

Authors' response:

HESS-2017-85: Xu et al., Numerical modeling and sensitivity analysis of seawater intrusion in a dual-permeability coastal karst aquifer with conduit networks, Hydrol. Earth Syst. Sci. Discuss.,

5

Anonymous Referee #1

Received and published: 19 April 2017

In the submitted paper Xu et al. apply local and global sensitivity analysis on a density driven distributed model (SEAWAT) to simulate a coastal aquifer in Florida (US). They use the knowledge of previous studies to define the boundary conditions and initial parameter sets of the model. Then they apply a local sensitivity analysis on the 11 model parameters in respect to various output variables of the simulated matrix and conduit systems. The same analysis is repeated with a global sensitivity analysis method (Morris) to account for interactions among the model parameters. The parameter describing the salinity at the submarine spring outlet was found to be most sensitive but also the parameters describing the conduit properties were found to influence both the conduit and the matrix behaviour. The results of the more elaborate global sensitivity analysis scheme differ for several model parameters indicating that parameter interactions have to be considered. Finally, the authors use the simulations obtained by the sensitivity analysis to conclude about the sensitivity of the karst system to external changes and about the most gaining observations concerning model parameter identification.

The paper tackles a very interesting field of research, which is the evaluation of distributed models via sensitivity analysis. The authors clearly show that such analysis provides valuable understanding of the model and system and they also highlight that the choice of the sensitivity analysis method has strong impact on the results and conclusions. For those reasons I definitely recommend this paper for publication in Hydrology and Earth System Sciences. However, some weaknesses have to be removed first:

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Response: Thanks for the positive evaluation of our work, and we agree that a revision is necessary to improve the quality of the manuscript for publication in HESS. Below are our responses to address the review comments. We would like to further revise the manuscript after the editor makes a decision on this paper.

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1. The paper is much too long. In their last paragraph of the conclusions (and also in the abstract) the authors clearly state the main outcomes of their research. However, within the body of the manuscript, they lose themselves in details too often.

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Response: We agree that it is necessary to reduce the manuscript length. We plan to shorten the introduction section and to remove the redundancy in the result section. The main outcomes of this study will be highlighted in the conclusion part and throughout the manuscript.

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2. The usage of two sensitivity analysis schemes provides a lot of insights into their differences. However, the authors do not explain why they actually compare them. For many modellers the interaction among parameters is an accepted fact. So for the sake of focus and length of the manuscript: Is it really necessary including the local sensitivity analysis? If not, delete. If yes, provide more explanation why.

50

Response: We believe it is still necessary to include the local sensitivity analysis in the paper, since it presents the parameter sensitivities in the maximum seawater intrusion case, in which seawater intrudes significantly inland. The authors and readers have special interests in understanding the seawater intrusion under such particular scenario. In addition, local sensitivity study is cheap in computational, and easy to compute.

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Comparing the results of local/global sensitivity analysis may help us understand: (1) whether the parameter correlation affect the identification of important parameters, (2) whether the nonlinearity of the model affect the identification of important parameters.

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The parameter correlation and nonlinear significantly affect the results of sensitivity

analysis, as we see different ranking of important model parameters. Therefore, we need pay special attention to these issues when we conduct model calibration and/or uncertainty analysis.

65 3. Some more links between the model setup and field observations/previous work is necessary. It is clear that a lot of previous work was done at the study site. But sometimes it would be helpful providing some summarizing information in addition to the reference to the previous studies.

70 Response: We thank the reviewer for this suggestion, and will add a more detailed introduction of model setup with its connection to previous studies in this area. We will also add a brief summary of the implications from previous modeling studies in the model setup section. With respect to previous work on sensitivity analysis, Shoemaker et al. (2004) is the only paper that we are aware of for parameter sensitivities in seawater
75 intrusion, although there are several studies about parameter sensitivities and uncertainty quantification in karst aquifer. We plan to include these literatures in this paper during the revision.

4. The elaboration of Morris's method has to be improved.

80 Response: We will refine the elaboration of Morris' method with an improved introduction.

5. A clear discussion relating these results to the result of other is missing.

85 Response: We don't fully understand the reviewer's question. If the reviewer wants us to compare this study with other studies, however, there is no other studies ever addressed the same issue before. In previous answers, we also answered that a more detailed discussion of the previous studies on sensitivity analysis (Shoemaker et al. 2004) will be
90 included in the revised manuscript.

6. No state of the art of sensitivity analysis is missing (and no comparison to other sensitivity analysis studies with lumped or distributed approaches in karst).

95 **Response: We are only aware of several papers on sensitivity analysis for karst aquifers, and will compare the previous studies with this study, although the researches focus on different site and scientific questions. The meaning and benefits of sensitivity analysis of this and other researches will be highlighted in the introduction and conclusion parts to better present the overall objectives of this study.**

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I think these corrections can all be done within the frame of moderate revisions. Please find some more specific comments in the attached and commented pdf.

Response: We thank the reviewer for the detailed comments, and will address them during the revision.

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Anonymous Referee #2

The paper by Xu et al. presents the analysis of results with using local and global sensitivity analysis and different scenarios on a karst coastal aquifer system with seawater intrusion. The topic is potentially very interesting but to be useful to the reader, the paper needs significant improvements. The main concern is about the overall goal of the study. The abstract concentrate mainly on the comparison between local and global sensitivity results, but then a significant portion of the paper deals with scenarios.

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From a first reading, it is not clear the purpose of developing all these scenarios and how this connects to the previous sensitivity analysis. From my understanding, the scenarios are developed based on the most sensitive parameters and are expected to show how changes in those parameters can affect the results, but this needs to be more clearly explained.

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Response: The reviewer is right about the purpose of having the scenarios in the sensitivity analysis. Based on the sensitivity analysis results, we set up the scenarios by changing the important parameters. The physical meanings of the changing parameters indicate either sea level, precipitation discharge or the length of drought period. For example, the extent of seawater intrusion is quantitatively measured in the scenarios of various sea levels. Although hydraulic conductivity is relatively an important parameter as well, the scenarios of various K are not simulated since it is a constant in a specified study site without change with time. We will attach a clearer explanation in the revised manuscript.

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I have serious concerns about how the local sensitivity results are presented: the analysis lacks completely the presentation of the parameter correlation coefficients which are provided as output by UCODE, but are not presented here. CSS without parameter correlation coefficients is not informative and needs to be combined to the correlation analysis.

135

Response: We respectfully disagree with the reviewer for several reasons. First of all, our local sensitivity analysis is based on CSS, which was defined in Section 2.1 of the manuscript. In addition, if we are not mistaken, CSS does not consider parameter correlation but data correlation. Taking equation (2) of our manuscript (equation 4.5 of the book of Hill and Tiedeman cited in the manuscript), the covariance matrix, ω , is for data, not for parameters. In fact, the conventional local sensitivity analysis (e.g., the one used in UCODE and also in this study) does not address parameter correlation. This was part of the reason of conducting the Morris-based global sensitivity analysis.

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Furthermore, there is not good explanation of which observations are used in this analysis. There should be heads and salinity field observations, but it is not clear how many, where and mostly which is the weight which is applied to each observation.

150 Response: When conducting sensitivity analysis, we do not need to have “field
observations”. We only need to know which “model simulations” are sensitivity to which
parameters. We can have many model simulations. Very little head and salinity
observations can be used in this analysis, since it is extremely difficult to collect water
155 samples or install sensors in the subsurface karst conduits (100 meter deep). Xu et al.
(2016) summarized the existed field observations within the conduit system. However,
these measurements are far inland and not applicable to be used for model calibration in
this study.

How are the local sensitivity analysis results used to build the simulations for global
160 sensitivity analysis? Are the same parameters included in both the analyses? Which are
the key additional information that we are getting from this double analysis? Often local
sensitivity results can be used to discriminate which parameters should be included in the
global sensitivity analysis, but this does not seem to be the case in this paper. The two
analyses seem to be performed exactly on the same set of parameters.

165 Response: We did not use the local sensitivity results to build the simulations for global
sensitivity analysis. Both the local and global sensitivity analyses evaluate the same
parameters. However, the global analysis evaluates parameters within a certain range,
while the local analysis only evaluates the specified parameter values specifically for the
170 study region (WKP). The key additional information in global sensitivity analysis is the
assessments of parameter sensitivities within the range and the parameter
interaction/correlation with each other.

The introduction is too long and does not get exactly to the point of the paper. Sensitivity
175 analysis and calibration of similar models have already been performed and it would be
good to point out where. The discussion of the sensitivity analysis results and of the
different scenarios should be organized and made more concise. There are also some
inconsistencies with the parameter names that should be checked. My suggestion would

180 be to develop a summary table with all the results for both sensitivity and again for the
scenarios to help the reader understanding which are the key findings of this analysis.

185 **Response:** We thank the reviewer for the excellent suggestion. We will shorten the
introduction, link this research with previous sensitivity studies in karst, and highlight the
overall objective of this study. The result and discussion parts will be re-written and re-
organized. A summary with bullet points are made in the conclusion section to highlight
the major findings in this study.

Some more specific comments include:

190 1.48-49: are the parameters mentioned here calibrated parameters?

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Response: These are the parameters and boundary conditions adjusted in the scenarios
simulations. All the parameters of aquifer characteristics are calibrated.

195 1. 132: Which are the issues with VDFST-CFP? Why cannot be used in this case?
Without explanation it is not clear why this other method should be mentioned.

200 **Response:** VDFST-CFP is not able to hand the issue addressed in this paper, because of
computational issues related to the aquifer geometry and the scale of spatial domain. The
numerical model in this study is setup to study seawater intrusion in a field scale, with the
real dimension and parameter values of the porous medium and the conduit in the aquifer.
The current version VDFST-CFP is not able to simulate groundwater flow and solute
transport within a large conduit network, because the discrete-continuum modeling
method requires the cell size to be at least one order of magnitude larger than the conduit
diameter. The computational cost is another constraint. For more details, please refer to
205 Xu and Hu (2017, WRR). We will add a brief explanation in the manuscript to explain
why VDFST-CFP is not applicable to this study.

L. 207: please spell out EEs

210 Response: EEs is the abbreviation for element effects, which was spelled out above
equation (4) of the manuscript. The reviewer probably missed the spell-out.

1. 287: the goal here seems to be just performing sensitivity analysis and not calibration.
But for running the scenarios, it should be clarified how the values of the parameters have
215 been selected. After which type of calibration? Or the values calibrated in previous
studies have been used?

Response: While the reviewer is correct that calibration is always performed to obtain the
nominal values used for local sensitivity analysis, we want to point out that the nominal
220 values can be selected based on literature data without conducting model calibration. This
may be a limitation for the local sensitivity analysis, because it is not an easy task to
selecting nominal parameter values. This problem can be resolved by conducting a global
sensitivity analysis, which does not require nominal parameters values but parameter
ranges (the ranges can be easily determined based on a literature review). In this study,
225 for the local sensitivity analysis, we did not conduct model calibration, since there is no
observational data available to calibrate the model, especially the simulations within the
conduit network. The parameter values of aquifer properties (hydraulic conductivity,
effective porosity, specific storage, and dispersion coefficient) used in this study are
based on a literature review of previous modeling studies in this study area. Information
230 on this regard was provided in section 3.1, but we will provide more detailed information
to clarify in the revised manuscript.

1. 453: why the arithmetic mean of CSS?

235 Response: Here we mean the average of CSS values in all evaluated locations (cell #25 -
#75 along the conduit/porous medium layer).

1.470: this was already said at line 455. The discussion should be more compact and better organized.

240

Response: We will delete the redundant sentence.

1. 568: “groundwater seepage velocity” : are these used as observations?

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Response: Groundwater seepage velocity is not used as observations or model simulation in this study. We actually don't have any observation in this study. See the answers above.

1. 610: clarify which are the field observations and how they have been weighted

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Response: We will clarify in the revised manuscript that we did not use any observations for the sensitivity analysis in this paper. As explained above, sensitivity analysis does not require observations. This paragraph is talking about the implication and significance of sensitivity analysis on understanding seawater intrusion in karst aquifer. This study points out that the head and salinity field observations and numerical simulations within the conduit network are particularly important.

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1. 619-621: check the English

Response: We will break this long sentence.

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1. 626: the DSP package was not mentioned earlier

Response: DSP means the dispersion package in SEAWAT. We tried to deactivate the DSP package to verify that dispersion is negligible within the conduit network in this study. We will clarify this in the revised manuscript

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l. 630: local sensitivity allows as well to understand interactions and correlations between parameters but it is not presented here

270 **Response:** We respectfully disagree with the review that the conventional local sensitivity analysis used in this study considers parameter interaction and correlation. Because the local sensitivity is based on the first order derivative of a model simulation with respect to a model parameter, it does not consider parameter interaction/correlation. We would appreciate, if the review could provide some references in which local sensitivity analysis address parameter interaction/correlation.
275

Chapter 5: how are the parameters for these scenarios defined? It would be useful to make a stronger link between the sensitivity analysis exercise presented above and these scenarios. What is the final goal?

280 **Response:** We thank the reviewer for the excellent suggestion for linking between the sensitivity analysis and the scenarios, and this will be added in the revised manuscript. The goal of having these scenarios is to quantitatively evaluate the distance of seawater intrusion within conduit and its effects on the surrounding porous medium, under different scenarios. The distance between the shoreline and the interface of seawater and freshwater mixing is measured as the quantity for evaluating seawater intrusion.
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l. 643: How “quantitatively”?

290 **Response:** Please see the answer above.

l. 684: “sensitivity analysis”: to which one do you refer? Global or local sensitivity analysis results? The distinction should be made more explicit for all the scenarios.

295 **Response:** We mean both local and global sensitivity analysis results. We will clarify this in the revised manuscript.

References:

300 Xu et al., 2016, Long distance seawater intrusion through a karst conduit network in the
Woodville Karst Plain, Florida, Scientific Report 6, 32235.

Xu, Z. and 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 Resources Research 53(1), 688-711.

305 Additional author comment:

Here is a brief summary of the changes made in the manuscript:

- 1) Shorten and restructure the introduction
- 2) Revise the elaboration of global sensitivity analysis by Morris method
- 3) Almost completely rewrite the section of sensitivity result part (section 4) by
310 discussing each major finding separately in the paragraph.
- 4) Clearly state that the local sensitivity analysis is necessary to be included, since it
presents the parameter sensitivities particularly for modeling seawater intrusion in the
WKP (with the specified values of parameters in WKP). The global sensitivity analysis
evaluates the parameter sensitivities within the ranges in general, in addition to the
315 parameter non-linearity and interaction.
- 5) Completely rewrite the conclusion section with bullet points to highlight the major
findings from sensitivities analysis

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Numerical modeling and sensitivity analysis of seawater intrusion in a dual-permeability coastal karst aquifer with conduit networks

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Submitted to Hydrology and Earth System Sciences

Abstract

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Long distance seawater intrusion is widely observed through the highly permeable subsurface conduit system, and contaminates groundwater resources **in coastal karst**

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350 aquifers. In this study, a two-dimensional density-dependent flow and transport SEAWAT model is created to study seawater intrusion in the dual-permeability karst aquifer with conduit networks. To understand seawater intrusion in such an aquifer, local and global sensitivity analysis are used to evaluate the effects of boundary conditions and hydrological characteristics, including hydraulic conductivity, effective porosity, specific storage and dispersivity of the conduit and the porous medium on modeling simulations.

355 The local sensitivity evaluates the parameters sensitivities specifically for modeling seawater intrusion in the WKP. The global sensitivity analysis provides a more comprehensive interpretation of parameter sensitivities within the ranges, due to the non-linear relationship between simulations and parameters. The conduit parameters are important to the simulations in the porous medium, because of the interaction between the two systems. Therefore, salinity and head simulations in the karst features, such as the

360 conduit system and submarine springs, are critical for understanding seawater intrusion in a coastal karst aquifer. In the continuum SEAWAT model, Darcy's equation does not accurately compute the conduit flow velocity by head difference and hydraulic conductivity. In addition, dispersivity is no longer an important parameter in advection-dominated karst aquifer with conduit system, compared to the sensitivity results in a

365 porous medium aquifer. Finally, the extents of seawater intrusion are quantitatively evaluated under the scenarios of changing the important parameters identified from sensitivity results, including salinity at the submarine spring with rainfall recharge, sea level rise and longer simulation time under an extended low rainfall period.

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420 Key Words: Seawater intrusion; Coastal karst aquifer; Variable-density numerical model;
Dual-permeability karst system; Sensitivity analysis

1. Introduction

425 Many serious environmental issues have been caused by seawater intrusion in the
coastal regions, such as soil salinization, marine and estuarine ecological changes, and
groundwater contamination (Bear, 1999). Werner et al. (2013) pointed out that climate
430 variations, groundwater pumping, and fluctuating sea levels are important factors to the
mixing of seawater and freshwater in the aquifer. Custodio (1987) and Shoemaker (2004)
summarized the control factors of seawater intrusion into a coastal aquifer, including the
geologic and lithological heterogeneity, localized surface recharge, paleo-
435 hydrogeological conditions and anthropogenic influences. Meanwhile, seawater intrusion
in a coastal aquifer is significantly impacted by sea level rise, which has been recognized
as a serious environmental threat in this century (Voss and Souza, 1987; Bear, 1999;
IPCC, 2007). The Ghyben-Herzberg relationship presents that a small rise of sea level
440 would cause extended seawater intrusion, and significantly moves the mixing interface
position further landward in a coastal aquifer (Werner and Simmons, 2009). Essink et al.
(2010) pointed out that seawater intrusion is exacerbated under sea level rise and global
climate change. Likewise, high tides associated with hurricanes or tropical storms have
been found to temporarily affect the extent of seawater intrusion in a coastal aquifer
(Moore and Wilson, 2005; Wilson et al., 2011).

Modeling seawater intrusion in a coastal aquifer requires a coupled density-
dependent flow and salt transport groundwater model. The solution of salinity simulation

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is computed by the groundwater velocity field from flow modeling, and salinity in turn determines water density and affects the simulation of flow field. Several variable-density numerical models have been developed and widely used to study seawater intrusion, including SUTRA (Voss and Provost, 1984) and FEFLOW (Diersch, 2002). SEAWAT is a widely used density-dependent model, which solves flow equations by finite difference method, and transport equations by three major classes of numerical techniques (Guo and Langevin, 2002; Langevin et al., 2003). Generally speaking, most variable-density models are numerically complicated and computational expensive, with smaller timestep and implicit procedure of solving flow and transport equations iteratively many times in each timestep (Werner et al., 2013).

On the other hand, a karst aquifer is particularly vulnerable to groundwater contamination including seawater intrusion in a coastal region, since the well-developed sinkholes and karst windows are usually connected by highly permeable subsurface conduit networks. Some karst caves are found open to the sea and become submarine springs below the sea level, connected with the conduit network as natural pathways for seawater intrusion. Fleury et al. (2007) reviewed the studies of freshwater discharge and seawater intrusion through karst conduits and submarine springs in coastal karst aquifers, and summarized the important control factors, including hydraulic gradient of equivalent freshwater head, hydraulic conductivity, and seasonal precipitation variation. For example, preferential flow within a conduit significantly intrudes landward and contaminate the groundwater in a coastal karst aquifer (Calvache and Pulido-Bosch, 1997). As an indicator of rainfall and regional freshwater recharges, salinity at the outlet of conduit system is diluted by freshwater discharge during a rainfall season, but remains

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constant as saline water during a low rainfall period (Martin and Dean, 2001; Martin et al., 2012).

Modeling groundwater flow in a dual-permeability karst aquifer is a challenging issue, since groundwater flow in a karst conduit system is often non-laminar (Davis, 1996; Shoemaker et al., 2008; Gallegos et al., 2013). Several discrete-continuum numerical models, such as MODFLOW-CFPM1 (Shoemaker et al., 2008) and CFPv2 (Reimann et al., 2014; Reimann et al., 2013; Xu et al., 2015a; Xu et al., 2015b), have been developed to simultaneously solve the non-laminar flow in the conduit, the Darcian flow in a porous medium and the exchanges between the two systems. However, these constant-density karst models are not applicable to simulate the density-dependent seawater intrusion processes in a coastal aquifer. Recently, the VDFST-CFP developed by Xu and Hu (2017) is a density-dependent discrete-continuum modeling approach to study seawater intrusion in a coastal karst aquifer with conduits. However, VDFST-CFP is not able to handle the issues addressed in this study, because of the computational constraints associated with the aquifer geometry and the domain scale. For more details, please refer to Xu and Hu (2017). Therefore, the variable-density SEAWAT model is still applied in this study, in which Darcy equation is used to compute flow not only in the porous medium, but also in the conduit with large values of hydraulic conductivity and effective porosity.

Several sensitivity studies have evaluated the parameters in karst aquifers.

Kaufmann and Braun (2000) reported that boundary conditions and sink recharges are important to the preferential flow path in a karst aquifer. Scanlon et al. (2003) also confirmed that recharge is important to karst spring discharge. Very few studies have addressed the parameter sensitivities of seawater intrusion in a coastal karst aquifer.

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- Deleted: The numerical model in this study is developed to study seawater intrusion in the field scale, with the real dimension and parameter values of the porous medium and the conduit in the aquifer, specifically in the Woodville Karst Plain (WKP). The The Woodville Karst Plain (WKP) is a typical coastal karst aquifer, where the Spring Creek Springs (SCS) is a first magnitude spring in the WKP, consisting of 14 submarine springs located in the Gulf of Mexico (Fig. 1). SCS is also an outlet of the subsurface conduit network and the entrance of seawater intrusion, exactly located at (... [4]
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675 Shoemaker (2004) performed a sensitivity analysis of the SEAWAT model for seawater intrusion to a homogeneous porous aquifer, concluded that dispersivity is an important parameter to the head, salinity and groundwater flow simulations and observations in the transition zone. Shoemaker (2004) also concluded that salinity observations are more effective than head observation, and the “toe” of the transition zone is the most effective location for head and salinity simulations and observations. The sensitivity results in this study confirm some conclusions in Shoemaker (2004), and highlight the significance of conduit network on seawater intrusion in a coastal karst aquifer with interaction of a karst conduit and a porous medium.

680 This study aims to understand the impact factors of seawater intrusion to a coastal karst aquifer, and provides guidelines for freshwater resources management. The parameter sensitivities are evaluated to address the effects of the two major challenges in this study, the density-dependent processes and the dual-permeability aquifer system in the model. To our knowledge, this is the first attempt to assess the parameter sensitivities for seawater intrusion to a vulnerable dual-permeability karst aquifer with a conduit network. The rest of the paper is arranged as follows: the details of local and global sensitivity analysis are introduced in Sect. 2. The model setup, hydrological conditions, model discretization, initial and boundary conditions are discussed in Sect. 3. The results of local and global sensitivity analysis are discussed in Sect. 4. The scenarios of seawater intrusion simulation with different boundary conditions and elapsed time are presented in Sect. 5. The conclusions are made in Sect. 6.

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720 **2. Methods**

The governing equations used in the SEAWAT model can be found in the Guo and Langevin (2002), including the variable-density flow equation with additional density terms, and the advection dispersion solute transport equation. The local and global sensitivity methods used in this study are briefly introduced below. Note that the sensitivity analysis does not necessarily need field observations, but only evaluates the model simulations with respect to parameters instead. Field observational data, especially the head and salinity measurements within the conduit, are usually not available. Model calibration is beyond the scope of this study, due to the lack of observational data in the WKP.

730

2.1 Local sensitivity analysis

In this study, UCODE_2005 (Poeter and Hill, 1998) is used in the local sensitivity analysis, which evaluates the derivatives of model simulations with respect to parameters at the specified values (Hill and Tiedeman, 2006). The forward difference approximation of sensitivity is calculated as the derivative of the *i*th simulation respect to the *j*th model parameters,

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$$\left. \frac{\partial y'_i}{\partial x_j} \right|_b \approx \frac{y'_i(x + \Delta x) - y'_i(x)}{\Delta x_j} \quad 1)$$

where y'_i is the value of the *i*th simulation; x_j is the *j*th estimated parameter; x is a vector of the specified values of estimated parameter; Δx is a vector of zeros except that the *j*th parameter equals Δx_j .

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750 The sensitivities are calculated by running the model once using the parameter values in x to obtain $y'_i(x)$, and then changing the j th parameter value and running the model again in $x + \Delta x$ to obtain $y'_i(x + \Delta x)$. Scaled sensitivities are used to compare the parameters sensitivities that may have different units. In UCODE_2005, a scaling method is used to calculate the dimensionless scaled sensitivities (DSS) by the following equation,

$$dss_{ij} = \left(\frac{\partial y'_i}{\partial x_j} \right) \Big|_x |x_j| \omega_{ii}^{1/2} \quad 2)$$

755 where dss_{ij} is the dimensionless scaled sensitivity of the i th simulation with respect to the j th parameter; ω_{ii} is the weight of the i th simulation.

The DSS values of different simulations with respect to each parameter are accumulated as the composite scaled sensitivities (CSS). The CSS of the j th parameter is evaluated via:

$$css_j = \sum_{i=1}^{ND} \left[(dss_{ij})^2 |x_j| / ND \right]^{1/2} \quad 3)$$

760 where ND is the number of simulated quantities, for example, the head and salinity simulations in this study.

2.2 Morris method for global sensitivity analysis

765 The local sensitivity analysis is conceptually straightforward and easy to compute without expensive computational cost. However, it calculates only at one specified value for each parameter instead of the entire parameter ranges. In addition, the indices are approximated in the first order derivative only, assuming a linear relationship of simulated quantities with respect to parameters.

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The global sensitivity analysis evaluates the parameters which may be considered to have the non-linear effects with simulations, and/or involved in interaction with other factors. Morris method is applied to evaluate the global parameter sensitivities in this study (Morris, 1991). The experimental plan proposed by Morris is composed of individually randomized “one-step-at-a-time” (OAT) experiment, which perturbs only one input parameter and gives a new value in each run. The Morris method is made by a number r of local changes at different points of the possible range of input values. In each parameter, a discrete number of values called levels are chosen with the parameter ranges of variation.

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In Morris method, the k -dimensional vector x of the model parameters has components x_i , to be divided into p uniform intervals. The global sensitivity is evaluated by the simulation results with changing one parameter at a time, which is called an elementary effect (EE), d_i , defined as

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$$d_i = \frac{1}{\tau_y} \frac{[y(x_1^*, \dots, x_{i-1}^*, x_i^* + \Delta, x_{i+1}^*, \dots, x_k^*) - y(x_1^*, \dots, x_k^*)]}{\Delta} \quad 4)$$

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where Δ is the relative distance in the coordinate; τ_y is the output scaling factor; $\{x_i^*\}$ is the parameter set selected in a sampling method.

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To compute the EE for the k parameters, $(k+1)$ simulations will run with perturbation of each parameter, which is called one “path” (Saltelli et al., 2004). An ensemble of EEs for each parameter is generated by multiple paths of parameter set. The total number of calculation is $r(k+1)$, where r is the number of paths.

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Two sensitivity measures are proposed by Morris method for each parameter: the mean μ estimates the overall influence of the factor on the output, and the standard

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parameters has components x_i , which can be divided into p uniform intervals. The effect of changing one parameter at a time is evaluated in turn by the elementary effect (EE), d_i , which is defined as, ... [7]

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Moved up [3]: To compute the EE for the k parameters, $(k+1)$ simulations are needed in the same way as local sensitivity method for the perturbation of each parameter, which is called one "path" (Saltelli et al., 2004). An ensemble of EEs for each parameter is generated by multiple paths of randomly generated parameter set. The total number of calculation is $r(k+1)$ when Monte Carlo random sampling is applied, where r is the number of paths.

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830 deviation σ estimates the non-linear effect between input and output, and/or the parameter interactions (Saltelli et al., 2004). The mean μ and standard deviation σ of the EEs are evaluated with the r independent paths in the Morris method,

$$\mu = \sum_{i=1}^r d_i / r$$

$$\sigma = \sqrt{\sum_{i=1}^r (d_i - \mu)^2 / r}$$

5)

6)

835 In this study, the EEs for the method of Morris are not generated by Monte Carlo random sampling, which usually needs extremely large numbers (>250) of paths for 11 parameters and takes a very long time to complete sensitivity computation without parallelization. To save the running time and computational cost but ensure the reliability of sensitivity results, the more efficient trajectory sampling is developed by Saltelli et al. (2004) and becomes a widely-used method to generate the ensembles of EEs for Morris method. In trajectory method, the choice of parameter p and Δ of the design is p even and $\Delta = \pm p / [2(p - 1)]$, either positive or negative. The trajectory method starts by randomly selecting a "base" value x^* for the vector x . Each component x_i of x^* is sampled from the set $(0, 1/(p-1), 2/(p-1), \dots, 1)$. The randomly selected vector x^* is used to generate the

840 other sampling points but not one of them, which means that the model is never evaluated at vector x^* . The first sampling point, $x^{(1)}$, is obtained by changing one or more components of x^* by Δ . The choice of components x^* to be increased or decreased is conditioned on that $x^{(1)}$ still being within the domain. The second sampling point, $x^{(2)}$, is

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890 generated from x^* but differs from $x^{(1)}$ in its i th component, that has been either
 increased or decreased by Δ , but conditioned on the domain, and the index j is randomly
 selected in the set $\{1, 2, \dots, k\}$. In other word, $x^{(2)} = (x_1^{(1)}, \dots, x_{i-1}^{(1)}, x_i^{(1)} \pm$
 $\Delta, x_{i+1}^{(1)}, \dots, x_k^{(1)})$. The third sampling point, $x^{(3)}$, differs from $x^{(2)}$ for only one component
 j , for any $j \neq i$, will be $x_j^{(3)} = x_j^{(2)} \pm \Delta$. A succession of $(k+1)$ sampling points
 895 $x^{(1)}, x^{(2)}, \dots, x^{(k+1)}$ is produced in the input parameters space called a trajectory, with the
 key characteristic that two consecutive points differ in only one component. In the
 trajectory sampling, any component i of the "base" vector x^* has been selected at least
 once by Δ in order to calculate one EE for each parameter.

Once a trajectory has been constructed and evaluated by Morris method, an EE
 900 for each parameter i , $i = 1, \dots, k$, can be computed. If $x^{(l)}$ and $x^{(l+1)}$, with l in the set in
 $(1, \dots, k)$, are two sampling points differing in their i th component, the EEs associated
 with the parameter i is computed as,

$$d_i(x^{(l)}) = \frac{|y(x^{(l+1)}) - y(x^{(l)})|}{\Delta}$$

A random sample of r EEs is selected at the beginning of sampling, and the
 starting point of each trajectory sampling is also randomly generated. The points
 905 belonging to the same trajectory are not independent, but the r points sampled from each
 distribution belonging to different trajectories are independent.

3. Model development

3.1 Study site

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925 The numerical model developed in this paper studies the real dimension and parameter values of a porous medium and a conduit in the aquifer at the Woodville Karst Plain (WKP). The Spring Creek Springs (SCS) is a first magnitude spring in the WKP, consisting of 14 submarine springs located in the Gulf of Mexico (Fig. 1). SCS is an outlet of the subsurface conduit network and the entrance of seawater intrusion, exactly located at the shoreline beneath the sea level. Davis and Verdi (2014) developed a groundwater cycling conceptual model to explain the hydrogeological conditions in the WKP. They introduced that seawater intrudes through subsurface conduit networks during low precipitation periods, while rainfall recharge pushes the intruded seawater out of the aquifer after a heavy storm event. Later on, this conceptual model of the seawater and freshwater interactions in the WKP is quantitatively simulated by a constant-density CFPv2 numerical model (Xu et al., 2015b). In this study, the seawater intrusion process via the SCS through the conduit network is simulated by the density-dependent 2D SEAWAT model. Tracer test studies and cave diving investigations indicate that the conduit system starts from the submarine spring and extends 18 km landward connecting with an inland spring called Wakulla Spring, although the exact locations of the subsurface conduits are unknown and difficult to explore (Kernagis et al., 2008; Kincaid and Werner, 2008). Evidence shows that seawater intrusion has been observed through subsurface conduit system for more than 18 km in the WKP (Xu et al., 2016). In addition, Davis and Verdi (2014) also point out that sea level rise at the Gulf of Mexico in the past century could be a reason for increasing discharge at an inland karst spring (Wakulla Spring) and decreasing discharge at SCS, when the hydraulic gradient between the two springs is directed towards the Gulf.

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(Insert Fig. 1 here)

In this study, a two-dimensional SEAWAT model is set up to simulate seawater intrusion through the major subsurface conduit network in the WKP (Fig. 1). Figure 2 presents the cross section schematic figure in a coastal karst aquifer with a conduit network and a submarine spring opening to the sea. The model spatial domain is not a straight line from the SCS to Wakulla Spring, but the cross section along the major conduit pathway of seawater intrusion between the two springs. The conduit geometry in the model is set as 18-km long and 91-meter deep with a diameter of 10 meters horizontally and 50 meters vertically.

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965 (Insert Fig. 2 here)

Since the main purpose of this study is to evaluate the effects of subsurface conduit parameters on modeling seawater intrusion in the coastal karst aquifer, seawater intrusion through the conduit network, salinity plume in the porous medium and the exchanges between the two systems are simulated only within the vertical cross section. The simulation of saltwater intrusion within the horizontal plane is beyond the scope of the two-dimensional SEAWAT model in this study. The assumption of two-dimensional model is reasonable and sufficient for understanding the parameter sensitivities, since the horizontal exchange flux between the conduit and the surrounding porous medium is trivial, when the exchange permeability on the conduit wall is much smaller than the large conduit hydraulic conductivity. In addition, most SEAWAT models are setup for two-dimensional cross section with high-resolution vertical discretization. Three-dimensional density-dependent flow and transport model is rarely seen and applied, due to the computational constraint.

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3.2 Hydrological parameters

Table 1 presents the hydrological parameter values of the Upper Floridan Aquifer (UFA) in the WKP and boundary conditions used in the model. These parameters have been calibrated in the regional-scale groundwater flow and solute transport models by

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Davis et al. (2010), and then been applied in many previous modeling studies (Gallegos et al., 2013; Xu et al., 2015a; Xu et al., 2015b). It should be pointed out that this study does not aim to re-calibrate the model, since the observational field data are insufficient.

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The head and salinity measurements in the conduit are rarely available, considering the difficulties of monitoring devices installation in the subsurface conduit. The parameter values are evaluated in the following local sensitivity analysis and applied in the seawater intrusion scenarios in Sect. 5.

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(Insert Table 1 here)

The values of hydrological parameters (hydraulic conductivity, specific storage and effective porosity) in the conduit are generally greater than those surrounding porous medium. Hydraulic conductivity of the porous medium is assigned as 2286 m/day (7500 ft/day), and as large as 610,000 m/day (2,000,000 ft/day) for the conduit system. Even the hydraulic conductivity of porous medium in the study region is larger than most alluvial aquifers, because numerous small fractures and relatively large pores existed in the karst aquifer due to dissolution of carbonate rocks. Specific storage and effective porosity in the porous medium are assumed as 5×10^{-7} and 0.003, respectively. Specific storage and effective porosity are 0.005 and 0.300 in the conduit layer, respectively. The longitudinal dispersivity is estimated as 10 m in the porous medium, but is assumed a very small value

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1095 (0.3 m) in the conduit, because advection is dominated and dispersion is negligible in the
solution of transport in the conduit.

3.3 Spatial and temporal discretization

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The grid discretization and boundary conditions of the two-dimensional
1100 SEAWAT numerical model are shown in Fig. 3, ~~with~~ 140 columns and 37 layers in the
cross section. Guo and Langevin (2002); Werner et al. (2013) pointed out that ~~refining~~
~~vertical grid~~ resolution is required for ~~accurately~~ modeling the density-dependent flow
~~and solute transport~~. The vertical thickness of each ~~grid~~ cell is set uniformly as 3.048 m
(10 ft) in this study, ~~significantly smaller~~ than the 152 m (500 ft) thickness in many
1105 previous constant-density modeling studies in the WKP, for example, Davis and Katz
(2007); Davis et al. (2010); Xu et al. (2015a); Gallegos et al. (2013); Xu et al. (2015b).
(Insert Fig. 3 here)

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The horizontal ~~discretization~~ for each cell is set uniformly ~~as~~ 152 m (500 ft) as the
1110 scales in the field, except columns #22 and #139, which are 15.2 m (50 ft) as the vertical
conduit network connecting the submarine spring (SCS) and inland spring (Wakulla
Spring), respectively. The sizes of spring outlets and the conduit are based on the
observational ~~field~~ data and the calibrated ~~values from the~~ previous studies (Gallegos et
al., 2013). However, the diameter of horizontal conduit network is assumed ~~constant in~~
1115 this study. The outlet of vertical conduit system is the submarine spring (SCS) located at
the shoreline at column #22. The conduit system starts from the submarine spring,
descends downward to layer #29 (nearly 100 m below sea level), horizontally extends
nearly 18 km from column #22 to column #139, and then rises upward to the top through

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column #139. Seawater intrudes at the SCS on the first layer of column #22, and then flows vertically downward into the conduit system. The inland spring is simulated by the DRAIN package as general head boundary condition in the SEAWAT model. All layers are simulated as confined aquifer since the conduit is fully saturated, which are consistent to the previous numerical models used in Davis et al. (2010); Xu et al. (2015a); Xu et al. (2015b) in the WKP.

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A transient 7-day stress in the SEAWAT model is evaluated throughout this study. The scenarios of longer simulation time are exceptions for evaluating seawater intrusion under an extended low rainfall period in Sect. 5.4. The timestep of flow model is set as 0.1 days, and the timestep of transport model is determined by SEAWAT automatically.

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3.4 Initial and boundary conditions

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The initial condition of head is constant within each layer, set as 0.0 m as the present-day sea level for the cells from the boundary on the left (column #1) to the shoreline (column #22), and gradually rises to 1.52 m (5.0 ft) at inland boundary on the right, determined by the elevation of Wakulla Spring. Note that the head values are written in the input files of SEAWAT model instead of equivalent freshwater head. The initial conditions of salinity are assumed as a constant value of 35.0 PSU (Practical Salinity Unit) with each layer as seawater without mixing at the sea boundary and the leftmost 10 columns. The seawater/freshwater mixing zone is assumed from 35 PSU at column #11 to 0 PSU at column #45, with a gradient of 1.0 PSU per column. Salinity is set uniformly as 0.0 PSU from column #46 to the inland boundary on the right, as

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1175 uncontaminated freshwater before seawater intrudes. Several testing cases have been made to confirm that the initial conditions trivially affect the modeling results.

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The boundary conditions are also presented in Fig. 3. The less-permeable confining unit of the UFA base is simulated at the bottom of model domain as no-flow boundary condition. The constant head and concentration inland boundary condition on the right is 1.5 m (5.0 ft) as the elevation of inland spring, and 0.0 PSU as

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1180 uncontaminated freshwater. The seawater boundary on the left is 3.38 km away from the shoreline, set as 0.0 m constant head as the present-day sea level and 35.0 PSU constant concentration as seawater without mixing. The boundary conditions of head and salinity at the submarine spring (column #22, layer #1) are adjusted and evaluated in the scenarios of different sea level, salinity and rainfall conditions in Sect. 5.

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1185 4. Sensitivity Analysis

Sensitivity analysis evaluates the uncertainties of salinity and head simulations with respect to eleven parameters, helps to understand the effects of variations of aquifer parameters and boundary conditions on simulation. The symbols and definitions of the eleven parameters are listed in Table 1, as well as the values computed in the local sensitivity analysis, and the parameter ranges evaluated in the global sensitivity analysis (Table 1). There are six parameters in the groundwater flow model, including hydraulic conductivity (HY_P and HY_C), specific storage (SS_P and SS_C) of the conduit and the porous medium, recharge rate (RCH) and the sea level at the submarine spring (H_SL).

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1195 The other five parameters, including effective porosity (PO_P and PO_C), dispersivity

(DISP_P and DISP_C) of the conduit and the porous medium, and the salinity at the submarine spring (SC), are in the solute transport model.

1215 4.1 Local sensitivity analysis

In the local sensitivity analysis, the CSS_s (composited scaled sensitivities) of parameters with respect to head and salinity simulations are calculated along the conduit network and within the porous medium. The CSSs are computed for the parameter values of the maximum seawater intrusion benchmark case in Sect. 5.1, which is developed to quantitatively evaluate the extent of seawater intrusion in a coastal karst aquifer, specifically with the hydrological parameters in the WKP. The local sensitivity analysis is also used to determine the parameters to be adjusted and evaluated in the scenarios.

Parameter sensitivities are computed at several locations, from column #25 to column #75 with an interval of 5 cells along the horizontal conduit (layer #29), where column #25 is the near shore aquifer fully contaminated by seawater, and column #75 is assumed as the uncontaminated freshwater aquifer. The parameter sensitivities of simulations in a porous medium are evaluated at layer #24, 15.2 m (50 ft) or 5 layers above the conduit layer, from column #25 to column #75 with an interval of 5 cells along the horizontal direction.

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4.1.1 Local sensitivity analysis of simulations in the conduit

Figure 4 shows the arithmetic mean of CSS_s computed in the evaluated locations along the conduit layer. The largest CSS value indicates that salinity at the submarine spring (SC) is the most important parameter to both salinity and head simulations.

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Hydraulic conductivity, specific storage and effective porosity of the conduit (HY_C, SS_C and PO_C), as well as the sea level at the submarine spring (H_SL) are also important parameters. Simulations are not sensitive to hydraulic conductivity, specific storage and effective porosity of the porous medium (HY_P, SS_P and PO_P), recharge rate (RCH) and dispersivity (DISP_C and DISP_P). Generally speaking, the parameter sensitivities with respect to head simulations are similar and consistent with salinity simulations.

(Insert Fig. 4 here)

The boundary conditions of the conduit system, including salinity and sea level at the submarine spring (SC and H_SL), are important in modeling seawater intrusion in the WKP. Seawater enters the conduit system at the submarine spring, and intrudes landward through the subsurface conduit system. The most important parameter is identified as the salinity at the submarine spring (SC), which determines the equivalent freshwater head in terms of water density at the inlet of conduit system, and affects flow simulation within the conduit system as well as the surrounding porous medium via exchange on the conduit wall. The salinity at the submarine spring (SC) is determined by freshwater mixing and dilution from the conduit network, in other words, is controlled by the rainfall recharges and freshwater discharge from the aquifer to the sea. In this study, rainfall recharge is represented by salinity at submarine spring with freshwater dilution. Recharge flux on the surface (RCH) is not an important parameter, and is not applicable to represent the total rainfall recharge in a two-dimensional SEAWAT model. On the other hand, the sea level at the submarine spring (H_SL) also has an intermediate CSS rule on flow field and salinity transport simulations. However, it is not as important as the

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salinity at the submarine spring (SC). In other words, the extent of seawater intrusion in the conduit is more sensitive to rainfall recharge and freshwater discharge represented by the parameter SC, rather than the sea level and/or tide level variations.

Dispersivity is usually an important parameter in the sensitivity analysis of transport modeling in a porous medium aquifer. However, the conduit and porous medium dispersivities (DISP_C and DISP_P) are not important parameters for salinity and head simulations in this study. Advection is dominated in the transport of seawater within the highly permeable conduit network, while dispersion is negligible in such high-speed flow condition. Meanwhile, the dispersion solution and dispersivity sensitivities in the conduit are inaccurately calculated when conduit flow becomes turbulent. On the other hand, the numerical dispersion is significantly greater than the solution of physical dispersion in the conduit. The Peclet number can be as great as 2500, far beyond the theoretical criteria (<4) for solving the advection dispersion transport equation by finite difference method. The dispersivity sensitivities are computed with large uncertainty, indicating that the continuum SEAWAT model is not applicable to accurately compute the salinity dispersion in the conduit.

The parameters with the six largest CSS are presented in Fig. 5, with respect to the combination of head and salinity simulations in the evaluated locations along the conduit network, from column #25 to column #75. The largest CSS values are found at either column #50 or #55 within the conduit, matches the position of seawater/freshwater mixing zone along the conduit network in the maximum seawater intrusion case (Sect. 5.1). All parameters have the CSS values at the mixing zone than anywhere else, because

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head and salinity simulations only change significantly near the mixing zone but remain constant in other locations.

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4.1.2 Local sensitivity analysis of simulations in the porous medium

Figure 6 shows the arithmetic mean of CSSs computed in the evaluated locations in the porous medium (layer #24). The largest CSS value indicates that salinity at the submarine spring (SC) is also the most important parameter with respect to simulations in the porous medium, although it is a boundary condition of the conduit system. However, some parameter sensitivities are different from the results of simulations in the conduit. The hydraulic conductivity and effective porosity of both the conduit and porous medium (HY_C, HY_P, PO_C & PO_P), specific storage of the conduit (SS_C) and dispersivity of the porous medium (DISP_P), have intermediate CSS values. The CSS values at different evaluated locations along the layer of porous medium are plot in Fig. 7, except the three unimportant parameters. Similar to the sensitivity analysis of simulations along the conduit, the largest CSSs are found at either column #35 or #40, which is the mixing zone position in the porous medium in the maximum seawater intrusion case (Sect. 5.1).

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The important rules of the boundary condition and hydrological parameters of the conduit system on simulations in the porous medium are highlighted in the local sensitivity analysis. Salinity at the submarine spring (SC) remains the most important parameter and determines the seawater intrusion plume in the porous medium. The conduit hydrological parameters, such as hydraulic conductivity, effective porosity and

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specific storage (HY_C, PO_C and SS_C), are also important for the simulations in the porous medium. The CSSs of conduit parameters indicate that groundwater flow and seawater transport through the conduit system have significant impact on the head and salinity simulations in the surrounding porous medium. In summary, simulations in the porous medium are sensitive to the hydrological parameters of both the conduit and the porous medium, indicating that the interaction between the two domains are important for simulating seawater intrusion in the dual-permeability WKP coastal karst aquifer. As a result, simulations and observations of salinity and head in the conduits and other karst features have significance on calibrating numerical models and values for understanding seawater intrusion in the WKP.

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4.2 Global sensitivity analysis

The local sensitivity analysis is conducted to analyze the parameter sensitivities specifically for the seawater intrusion in the WKP after a 7-day low precipitation period, as the maximum seawater intrusion cases in Sect. 5.1. However, local sensitivity result is lack of representative for the entire parameter ranges, higher-order derivatives. The global sensitivity analysis is necessary to evaluate a comprehensive relationship between simulations and parameters for modeling seawater intrusion to a coastal karst aquifer.

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Figure 8 presents the derivatives of simulations with respect to the selected parameters in order to evaluate if the CSS values in the local sensitivity analysis is representative within the entire parameter range. For example, head and salinity simulations in the conduit are nearly constant to the variation of the unimportant parameter (DISP_P) in the local sensitivity study. Simulations in the porous medium are

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linear to parameter HY_P, with an intermediate value. However, both head and salinity simulations are non-linear to salinity at the submarine spring (SC), which is the most important parameter identified in the local sensitivity analysis (Fig. 8). The CSS value of parameter SC is computed at the largest derivative value where salinity is 35 PSU.

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The locations in the conduit and porous medium systems with the largest CSS values from the local sensitivity analysis are evaluated in the global sensitivity analysis.

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Parameter sensitivities are computed at the specified location in the conduit (column #50, layer 29) and the porous medium (column #35, layer #24), respectively. The Trajectory sampling method developed by Saltelli et al. (2004) is introduced in Sect. 2.2 and applied in this study, with the recommended choice of $p = 4$ and $r = 10$ by Saltelli et al. (2004).

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4.2.1 Global sensitivity analysis of simulations in the conduit

In the global sensitivity analysis, the mean and standard deviation of the EEs for salinity simulation in the conduit (column #50, layer #29) are presented in Fig. 9a. The largest EE mean value indicates that parameter SC is the most important parameter to salinity simulations. It is consistent with the local sensitivity result, since the submarine spring is the boundary condition of the major pathway for seawater intrusion to the aquifer. The largest standard deviation of the EEs is due to the non-linear relationship between salinity simulation and parameter SC shown in Fig. 8, in which the derivatives vary with different parameter values. The hydraulic conductivity and effective porosity of the conduit (HY_C and PO_C), as well as sea level (H_SL), are all important to salinity simulation with relatively large mean and standard deviation values of EEs. Generally

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speaking, the global sensitivity study results for salinity simulation in the conduit are similar to the local sensitivity ~~results.~~

(Insert Fig. 9 here)

The global sensitivities ~~of head simulations with respect to parameters are more~~ complicated ~~than salinity simulations~~ (Fig. 9b). ~~The mean and standard deviation of EEs for head simulations are smaller than those for salinity simulations, consistent with the conclusion that salinity simulation is more effective than head (Shoemaker, 2004).~~

~~Different from salinity simulation, salinity at the submarine spring (SC) no longer has the largest mean but standard deviation, due to the non-linear relationship to head simulation shown in Fig. 8. Head simulations are also sensitive to the boundary conditions of salinity in the transport model when salinity is high, because equivalent freshwater head is a function of density in terms of salinity in the coupled variable-density flow and transport model for simulating seawater intrusion.~~

~~In this study, parameters in transport model are also important to the head simulation in a coupled density-dependent flow and transport model. The two largest mean values of EEs show that the specific storage (SS_C) and effective porosity (PO_C) of the conduit are the two most important parameters. Specific storage and effective porosity are parameters in the coupled density-dependent flow and transport model, respectively, determined by the void space in the aquifer from field measurement. Head~~

~~simulation is usually not a function of effective porosity when transport equation is solved separately after the flow model is computed in the constant-density simulation. Effective porosity is important in head simulation since the solution of salinity transport in turn determines the density and impact flow calculation in the model, particularly in~~

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1620 the study of density-dependent seawater intrusion. This is also consistent with the
previous sensitivity study using the SEAWAT model (Shoemaker, 2004).

The other major finding in the global sensitivity analysis is that the hydraulic
conductivity of the conduit (HY_C) is no longer the most important parameter, with
smaller means and standard deviations of EEs than the other two parameters (PO_C and
1625 SS_C). The sensitivity result is different from the common knowledge and empirical
experience in hydrogeological modeling, but is actually reasonable in karst aquifer with
the non-laminar conduit flow. In the SEAWAT model, Darcy equation is used to
calculate the flow velocity in the whole model domain including the conduit system,

however, is only accurate for laminar seepage flow in the porous medium. Groundwater
1630 flow easily becomes non-laminar even turbulent in the giant conduit system, when the
conduit flow discharge is non-linear to head gradient and hydraulic conductivity. The
simulation of conduit flow is beyond the applicability of Darcy equation in SEAWAT
model, with relatively large error and uncertainty in the relationship between hydraulic
conductivity and head simulation.

1635 4.2.2 Global sensitivity analysis of simulations in the porous medium

The global sensitivity analysis has different results for some non-linear parameter
sensitivities, highlights the interaction between the conduit and porous medium systems.
Parameters HY_P and SC are identified as the two most important parameters for salinity
1640 simulations in the porous medium (Fig. 10a). Compared with hydraulic conductivity of
the porous medium (HY_P), the parameter SC has much larger CSS value in the local
sensitivity analysis (Fig. 6), and also larger mean of EE in the global sensitivity analysis,

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1745 Simulations are non-linear to the parameter SC, which is evaluated at 35.0 PSU, with the largest derivative in the local sensitivity analysis (Fig. 8). In other words, local sensitivity analysis overestimates the sensitivity of parameter SC within the range, and global sensitivity analysis provides a more comprehensive understanding of the variability of rainfall recharges and freshwater discharge. As the boundary condition of conduit system, salinity at the submarine spring (SC) determines the equivalent freshwater head at the inlet of seawater intrusion and affects simulations in the conduit, and also the surrounding porous medium via exchanges between the two systems. Similar to the largest CSS value of parameter SC in the local sensitivity result, the global sensitivity result highlights the significance of the interaction between the conduit and the porous medium domains in a dual-permeability aquifer. Similar to salinity at the submarine spring (SC), the relatively large mean of EEs for sea level (H_SL), effective porosity and specific storage of the conduit (PO_C and SS_C) highlight the values of dynamic interaction between the conduit and the porous medium in this study.

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(Insert Fig. 10 here)

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1760 On the other hand, parameter sensitivities for simulations in the porous medium exhibit different characteristics from those in the conduit. The porous medium hydraulic conductivity (HY_P) is an important term in the flow equation for solving head and advective velocity for the transport equation (Fig. 10b), similar to most sensitivity result of hydrological modeling for flow in a porous medium. Please note this is different from the global sensitivity results of simulations in the conduit, in which the EEs of effective porosity and specific storage of the conduit (PO_C and SS_C) have larger mean and standard deviation values than hydraulic conductivity (HY_C), because of the uncertainty

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1800 of conduit flow calculation by Darcy's equation in the continuum SEAWAT model. As the boundary condition of the conduit, parameter H_SL affects head solutions in the surrounding porous medium by determining the head-dependent exchange flux between the two domains. Generally, the impacts of boundary conditions (SC and H_SL) and hydrological properties (SS_C, HY_C and PO_C) of the conduit system on head simulations in the porous medium are significant and important. In addition, effective porosity of the porous medium (PO_P) also has relatively large mean and standard deviation of EEs for head simulations, since the density-dependent flow and transport models are coupled for simulating seawater intrusion.

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Dispersivity is no longer an important parameter in such a dual-permeability aquifer, conflicted with Shoemaker's (2004) result that dispersivity is an important parameter in a homogeneous porous medium domain without the preferential advective flow. In a dual-permeability karst aquifer system, advection transport is dominated in the conduit and the surrounding porous medium as well, while dispersion becomes unimportant. In this study, the uncertainty of dispersivity sensitivities can be significant when the Peclet number in the conduit is large beyond its criteria for solving transport equation by finite difference method, which requires the Peclet number to be smaller than 4. An experiment of deactivating the DSP (dispersion) package in SEAWAT confirms that dispersion is negligible within the conduit network in this study, and the mixing is mostly due to the numerical dispersion instead of the solution of dispersion equation in this study.

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- Deleted:** Both local and global sensitivity analysis highlight that field observations and numerical simulations of the karst features, including the boundary conditions and hydrological characteristics of sinkholes, karst windows and subsurface conduit system, are important to model uncertainty analysis. Simulations in the porous medium are sensitive to hydrological characteristics and boundary conditions of the conduit, indicating the significance of conduit system on modeling seawater intrusion in a dual-permeability karst aquifer. The conduit system serves as the major pathway for seawater intrusion further landward and groundwater contamination in the aquifer. Any field observational data within the conduit, if available, will be important to. On the other hand,
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5. Seawater Intrusions Scenarios

In this section, the the extents of seawater intrusion are quantitatively measured and evaluated under scenarios of boundary conditions, which are identified as the important parameters in the local sensitivity analysis. In each scenario, only one parameter is adjusted and others remain the same as the original values in the maximum seawater intrusion benchmark case.

5.1 The maximum seawater intrusion benchmark case

The head and salinity boundary conditions are set as 0.0 m as the present-day sea level, and 35.0 PSU as seawater without dilution at the conduit system outlet, respectively. The local sensitivity analysis computes the sensitivities of parameter values in the maximum seawater intrusion benchmark case. Salinity and sea level at the submarine spring (SC and H_SL) are identified as two important parameters and then adjusted in the following two scenarios. In this case, the longest distance of seawater intrusion is simulated by assuming that freshwater recharge is negligible, and the outlet of conduit system is filled with undiluted seawater. Figure 11 presents the simulated salinity and head profile in the cross section after a 7-day simulation.

(Insert Fig. 11 here)

According to the Ghyben-Herzberg relationship, high-density seawater intrudes landward through the bottom of the aquifer beneath the freshwater flowing seaward on the top. The equivalent freshwater head at the submarine spring is calculated as 2.29 m (7.5 ft) when salinity is 35.0 PSU at the submarine spring, and undiluted seawater is filled within the 91 meters deep submarine cave connecting to the conduit. The equivalent

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freshwater head at the submarine spring is higher than the 1.52 m (5.0 ft) constant head at the inland spring, diverts the hydraulic gradient landward and causes seawater to intrude into the aquifer. Seawater intrudes further landward through the highly permeable conduit network, also contaminates the surrounding porous medium via exchange on the conduit wall. The seawater/freshwater mixing zone in the deep porous medium beneath the conduit is only slightly behind the seawater front in the conduit, because high-density saline water easily descends from the conduit. The area with relatively smaller salinity to the left of the vertical conduit network near shore is due to the freshwater discharge dilution from the aquifer to the sea, since the equivalent freshwater head is only set as 2.29 m at the submarine spring but remains as 0 m in other areas. The simulated salinity profile shows that the mixing zone position in the conduit, defined as the location with salinity of 5.0 PSU, is nearly 5.80 km landward from the shoreline. The width of mixing interface, defined as the distance between the locations with salinity of 1.0 PSU and 25.0 PSU, is about 7 grid cells or 1.13 km (0.7 miles) and roughly the same in both the conduit and porous medium.

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5.2 Salinity variation at the submarine spring (SC)

Sensitivity analysis indicates that the salinity at the submarine spring (SC), controlled by the rainfall dilution and regional freshwater recharge, is generally the most important parameter for simulations in both the conduit and the porous medium. Salinity at the submarine spring is diluted by large amount of rainfall recharge and freshwater discharge after a significant precipitation event, but remains high after an extended low rainfall period, as shown in the maximum seawater intrusion benchmark case in Sect. 5.1.

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2000 The equivalent freshwater head at the submarine spring is 2.29 m (7.5 ft) when salinity is 35.0 PSU, proportionally decreases to 0.0 m, where salinity is 0.0 PSU and freshwater is filled with in the conduit system. The impact of freshwater recharge on seawater intrusion is evaluated in four scenarios with different salinity of 0.0 PSU, 10.0 PSU, 20.0 PSU and 30.0 PSU at the submarine spring (Fig. 12). The mixing zone in both the conduit and porous medium are located at 4.0 (4.5) km away from the shoreline in the cases of salinity of 10.0 (20.0) PSU at the submarine spring. Compared to the maximum seawater intrusion benchmark case, rainfall recharge and freshwater discharge move the interface significantly seaward. The mixing zone is very close to the shoreline when salinity is 0.0 PSU at the submarine spring and seawater intrusion is blocked by large amount of freshwater dilution. The shape of mixing interface is similar to the maximum seawater intrusion benchmark, but the width is significantly wider due to the smaller or even reversed hydraulic gradient from the aquifer to the sea. In the scenarios of freshwater dilution, the solution of dispersion becomes more accurate and important in salinity transport with slower groundwater seepage flow. Generally speaking, seawater no longer intrudes significantly inland after a heavy rainfall event, and the mixing interface moves seaward when freshwater dilutes the salinity within the conduit and the submarine spring.

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5.3 Sea level variation at the submarine spring (H_SL)

2020 In addition to salinity, sensitivity analysis indicates that sea level at the submarine spring is also an important parameter. IPCC (2007) predicted an approximation of 1.0 m sea level rise at the beginning of next century, which has significant impacts on seawater

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intrusion in a coastal karst aquifer. The extents of seawater intrusion in the conduit and porous medium under 0.91 m (3.0 ft) and 1.82 m (6.0 ft) sea level rise conditions are quantitatively evaluated in this study (Fig. 13). Salinity at the submarine spring remains

2055 35.0 PSU as the maximum seawater intrusion benchmark, but the head at the submarine spring increases as rising sea level. The simulated salinity profiles show that the width and shape of the mixing zone are similar to the simulated result in the maximum seawater

intrusion benchmark. However, the mixing zone is pushed landward along the conduit to almost 7.08 km from the shoreline with 0.91 m (3.0 ft) sea level rises, which is 1.28 km

2060 further inland than the simulation with the present-day sea level. In the other extreme case of 1.82 m (6.0 ft) sea level rise, seawater intrudes additional 0.97 km further inland along the conduit than the simulated result of 0.91 m (3.0 ft) sea level rise, or 2.25 km further inland than the simulation with present-day sea level. Compared with the usual

alluvial aquifer of porous medium, seawater intrudes further landward through the conduit network in the a dual-permeability karst aquifer under sea level rise. This scenario confirms the concerns of severe seawater intrusion in the coastal karst aquifer

under sea level rise, also highlights the values of conduit system as the major pathway for long-distance seawater intrusion. In addition, sea level rise possibly have great impacts on the regional flow field and hydrological conditions in a coastal aquifer. Davis and

2070 Verdi (2014) reported an increasing groundwater discharge at the inland Wakulla Spring in the WKP associated with the rising sea level in the past decades. The relationship between spring discharge and sea level was quantitatively simulated by a CFPv2

numerical model in Xu et al. (2015b). However, the changes of flow field and hydrological conditions are beyond the scope of this study.

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5.4 Extended low rainfall period

2105 The elapsed time in simulations are set constant in the sensitivity analysis and the previous scenarios for consistent comparison purposes. However, extents of seawater intrusion under scenarios of extended low rainfall periods are presented in Fig. 14, with the extended simulated time of 14, 21 and 28 days. The boundary conditions of salinity and sea level at the submarine spring remain 35.0 PSU and 0.0 m, respectively, as the maximum seawater intrusion benchmark.

(Insert Fig. 14 here)

2110 Seawater intrudes through both the conduit and the porous medium domains persistently during the extended low rainfall period, since the 2.29 m (7.5 ft) equivalent freshwater head at the submarine spring is constantly higher than the inland freshwater boundary. Compared with the maximum seawater intrusion benchmark with a stress period of 7-day elapsed time in simulation, the mixing zone position moves additional

2115 1.29 km landward in the conduit and the surrounding porous medium in the 14-day simulation. In the predictions of 21 (28)-day extended low rainfall period, the mixing zone finally arrives at 7.56 (7.89) km from the shoreline. Above all, seawater intrudes further inland through conduit network during an extended low rainfall period, contaminates fresh groundwater resources in the aquifer and becomes an environmental

2120 issue in coastal regions.

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6. Conclusion

In this study, a two-dimensional SEAWAT model is developed to study seawater intrusion in a dual-permeability coastal karst aquifer with a conduit network. Local and global sensitivity analysis are used to evaluate the parameter sensitivities then help understand the values and importance of karst features in seawater intrusion. Some major conclusions from sensitivity analysis are summarized here,

1) The global sensitivity analysis is necessary to accurately estimate the parameter sensitivities in wider ranges, mainly due to the non-linear relationship between simulations and parameters. The parameter interactions are also important in this study. In the coupled density-dependent flow and transport model, head simulations are sensitive to boundary conditions and parameters of transport equation, since the solution of salinity in terms of density affects the equivalent freshwater head calculation.

2) Salinity at the submarine spring (SC) is the overall most important parameter. The boundary conditions and hydrological parameters of the conduit system are important to not only the simulations in the conduit, but also the porous medium via exchanges between the two systems. The submarine spring and conduit system are the major entrance and pathway, respectively, for seawater intrusion in the coastal karst aquifer. Sensitivity analysis indicates that the simulations in the conduit are especially important for understanding the hydrogeological processes seawater intrusion in such a dual-permeability karst aquifer, and field observational data within the conduit system are necessary for the model calibration.

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2180 3) Different from the previous studies in Shoemaker (2004), dispersivity is no longer an important parameter for simulations in the conduit. Advection is dominant but dispersion is negligible in the solution of salinity transport with turbulent flow in the conduit, and the relatively fast seepage flow in the surrounding porous medium. The interaction between conduit and porous medium significantly change the flow field and affect the applicability of transport model. In the simulated salinity profile, the mixing is mostly due to numerical dispersion instead of the solution of dispersion equation, since the Peclet number is extremely large in the domain and beyond the criteria of solving transport equation by finite difference method.

2185

2190 4) Hydraulic conductivity is no longer an important parameter for simulations in the conduit. Conduit flow easily becomes non-laminar and beyond the capability of Darcy equation in SEAWAT model, which assumes a linear relationship between specific discharge and head gradient. Therefore, the uncertainty of conduit permeability is difficult to be accurately evaluated by hydraulic conductivity in the continuum model.

2195 The extents of seawater intrusion and width of mixing interface are quantitatively measured with the variations of salinity and sea level at the submarine spring, which are identified as important parameters in the sensitivity study. In the maximum seawater intrusion benchmark case with salinity and head as 35.0 PSU and 0.0 m at the submarine spring, respectively, the mixing zone in the conduit moves to 5.80 km from the shoreline with 1.13 km wide after a 7-day low rainfall period. Rainfall and regional recharges dilute the salinity at the submarine spring (SC), and significantly shift the mixing zone

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position seaward to 4.0 (4.5) km away from the shoreline with salinity of 10.0 (20.0) PSU.

2270 Compared with the benchmark, seawater intrudes additional 1.29 (2.25) km further
landward along the conduit under 0.91 (1.82) m sea level rise at the submarine spring
(H_SL). In addition, the impacts of an extended low rainfall period on seawater intrusion
through conduit network are also quantitatively assessed with longer elapsed time in
simulation. The mixing zone moves to 7.56 (7.89) km from the shoreline, after a 21 (28)-
2275 day low precipitation period.

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In a summary, the modeling and field observations in the karst features, including
the subsurface conduit network, the submarine spring and karst windows, are critical for
understanding seawater intrusion in a coastal karst aquifer, and important for model
calibration. The discrete-continuum density-dependent flow and transport model is
2280 necessary to accurately simulate seawater intrusion and assess parameter sensitivities in
the coastal karst aquifer with conduit networks. The advanced numerical methods are
expected to solve the issue of Peclet number limitation in this study and compute more
accurate solution of dispersion.

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2285 Competing interests

The authors declare that they have no conflict of interest.

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Table 1. The symbols and definitions of parameters used in this study, the specified evaluated values in local sensitivity study and evaluation ranges (the lower and upper constraints) of each parameter in global sensitivity analysis.

Parameter	Definitions	Lower	Upper	Evaluated value	Unit
HY_P	Hydraulic conductivity (porous medium)	1.524	4.572	2.286	($\times 10^3$) meters/day <input type="text" value="Deleted: (<math>\times 10^3</math>)"/>
HY_C	Hydraulic conductivity (conduit)	3.048	9.144	6.096	($\times 10^5$) meters/day <input type="text" value="Deleted: (<math>\times 10^5</math>)"/>
SS_P	Specific storage (porous medium)	4.00	6.00	5.00	($\times 10^{-7}$) dimensionless <input type="text" value="Deleted: (<math>\times 10^{-7}</math>)"/>
SS_C	Specific storage (conduit)	0.03	0.07	0.05	dimensionless
RCH	Recharge rate on the surface	0.00	0.03	0.01	meters/day
H_SL	Sea level at the submarine spring	-0.305	0.914	0.305	meters
PO_P	Porosity (porous medium)	0.001	0.005	0.003	dimensionless
PO_C	Porosity (conduit)	0.200	0.400	0.300	dimensionless
SC	Salinity at the submarine spring	0.0	35.0	35.0	PSU
DISP_P	Longitudinal dispersivity (porous medium)	6.10	12.20	10.00	meters
DISP_C	Longitudinal dispersivity (conduit)	0.15	0.60	0.30	meters

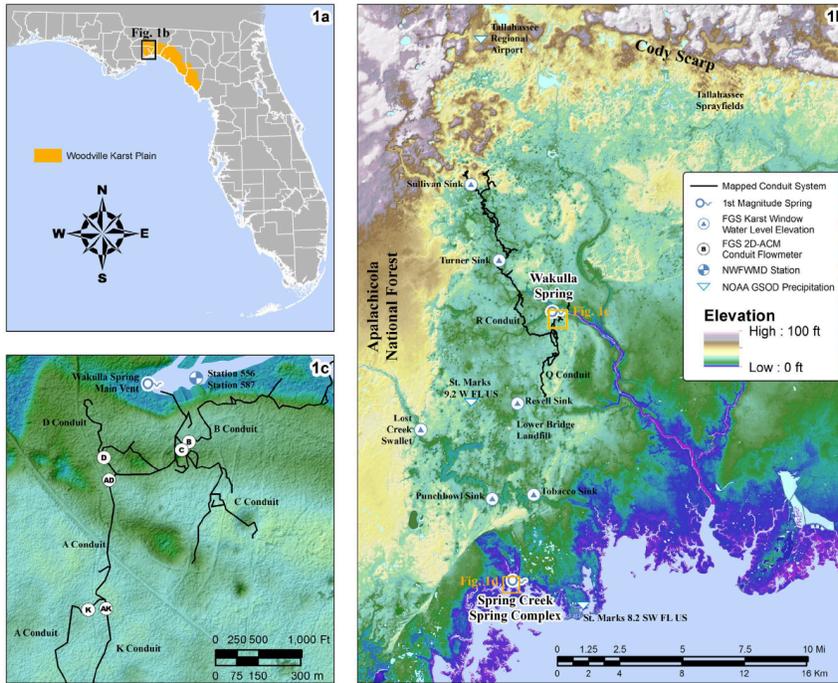


Figure 1. a) Locations of the Woodville Karst Plain (WKP) and the study site; b) The map of the Woodville Karst Plain showing the locations of features of note with the study; c) The detail of cave system near Wakulla Springs. Modified from Xu et al., (2016).

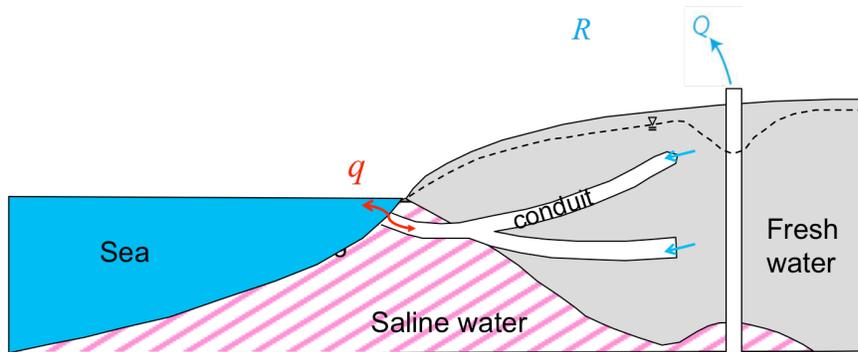
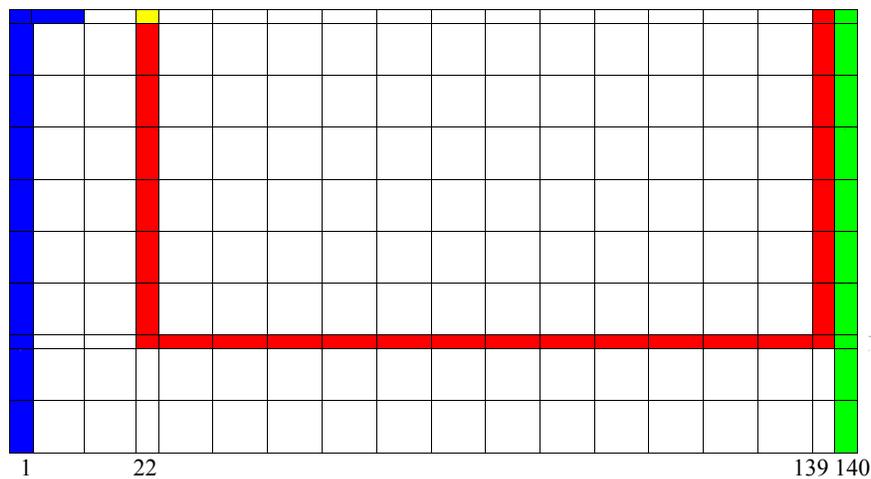


Figure 2. Schematic figure of a coastal karst aquifer with conduit networks and a submarine spring opening to the sea in a cross section. Flow direction q would be seaward when sea level drops, pumping rate Q is low and precipitation recharge R is large; however, reversal flow occurs when sea level rises, pumping rate Q is high or precipitation recharge R is small.



Explanations:

- Constant head and constant concentration of the submarine spring and outlet of karst conduit system, however, various in different cases of numerical models
- Sea-edge boundary: constant head (0.0 ft in normal sea level case) and constant concentration (35 PSU)
- Inland boundary: constant head (5.0 ft) and constant concentration (0 PSU)
- Conduit: high hydraulic conductivity, porosity and specific storage
- Porous medium: low hydraulic conductivity, porosity and specific storage

Figure 3. Schematic figure of finite difference grid discretization and boundary conditions applied in the SEAWAT model. Every cell represents 10 horizontal cells and 4 vertical cells, except the boundary and conduit layer in color with smaller width. The submarine spring is located at column #22, layer #1, and the inland spring is located at column #139, layer #1. The conduit system starts from the top of column #22, descends downward to layer #29, horizontally extends to column #139, and then rises upward to the top through column #139.

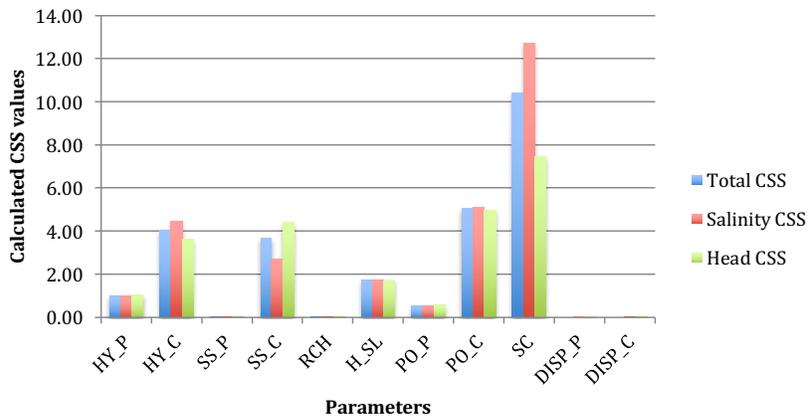


Figure 4. The CSSs (Composite Scaled Sensitivities) of all parameters with respect to simulations in the conduit (layer #29) in the local sensitivity analysis.

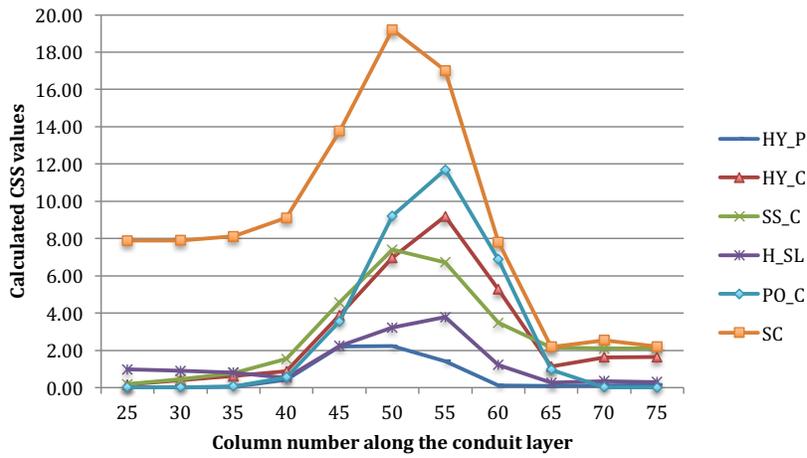


Figure 5. The CSSs (Composite Scaled Sensitivities) of selected parameters at different locations along the conduit layer (from column #25 to column #75) in the local sensitivity analysis.

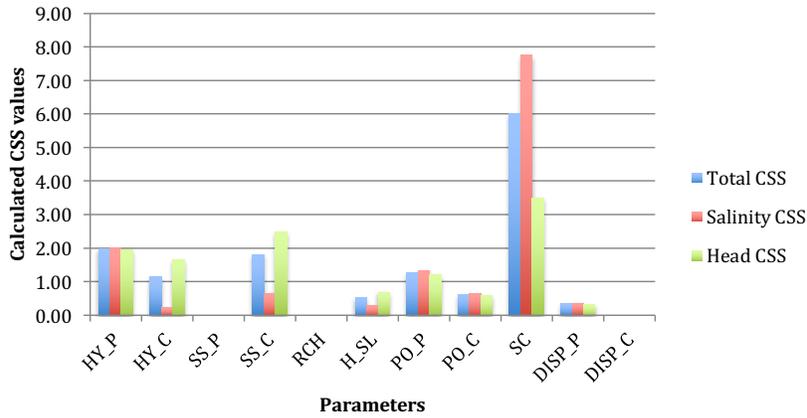


Figure 6. The CSSs (Composite Scaled Sensitivities) of all parameters with respect to simulations in the porous medium (layer #24) in the local sensitivity analysis.

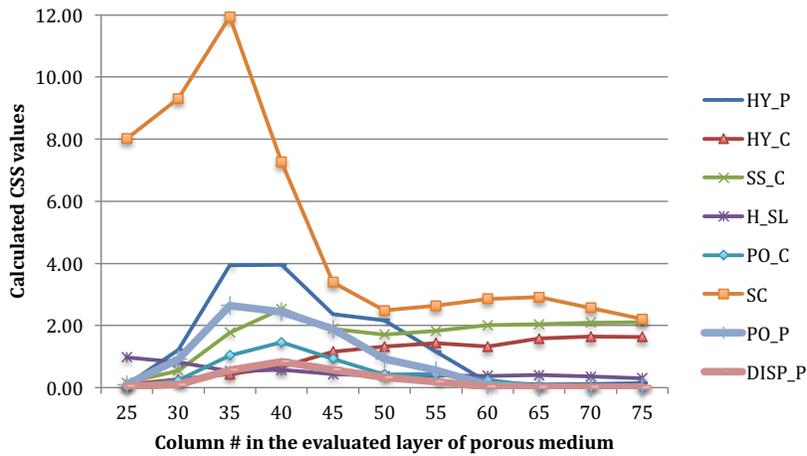


Figure 7. The CSSs (Composite Scaled Sensitivities) at different locations in the porous medium (from column #25 to column #75 at layer #24) in the local sensitivity analysis.

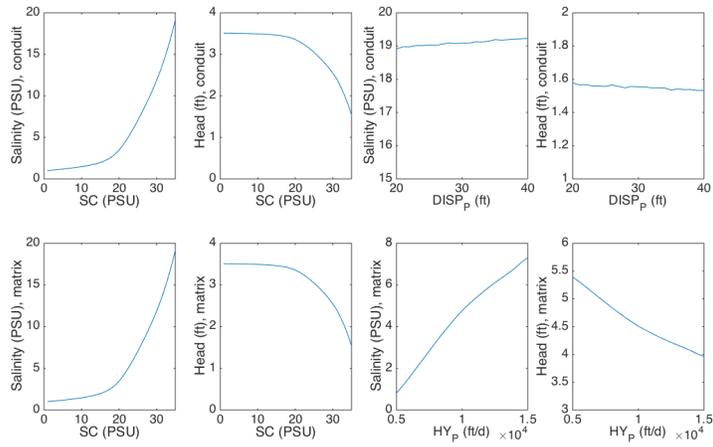


Figure 8. The non-linear relationship between head and salinity simulations with respect to parameters SC, DISP_P and HY_P. (Note that the scale for each plot is different).

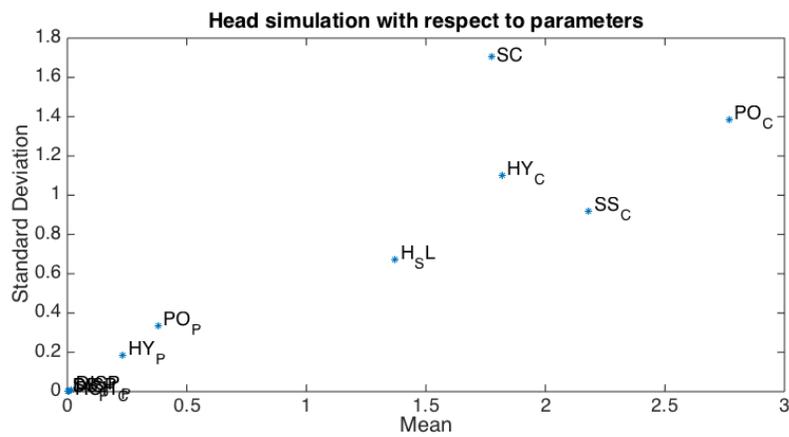
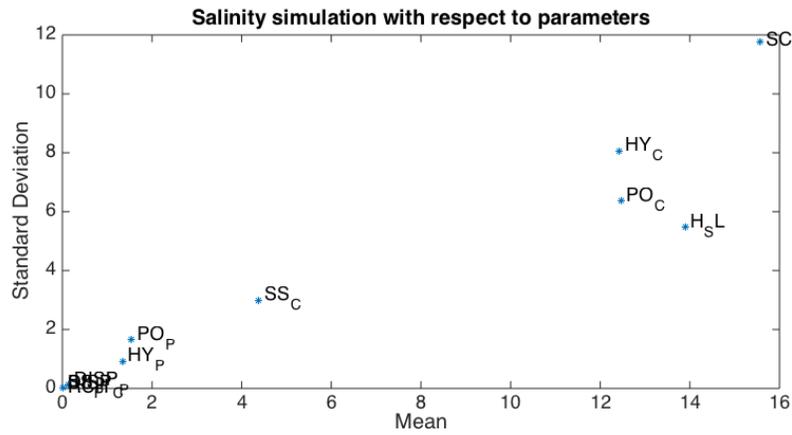


Figure 9. Mean and standard deviation of the EEs (elementary effects) of parameters with respect to simulations in the conduit (column #50, layer #29) in the global sensitivity analysis by Morris method; a) salinity simulation (top); b) head simulation (bottom).

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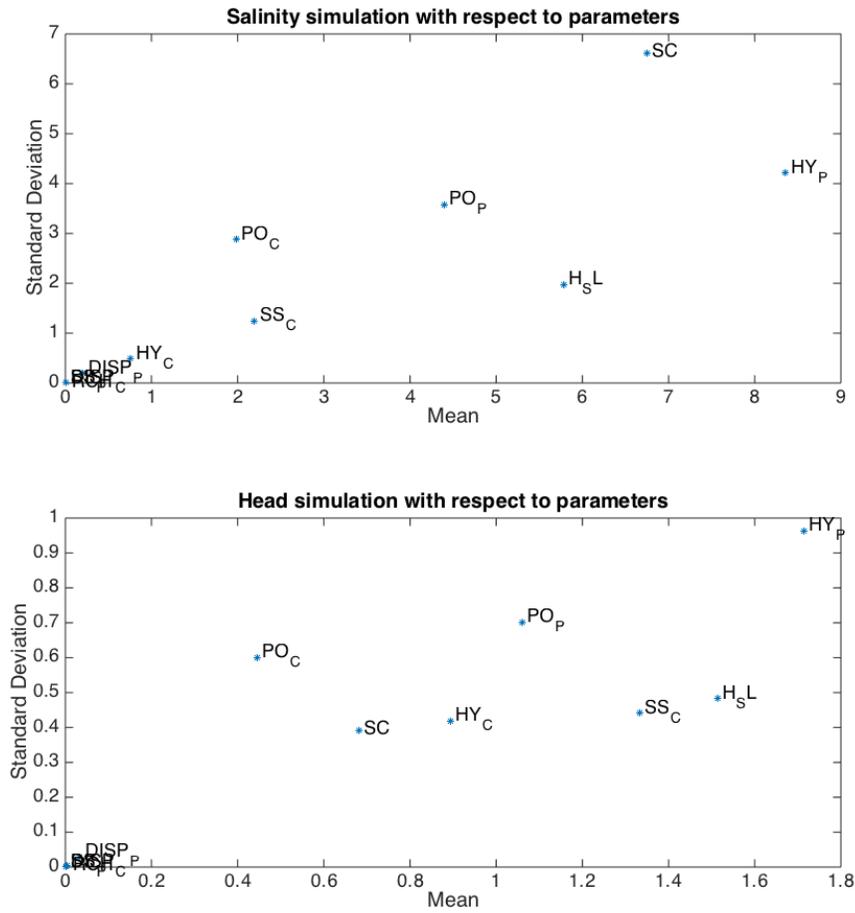


Figure 10. Mean and standard deviation of the EEs (elementary effects) of parameters with respect to simulations in the porous medium (column #35, layer #24) in the global sensitivity analysis by Morris method; a) salinity simulation (top); b) head simulation (bottom).

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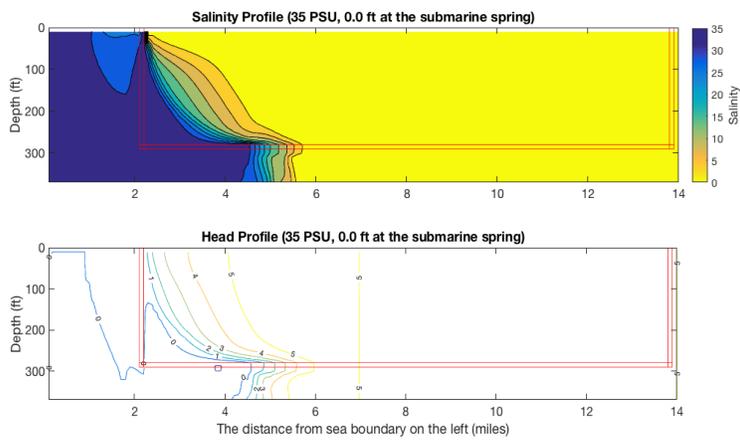


Figure 11. Salinity (top) and head (bottom) simulations of the maximum seawater intrusion benchmark case (35 PSU, 0.0 ft at the submarine spring).

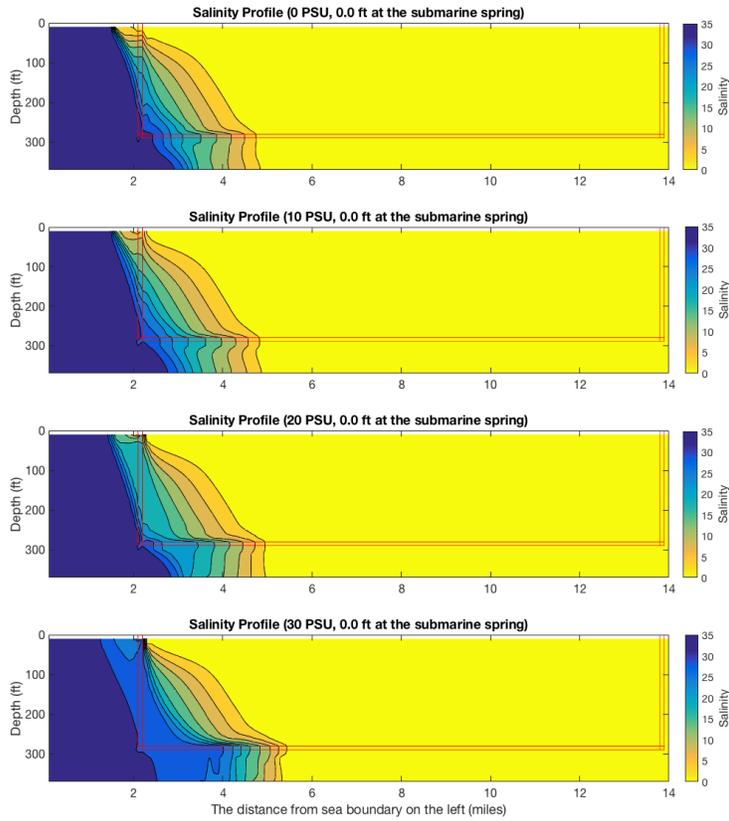


Figure 12. Salinity simulation of seawater intrusion with various salinity at the submarine spring, indicating different rainfall recharge and freshwater discharge conditions: A) 0.0 PSU, 0.0 ft at the submarine spring; B) 10.0 PSU, 0.0 ft at the submarine spring; C) 20.0 PSU, 0.0 ft at the submarine spring; D) 30.0 PSU, 0.0 ft at the submarine spring (from top to bottom).

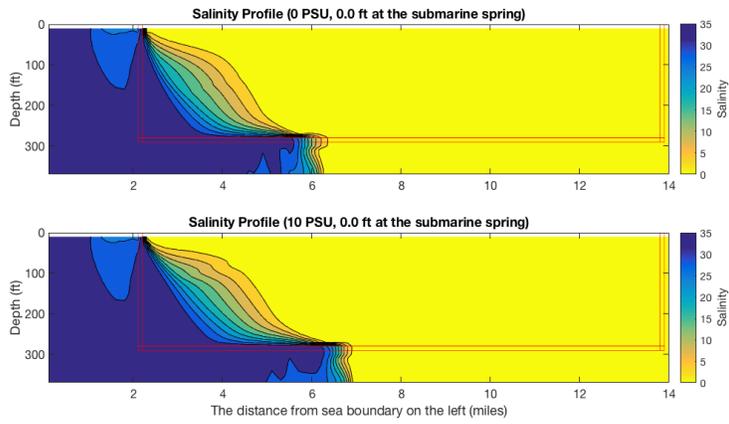


Figure 13. Salinity simulation of seawater intrusion with various sea level conditions: A) 35.0 PSU, 3.0 ft at the submarine spring; B) 35.0 PSU, 6.0 ft at the submarine spring (from top to bottom).

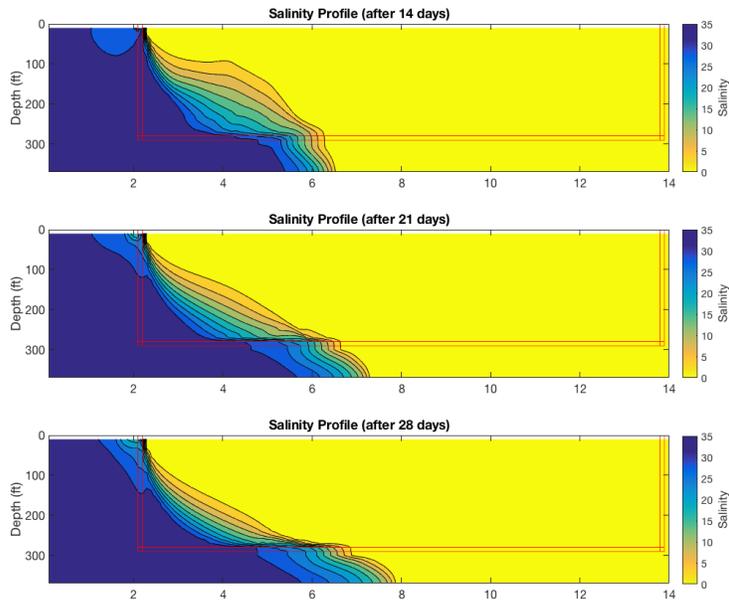


Figure 14. Salinity simulation of the maximum seawater intrusion benchmark case (35 PSU, 0.0 ft at the submarine spring) with extend simulation time during a low rainfall period: A) 14-day simulation period; B) 21-day simulation period; C) 28-day simulation period (from top to bottom).

The most important parameter for simulations in both domains is salinity at the submarine spring, which is also the boundary condition of the conduit. The hydrological characteristics of the conduit network are not only important to the simulations in the conduit, but also significantly affect the simulations in the porous medium, due to the interactions between the two systems.

Compared to the local sensitivity analysis, the global sensitivity results are different in several parameters (hydraulic conductivity, porosity and the boundary conditions at the submarine spring), mainly due to the non-linear relationship of the parameters with respect to the simulations. The results of global sensitivity analysis also indicate that the

The numerical model in this study is developed to study seawater intrusion in the field scale, with the real dimension and parameter values of the porous medium and the conduit in the aquifer, specifically in the Woodville Karst Plain (WKP). The Woodville Karst Plain (WKP) is a typical coastal karst aquifer, where the Spring Creek Springs (SCS) is a first magnitude spring in the WKP, consisting of 14 submarine springs located in the Gulf of Mexico (Fig. 1). SCS is also an outlet of the subsurface conduit network and the entrance of seawater intrusion, exactly located at the shoreline beneath the sea level. Tracer test studies and cave diving investigations indicate that the conduit system starts from the submarine spring and extends 18 km landward connecting with an inland spring called Wakulla Spring, although the

exact locations of the subsurface conduits are unknown and difficult to explore (Kernagis et al., 2008; Kincaid and Werner, 2008). Some evidence shows that seawater intrusion has been observed through subsurface conduit system for more than 18 km in the WKP (Xu et al., 2016). The groundwater cycling conceptual model in The relationship of seawater intrusion, groundwater flow and rainfall recharges in the WKP was described by a conceptual model of groundwater flow cycling in Davis and Verdi (2014) introduced that seawater intrudes through subsurface conduit networks during low precipitation periods, while rainfall recharge pushes the intruded seawater out of the aquifer after a heavy storm event. Later on, , and then this conceptual model of the seawater and freshwater interactions in the WKP is quantitatively simulated by a constant-density CFPv2 numerical model in Xu et al. (2015b). In this study, the seawater intrusion process via the SCS through the conduit network is simulated by the density-dependent 2D SEAWAT model. Tracer test studies and cave diving investigations indicate that the conduit system starts from the submarine spring and extends 18 km landward connecting with an inland spring called Wakulla Spring, although the exact locations of the subsurface conduits are unknown and difficult to explore (Kernagis et al., 2008; Kincaid and Werner, 2008). Some evidence shows that seawater intrusion has been observed through subsurface conduit system for more than 18 km in the WKP (Xu et al., 2016). In addition, Davis and Verdi (2014) also point out that sea level rise at the Gulf of Mexico in the past century could be a reason for the increasing discharge at an inland karst spring (Wakulla Spring) and decreasing discharge at SCS, when the hydraulic gradient towards the Gulf between the two springs decreases.

(Insert Fig. 1 here)

Tracer test studies and cave diving investigations indicate that the conduit system starts from the submarine spring and extends 18 km landward connecting with an inland spring called Wakulla Spring, although the exact locations of the subsurface conduits are unknown and difficult to explore (Kernagis et al., 2008; Kincaid and Werner, 2008). Some evidence shows that seawater intrusion has been observed through subsurface conduit system for more than 18 km in the WKP (Xu et al., 2016).

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Modeling groundwater flow in a dual-permeability karst aquifer is challenging, because of the non-laminar flow calculation in a karst conduit system (Davis, 1996; Shoemaker et al., 2008; Gallegos et al., 2013). Several coupled discrete-continuum numerical models have been developed and applied to solve the non-laminar flow in the conduit and the Darcian flow in a porous medium simultaneously, such as MODFLOW-CFPM1 (Shoemaker et al., 2008) and CFPv2 (Reimann et al., 2014; Reimann et al., 2013; Xu et al., 2015a; Xu et al., 2015b). However, these models only solve constant density governing equations, which are not applicable for simulating the density-dependent seawater intrusion processes in a coastal aquifer. The VDFST-CFP developed by Xu and Hu (2017) is a density-dependent discrete-continuum modeling approach to study seawater intrusion in a coastal karst aquifer with conduits, however, is only able to simulate synthetic cases but not yet for the field scale applications. Therefore, the variable-density SEAWAT model is still used in this study, in which Darcy equation is not only used to calculate flow rate in the porous medium, but also the conduit flow rate with large values of hydraulic conductivity and effective porosity.

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The k -dimensional vector x of the model parameters has components x_i , which can be divided into p uniform intervals. The effect of changing one parameter at a time is evaluated in turn by the elementary effect (EE), d_i , which is defined as,

$$d_i = \frac{1}{\tau_y} \frac{[y(x_1^*, \dots, x_{i-1}^*, x_i^* + \Delta, x_{i+1}^*, \dots, x_k^*) - y(x_1^*, \dots, x_k^*)]}{\Delta}$$

where Δ is the relative distance in the coordinate; τ_y is the output scaling factor; $\{x_i^*\}$ is the parameter set selected by different sampling method.

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The k -dimensional vector x of the model parameters has components x_i , which can be divided into p uniform intervals. The effect of changing one parameter at a time is evaluated in turn by the elementary effect (EE), d_i , which is defined as,

$$d_i = \frac{1}{\tau_y} \frac{[y(x_1^*, \dots, x_{i-1}^*, x_i^* + \Delta, x_{i+1}^*, \dots, x_k^*) - y(x_1^*, \dots, x_k^*)]}{\Delta}$$

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where Δ is the relative distance in the coordinate; τ_y is the output scaling factor; $\{x_i^*\}$ is the parameter set selected by different sampling method.

To compute the EE for the k parameters, $(k+1)$ simulations are needed in the same way as local sensitivity method for the perturbation of each parameter, which is called one “path” (Saltelli et al., 2004). An ensemble of EEs for each parameter is generated by multiple paths of randomly generated parameter set. The total number of calculation is $r(k+1)$ when Monte Carlo random sampling is applied, where r is the number of paths.

However where Δ is the relative distance in the coordinate; τ_y is the output scaling factor; $\{x_i^*\}$ is the parameter set selected by different sampling method.

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These parameters are either the hydrological characteristics or the boundary conditions of conduit network that determine the extent of seawater intrusion within the conduit. However, other parameters are relatively less important with small mean and standard deviation of EEs.

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Different from salinity simulation, Although salinity at the submarine spring (SC) no longer has does not have the largest mean of EEs but is still, it is still an important parameter for head simulation. However, parameter SC still has the with a large standard deviation of EEs, since the derivatives vary in different evaluated locations, with due to its non-linear relationship to head simulation shown in (Fig. 8). The parameter SC, indicates that the hHead simulations are also sensitive to the boundary conditions of salinity in the transport model, because equivalent freshwater head is a function of density in terms of salinity simultaneously in the coupled variable-density flow and transport model for simulating seawater intrusion.

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for effective porosity and specific storage of the conduit

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are much larger than hydraulic conductivity (HY_C), indicating that head simulation in the conduit is more sensitive to effective porosity and specific storage, rather than the hydraulic conductivity

analysis result of parameter SC highlights the significance of the interaction between the conduit and the porous medium domains in a dual-permeability aquifer. However, salinity at the submarine spring (SC) with respect to simulations in the porous medium has the largest CSS in the local sensitivity study, while t

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than the CSS of hydraulic conductivity of the porous medium (HY_P) is has much smaller CSS value in the local sensitivity result (Fig. 6), but however, and also has larger mean of EEs in the global sensitivity study than parameter SC

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In general, parameter sensitivities of simulations in the porous medium are more complicated than those in the conduit, especially for the head simulations. The global sensitivity analysis provides an insight of the parameter interactions and the higher-order relationship with respect to simulations.

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are simulated by the SEAWAT model and quantitatively measured and measured analyzed

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In addition, the length of elapsed time in simulation is constant in the sensitivity analysis for consistent comparison purposes. In Sect. 5.4, tThe extents of seawater intrusion in a coastal karst aquifer during under an extended low rainfall periods conditions are evaluated by extending the elapsed time in simulation in Sect. 5.4, although which is constant in the sensitivity analysis for consistent comparison purposes.

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are evaluated at the specified parameter values in this case

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This case is also set as the benchmark for the following scenarios.

Salinity at the submarine spring (SC) is identified as the most important parameter to the simulations in both two domains, because the submarine spring is the major entrance of seawater intrusion into the conduit as pathway in the aquifer. The boundary conditions and hydrological characteristics of the conduit, including sea level at the submarine spring (H_SL), hydraulic conductivity (HY_C) and effective porosity (PO_C) are important to the simulations in the conduit as well. On the other hand, the simulations in the porous medium also are sensitive to the boundary conditions (SC and H_SL) and hydrological characteristics of the conduit, such as specific storage and effective porosity (SS_C and PO_C), due to the interaction and exchange between the two domains. Sensitivity analysis indicates that the observations and simulations in the conduit are especially important for understanding hydrogeological processes and modeling seawater intrusion in such a dual-permeability karst aquifer. In addition, the largest CSS values of parameter sensitivities can be found around the mixing zone position. The local sensitivity analysis in this study confirms the conclusions of sensitivity studies in a homogeneous aquifer in Shoemaker (2004), also highlights the values of conduit network in modeling seawater intrusion in a coastal karst aquifer.

The global sensitivity analysis indicates that head simulation in the conduit is more sensitive to effective porosity (PO_C) and specific storage of the conduit (SS_C), instead of hydraulic conductivity. The conduit flow easily becomes non-laminar and beyond the capability of Darcy equation in SEAWAT model, which assumes a linear relationship between specific discharge and head gradient. Therefore, the uncertainty of conduit permeability is difficult to be accurately evaluated by hydraulic conductivity in the continuum model. Different from the local sensitivity study, hydraulic conductivity of the porous medium (HY_P) has the largest mean of

EEs with respect to head simulation in the porous medium Simulations are non-linear to parameter SC, which has the largest derivative in the specified evaluated location in the local sensitivity study., Dispersivity is no longer an important parameter for simulations in the conduit, which is different from Shoemaker (2004), because advection is dominated in the solution of saline water transport with turbulent flow in the conduit, as well as the relatively fast seepage flow in the surrounding porous medium. In the salinity profile, the mixing is mostly due to numerical dispersion instead of the solution of dispersion equation, since Peclet number is extremely large and beyond the criteria of solving transport equation by finite difference method.

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Seawater intrudes significantly further landward through the conduit, and flows into the surrounding porous medium via the exchange on the pipe wall.