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Assessing impacts of sea level rise on seawater intrusion in a coastal aquifer with sloped shoreline boundary

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Abstract

This paper investigates the effect of gradual and instantaneous sea level rise (SLR) on the seawater intrusion (SWI) process in coastal aquifer systems with different levels of land-surface inundation. A set of hypothetical case studies with different shoreline slopes is used to conduct this numerical experiment. For the purpose of numerical modelling, a future rate of SLR from 2015 to 2100 is considered based on the moderate expectation of the Intergovernmental Panel on Climate Change (IPCC, 2001). The gradual SLR is implemented in two different stages. First, continuous and nonlinear rising of sea level is imposed starting from year 2015 up to the end of the century. After that the final value of sea level is maintained as constant in order to assess the response time spanning to a new steady state condition. The effects of pumping resulting in lowering of groundwater level are also considered together with the dynamic variation of sea level. The results show that the rate and the amount of SWI are considerably greater in aquifers with flat shoreline slopes compared with those with steep slopes. Moreover, a shorter period of time is required to reach a new steady state condition in systems with flatter slopes. The SWI process is followed by a significant depletion in quantity of freshwater resources at the end of the century. The situation is exacerbated with combined action of SLR and over-abstraction. Finally, by considering the effect of inundation of the shoreline due to gradual SLR, the sensitivity of the system to the main aquifer parameters including molecular diffusion of solute, dispersion, hydraulic conductivity and porosity is investigated.

Keywords: Saltwater intrusion; Sea level rise; Climate change; Freshwater; Coastal aquifer

1. Introduction

It is generally accepted that thermal expansion of oceans and seas and melting and calving of glaciers and small ice caps (e.g., in Greenland and Antarctic) are the main consequences of the global warming leading to gradual rising of the seawater levels (Oude Essink, 1996; IPCC, 2013). Besides this, the global warming decreases the atmospheric pressure, which in turn leads to increase of water level in oceans and seas. According to IPCC (2001) future SLR is expected to occur at a rate greatly exceeding that of the recent past. Sea levels have risen about 10–20 cm during the past century. By year 2100 it is expected that the rise in sea levels would be between 20 cm and 88 cm (IPCC, 2001). However, a relatively higher range (28–98 cm) of SLR has been reported by IPCC (2013) for the year 2100.

SLR has been highlighted in the literature as one of main natural factors that are negatively correlated with the hydrodynamic balance condition of aquifers in line with other natural factors (e.g. tides) and human-made factors (e.g. over pumping) (Uddameri et al., 2014; Werner et al., 2013). SLR could cause problems such as impeded drainage, wetland loss (and change), erosion and inundation of the land-surface and also saltwater intrusion (Bricker, 2009; FitzGerald et al., 2008; Nicholls, 2010, 2015). These changes in ecosystem properties and processes have several direct socio-economic impacts on a wide range of sectors and issues (Nicholls, 2015; Sušnik et al., 2015). Saltwater intrusion threatens the quantity and quality of groundwater resources. Therefore, qualification of the impacts of SLR on SWI is the main focus of the present research.

During SLR, the imposed hydraulic head on the saline water body in coastal boundaries is increased. This is followed by acceleration of the lateral intrusion of seawater. According to Ghyben-Herzberg analytical relationship the effects of 1 m SLR is followed by 40 m reduction of freshwater thickness. In addition, overexploitation of the groundwater coupled with the SLR has been considered as a dominant factor causing

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saltwater intrusion in aquifers (Bobba, 2002; Carretero et al., 2013; Langevin and Zygnerski, 2013; Loáiciga et al., 2012; Rasmussen et al., 2013; Sefelnasr and Sherif, 2014).

Sherif and Singh (1999) showed that rising of sea level by 0.5 m in the Mediterranean Sea would increase the lateral intrusion of seawater by further 9 km in the Nile delta aquifer under steady condition. This finding was confirmed by Werner and Simmons (2009) by calculating 5 km of inland penetration of saline toe for the same aquifer using the sharp interface theory. On the contrary, Shrivastava (1998) notes that the lateral intrusion of seawater in a regional confined aquifer in Jamaica would be insignificant during the SLR. The insignificant SWI progress has also been reported by Abd-Elhamid and Javadi (2011) for confined aquifers. This contradictory behaviour of SWI in confined and unconfined aquifers due to SLR has been discussed by Chang et al. (2011) in detail. They argue that the lifting process of groundwater table associated with SLR is the key factor in this mechanism. Under these circumstances, the lifting of sea level in unconfined systems is followed by increasing the thickness of the saturated zone (or transmissivity) of the aquifer, which allows the saltwater wedge to penetrate further. However, the analysis of transient progress of seawater in confined aquifer has shown that there is a landward movement of the toe in the beginning followed by the reversal process until it reaches to its initial condition (Chang et al., 2011). In other words, the lifting process of groundwater would fully offset the impacts of instantaneous SLR and thus SLR would not show any significant effects on the long-term progress of the SWI. This "forward-backward" mechanism is the common trend in the results of Chang et al. (2011), which are simulated under unrealistic and higher than usual rates of SLR. Watson et al. (2010) studied unconfined aquifers and introduced this "forward-backward" pattern of toe movement as "overshooting" mechanism, which was also observed during the instantaneous rising of sea level.

Two different types of boundary conditions (flux-controlled and head-controlled boundary conditions) have been assessed by Werner and Simmons (2009), Webb and Howard (2011), and Carretero et al. (2013) in conceptual models. In the first system, the discharge of water to sea was kept constant by maintaining the seaward hydraulic gradient of the system despite rising of the sea level. For this purposes the inland head was raised to compensate the disturbance of SLR on the hydraulic gradient. Webb and Howard (2011) considered this method as the lower bound of the SWI, which is associated with minimum seawater intrusion as a result of SLR. In the second system, with upper bound strategy (head controlled system), the inland head of water was maintained despite rising of sea levels, and this is associated with maximum seawater intrusion as a result of SLR.

Transient response time of different quantitative indicators of aquifer systems due to changes in sea level has been studied by a number of researchers. The response time represents the time required for each of these indictors to reach steady state condition. Kiro et al. (2008) studied the transient response time of the water table and transition zone to instantaneous and continuous drop in sea levels (SLD). Following the same principle, Watson et al. (2010) evaluated the effects of transient response time of other indicators such as submarine discharge, toe location, total mass of salt, etc. to 1 m instantaneous rise in sea level. The results concluded that the response time varies depending on the type of the indicators considered. For example in cases where the toe location is the main indicator, the response time could vary from decades to centuries while the approximate time for the water table response is about 1 decade. Chang et al. (2011) carried out a sensitivity analysis of a confined system to different parameters and showed that the system could experience a shorter response time in cases with the large values of inland freshwater flux, with small hydraulic conductivity and also in cases with high rates of the SLR.

Kooi et al. (2000) proposed an equation to assess the distance-lag between the inland migration of saltwater wedge and the shoreline during the transgression event of SLR. However, the results of their numerical experiments, simulated with 0.001 slope of the land surface, are inconsistent with the critical limit (lag index) predicted by that equation prior to numerical simulation. The implementation of relatively smaller hydrodynamic dispersion compared to molecular diffusion, in numerical simulation, has been stated as a reason for the mentioned contradictory results (Laattoe et al., 2013). The suggested equation by Kooi et al. (2000) generally implies that under high rates of SLR, low permeability, and also low topographical slope of land, the rate of coastal transgression is faster than the lateral intrusion of saltwater. Under these circumstances the free convective density driven flow associated with the vertical mixing and fingering of salt are the common modes of the saltwater intrusion (Kooi et al., 2000; Laattoe et al., 2013).

The majority of the published literature on the study of the effects of SLR on SWI in coastal aquifers under a wide range of plausible hydraulic factors is limited to some parametric studies conducted on hypothetical case studies or small conceptual models of real flow systems (e.g. Werner and Simmons, 2009; Watson et al., 2010; Chang et al., 2011; Webb and Howard, 2011; Terry and Chui, 2012; Ataie-Ashtiani et al., 2013; Laattoe et al., 2013; Ketabchi et al., 2014). Similarly, in this paper the response of a set of hypothetical unconfined aquifers (with different sloped shorelines) to different SLR scenarios is studied. The SWI in coastal aquifers due to realistic values of projected SLR is simulated using a density-dependent finite element model SUTRA (Saturated-Unsaturated TRAnsport) code developed by Voss and Provost (2010), considering the effects of the unsaturated (vadose) zone. For the SLR scenarios, the sloped systems are first subjected to gradual rising of the sea level starting from the current steady state condition (year 2015) up to the end of the century (year 2100). Then the final value of the SLR is maintained through an extra simulation period in order to obtain new steady state condition that allows for investigating the approximate response time. The effects of instantaneous rising of sea level are also investigated in sloped aquifers. Meanwhile, these sloped systems are studied under the coupled action of SLR and lowering in the inland groundwater level (e.g. due to over pumping). Finally, the roles of different hydro-physical parameters of coastal aquifer systems on the inland encroachment of the saltwater are investigated through a sensitivity analysis, considering the effect of SLR.