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Sea level rise effect on seawater intrusion into layered coastal aquifers (simulation using dispersive and sharp-interface approaches)

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ABSTRACT

Concerning about sea level rise (SLR) effect on seawater intrusion (SWI) has been grown up for the last decade and numerous studies have addressed the extents, rates and timescales associated with SWI induced by SLR mostly for homogeneous cases. In layered aquifers, vertical leakage through layers makes the intrusion mechanism different compared to homogeneous one. In this study, series of simulations using dispersive SEAWAT and a developed sharp-interface models have been carried out to investigate gradual and instantaneous SLR (respectively named GSLR and ISLR) effect on SWI into field-scale layered aquifer with constant freshwater inflow boundary condition. Two scenarios have been defined for this purpose, including an aquitard with two different hydraulic conductivities (i.e. K' [L/T] = 0.01 and 0.0001 m/d) that is placed between two extensively higher permeable layers. By SEAWAT, it is found that for ISLR problem with higher aquitard K' value, where freshwater can leak upward across the aquitard, seawater intrude more appreciable into bottom layer rather than the upper one. For the upper layer, seawater intrude toward land at early times but then naturally driven back to almost its original position (called as overshoot). At the second scenario with lower K' where almost no freshwater can leak upward, the ambient freshwater inflow push the lower layer salt wedge back toward the sea. For the GSLR, gradual increment of seawater head lets the freshwater to be delivered into unsaturated part of the upper layer and hence seawater intrudes through the system but with low rate. At the lower layer of higher K' scenario with GSLR, freshwater upward leakage causes SWI more obvious compare to the other scenario and horizontal freshwater flow prevents seawater to intrude through the lower layer. The sharp-interface model successfully predicted the same trend compare to dispersive SEAWAT model but over-predicted the interface line. It weaker matched with SEAWAT result for lower K'scenario where it cannot successfully predict the correct amount of freshwater upward leakage.

1. Introduction

In many parts of the world, coastal aquifers constitute an important source of water supply (Bear et al., 1999). Any changes in coastal hydrology results in movement of saltwater-freshwater interface toward land (Watson et al., 2010) commonly named as seawater intrusion (SWI) problem. Pumping from aquifers and lack of adequate freshwater recharge due to land use change and urbanization considered as the main anthropogenic activities, however increase in sea level as a part of climate change can accelerate it.

Concerning about sea level rise (SLR) has been grown up for the last decade and numerous studies have addressed the extents, rates and timescales associated with SWI induced by SLR (e.g. Ranjan et al., 2006a, b, 2009; Masterson and Garabedian, 2007; Werner and Simmons, 2009; Werner et al., 2012). Large number of case studies have also been studied to show how SLR can endanger coastal areas (e.g. Melloul and Collin, 2006, 2009; Feseker, 2007; Giambastiani et al., 2007; Vandenbohede et al., 2008; Moustadraf et al., 2008; Snoussi et al., 2009; Sefelnasr and Sherif, 2013). At recent years, the SLR subject has been developed by considering two distinguish phenomena that have been neglected in most previous studies but play an important role on intrusion mechanism: (1) Land surface inundation (LSI) and (2) Overshoot occurrence.

LSI (i.e. inland migration of the shoreline in response to SLR for

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sloping coast) has been studied in details by Kooi et al. (2000). They defined a dimensionless lag index parameter of Γ based on coast slope and SLR rate and showed in cases where Γ value is significantly greater than unity, LSI advances faster than the lateral movement of the salt wedge, leading to density instabilities and thus generating vertical free convection SWI. Laattoe et al. (2013) continued Kooi et al. (2000) study by producing new scenarios including new hydraulic conductivities (K:L/T) using both specified head and specified flux as inland boundary condition. They concluded that simulations without considering LSI underestimate the SWI extents in homogeneous aquifer, consistently with the findings of Ataie-Ashtiani et al. (2013) who analytically showed the importance of LSI consideration.

The overshoot shows the freshwater-saltwater interface moves toward inland but the transient interface position is beyond the final steady-state position. Overshoot is simulated numerically for homogeneous aquifer by Watson et al. (2010), Chang et al. (2011) and Morgan et al. (2015) and experimentally by Morgan et al. (2013). Findings of previous studies indicate that overshoot happens for fixed-flux freshwater boundary rather than fixed-head boundary where the emission of constant freshwater flux can push back the salt wedge. The overshoot is more dominant in confined case rather than unconfined system and its occurrence is obvious at instantaneous SLR (ISLR) compared to gradual SLR (GSLR). In unconfined aquifer, ISLR leads to sudden groundwater table rise near the sea area and despite the confined system, the aquifer transmissivity ($T = Kb$: L^2/T; where b refers to average aquifer depth) increases. It makes the seawater to penetrate further toward the land and consequently reduces the overshoot phenomenon.

Most regional scale coastal aquifers that are naturally widespread comprise layers of geology strata with limited investigation on understanding SWI process over them (Lu et al., 2013; Werner et al., 2013). Previous recent studies on layered coastal aquifers deal with other aspect of SWI rather than SLR effect (e.g. Lu et al., 2013; Ketabchi et al., 2014; Liu et al., 2014; Dose et al., 2014; Mehdizadeh et al., 2014) and the role of heterogeneity, which can modify rates of vertical SWI need to be examined (Laattoe et al., 2013). In layered aquifers subjected to SLR, SWI in one layer may extend beyond the other layers, thereby potentially leading to situation of upward/downward leakage. The extent and type of this leakage need to be quantified.

Numerical investigation of SWI into coastal aquifers routinely divided into two categories, namely sharp-interface and dispersive-interface approaches. The effect of hydrodynamic dispersion is considered at dispersive approach but the sharp-interface approach assumes immiscibility of freshwater and saltwater. Dispersive approach provides more details concerning the mixing zone (Abd-Elhamid and Javadi, 2011) and sharp-interface approach is more practical for its simplicity (Llopis-Albert and Pulido-Velazquez, 2014). Both approaches have been applied previously to predict SWI for homogeneous and layered aquifers successfully but the applicability of sharp-interface modeling has not been studied for SLR problem at layered aquifers. In this study, conceptual field-scale homogeneous and layered aquifers are exposed to ISLR and GSLR. The GSLR rate is adopted with the conditions predicted by the Intergovernmental Panel for Climate Change (IPCC). Simulations using sharp-interface and dispersive models have been carried out for vertical shoreline layered field-scale coastal aquifer and the keys influence SWI have been identified and highlighted.

2. Material and methods

2.1. Regional scale layered coastal aquifer and modeling scenarios

The aquifer geometry and physical properties were adopted from a conceptual model of field study completed at Pioneer Valley, Australia studied by Werner and Gallagher (2006). The original problem was real heterogeneous aquifer. Some modifications have been applied to consider homogeneous unconfined and confined aquifer by Werner and Simmons (2009) and Chang et al. (2011). At the current study, all the main properties and length scale were kept the same as the primary study except one modification: the aquifer height is partitioned into three horizontally layers of differing K value (two 14.0 m high K layer at top and bottom and a 2.0 m aquitard between them). The simulation domain extended 1000 m landward and the total height of the model is considered 30 m (Fig. 1). The sea boundary is vertical and the constant freshwater flux sets to 0.15 m^2/d. The system geometry, fluid and soil properties are listed at Table 1.

According to Table 1, the specific storage (S_s:L^{-1}) and specific yield (S_y) assigned to be 0.008 m^{-1} and 0.1 respectively. The S_s value is not a typical value for field-scale aquifer and is unrealistically high but it is needed to show us clearly the presence or absence of overshoot phenomenon as it maximizes the salt wedge toe position (X_T). Chang et al. (2011) stated that the maximum value of X_T was more sensitive to S_s rather than the duration of intrusion and confined system with higher S_s produced larger X_T under the continuous rise scenario.

Four models including two homogeneous confined and unconfined cases were defined to investigate the aquifer response to SLR. Layered scenarios differ at aquitard conductivity (K':L/T) value (i.e. $K' = 0.01$ m/d and 0.0001 m/d). Two different seaward conditions were applied. The initial sea level (prior to rise) was assumed to be at 30 m. The sea level was then permitted to rise instantaneously to 32.0 m. This is not a real implementation of SLR but it can be considered as the worst-case scenario (Chang et al., 2011; Sefelnasr and Sherif, 2013). The second boundary adopted a 10 mm/year infinite rise rate, which assumed as GSLR condition. IPCC predicted a 21st century SLR of 0.18–0.59 m (Bates et al., 2008). They then have recognized that SLR by 2100 may be 0.10–0.20 m higher than predicted values based on uncertainties of climate change variability (Mcleod et al., 2010). Scientists now have anticipated that values equal or greater than 1 m during the 21st century are realistic (Watson et al., 2010). This amount of prediction matches the rate assumed at the current study.

It should be noted that, numerous parameters including inflow rates, K contrasts, thickness of layers, dispersivity and aquifer geometry might have impact on SWI at layered aquifers. The current investigation does not intend to do a sensitivity analysis to explore the mentioned parameters effect but to explore leakage importance on intrusion amount for SLR problem and to test the sharp-interface modeling ability when leakage plays a role on intrusion. Lu et al. (2013) and Mehdizadeh et al. (2014) for layered aquifers and Ketabchi et al. (2016) for homogeneous cases had undertaken sensitivity analysis of parameters influence the SWI amount that could be referred.

2.2. Dispersive SEAWAT model

The present study used the finite-difference model SEAWAT (Version 4.00.05) to simulate three-dimensional, variable density, transient groundwater flow in porous media. SEAWAT initially released at 1998 by Guo and Bennett and the 4th version developed by Langevin et al. (2008). It combines the modified MODFLOW and MT3DMS into a single program that solves the coupled groundwater flow and solute transport equations. SEAWAT is widely used and is not explained in details here for brevity. A rectangular numerical grid with $\Delta x = 2.0$ m and $\Delta z = 0.5$ m applied for the aquifer domain. The grid size satisfactory desired the Peclet number criteria (i.e. Pe $\approx \Delta L/\alpha_L = 2.0 < 4.0$ as stated by Voss and Souza,