The Lost Creek Sink is contaminated in extreme precipitation case due to a wider plume range, while the Wakulla Spring is contaminated in the 1.0-meter extreme sea level case.

5.3. Groundwater pumping

The local water usage is mainly supplied by groundwater, the major groundwater pumping is in the Tallahassee City on the north boundary of the study area. The long-term pumping may cause water depletion and hydraulic head drawdown on the north boundary. As the groundwater pumping amount is difficult to be accurately estimated, the effect of groundwater pumping was simplified as the decreased head at the north boundary in the city area, four scenarios were considered: head drops 0.5 m, 1.0 m, 1.5 m and 2.0 m. Other boundary conditions remained same as those in the Section 4.

The spring discharges and seawater intrusion distances under different inland heads in the Tallahassee City are shown in Fig. 8. The results show that head decrease in the city area on the north boundary of the WKP does not have a strong impact on the coastal seawater intrusion. Two reasons lead to this phenomenon: First, the seawaterfreshwater cycling in this area is mainly controlled by the precipitation, the head drawdown is replenished by the water recharge during the wet season. Second, the city area is not located at the region with intense karstification, the cells with decreased hydraulic heads are not directly connected to the karst conduit system. The water flow in the conduit zones are mainly influenced by the sea level not the groundwater level in the aquifer.

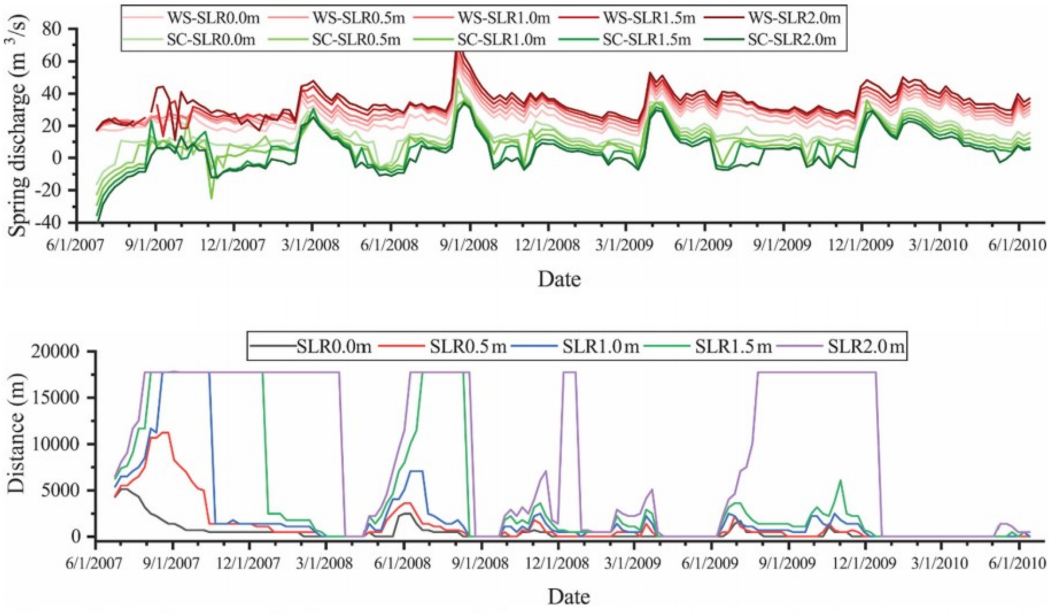

Fig 6. Simulation results of predictions on sea level rising, 4 cases of sea level rising are considered: 0.5 m, 1.0 m, 1.5 m, 2.0 m. Because other conditions such as precipitation is not modified, the results still follow three-phases pattern. Top: spring discharges at Wakulla Spring and SCSC under different sea level rising, WS is Wakulla Spring, SC is Spring Creek Spring Complex; Bottom: the distance of seawater intrusion in conduit system under different sea level rising, the sea-fresh water profile is defined as 2 PSU.

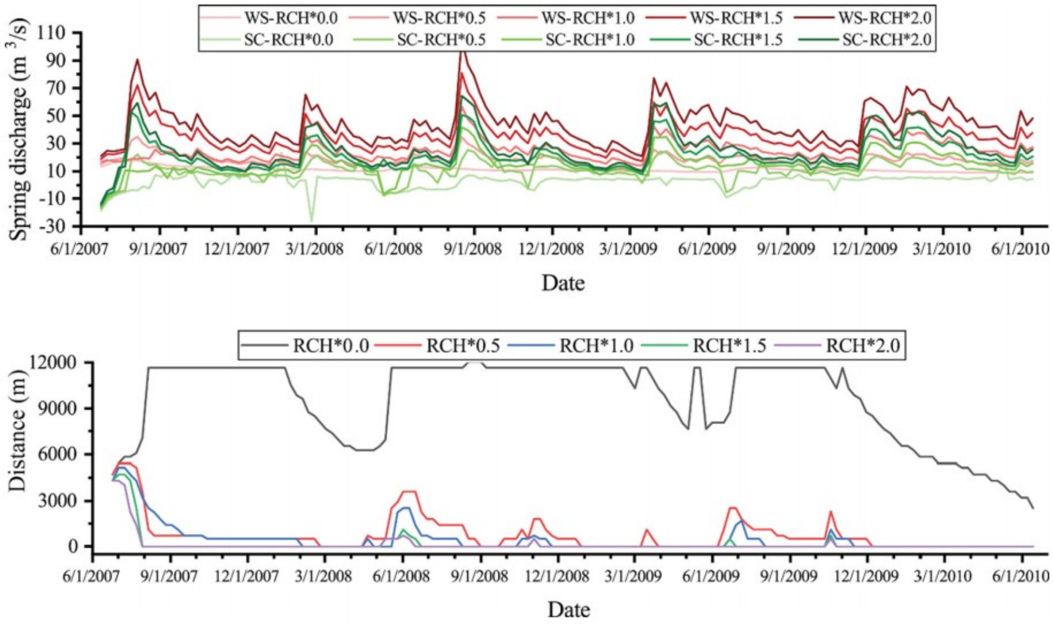

Fig 7. Simulation results of predictions on various extreme precipitation conditions, 4 cases of precipitation are considered: 0.0, 0.5, 1.5 and 2.0 times of current precipitation. Top: spring discharges at Wakulla Spring and SCSC under different precipitation conditions, WS is Wakulla Spring, SC is Spring Creek Spring Complex; Bottom: the distance of seawater intrusion in conduit system under different precipitation conditions, the sea-fresh water profile is defined as 2 PSU.

6. Discussion

Spring discharge is used to calibrate the conduit hydraulic parameters. the Nash–Sutcliffe model efficiency coefficient values between the simulation results and observed data are calculated. However, this calibration does not perform as well as the previous CFPv2 model (Xu et al., 2015b), two major reasons may cause this problem. Firstly, because a much finer vertical discretization is required in variable-density groundwater model for accurately simulating equivalent freshwater head (Werner et al., 2013), the horizontal resolution has to be reduced in comparison with CFPv2 model (Xu et al., 2015b) to save computation cost. The uncertainty in location and dimension of conduit system, and the numerical dispersion in the model may increase in this study. Secondly, conduit flow could be non-laminar or even turbulent, which, however, is not accurately simulated in the SEAWAT model since the laminar Darcy equation is used to solve the flow in conduits. This may result in relatively large error, particularly in the estimation of seawater intrusion along the conduit network where flow velocity is high and non-laminar. In Xu et al. (2015b), a discrete-continuum model CFPv2 is developed to address this issue by coupling the non-laminar flow in karst conduit and laminar flow in porous medium. However, in their study, seawater intrusion is not simulated by variable-density processes and salinity distribution could not be simulated.

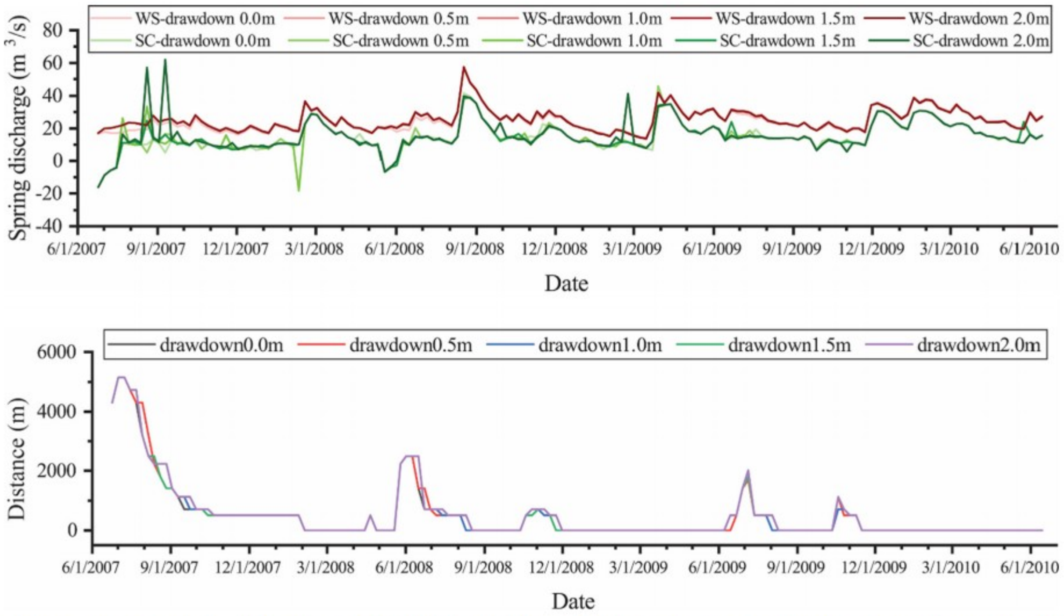

Fig 8. Simulation results of predictions on different head drops in city area due to water pumping, 4 cases of precipitation are considered: 0.5, 1.0, 1.5 and 2.0 m drops from current head value on the north boundary. Top: spring discharges at Wakulla Spring and SCSC under different head drops, WS is Wakulla Spring, SC is Spring Creek Spring Complex; Bottom: the distance of seawater intrusion in conduit system under different head drops, the sea-fresh water profile is defined as 2 PSU.

Other uncertainty factors in this model include (Xu et al., 2015b): 1) Data availability, quality and accuracy since salinity data in the WKP is seldomly measured. Currently, only several flowmeters are installed to collect salinity data from two springs and karst vents. Unfortunately, salinity observations in the monitoring wells in the aquifer are not available but could be very helpful for model calibration and validation; 2) The temporal resolution in the model is 7 days, which is hard to capture the daily variation, such as a heavy rain and tidal effect, which generally last less than 24 h; 3) The geometry of subsurface conduit network and the depth of caves at Spring Creek Spring is still unknown and highly risk to explore. The assumed depth in this study is

91.4 m based on cave diver exploration, however, a higher or lower depth may affect the simulation result; 4) No precipitation data are available at south part of the WKP in the time period of this study, as precipitation data recorded at Tallahassee Airport may be different from the coastal area. The inconsistence between observations and measurements is partially due to the precipitation heterogeneity. For example, a large rainfall period at August 2007 did not significantly decrease the observed salinity at SCSC, but still caused a big effect on simulation result.

Furthermore, groundwater pumping is another concern, which is still unclear. In this study, we simply analyzed the water pumping as head drops, while the exact pumping rate, water usage in a long time period and population growth are not fully addressed. Currently, major pumping is far away from coastal area and karst conduit system in the study area, and has not caused a significant freshwater reduction. Also, the major contribution areas of supply wells in the Tallahassee City are mainly in the north (Davis and Katz, 2007), which has limited impact on the water flow in the conduit system.

7. Conclusion

In this study, a three-dimensional SEAWAT model is developed in a coastal karst aquifer to study variable-density flow and seawater intrusion through the conduit network in the Woodville Karst Plain. The extents of seawater intrusion under different periods of the groundwater flow cycling with precipitation, spring discharge and salinity distribution are investigated. Based on the simulation results, the major conclusions are listed below:

1. The developed model is applied to simulate the salinity distributions and estimate the extent of seawater intrusion through conduit networks in the WKP from 2007 to 2010. The results show that both spring discharge and salinity distribution are very sensitive to the precipitation variation. The salinity and discharge variations based on the three-phase conceptual model (Davis and Verdi, 2014) are well simulated by the three-dimensional SEAWAT model. This study examines and verifies the capability of simulating seawater and freshwater interaction using a three-dimensional model in a regional scale.

2. The seawater intrusion distance in the conduit system and porous media are quantitatively estimated. The seawater mainly intrudes the aquifer through conduit system, the intrusion reaches 5 km in the phase 1 and intruded seawater is pushed out of the conduit during high rainfall event. The seawater intrusion to porous medium keeps relatively constant in different phases. In general, the seawater intrusion in porous medium during extended no rainfall period 1 is slightly further landward than conduit system in Phase 2 and Phase 3, the width of salt plume in porous medium around the conduit network is 500 to 1000 m. The porous medium below the conduit system is strongly contaminated by the seawater intrusion in the conduit. While, some saltwater still remains in the porous medium in the wet season even though the saltwater in the

conduit system is pushed out. In a long-time process, more salt remains in this region, which may further deteriorate the local freshwater system.

3. Three scenario cases are studied in this paper, including sea level rise, extreme precipitation and groundwater pumping. The results show that seawater intrusion is extended and becomes a serious environmental problem in the sea level rise and no precipitation conditions. Salinity plume in the sea level rise condition shows a long-distance seawater intrusion in the conduit system. The intrusion distance could extend to 17 km inland in 2.0 m sea level rise condition, and extensive contamination occurs, even reach Wakulla Spring. Salinity plume under a low precipitation condition shows a much wider distribution in the porous media. However, the groundwater pumping in the Tallahassee City has limited effect on the seawater intrusion.

In summary, this study provides a quantitative estimation of seawater intrusion and freshwater discharge along the conduit network and the surrounding porous medium. The study results could help future environmental protection in sea level rise and extreme precipitation events due to climate change, and improve our understanding on seawater intrusion and salinity distribution in the Woodville Karst Plain.

Based on the study results, we suggest new stations need to be installed to monitor long-term salinity variation in the study area. More field observations and experiments are needed to provide more detailed groundwater flow field and conduit distribution among Wakulla Spring, Lost Creek Sink and SCSC. For modeling the seawater intrusion in this coastal karst aquifer, more advanced numerical approach is needed to couple the variable-density flow and discrete continuum model. If the computation time can be reduced in the future or parallel computing can be implemented, higher resolution, smaller time discretization should be applied and surface water-groundwater exchange can be modeled. Seawater flooding and tidal fluctuations should be monitored in detail and considered in the numerical simulation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was partially supported by National Nature Science Foundation of China (Grant No. 41530316). The authors would like to thank Dr. Ming Ye and Dr. Stephen Kish at Florida State University, United States for providing useful insights and comments during the development of the numerical model. The authors want to express appreciation to Dr. Hal Davis for the primary groundwater model of Woodville Karst Plain. We also would like to thank the editors and reviewers' constructive comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.124171.

References

Abdollahi-Nasab, A., Boufadel, M.C., Li, H., Weaver, J., 2010. Saltwater flushing by freshwater in a laboratory beach. J. Hydrol. 386, 1–12.

Arfib, B., Cavalera, T., Gilli, E., 2006. Influence de l’hydrodynamique sur l’intrusion saline en aquifer karstiquecotier (Influence of hydrodynamics on saline intrusion in the karstic coastal aquifer). ComptesRendus Geosci. 11.

Bakker, M., 1998. Transient Dupuit interface flow with partially penetrating features. Water Resour. Res 34, 2911–2918.

Bear, J., Beljin, M.S., Ross, R.R., 1992. Fundamentals of ground-water modelling. EPA: Ground Water Issue 540/S-92/005.

Bear, J., Cheng, A.H.-D., Sorek, S., Ouazar, D., Herrera, I., 1999. Seawater Intrusion in Coastal Aquifers. Springer. Benoit, A.T., 1992. Characterization of karst development in Leon County, Florida, for the delineation of wellhead protection areas. Water Resour. Specl. Rep. 92–8, 83 p.

Boufadel, M.C., Suidan, M.T., Venosa, A.D., 1999. A numerical model for density-andviscosity-dependent flows in two-dimensional variably-saturated porous media. J. Contam. Hydrol. 36, 1–20.

Bush, P.W., Johnston, R.H., 1988. Ground-water hydraulics, regional flow, andgroundwater development of the Floridan aquifer system in Florida andparts of Georgia, South Carolina, and Alabama. U.S. Geol. Survey Professional Paper 1403-C, 80 p.

Chang, Y., Hu, B.X., Xu, Z., Li, Xue, Tong, J., Chen, L., Zhang, H., Miao, J., Liu, H., Ma, Z., 2018. Numerical simulation of seawater intrusion to coastal aquifers and brine water/freshwater interaction in south coast of Laizhou Bay, China. J. Contamin. Hydrol. 215, 1–10.

Davis, J.H. and Katz, B.G., 2007. Hydrogeologic investigation, water chemistryanalysis, and modeldelineation of contributing areas for City of Tallahasseepublic-supply wells, Tallahassee, Florida. U.S. Geological Survey ScientificInvestigations Report 2007–5070. USGS, Tallahassee, Florida, pp. 67.

Davis, J.H., Katz, B.G., Griffin, D.W., 2010. Nitrate-N movement in groundwater from the land application of treated municipal wastewater and other sources in the Wakulla Springs Springshed, Leon and Wakulla counties, Florida, 1966–2018. US. GeolSurv. Sci. Invest. Rep. 5099, 90 p.

Davis, J.H., Verdi, R., 2014. Groundwater flow cycling between a submarine spring and an inland fresh water spring. Groundwater 52 (5), 705–716.

Dagan, G., Zeitoun, D.G., 1998. Seawater–freshwater interface in a stratified aquifer of random permeability distribution. J. ContamHydrol. 29, 185–203.

Dyer, S.B., 2015. Dye tracing confirms conduit connections from Lost Creek Swallet to Spring Creek Springs and the Leon Sinks - Wakulla cave system. Master Thesis. Florida State University, Tallahassee, Florida.

Famiglietti, J.S., 2014. The global groundwater crisis. Nat. Clim. Chang 4, 945–948.

Faulkner, J., Hu, B.X., Kish, S., Hua, F., 2009. Laboratory analog and Numerical study of groundwater flow and solute transport in a karst aquifer with conduit and matrix domains. J. Contamin. Hydrol. 110, 34–44.

Fleury, P., Bakalowicz, M., de Marsily, G., 2007. Submarine springs and coastal karst aquifers: a review. J. Hydrol. 339 (1), 79–92.

FLDEP, 2008. Unpublished map of sinkholes and closed depressions in Wakulla County. Florida Department of Environmental Protection-Springs Initiative Program, Tallahassee, Florida.

Florida Springs Task Force, 2000. Florida’s springs: strategies for protection and restoration. Florida Department of Environmental Protection, Florida, United States.

Fretwell, J.D., Stewart, M.T., 1981. Resistivity study of a coastal karst terrain, Florida. Ground Water 19, 156–162.

Gallegos, J.J., Hu, B.X., Davis, H., 2013. Simulating flow in karst aquifers at laboratory and sub-regional scales using MODFLOW-CFP. Hydrogeology 21, 1749–1760.

Ginsberg, A., Levanon, A., 1976. Determination of a salt–water interface by electrical resistivity soundings. Hydrol. Sci. Bull. 21, 561–568.

Greaver, T.L., Sternberg, L.S.L., 2010. Decreased precipitation exacerbates the effects of sealevel on coastal dune ecosystems in open ocean islands. Global Change Biol. 16, 1860–1869.

Guo, W., Langevin, C. 2002. User's guide to SEWAT: a computer program for simulation of three-dimensional variable-density ground-water flow. Water Resources Investigations Report. U.S. Geological Survey Techniques and Methods Book 6, Chapter A7, pp. 77.

IPCC, 2007. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,104 pp., Geneva, Switzerland.

Kincaid, T.R., Hazlett, T.J., Davies, G.J., 2005. Quantitative groundwater tracing and effective numerical modeling in karst: an example from the Woodville Karst Plain of North Florida. Sinkholes and the engineering and environmental impacts of karst, pp. 114–121.

Kipp, K.L., 1997. Guide to the revised heat and solute transport simulator: HST3D-Version 2. U.S.Geological Survey Water-Resources Investigations Report 97–4157. pp. 149.

Harbaugh, A.W., 2005. MODFLOW-2005, the US Geological Survey modular groundwater model: the ground-water flow process. US Department of the Interior, USGS Reston, VA, USA.

Kincaid, T., Davies, G., Werner, C., Dehan, R., 2012. Demonstrating interconnection between a wastewater application facility and a first magnitude spring in a karstic watershed: tracer study of the southeast farm wastewater reuse facility, Tallahassee, Florida. Florida Geol. Survey ISSN 0160-0931.

Lane, E., 2001. The Spring Creek Submarine Springs Group. Wakulla County, Florida Florida Geological Survey.

Langevin, C.D., Shoemaker, W.B. and Guo, W. (2003) MODFLOW-2000, the US Geological Survey Modular Ground-Water Model–Documentation of the SEAWAT2000 Version with the Variable-Density Flow Process (VDF) and the Integrated MT3DMS Transport Process (IMT). US Department of the Interior, US Geological Survey, Open File Report pp. 43.

Langevin, C.D., Thorne, D.T., Dausman, A.M., Sukop, M.C. and Guo, W., 2008. SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport. U.S. Geological Survey Techniques and Methods Book 6, Chapter A22: pp. 39.

Langevin, C.D., Dausman, A.M., Sukop, M.C., 2010. Solute and heat transport model of the Henry and Hilleke laboratory experiment. Ground Water 48, 757–770.

Li, G., 2012. Calculation of karst conduit flow using dye tracing experiments. Transp. Porous Med. 95, 551–562.

Li, H.L., Boufadel, M.C., 2010. Long-term persistence of oil from the Exxon Valdez spill in two-layer beaches. Nat. Geosci. 3 (2), 96–99.

Li, X., Hu, Burnett, B.X., Santos, B., Chanton, I.R., Chanton, J.P., 2009. Submarine ground water discharge driven by tidal pumping in a heterogeneous aquifer. Ground Water 47 (4), 558–568.

Loper, D.E., Werner, C.L., Chicken, E., Davies, G., Kincaid, T., 2005. Coastal carbonate aquifer sensitivity to tides. Eos, Trans. Am. Geophys. Union 86 (39), 353–357.

Paster, A., Dagan, G., Guttman, J., 2006. The salt-water body in the Northern part ofYarkon-Taninim aquifer: field data analysis, conceptual model andprediction. J. Hydrol. 323, 154–167.

Poeter, E.P., Hill, M.C., Banta, E.R., Mehl, Steffen, Christensen, Steen, 2005. UCODE_2005 and six other computer codes for universal sensitivity analysis, calibration, and uncertainty evaluation. U.S. Geol. Surv. Techniq. Methods 6–A11, 283p.

Reilly, T.E., Goodman, A.S., 1985. Quantitative-analysis of saltwater fresh-water relationships in groundwater systems – a historical perspective. J. Hydrol. 80, 125–160.

Reimann, T., Geyer, T., Shoemaker, W.B., Liedl, R., Sauter, M., 2011. Effects of dynamically variable saturation and matrix-conduit coupling of flow in karst aquifers. Water Resour. Res. 47 (11).

Reimann, T., Liedl, R., Giese, M., Geyer, T., Maréchal, J-C., Dörfliger, N., Bauer, S., Birk, S., 2013. Addition and Enhancement of Flow and Transport processes to the MODFLOW-2005 Conduit Flow Process. 2013 NGWA Summit-The National and International Conference on Groundwater, 28 April–2 May San Antonio, TX.

Reimann, T., Giese, M., Geyer, T., Liedl, R., Maréchal, J.-C., Shoemaker, W.B., 2014. Representation of water abstraction from a karst conduit with numerical discretecontinuum models. Hydrol. Earth Syst. Sci. 18 (1), 227–241.

Sanford, W.E., Konikow, L.F. 1985. A two-constituent solute-transport model for groundwater having variable density. U.S. Geological Survey Water-Resources Investigations Report 85-4279: pp. 88.

Shalev, E., Lazar, A., Wollman, S., Kington, S., Yechieli, Y., Gvirtzman, H., 2009. Biasedmonitoring of fresh water-salt water mixing zone in coastal aquifers. GroundWater 47, 49–56.

Shoemaker, W.B., Kuniansky, E.L., Birk, S., Bauer, S., Swain, E.D., 2008. Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005. U.S. Geological Survey Techniques and Methods, Book 6, Chapter A24, pp. 50.

USGS (United States Geological Survey)(2013)http://fl.water.usgs.gov/et/data/2013/ index.html.

USGS (United States Geological Survey) (2019) USGS gage 02327000 Wakulla Spring near Crawfordville, Fl. https://waterdata.usgs.gov/nwis/inventory/?site_ no=02327000.

Varis, O., Biswas, A.K., Tortajada, C., Lundqvist, J., 2006. Megacities and water management. Int. J. Water Resour. Dev. 22, 377–394.

Voss, C.I., 1984. A finite-element simulation model for saturated-unsaturated, fluiddensity-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport. U.S. Geological Survey Water-Resources Investigation Report 84-4369 pp. 409.

Wada, Y., et al., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37, L20402.

Werner, A.D., et al., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv. Water Resour. 51, 3–26.

Xu, Z., Hu, B.X., Davis, H., Cao, J., 2015a. Simulating long term nitrate-N contamination processes in the Woodville Karst Plain using CFPv2 with UMT3D. J. Hydrol. 524, 72–88.

Xu, Z., Hu, B.X., Davis, H., Kish, S., 2015b. Numerical study of groundwater flow cycling controlled by seawater/freshwater interaction in a coastal karst aquifer through conduit network using CFPv2. J. Contam. Hydrol. 182, 131–145.

Xu, Z., Bassett, S.W., Hu, B.X., Dyer, S.B., 2016. Long distance seawater intrusion through a karst conduit network in the Woodville Karst Plain, Florida. Scient. Rep. 6, 32235.

Xu, Z., Hu, B.X., 2017. Development of a discrete-continuum VDFST-CFP numerical model for simulating seawater intrusion to a coastal karst aquifer with a conduit system. Water Resour. Res. 53, 688–711. https://doi.org/10.1002/2016WR018758.

Xu, Z., Hu, B.X., Ye, M., 2018a. Numerical modeling and sensitivity analysis of seawater intrusion in a dual-permeability coastal karst aquifer with conduit networks. Hydrol. Earth Syst. Sci. 22, 221–239.

Xu, Z., Massei, N., Padilia, I., Hartmann, A., Hu, B.X., 2018b. Characterization, modelling and remediation of karst in a changing environment. Environ. Earth Sci. 77 (12), 476–478.

Xu, Z., Hu, B.X., Xu, Z., Wu, X., 2019. Simulating seawater intrusion in a complex coastal karst aquifer using an improved variable-density flow and solute transport–conduit flow process model. Hydrogeol. J. 27 (4), 1277–1289.

Zheng, C., Wang, P. P. 1999. MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide, DTIC Document.