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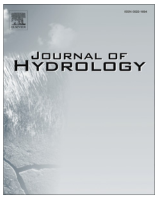

Technical Note

Seawater intrusion in response to sea-level rise in a coastal aquifer with a general-head inland boundary

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SUMMARY

Seawater intrusion in response to sea-level rise has been studied extensively in recent years by assuming largely a constant-head or constant-flux inland boundary condition. However, these two types of boundary conditions are not sufficient when the inland edge of the model domain is neither natural groundwater nor known hydraulic boundaries. Under these circumstances, a general-head inland boundary condition capable of characterizing the hydraulic response of model boundaries is needed. Previous studies adopting the general-head inland boundary condition to assess coastal aquifer vulnerability to sea-level rise are limited and all based on numerical modeling. In this study, we derive analytical solutions of the interface toe location in both confined and unconfined coastal systems with a general-head inland boundary condition. Comparison among the performances of the three different types of inland boundary conditions in evaluating the sea-level rise impact on aquifer salinization is carried out by assuming the same initial system condition. It is found that the displacement of the interface toe predicted using a general-head inland boundary is between those of using a constant-head (upper bound) and constant-flux (lower bound) inland boundary, depending on the values of two general-head boundary parameters (i.e., hydraulic conductance and reference head). More importantly, analytical solutions developed could serve as a tool for calibrating the two boundary parameters defined in the general-head boundary condition for site-specific assessments.

1. Introduction

Sea-level rise (SLR), as an indicator and a consequence of climate change, has a significant impact on coastal hydrogeological and ecological systems (Nicholls and Cazenave, 2010). Increase in sea level may alter the hydraulic gradient between land and sea and may exacerbate seawater intrusion, a global issue that reduces freshwater volume and constrains groundwater pumping in coastal regions. In recent years, there is an increasing interest in evaluating the extent of seawater intrusion in response to SLR (Werner et al., 2013).

The impact of SLR on seawater intrusion has been explored extensively through national- or global-scale assessments (Ferguson and Gleeson, 2012; Michael et al., 2013), case studies at particular sites (e.g., Vandenbohede et al., 2008; Hughes et al., 2009; Oude Essink et al., 2010; Loaiciga et al., 2012; Langevin and Zygnerski, 2013; Sefelnasr and Sherif, 2004), and general investigations based on hypothetical and idealized conceptual models (e.g., Masterson and Garabedian, 2007; Werner and Simmons, 2009; Werner et al., 2012; Ataie-Ashtiani et al., 2013; Mazi et al., 2013; Ketabchi et al., 2014; Morgan and Werner, 2014). These studies have generated significant insights into various geologic and hydrological controls on the vulnerability of coastal groundwater systems. One key finding, among others, is that inland boundary conditions are critical to assessing the SLR impact on aquifer salinization. For example, a simple analytical study indicated that an unconfined coastal aquifer with a constant-head inland boundary (i.e., head-controlled coastal system) is remarkably more vulnerable to the SLR impact, in comparison to that with a constant-flux inland boundary (i.e., flux-controlled coastal system) under otherwise the same conditions (Werner and Simmons, 2009). Later, Werner et al. (2012) found that confined aquifers are insensitive to SLR under flux-controlled conditions and like unconfined aquifers, are more sensitive to SLR under head-controlled conditions. Moreover, numerical modeling

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and laboratory experiments showed that SLR in flux-controlled coastal systems could cause a temporal overshoot of the freshwater–seawater interface toe (i.e., the interface toe temporarily exceeds its final steady-state location after SLR) (Watson et al., 2010; Chang et al., 2011; Morgan et al., 2014). This overshoot phenomenon, however, has not been reported in head-controlled coastal systems (Webb and Howard, 2010; Lu and Werner, 2013). All these findings convey the information that an accurate inland boundary condition is required in the assessment of SLR impacts on seawater intrusion in coastal aquifers, otherwise a significant error may occur.

Despite wide applications in previous studies, constant-head and constant-flux boundary conditions have their inherent limitations in practical use, especially when the locations of hydraulic boundaries (i.e., rivers, faults, etc.) are not known. For example, the constant-head boundary condition, acting as an infinite source of water entering the system or as an infinite sink for water leaving the system, may lead to unrealistic predictions. To overcome this issue, a general-head boundary (GHB) was introduced to represent a more realistic boundary by relating the flux to the head at the inland boundary. This boundary condition has been adopted to predict the SLR impact on seawater intrusion for a number of sites (e.g., Dausman and Langevin, 2005; Oude Essink et al., 2010). To the best of our knowledge, however, previous studies using a GHB in the model all relied on numerical modeling, and an analytical solution is currently unavailable. Furthermore, there is a lack of comparison among the performances of the general-head, constant-head, and constant-flux inland boundary conditions in predicting SLR-induced seawater intrusion.

2. General-head boundary

GHB is the simplest head-dependent flux boundary. Flow entering or leaving the system is in proportion to the difference between the head at the GHB and the reference head (representing the head at the external hydraulic boundary), and mathematically expressed through a linear equation (Harbaugh et al., 2000):

$$q = -C(H - H_{ref}) \tag{1}$$

in which q [L^2/T] is the flow rate per unit aquifer width, C [L/T] is the hydraulic conductance, and H [L] and H_{ref} [L] are the head at the GHB and the reference head, respectively. C is a parameter that represents the resistance to flow between the model domain and the external hydraulic boundary. It can be easily interpreted from the equation that q is zero, when $H = H_{ref}$; water enters the groundwater system through the GHB, when $H < H_{ref}$ (i.e., $q > 0$); otherwise, water leaves the groundwater system through the GHB (i.e., $q < 0$).

GHB conditions are used typically to represent heads in a groundwater model that are influenced by a large surface water body outside the model domain with a known water elevation (i.e., H_{ref}). In contrast to constant-head and constant-flux boundary conditions, GHB conditions are capable of characterizing the hydraulic response of the boundaries to the groundwater condition variations, if appropriate values of C and H_{ref} are selected. In other words, the head and flux at the GHB are changeable in response to hydraulic stresses.

3. Analytical solution

3.1. Conceptual model

Idealized confined and unconfined homogeneous isotropic coastal aquifers are considered, as shown in Fig. 1. The aquifers are underlain by a horizontal impermeable base with negligible surface recharge. The direction of freshwater flow is horizontal and perpendicular to the coastline. With the mixing between freshwater and seawater neglected, a sharp interface is assumed to separate the two fluids. As such, two zones can be identified: a freshwater–saltwater zone (Zone 1) and a freshwater-only zone (Zone 2). At the coastal boundary, tides and waves are neglected for assuming a steady-state groundwater system. These assumptions have been employed in previous analytical studies of seawater intrusion problem (e.g., Strack, 1976; Werner and Simmons, 2009; Lu et al., 2014).

H_s [L] is the mean sea level above the aquifer bottom. The thickness between the confining layer and the aquifer bottom is B [L]. h_f [L] is the thickness of the freshwater lens (i.e., the thickness between the water table and aquifer base or the freshwater–seawater interface). The interface toe is located x_t [L] inland of the coastline. Three different boundary conditions of constant-head, constant-flux, and general-head are assumed respectively at the inland boundary. To facilitate the analysis, we denote correspondingly the interface toe lengths in coastal systems with a constant-head, constant-flux, and general-head inland boundary condition as x_t(CHB), x_t(CFB), and x_t(GHB). For the flux-controlled system, a regional flow with a constant rate of q_f [L^2/T] discharges from an infinite distance to the sea, while a fixed head H_f [L] is set at a distance of L [L] from the coastline for the head-controlled system. For the coastal system with a general-head inland boundary, the GHB is defined at a distance of L from the coastline. As a result, the domain lengths for aquifers with constant-head and general-head inland boundary conditions are the same. For simplicity, the x-axis is placed along the aquifer base (pointing to inland) with the origin located at the coastline.

3.2. Potential theory

We first derive the analytical solution of x_t in flux-controlled coastal systems (i.e., x_t(CFB)), following Strack (2000) single potential theory. A potential, Φ [L^2], can be expressed respectively for Zones 1 and 2 as follows:

Confined:

$$\text{Zone 1}: \Phi = \frac{1}{2\alpha}\left(\alpha h_f - H_s(1+\alpha) + B\right)^2 \tag{2}$$

$$\text{Zone 2}: \Phi = h_f B + \frac{1}{2\alpha}B^2 - BH_s\left(\frac{1}{\alpha} + 1\right) \tag{3}$$

Unconfined:

$$\text{Zone 1}: \Phi = \frac{1}{2}(1+\alpha)(h_f - H_s)^2 \tag{4}$$

$$\text{Zone 2}: \Phi = \frac{1}{2}\left(h_f^2 - \left(\frac{1}{\alpha} + 1\right)H_s^2\right) \tag{5}$$

in which α [–] is the density ratio and equals to 40. The potential at the interface toe, Φ_t [L^2], can be derived by solving equations (Eqs. (2) and (3) for confined aquifers and Eqs. (4) and (5) for unconfined aquifers) simultaneously in accordance to the continuity of flow as:

Confined:

$$\Phi_t = \frac{1}{2\alpha}B^2 \tag{6}$$

Unconfined

$$\Phi_t = \frac{1+\alpha}{2\alpha^2}H_s^2 \tag{7}$$

The position of the interface toe is then obtained by substituting the freshwater discharge potential $\Phi = \frac{q_f x}{K}$ (K [L/T] is the hydraulic conductivity of the aquifer) into Eqs. (6) and (7), respectively: