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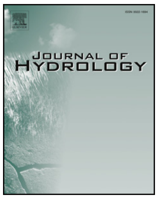

Research papers

Assessment of the impact of sea-level rise on steady-state seawater intrusion in a layered coastal aquifer

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ABSTRACT

Previous studies on the impact of sea-level rise (SLR) on seawater intrusion (SWI) are mostly based on the assumption of a homogeneous coastal aquifer. In this study, we extend those studies by investigating SLR-induced SWI in a layered coastal aquifer using the analytical method developed by Strack and Ausk (2015). We provide analytical solutions for steady-state SWI in confined and unconfined coastal aquifers, where both constant-head and constant-flux inland boundary conditions are considered. The analysis based on a three-layer aquifer indicates that in general aquifer stratification affects either or both the initial location and response distance of the interface toe. Specifically, for flux-controlled unconfined coastal systems, the toe response distance driven by SLR is a linear function of the hydraulic conductivity of the top layer and independent of hydraulic conductivities of lower layers. Using an equivalent homogeneous hydraulic conductivity (derived based on the initial interface toe location before SLR) would result in overestimation or underestimation of the toe response distance, depending on the hydraulic conductivities and thicknesses of the layers. For flux-controlled confined layered coastal systems, by contrast, SLR can not cause variation of the steady-state interface toe location, which is consistent with previous findings for homogeneous coastal aquifers. The interface toe location in head-controlled layered coastal systems is only a function of relative hydraulic conductivities between the layers. Moreover, the effect of the layer thickness on the interface toe location and response distance in the head-controlled system exhibits a more complicated pattern than in the flux-controlled coastal system, as changing the layer thickness changes both the overall aquifer transmissivity and inland freshwater flux. The results obtained enhance the understanding of the impact of SLR on SWI, which could provide a first-order assessment tool for relevant practitioners.

1. Introduction

Seawater intrusion (SWI) is the movement of saline water into freshwater aquifers, and it is generally believed that the over-exploitation of coastal aquifers, extended drought period, and sea-level rise (SLR) are the main causes (Werner et al., 2013). The problem of SWI has been regarded as one of the most important issues in managing coastal zones, as it can significantly degrade the coastal hydrogeological and ecological systems (Darwish et al., 2005; Qi and Qiu, 2011) and impede coastal economic and social development. Thus, the management of SWI is an important imperative for sustainable development of coastal regions.

SWI has been studied for over one century using analytical, numerical, and experimental methods (Werner et al., 2013). In terms of causing factors, the impact of SLR on SWI has interested researchers in the recent decade (Ketabchi et al., 2016), because of the obvious tendency of SLR reported by the Intergovernmental Panel on Climate Change (IPCC, 2007, 2013). The study of the impact of SLR on SWI can be generally categorized into two types in terms of the state of the problem. The first type of research considers only the steady-state condition and neglects transience of the process (e.g., Werner and Simmons, 2009; Ferguson and Gleeson, 2012; Ataie-Ashtiani et al., 2013; Lu et al., 2015). Based on this assumption together with the sharp-interface approximation, analytical solutions of the interface toe location and saltwater volume can be developed based on the potential theory, providing a convenient tool for the first-order assessment of SWI

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(Werner, et al., 2012). The second type of research, by contrast, explores various quantitative indicators (e.g., seawater isochlors, total salt mass and wedge center-of-mass) during the transient SWI process (e.g., Watson et al., 2010; Chang et al., 2011; Webb and Howard, 2011; Mehdizadeh et al., 2017). The selection of the research method depends mainly on the purpose of the study and the availability of data.

Werner and Simmons (2009) conducted a precursory theoretical study on the impact of SLR on SWI using the simple analytical method based on the potential theory. The authors assumed conceptual models with two different types of inland boundary conditions (i.e., fixed-head and fixed-flux) and found that SLR in the coastal system with a fixed-head inland boundary condition would incur large interface toe migration, highlighting the importance of the inland boundary condition in assessing the impact of SLR on SWI. This study was later extended by Lu et al. (2015) by considering an additional general-head inland boundary condition with two special parameters (i.e., hydraulic conductance and reference head). The general-head inland boundary condition represents an intermediate inland boundary in predicting the vulnerability of coastal aquifers to SLR. Lu et al. (2013b) also pointed out the importance of the inland boundary condition in evaluating the relative vulnerability of coastal aquifers to groundwater pumping and SLR (Ferguson and Gleeson, 2012).

In addition to the inland boundary condition, the impact of land-surface inundation on aquifer salinization caused by SLR has been investigated using the analytical method (Ataie-Ashtiani et al., 2013). It was shown that the effect of land-surface inundation would be a dominant factor on the steady-state interface position in unconfined coastal aquifers with a small beach slope. Moreover, analytical solutions have been developed to explore the influence of the sloping confining bed of an unconfined aquifer on SWI under SLR (Koussis et al., 2012; Mazi et al., 2013). The results showed high nonlinearity in the responses of SWI to SLR and indicated the existence of important thresholds or tipping points, beyond which the shift of the interface toe becomes abrupt.

Transient SWI processes in response to SLR is often investigated through the numerical method on the basis of the variable-density flow and solute transport model (e.g., Webb and Howard, 2011). For example, Watson et al. (2010) explored transience of SWI in response to SLR using a variety of quantitative indicators and observed the temporal asymmetry between SWI responses to SLR and sea-level drop. Moreover, some simulations in their study exhibit temporary 'overshoot' of the steady-state interface. This 'overshoot' phenomenon has been reproduced in a laboratory-scale sand tank experiment (Morgan et al., 2015). Other important studies about SLR-induced transient SWI can be found in the recent review paper of Ketabchi et al. (2016).

Most of previous studies assume a homogeneous aquifer and therefore neglect various patterns of geologic heterogeneity, which is considered as an important factor controlling the extent of SWI (e.g., Dagan and Zeitoun, 1998; Lu et al., 2013a). Coastal aquifers are often comprised of layers of different geologic strata (e.g., Oki et al., 1998; Nakagawa et al., 2000); however, limited research on SWI subject to SLR in layered coastal aquifers is available. Ketabchi et al. (2014) investigated analytically fresh groundwater lenses in two-layer small islands subject to the combined impact of SLR and land-surface inundation. Recently, Mehdizadeh et al. (2017) numerically explored the SLR effect on transient SWI in a coastal aquifer, in which a horizontal aquitard layer is located between two horizontal permeable layers. However, the general impact of SLR on SWI for a layered coastal aquifer is still unknown. To fill this scientific gap, we explore SLR-induced SWI in both confined and unconfined layered coastal aquifers. Given the importance of the type of the inland boundary, both fixed-head and fixed-flux inland boundary conditions are considered.

Our study relies an analytical solution for the interface toe location in a three-layer coastal aquifer with different combinations of the aquifer type, inland boundary condition, and stratification. The analytical method employed follows that developed by Strack and Ausk (2015) using a comprehensive discharge potential, in which the gradient of the comprehensive potential results in the vertically integrated discharge throughout the aquifer. The comprehensive potential along the coastal boundary is derived precisely based on the geometry of the aquifer. The interface elevations, piezometric heads, and the vertical distribution of flow can be determined by adopting the Dupuit-Forchheimer approximation (Dupuit, 1863; Forchheimer, 1886) and the Ghyben-Herzberg equation (Badon Ghyben and Drabbe, 1888; Herzberg, 1901). Although the method used to derive the analytical solution of seawater intrusion in a layered coastal aquifer has been proposed by Strack and Ausk (2015), the impact of SLR on seawater intrusion in a layered coastal system has not been evaluated. Therefore, the current investigation extends most previous studies (e.g., Werner and Simmons, 2009; Ferguson and Gleeson, 2012; Ataie-Ashtiani et al., 2013; Lu et al., 2015) by considering a multi-layer coastal system rather than a simplified homogeneous coastal system, in which SLR is occurring. For the sake of simplicity, a three-layer coastal aquifer is adopted to assess the SLR impact on SWI, though analytical solutions for coastal aquifers with *N* layers will first be given.

2. Conceptual model

We first considered idealized confined and unconfined coastal aquifers with *N* layers, as shown in Fig. 1. The following assumptions are made: (1) the flow systems are under steady state; (2) the density of groundwater and the resting saline water are separated by a sharp interface, i.e., the two fluids are assumed immiscible; (3) the coastal boundary is vertical such that land surface inundation is not considered; and (4) the flow in the vertical direction is neglected (i.e., the Dupuit-Forchheimer approximation is adopted). These assumptions are frequently employed in previous analytical studies of SWI (e.g., Strack, 1976; Kacimov and Sherif, 2006; Strack and Ausk, 2015).

As shown, the strata are sequentially denoted as $j = 1, 2, \ldots, N$ from the bottom up. We use b_j [L] to represent the base elevation of each layer ($b_1 = 0$). m, n, and μ represent the layer that contains the saltwater interface, water table, and sea level, respectively. H_j [L] and K_j [L/T] represent the thickness and hydraulic conductivity of each layer. We place the origin of coordinate system at the intersection of the vertical coastline and the horizontally impermeable base. Furthermore, the z-axis is vertically upward, and the x-axis is pointing horizontally landward. The level of the horizontal base (i.e. (x, y)-plane) is used as the datum for the aquifer system. φ [L] is the height of the water table above the sea level, h_s [L] is the vertical distance between the sea level and the interface, h_f [L] is the elevation of the phreatic surface, and H_s [L] is the elevation of the sea level. H_L [L] is the hydraulic head at the distance L [L] from the coastline. Q_f [L^2/T] is a constant freshwater discharge from inland per unit length of coastline. By applying one of the two inland boundary conditions (i.e. either Q_f or H_L), the flux-controlled or head-controlled coastal system is considered. For the head-controlled coastal system, we set the freshwater flux after SLR as

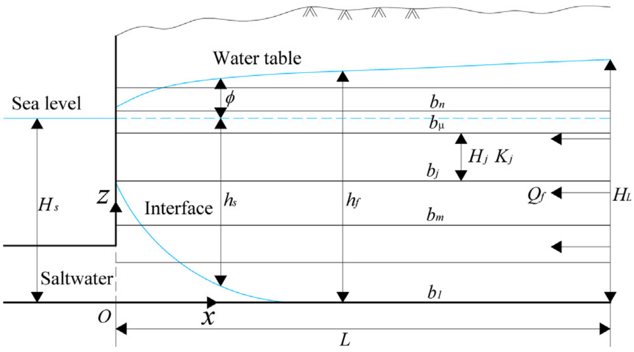

Fig. 1. Conceptual model of a coastal aquifer with *N* layers.