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Conceptualization of a fresh groundwater lens influenced by climate change: A modeling study of an arid-region island in the Persian Gulf, Iran

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SUMMARY

Understanding the fresh groundwater lens (FGL) behavior and potential threat of climatic-induced seawater intrusion (SWI) are significant for the future water resources management of many small islands. In this paper, the FGL of Kish Island, an arid-region case in the Persian Gulf, Iran, is modeled using two-dimensional (2D) and three-dimensional (3D) simulations. These simulations are based on the application of SUTRA, a density-dependent groundwater numerical model. Also, the numerical model parameters are calibrated using PEST, an automated parameter estimation code.

Firstly a detailed conceptualization of the FGL model is completed to understand the sensitivity of the FGL to some particular aspects of the model prior to analysis of climate change simulations. For these investigations, the FGL system is defined based on Kish Island system to accomplish the integrated comparison of features of a conceptual model that are representative of real-world systems. This is the first study which adopts such an approach. The comparison of cross-sectional simulations suggests that the two-layer properties of the Kish Island aquifer have a significant influence on the FGL while the impacts of lateral-boundary irregularities are negligible. The impacts of sea-level rise (SLR), associated land-surface inundation (LSI), and variations in recharge rate on the FGL salinization of Kish Island are investigated numerically. Variations of SLR value (1–4 m) and net recharge rate (17–24 mm/year) are considered to cover a possible range of climatic scenarios in this arid-region island. The 2D and 3D simulation results demonstrate that LSI caused by SLR and recharge rate variation impacts are more important factors in the FGL in comparison to estimated SLR impacts without LSI. It is also shown that climate change impacts on the FGL are long-term to reach a new FGL equilibrium in the case of Kish Island's aquifer system. The comparative analysis of 2D and 3D results shows that three-dimensionality is a significant factor, especially in large-scale 3D systems of small islands. The results of this study are expected to have implications for the understanding and management of the fresh groundwater resources of Kish Island and are also expected to be relevant to the study of the impact of climate change on groundwater resources on islands worldwide.

1. Introduction

Small islands, typically identified to be less than 2000 km^2 in areal extent, have particular physical features and unique and delicately balanced hydrological systems. Groundwater in small islands occurs as fresh groundwater lenses (FGLs), a relatively thin layer of freshwater overlying seawater as a result of recharge. FGL salinization caused by seawater intrusion (SWI) has a great impact on groundwater quality and it can prevent FGL utilization (Falkland, 1991; White and Falkland, 2010).

Climate change is one potentially significant factor that is expected to play a role in SWI status. The Intergovernmental Panel on Climate Change (IPCC, 2013) assessment report identifies the small island states as being the most vulnerable areas of the world to the adverse impacts of climate change including sea level rise (SLR), and recharge rate variations. SLR of between 0.26 and 1.8 m could be expected by the end of the 21st century (e.g., Melloul and Collin, 2006; IPCC, 2013; Vermeer and Rahmstorf, 2009). This SLR may lead to significant land-surface inundation

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(LSI), particularly in low-topography small islands (Bricker, 2007; Ketabchi et al., 2014). Also, annual mean precipitation and therefore recharge rate could vary by up to ±50% (IPCC, 2013).

Ataie-Ashtiani et al. (2013b) briefly reviewed the recent studies regarding the SLR impact on unconfined shallow aquifers and they showed that LSI caused significantly more extensive SWI, with inland penetration up to an order of magnitude larger in some cases in unconfined coastal aquifers with realistic parameters, compared to the effects of pressure changes at the coastline. They also outlined some of the remaining research challenges in related areas, concluding that LSI impacts are among other important research questions regarding the SLR-SWI problems that have not been addressed, including the effects of real-world three dimensionality and the combined impacts of climate change. They also highlighted the lack of research on the SLR impacts for the groundwater resources of islands.

Masterson and Garabedian (2007) simulated a simplified hypothetical FGL similar to coastal aquifers found along the Atlantic coast of the United States considering the effects of SLR of 2.65 mm/year from 1929 to 2050 and recharge rate of 700 mm/year on the FGL shape using the SEAWAT model. Bailey et al. (2009) employed a conceptual model for atoll-island aquifers in a numerical modeling study to evaluate the response of the FGL to some controlling climatic and geologic variables. Payne (2010) considered the contribution of SLR (0, 0.3, and 0.6 m) and changes in precipitation patterns to the characteristics of SWI in the Hilton Head Island, South Carolina area using the SUTRA model. Rozell and Wong (2010) investigated SLR impacts on a small sandy island of Shelter located in New York State, United States, using SEAWAT. Predicted changes in recharge rate (540–640 mm/year) and SLR of 0–0.61 m over the next century were used to create three future climate scenarios. The model did not consider surface topography and the LSI that would occur under SLR. Sulzbacher et al. (2012) applied FEFLOW to estimate climate change impacts on the North Sea Island of Borkum. For simulating future changes in this coastal groundwater system, the climate change scenario until the year 2100 was specified based on climate change projections by IPCC (2007), combined with data for the German North Sea coast.

From an analysis and review of the literature, it can be concluded that no FGL studies have considered LSI impacts of SLR. Sefelnasr and Sherif (2014) investigated the possible effects of SLR in the Mediterranean Sea on the SWI problem in the Nile Delta Aquifer using FEFLOW considering the effect of the LSI, using digital elevation models. SLRs of 0.5 and 1 m in combination with 50% reduction and 200% increase in current groundwater pumping were considered. They showed that 19–32% of the total area of the Nile Delta became submerged due to the LSI.

Recently, Ketabchi et al. (2014) provided an extensive review on the influence of SLR on FGLs. They extended an explicit analytical steady-state, sharp-interface solution to study the behavior of FGLs influenced by SLR and LSI in two-layer oceanic islands. The impact of recharge rate, coastline slope, and geologic conceptualization (thickness and hydraulic conductivities) on the thickness and the volume of FGLs were studied. They clearly demonstrated that the inclusion of the two-layer geology leads to profound and significant changes to FGLs on small islands and that a one-layer model is overly simplistic in many cases. Their study concluded that FGL volumes and thicknesses were most sensitive to recharge rate, followed by coastline slope, aquifer layer thickness and hydraulic conductivity, rather than SLR impacts, in the range of parameters considered in their study. One of the main shortcomings of their work was considering simplistic hypothetical cases, without the real-world complexities, and this is also the case for other studies (Ataie-Ashtiani et al., 2013b). The real-world complexities such as three-dimensionality, irregularity in boundary shapes, aquifer layering contours, and topography are just a few matters that have not been considered. Understanding when and how these factors should be treated in both conceptual and numerical modeling remains an unresolved challenge and requires a systematic and quantitative evaluation in support of evidence based modeling decision making.

The objective of this work is to address the abovementioned shortcomings of previous work and to extend the work of Ketabchi et al. (2014) to a real-case study island in order to comprehensively investigate relationships between potential climate change scenarios and FGL responses. For this purpose, Kish Island, an arid-region case study, which has been extensively studied before (Ataie-Ashtiani et al., 2013a, 2014) is considered. The real case study allows a detailed exploration of processes that extend well beyond simplified and hypothetical analyses, whilst at the same time providing new insights about the Kish Island system as well as generalizable outcomes relevant to many island systems worldwide. Therefore, this work is novel because we provide a qualitative and systematic comparative study of the impacts of some important simplifications and conceptualization in the modeling processes, using the groundwater system of Kish Island rather than just providing a site-specific case or a completely hypothetical situation.

To provide a better understanding of the FGL dynamics, density-dependent groundwater modeling using SUTRA (Voss and Provost, 2010) is applied for this study which is a more accurate modeling approach in comparison with analytical solutions applied for example, by Ketabchi et al. (2014). Hence, the present paper describes the Kish Island modeling and highlights the potential limitations of such complex and real-case modeling, applied to quantify the influence of climate change factors on the FGL. Here, we address (1) how the conceptual aspects of real-case small island modeling (aquifer layering, lateral boundary geometries, unsaturated zone conditions, and dimensionality) affect the shape of the FGL, and (2) how the combined climatic parameters (including SLR, LSI, and variations in net recharge rate) potentially impact the FGL status. This is the first study to explore the range of potential conceptualizations and their impact on modeling results. The modeling results presented here can therefore help to guide better conceptual and numerical modeling for real island aquifer systems such as the one presented here.

2. Kish Island, Iran

Kish Island is located in the Persian Gulf, approximately 17 km off the southern coast of Iran at 26°29′ to 26°35′N latitude and 53°53′ to 54° 04′E longitude. It has a nearly elliptical shape with major axis in the west-east direction. In 2010, this island supported a population of about 84,200 including locals and tourists. Since the 1980s, this island has been a free trade zone and a highly well-known holiday destination. It is currently expected that about one million tourists visit this island once a year (Kish Free Zone Organization, 2006; Ataie-Ashtiani et al., 2014). Kish Island occupies a land area of about 90 km^2 and at its highest location rises to about 40 m above mean sea level (MSL). Fig. 1 shows Kish Island's location and its surface topography.

The geology of this island mainly consists of two layers. The upper layer contains condensed sand, coral sediments, lumachelle limestone, crushed coral and reef limestone shells discordantly overlying the formation of the thicker bedrock containing clay marl with lenses of silt that are denser and less permeable. Hydraulic conductivity measurements for the upper layer vary between 1.0×10^{-5} and 1.0×10^{-3} m/s while for base layer, they vary between 1.0×10^{-7} and 1.0×10^{-4} m/s (Ataie-Ashtiani, 2010; Ataie-Ashtiani et al., 2013a).