How important is the impact of land-surface inundation on seawater intrusion caused by sea-level rise?

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Abstract The influence of sea-level rise (SLR) on seawater intrusion (SWI) has been the subject of several publications, which consider collectively a range of functional relationships within various hydrogeological and SLR settings. Most of the recent generalized analyses of SWI under SLR neglect land-surface inundation (LSI) by seawater. A simple analytical method is applied to quantitatively assess the influence and importance of LSI on SLR–SWI problems under idealized conditions. The results demonstrate that LSI induces significantly more extensive SWI, with inland penetration up to an order of magnitude larger in the worst case, compared to the effects of pressure changes at the shoreline in unconfined coastal aquifers with realistic parameters. The study also outlines 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 aquifer heterogeneities, real-world three dimensionality, and mitigation measures.

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Introduction

Concerns about the effects of climate change and sea-level rise (SLR) on coastal groundwater resources are increasing, evidenced by the recent surge in the number of publications on the topic (Werner et al. 2013). The Intergovernmental Panel on Climate Change (IPCC) predicts that global seas may rise between 18 and 59 cm by the end of the century (IPCC 2007), although SLR predictions up to 180 cm have also been suggested (e.g., Vermeer and Rahmstorf 2009). Wada et al. (2010) suggest that global groundwater depletion accounts for 0.8 mm/year or one-quarter of the current rate of SLR of 3.1 mm/year. Global groundwater depletion therefore impacts on coastal aquifers in two ways: aquifer head decline and SLR.

Seawater intrusion (SWI) arising from SLR has been evaluated using various simplified aquifer types to provide general guidance on functional relationships, and a number of case studies have been completed (e.g., Werner et al. 2012). Sherif and Singh (1999) provided one of the first predictive case studies of SLR impacts on SWI. They investigated the effect of likely climate change on SWI in two coastal aquifers, one in Egypt and the other in India. They used a two-dimensional (2D) vertical cross-sectional model to show that a 50-cm SLR would cause SWI of 9 km in the Nile Delta aquifer and 0.4 km in the Bay of Bengal aquifer. Kooi et al. (2000) studied SWI during SLR across geological timescales and considered the effects of seawater transgression using numerical and analytical approaches. They showed that saltwater free convection occurs and that various modes of SWI can take place under transient conditions. Feseker (2007) studied a hypothetical case study of the impact of climate change, SLR and changes in land use on the salt distribution in a field site on the German North Sea coast. A density-dependent solute transport model was used to simulate the steady-state salt distribution in cross section. They showed that rising sea levels would cause a rapid increase in the groundwater salinity close to the shoreline, whereas an extensive drainage network compensated for changes in groundwater recharge. Oude Essink et al. (2010) studied

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the effects of future SLR, land subsidence and changes in recharge in the low–lying Dutch Delta, using the MOCDENS3D model. They found that the future impact of SLR was limited to areas within 10 km of the coastline of the Netherlands due mainly to the highly permeability of a Holocene confining layer. Loaiciga et al. (2012) applied FEFLOW to model SLR and pumping controls on SWI near Monterey (USA). They showed that groundwater extraction, rather than SLR, was the predominant driver of SWI in the study area.

General guidance on the extent of SLR–SWI is given by Werner and Simmons (2009) and Werner et al. (2012). They represented SWI as the shift in a sharp freshwater–seawater interface, from one steady state to another, for both fixed-head and fixed-flux inland boundary conditions and for a range of aquifer parameters and stresses. The extent of SWI was in the order of tens of meters for flux-controlled landward conditions, and up to several kilometers for head-controlled conditions. In flux-controlled confined aquifers, SLR was shown to cause no SWI, in the cases that seawater overtopping is neglected, i.e., from the perspective of a shift in the steady-state interface position (Werner et al. 2012).

Transient processes accompanying SLR–SWI were examined using numerical simulations of coastal aquifer cross sections by Watson et al. (2010), Webb and Howard (2011), and Chang et al. (2011). Collectively, they assessed SWI in idealized aquifer settings subjected to various boundary conditions and rates of SLR. Watson et al. (2010) and Webb and Howard (2011) found that time scales of decades to centuries were required for the toe to stabilize following SLR. Watson et al. (2010) and Chang et al. (2011) observed a temporary "overshoot" of the steady-state interface position in some simulations, contradicting the common assumption that steady-state SWI is the worst case.

In each of the aforementioned studies, land surface inundation (LSI) arising from the landward movement of the coastline, accompanying SLR was not considered. Recently, Ferguson and Gleeson (2012) studied coastal aquifer vulnerability by combining a modified analytical model for simulation of SWI and LSI, with a geographic information system that included hydrogeological and population parameters. They suggest that coastal aquifers are more vulnerable to excessive groundwater extraction in comparison to SLR. Despite progress in understanding the influence of SLR on SWI, there are several remaining questions requiring further investigation. In particular, the influence of LSI is often neglected in SLR studies. While Kooi et al. (2000), Loaiciga et al. (2012) and Ferguson and Gleeson (2012) considered LSI in their modeling research of SLR, they did not quantify the importance of LSI impacts relative to SLR effects when only the pressure increase at the coast is considered; i.e. considering a vertical shoreline. The current study undertakes an examination of this issue using a simple steady-state, sharp-interface analytical solution that accounts for LSI. Further, other important aspects of the SLR–SWI problem that have not been addressed, arising from our review of the literature, are outlined.

Impact of LSI by seawater

In this section, a preliminary study of the impact of LSI caused by SLR on SWI is carried out using a simple conceptualization and sharp-interface analytical modeling. Two alternative conceptualizations of the coastal boundary representation of SLR–SWI are illustrated in Fig. 1. In the first case (Fig. 1a), only the vertical movement of SLR is considered, thereby neglecting LSI and assuming a vertical coastal boundary. In the second case (Fig. 1b), both vertical and horizontal movements of seawater are considered. Although the first conceptualization is arguably suitable for confined aquifers, the second conceptualization is clearly a more thorough treatment of the conditions encountered in many unconfined aquifers, where SLR is large enough and the land surface is low enough for LSI to occur.

The situation of Fig. 1a involving no LSI has been assessed previously using the method of Strack (1976), which provides a solution for the seawater wedge toe location, assuming steady-state, sharp-interface conditions and a homogeneous isotropic unconfined coastal aquifer, subject to constant aquifer recharge and sea level. The toe position (X_T) in this case can be predicted using the following expression (Custodio and Bruggeman 1987; Chang et al. 2011):

$$X_T = \left(\frac{q}{W}+L\right)-\sqrt{\left(\frac{q}{W}+L\right)^2-\frac{K\delta(1+\delta)z_0^2}{W}} \tag{1}$$

where K (L T^{-1}) is hydraulic conductivity, L (L) is aquifer length, q (L^2 T^{-1}) freshwater flow through the coastal boundary per unit width of coastline, z_0 (L) is the depth of aquifer bottom measured from mean sea level, W (L T^{-1}) is the uniform recharge rate, and δ (−) is the dimensionless density term equal to $(\rho_s-\rho_f)/\rho_f$, where ρ_f (M L^{-3}) is the density of freshwater and ρ_s (M L^{-3}) is the density of seawater. The common value of 0.025 is adopted for δ.

For the case of a constant-head inland boundary condition, the depth-averaged coastal discharge in Eq. (1) can be obtained from the integration of $q+W(L-x)=Kh(1+1/\delta)\frac{dh}{dx}$, which results into:

$$q=\frac{K\left((h_b+z_0)^2-(1+\delta)z_0^2\right)}{2L}-\frac{WL}{2} \tag{2}$$

where h_b (L) is the freshwater head above mean sea level at the inland boundary (x=L). For the case of the same density (δ=0) and water level at the both sides (h_b=0), a groundwater mound is developed in the center and the magnitude of q is $WL/2$ at the coastal boundary. Considering a shift in the position of the sea boundary caused by SLR, as shown in Fig. 1b, the new steady-state

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SWI toe position for both constant-flux and constant-head inland boundaries is given by:

$$X'_{\mathrm{T}}=\left(\frac{q}{W}+L-\frac{\Delta z}{s}\right)-\sqrt{\left(\frac{q}{W}+L-\frac{\Delta z}{s}\right)^2-\frac{K\delta(1+\delta)(z_0+\Delta z)^2}{W}}+\frac{\Delta z}{s} \quad (3)$$

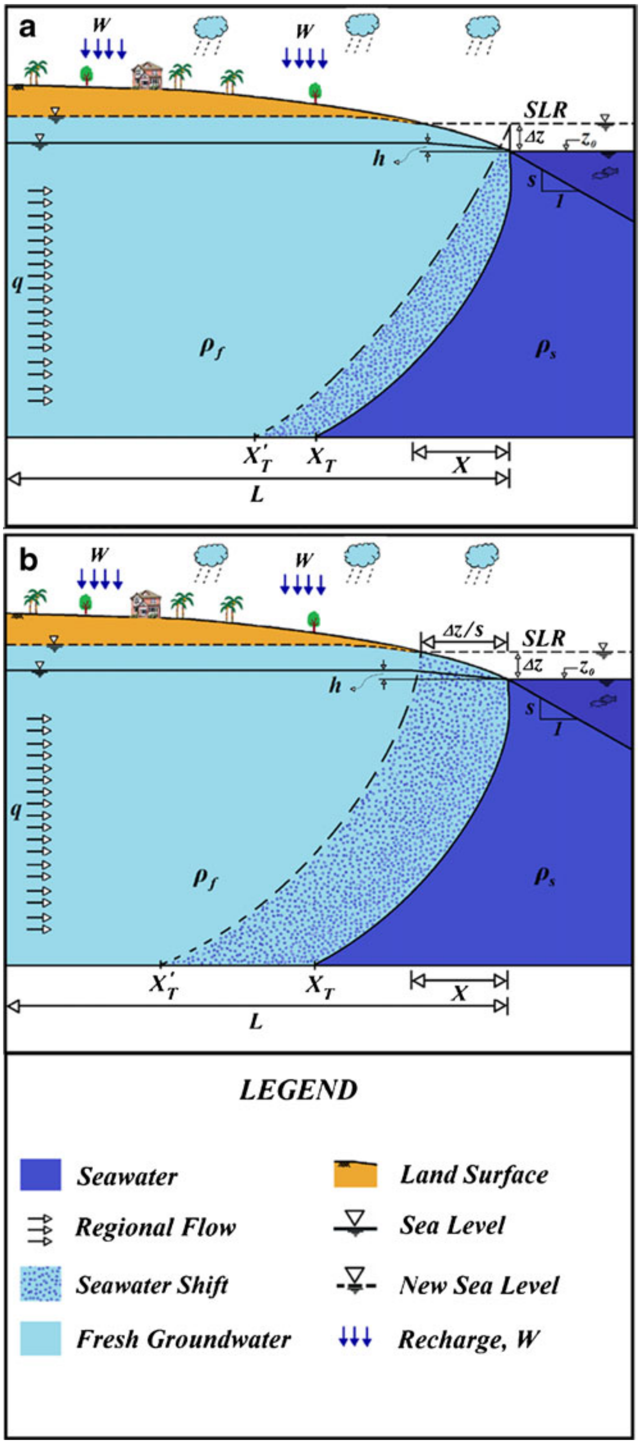

Fig. 1 Schematic of the seawater intrusion (SWI) wedge: **a** assuming vertical face with sea-level rise (*SLR*), and **b** considering slope face with SLR (for simplicity, only flux-controlled conditions are shown here)

where Δz (L) is the SLR, and s (−) is the slope of the aquifer's seaward boundary. The value of q in Eq. (3) is modified by SLR, for the case of a constant-head inland boundary, and is given as:

$$q=\frac{K\left((h_{\mathrm{b}}+z_0)^2-(1+\delta)(z_0+\Delta z)^2\right)}{2\left(L-\frac{\Delta z}{s}\right)}-\frac{W\left(L-\frac{\Delta z}{s}\right)}{2} \quad (4)$$

In order to quantify the influence of LSI on SLR-induced SWI, a ratio parameter, R, is defined as:

$$R=\frac{X_{\mathrm{T}}^{s}-X_{\mathrm{T}}^{v}}{X_{\mathrm{T}}^{v}-X_{\mathrm{T}}} \quad (5)$$

where $X_{\mathrm{T}}^{\mathrm{s}}$, $X_{\mathrm{T}}^{\mathrm{v}}$, and X_{T} are toe positions for aquifers with sloping coastal boundaries and vertical coastal boundaries, and the toe position prior to SLR, respectively. The analysis is applied to a number of unconfined aquifer settings, using parameters taken from Werner et al. (2012) that include the following cases: Gaza aquifer, Palestine (Moe et al. 2001; cases 1a–1c), Pioneer Valley, Australia (Werner and Gallagher 2006; cases 2a–2b) and Uley South, Australia (Zulfic et al. 2007; Werner et al. 2011; case 3).

Table 1 provides the values of the parameters for the considered cases, and the toe position results for situations of no SLR, SLR without LSI ($\Delta z/s$=0), and SLR with LSI ($\Delta z/s$>0). A SLR (Δz) of 2 m is assumed in all cases. The toe location for two different landward boundary conditions of constant-head and constant-flux are given in Table 1. The R parameter, in Table 1, shows that the impact of LSI on the SWI toe position is of the same order as the impact of other factors for the cases with the steep slope of 0.1. The impact, for the case of a more realistic slope of 0.01, is significantly larger and in some cases an order-of-magnitude larger than the impact of other factors. For example, for the Gaza aquifer (case 1b), the SWI toe position is at 454, 473 and 675 m from the shoreline for the scenarios of no SLR, SLR without LSI, and SLR with LSI, respectively, in the case of inland constant-flux boundary condition. In other words, the shift in the toe position, relative to the pre-SLR situation, is 10.6 times larger for the case of SLR with LSI compared to the case without LSI. As shown in Table 1, in some of the cases where the landward boundary condition is treated as a constant-head boundary, LSI causes a negative flux (q<0) and unstable interface conditions, whereby the interface is moving inland and a steady-state condition cannot be calculated. Therefore, for both cases of constant-head and constant-flux inland boundary conditions, the LSI impact on SWI is significant. Under the worst conditions tested for the Gaza aquifer with the shoreline slope of 0.01, LSI causes a shift in the toe position of more than 10 times the toe shift in cases where LSI is neglected.

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Table 1 Parameters for the cases and toe position

							Flux inland BC			Head inland BC		
Case	K (m/day)	W (mm/year)	z_0 (m)	L (m)	Δz (m)	s	q (m^2/day)	X_T (m)	R	h_b (m)	X_T (m)	R
1a	15	58	100	10,000	0	–	1.7	593	–	16.5	593	–
					2	∞ (vertical)		617	–		684	–
					2	0.1		638	0.9		704	0.2
					2	0.01		823	8.6		878	2.1
1b	15	31	100	10,000	0	–	3.4	454	–	23.9	454	–
					2	∞ (vertical)		473	–		510	–
					2	0.1		493	1.1		529	0.3
					2	0.01		675	10.6		702	3.4
1c	15	31	100	10,000	0	–	1.8	734	–	15	734	–
					2	∞ (vertical)		764	–		866	–
					2	0.1		785	0.7		885	0.1
					2	0.01		969	6.8		1,055	1.4
2a	100	110	25	2,000	0	–	0.58	748	–	1	746	–
					2	∞ (vertical)		891	–		$q<0$	–
					2	0.1		917	0.7		$q<0$	–
					2	0.01		1,154	2.3		$q<0$	–
2b	100	110	25	1,000	0	–	4.3	175	–	2	176	–
					2	∞ (vertical)		204	–		$q<0$	–
					2	0.1		225	0.7		$q<0$	–
					2	0.01		407	7.0		$q<0$	–
3	200	100	25	2,000	0	–	1.5	828	–	1.0	830	–
					2	∞ (vertical)		976	–		$q<0$	–
					2	0.1		999	0.2		$q<0$	–
					2	0.01		1,207	1.6		$q<0$	–

Although the analysis provided here is based on a simple conceptualization, it highlights that important aspects of the SLR–SWI problem need to be considered further to properly characterize the key controlling factors. A review of the literature finds other important elements that also require additional assessment, aside from the influence of SLR-induced LSI. These are discussed in the following section.

Future research challenges

In addition to LSI, there are other challenges remaining in understanding the impact of SLR on SWI that should be recognized. For example, coastal geomorphological changes can be an important factor affecting SWI, especially when LSI is considered. These changes are interdependent with LSI due to the effects of coastal erosion and changes in beach morphology, and are further complicated by the combination of increased intensity and frequency of storm events as an additional effect of climate change that might accompany SLR (Revell et al. 2011). When the influence of LSI is considered, saltwater free convection can potentially occur and various modes of SWI can take place under transient conditions (Kooi et al. 2000; Kooi and Groen 2001; Illangasekare et al. 2006). The conditions for the onset of free convection during SLR were studied by Kooi et al. (2000) using numerical simulations. If the LSI front advances faster than the SWI wedge, free convection is likely to develop. When free convection occurs, downwards salinization occurs at a much faster rate than caused by diffusion, dispersion and advection alone, and it can play a significant role in the spatial and temporal variations of the SWI interface (Laattoe et al. 2013).

The former studies focus on situations where the freshwater is constrained at the lower boundary by the aquifer basement. However, many coastal aquifers are freshwater lenses such as those of small islands and under upwelling conditions of polders in the Netherlands and Belgium (e.g. de Louw et al. 2011). The lenses of small islands usually occur as thin veneers, which are often the only local source of freshwater, and are highly vulnerable to degradation from anthropogenic disturbances (Falkland 1991). Climate change impacts on small island freshwater lenses have received substantially less attention relative to continental coastal aquifers, aside from aquifer salinization due to episodic overtopping events (e.g. Terry and Falkland 2010; Chui and Terry 2012). The controlling processes associated with climate change impacts on island lenses include SLR, meteorological drought, storm surges and physical erosion, and these are ineluctably linked (e.g. Terry and Falkland 2010). Further, SLR–SWI on all small low-topography islands requires consideration of LSI given their characteristically flat topographical gradients (Chui and Terry 2012).

Many of the studies to date have examined single processes in isolation from many of the others which may be present. Often the other processes have been neglected without quantitative justification (e.g., Werner and Simmons 2009; Watson et al. 2010; Chang et al. 2011). Comprehensive analyses and case studies which include many, if not all, of the controlling factors within the same analysis framework are required to systematically and quantitatively evaluate sensitivity to those controlling factors and will assist in further improving our understanding of their relative importance. Exploring practical methods to control and lessen the damaging impacts and improve the effectiveness of engineering measures to mitigate SWI under SLR are among the most

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important future challenges. In particular, given the importance of LSI (including the salinization of surface-water bodies), as presented here, restricting LSI is clearly a key aspect of mitigating SLR–SWI. Further detailed case studies are required in order to explore the importance of various site-specific effects (e.g., real-world three dimensionality, spatial and temporal heterogeneity of aquifers properties, temporal variations of pumping and recharge).

Conclusions

In this work, a simple analytical analysis has shown that the influence of LSI is a dominant controlling factor on the SWI interface position due to SLR in unconfined coastal aquifers. Examining idealized cases with realistic parameters showed that the impact of LSI in some cases increases the SLR influence by an order of magnitude. The influence of LSI, in combination with other factors warrants further study. The authors believe that the simplicity of the provided formulation is an advantage of the method described in this article, as using the simplest possible mean provides an important and novel insight into the problem of SLR impacts on SWI. Also, this article identifies some of the important remaining challenges in the area of SLR-induced SWI. Further work to elucidate the effects of spatial dimensionality (2D vs. 3D), aquifer geologic heterogeneity, and transient features of SWI caused by SLR is required. Particular attention should be endowed to the combined effects of climate change, in addition to SLR impacts on freshwater lenses.

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