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NUMERICAL MODELLING OF THE IMPACTS OF SEA LEVEL RISE ON SEAWATER INTRUSION IN UNCONFINED COASTAL AQUIFERS

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ABSTRACT

This study presents the application of a density-dependent finite element model to simulate the transient effects of sea level rise (SLR) on seawater intrusion (SWI) in a conceptual case of unconfined aquifer. The model considers both the unsaturated and saturated flow conditions. To model the natural process of SLR, a time-dependent boundary condition is used to define the hydrostatic head imposed by seawater at the coastal boundary where the effect of the gradual rise in the sea level with time is considered. The specified values of SLR are chosen, in the range of that predicted by IPCC (Intergovernmental Panel on Climate Change), for five different periods of time in the current century (from 2014 to 2100). The results indicate that a considerable advance in SWI can be expected in the coastal aquifers until the end of century. The rising of sea level is followed by the lifting of the groundwater table, especially near the shoreline, which gradually declines towards the inland boundary. The effects of spatial variations of the shoreline slope on SWI under SLR condition are also investigated. The results highlight that the flatter slopes of the shoreline intensify the landward process of seawater intrusion.

Keywords: *seawater intrusion; sea level rise; numerical modelling; unsaturated flow; unconfined aquifer*

1. Introduction

Groundwater is a vital component of the global water cycle and it is a valuable resource for water supply. However, the quality of groundwater in the arid and semi-arid coastal areas is one of the environmental issues of the 21st century, which is continuously threatened by the landward intrusion of seawater. Under natural conditions, the replacement of freshwater in coastal aquifers by the seawater due to density-dependent landward movement of saline water body into the freshwater is known as SWI [4]. SWI is considered as the final outcome of this density-dependent interaction between freshwater and seawater and is responsible for dynamic equilibrium of groundwater movement. The hydrodynamic dispersion which is the combination of mechanical dispersion and physio-chemical dispersion (molecular diffusion) controls the spreading out of solute and the mixing process.

A distinct curved zone of saline water, known as the regional “saltwater wedge”, is created in the freshwater body and it is the source of contamination that degrades the quality and quantity of freshwater. The negative impacts of SWI would be intensified by the anthropogenic factors such as unplanned exploitation of groundwater and also by the natural factors such as sea level rise (SLR) and tidal effects. The reduction of atmospheric pressure and thermal expansion of oceans are the earliest outcomes of global warming which will in turn lead to the increase of water level in the oceans and seas. However, melting of mountain glaciers, small ice caps, and also melting of polar (Greenland and Antarctic) ice sheets will exacerbate its negative effects in terms of SWI by accelerating the SLR process [2].

Limited research has attempted to study the effects of gradual rise of sea levels on SWI in aquifers. The majority of previous works have focused on simulation of this problem in confined (and even unconfined aquifers) with vertical seaside boundary (without slopes) subjected to constant, timeindependent and unrealistic values of SLR in saturated flow condition. In the present work we study the transient effects of sea level rise on seawater intrusion over a century in a hypothetical unconfined aquifer, considering the effects of the unsaturated (vadose) zone and the shoreline slope.

2. Model Description

In this study, the SUTRA code [1] is used for numerical modelling of 2D case studies of unconfined aquifer. SUTRA implements a hybridization of finite element and integrated finite difference methods to solve the density-dependent flow and transport mass balance equations [1]. A rectangular aquifer with the dimensions 500 m by 30 m is considered as the base model. It is discretized using irregular mesh with 2483 elements and 2594 nodes. The idealized form of the base aquifer and the used boundary conditions are shown in Figure 1. The aquifer is divided vertically in two layers; an unsaturated layer overlying the bottom saturated layer. The hydraulic gradient in the system is 0.0032 corresponding to the defined head boundaries. The modelling parameters used for the groundwater flow, solute transport and porous medium are: D_m, coefficient of water molecular diffusion = $1.0*10^{-9}$ m^2/s; $\partial\rho/\partial C$, change of fluid density with concentration = 700.0 kg^2(seawater)/kg(dissolved solids).m^3; g, gravitational acceleration = 9.8 m/s^2; C_{sea}, solute mass fraction of seawater = 0.0357 kg(dissolved solids)/kg(seawater); ρ_{sea}, density of seawater = 1025 kg/m^3; ρ_o, density of fresh water = 1000 kg/m^3; μ, fluid viscosity = 0.001 kg/(m.s); αL, longitudinal dispersivity = 2.0 m; αT , transverse dispersivity = 0.2 m; permeability of top layer = $1.3*10^{-12}$ m^2; permeability of bottom layer = $1.3*10^{-11}$ m^2; porosity of top layer = 0.37; porosity of bottom layer = 0.35 and thickness of model = 1.0 m. The following unsaturated parameters were considered for Van Genuchten function $\alpha=12.5*10^{-4}$ $(m.s^2)/kg$, $n=3.5$ and $S_{res}=0.01$.

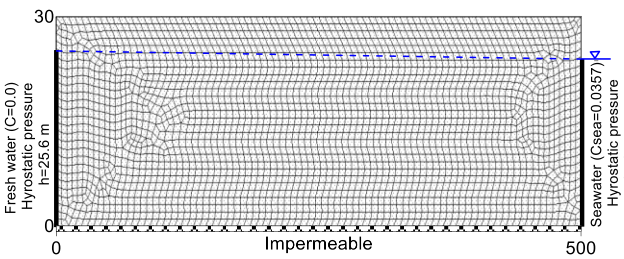

Figure 1: Boundary conditions of base model

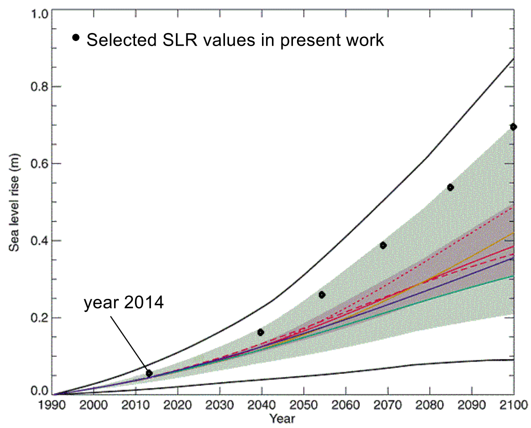

Figure 2: Global average SLR estimated by IPCC [3]

The unsaturated flow simulation in the model requires a fine temporal discretization to limit the instability and oscillatory results of calculated pressure and saturation values which may change sharply during wetting events [1]. To obtain the natural initial values of pressure within the domain, first a steady state solution is obtained through an extra simulation with the head boundary conditions described above at the inland and seaside boundaries of the aquifer. The system essentially reached a steady state after 10000 time steps, with time step of 0.25 days. In order to more closely replicate the behaviour of rising sea levels, the model is subjected to five different increments of rising sea levels starting from current time (year 2014) up to the end of century (year 2100). According to IPCC report [3] future SLR is expected to occur at a rate greatly exceeding that of the recent past. Figure 2 shows the estimated global average SLR between 1990 and 2100 based on different economic and technological development scenarios [3]. By 2100 it is expected that the rise in sea levels would be between 20 cm to 88 cm [3].

The current steady state condition of the model with the sea level located at elevation of 24 m is assumed to represent the hydrological situation for the year 2014 and it is used as the reference level for simulation of the system in the following time periods. The typical values for SLR used in the

present work are marked on Figure 2 for the years 2014, 2040, 2055, 2070, 2085 and 2100 which show the SLR of 0.1m, 0.2m, 0.35m, 0.5m and 0.65m (with respect to 2014 as the base line) in years 2040, 2055, 2070, 2085 and 2100 respectively. The corresponding hydraulic head boundary conditions defined at the seaside boundary in each rising period are increased linearly with time. The simulation outputs (pressure and salinity) of each time period are used as the initial condition for the next period.
Furthermore, the effect of different shoreline slopes (and the corresponding inundated surfaces) on SWI process is investigated under the gradual rise of sea level. The shoreline boundary of the base model is geometrically modified by implementing a different inland slope that starts from elevation of 15 m above the bottom boundary. For the purposes of comparison in this paper, the revised problems are simulated under the same hydraulic gradient (0.0032).

3. Results

An initial steady state simulation is used to estimate the current situation of saltwater wedge profile that exists in the system prior to SLR. The 50% iso-concentration line for this model is shown (by dashed line) in Figure 3. Under the present state (2014) the toe of the saline wedge is advanced by 70 m into the aquifer as a result of natural hydrodynamic dispersion. The results of the gradual rising of sea level at the end of each time period are also presented as 50% isochlor lines. The results show that the salinity wedge continues its inland intrusion to the extent that in year 2100 the toe will be located at 125 m from the coast boundary. The results of variation of groundwater level during the SLR process indicate that there is a significant lifting in water table especially in the vicinity with the sea boundary and it gradually declines towards the inland boundary. This variation of the hydraulic gradient during the SLR increases the thickness of the saturated layer of the system which results in the further inland penetration of saltwater/freshwater interface [5].

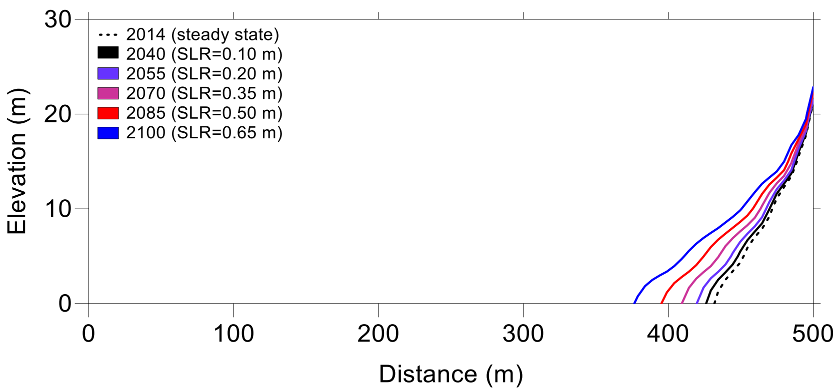

Figure 3: Variations of 50% iso-concentration lines of developed base model with SLR

The 50% iso-concentration profiles of the current steady state condition (year 2014) in aquifers with different shoreline slopes are illustrated in Figure 4a. The inundation surfaces resulting from different shoreline slopes provide the wider contact areas of the models with the seawater. In other word, a wider inundation surface resulting from a flatter slope accelerates the SWI process. These negative patterns of the inclined coastal boundaries also emerge during the rising of the mean sea levels. Figure 4b shows the variations of the same curve of saline/freshwater interface under gradual rising of sea level (up to 0.65 m) at the end of century. In the model with 10% slope the rising of sea level extends the inland location of saline wedge by 70 m compared with its current steady state condition. However, in the aquifer with 5% slope and under the same conditions, the toe location is advancement about 150 m during the same gradual SLR. Therefore the small variations of slopes play an important role in natural periodic progressive of SWI. Generally, the increasing of the inundation surface areas can result in reduction of fresh groundwater resources in the aquifer; lowering the capability of the groundwater discharge of the aquifer to cope with the intruded seawater.

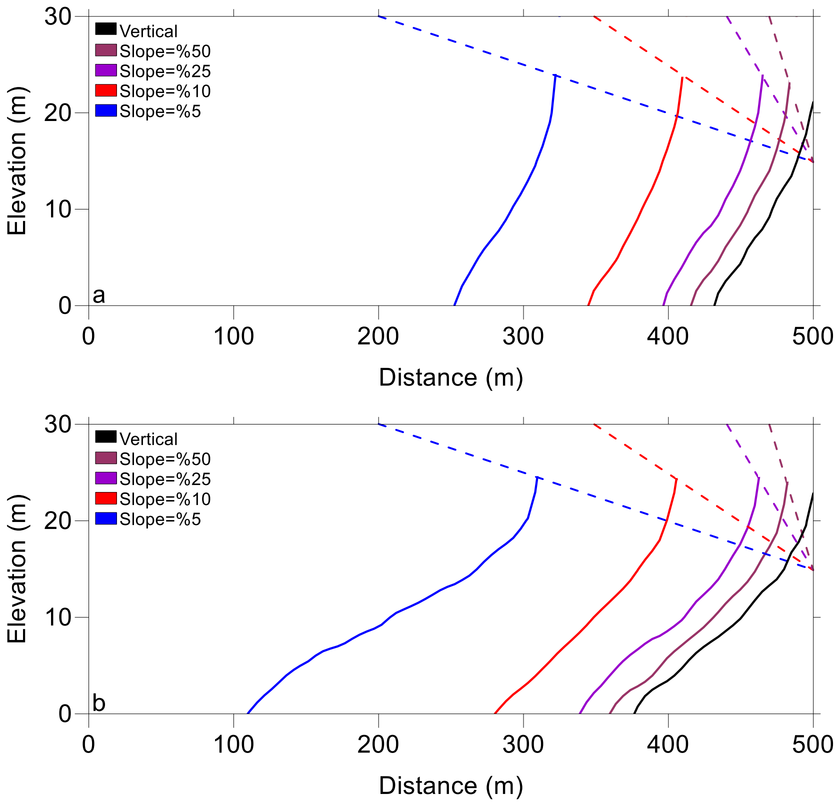

Figure 4: a) Current steady state variations of 50% iso-concentration lines of SWI in the aquifers with different coastal slopes; b) Variations of same isochlors with the SLR at the end of centaury

4. Conclusions

In this study, the transient effects of the gradual rising of sea levels (expected during the current century) on the SWI is investigated through a set of conceptual models of unconfined aquifers with different sloped coastal boundaries. It has been shown that rising of sea level leads to further inland advancement of seawater and the problem is intensified by the flatter slopes of shoreline boundary. An implication of these findings is that the threats and the unexpected outcomes of the SLR (and the global warming) could have serious consequences on the quality and quantity of fresh groundwater resources in real case studies coastal areas, especially in shallow unconfined aquifers.

Acknowledgements

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