Pumping of Brackish and Saline Water in Coastal Aquifers: An Effective Tool for Alleviation of Seawater Intrusion

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ABSTRACT
The increase of water demands in coastal areas is often covered by extensive pumping of fresh groundwater, upsetting the dynamic balance between freshwater and saline water bodies. The classical result of such a development is the seawater intrusion problem. In this paper, it is proposed to pump the brackish water, encountered between the freshwater and saline water bodies, to reduce the extension of seawater intrusion. To that end, SUTRA is used to examine different pumping scenarios. The simulation is conducted in the vertical view and the equi-concentration lines and velocity vectors were identified for the different cases. Results of numerical simulations indicated the effectiveness of this methodology in controlling the seawater intrusion and enhancing the groundwater quality in coastal aquifers.

INTRODUCTION
Seawater intrusion phenomena are of main concern in almost all coastal aquifers around the globe. The problem is more severe in arid and semi-arid regions where the groundwater constitutes the main freshwater resource. The growth of population in coastal areas and the associate increase in human, agricultural, and industrial activities have imposed an increasing demand for freshwater in such areas. This increase in water demand is often covered by extensive pumping of fresh groundwater, causing subsequent lowering of the water table (or piezometric head) and upsetting the dynamic balance between freshwater and saline water bodies.

The shape and degree of the seawater intrusion in a coastal aquifer depend on several factors. Some of these factors are natural and cannot be controlled while others are manmade and could, thus, be managed. These factors, include among others, the type of the costal aquifer (confined, phreatic, leaky, or multi-layer) and its geology and geometry, water table and/or piezometric head, seawater concentration and density, natural rate of flow, capacity and duration of water withdrawal or recharge, rainfall intensities and frequencies, evaporation rates, physical and geometric characteristics of the porous media, geometric and hydraulic boundaries, tidal effects, variations in barometric pressure, earth tides, earthquakes and other vibrational effects, water wave actions, and chemical changes. The depth of the aquifer at the seaside through which the seawater intrudes inland as well as pumping and recharge rates and locations are the most critical factors to be considered, Sherif and Singh (1996) [1]. Under natural conditions, fully steady state conditions in groundwater systems may not be achieved as pumping activities, recharge from surface water bodies and rainfall events can not be controlled. However, steady state simulation of seawater intrusion phenomenon may be considered to identify the ultimate intrusion conditions and also for comparison among different pumping/recharge scenarios.

EFFECT OF PUMPING FRESH AND BRACKISH/SALINE GROUNDWATER
The main purpose of this numerical simulation is to examine the possibility of restoration of the groundwater quality in coastal aquifers by pumping saline (or brackish) groundwater from the area in the vicinity of the shoreline. SUTRA (Voss and Provost, 2003) [2] is a variable-density ground-water flow with solute or energy transport model. It is an upgrade of the 1984 SUTRA

computer code (Voss, 1984) [3]. The code employs a two- or three- dimensional finite-element and finite difference method to approximate the groundwater flow and solute transport equations.

In order to demonstrate the effect of pumping of the intruded seawater from the coastal regions, an idealized vertical study domain of 1000 m in length and 50 m in depth was considered. The porosity was set equal to 0.25. The system was considered homogeneous but anisotropy. The horizontal permeability, k_x, was set equal to 10^{-6} m^2, while the vertical permeability, k_y, was set as 10^{-7} m^2. The dispersivities in the horizontal and vertical directions, α_L and α_T, were both set equal to 5m. The other parameters were set as the default values of SutraGUI (Winston and Voss, 2004) [4].

The upper and lower boundaries were considered impermeable, i.e., no flux of water or salt ions is allowed to cross these two boundaries. A specified head boundary condition, H_1 was used at the land side and the head was set equal to 6.0m. At the seaside boundary, the seawater head was set equal to 4.0m. The head at this boundary was calculated as equivalent freshwater hydraulic head (Sherif et al., 1988) [5]. Therefore, the freshwater head, H_2, at the seaside was describe as

$$H_2 = 4.0 + k\,(50 - y), \qquad (1)$$

where, k is a constant and can be expressed as

$$k = \frac{\rho_s - \rho_f}{\rho_f} \qquad (2)$$

in which ρ_s and ρ_f are the densities of the seawater and freshwater, respectively. Also, y in equ. (1) is the elevation (m) of the nodal point above the aquifer bottom. Considering ρ_s and ρ_f to be 1000 kg/m^3 and 1025 kg/m^3, respectively, the constant a will be equal to 0.025. The maximum equivalent freshwater head at the seaside boundary is at y = 0 and is equal to 5.25m.

The study domain was discretized using the Fishnet (Winston and Voss, 2004) [4]. The length of the domain was divided into 200 equal intervals each with a length of 5.0 m, while the depth was divided into 20 equal intervals each with a length of 2.5 m. The domain is discritized into a total of 4000 rectangular elements (5.0 x 2.5 m) with 4221 nodal points. All simulations were conducted under the steady state conditions.

In run-1, the simulation was performed without any pumping to identify the seawater intrusion that would result due to the density difference between the freshwater and saline water bodies. The resulted equi-concentration lines are presented in Fig. 1a and the velocity vectors are presented in Fig. 1b. Equi-concentration lines 0.0 and 0.035, which represent the fresh and sea waters, migrated inland to a distance of 150 m and 104 m, respectively, measured along the bottom boundary. Meanwhile, a clear cyclic flow pattern is observed near the shoreline where the seawater intrudes the aquifer from the bottom and rotates back to the sea through the upper part of seaside boundary as brackish water.

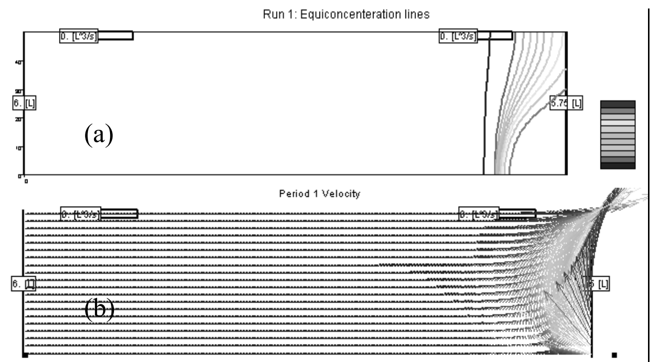

Figure 1. Equiconcentration lines and velocity vectors for run-1.

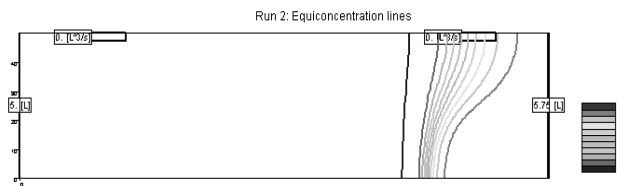

Figure 2. Equiconcentration lines for run-2.

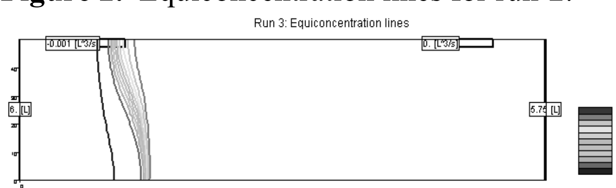

Figure 3. Equiconcentration lines for run-3.

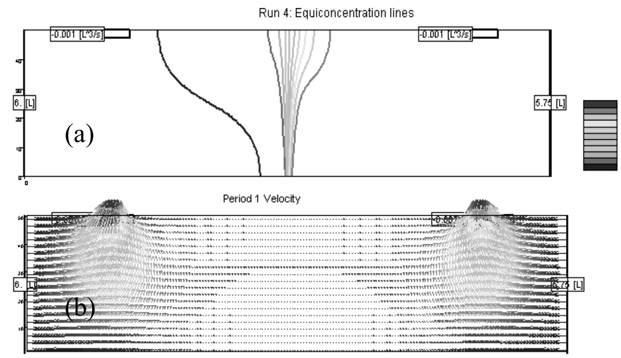

Figure 4. Equiconcentration lines and velocity vectors, run-4.

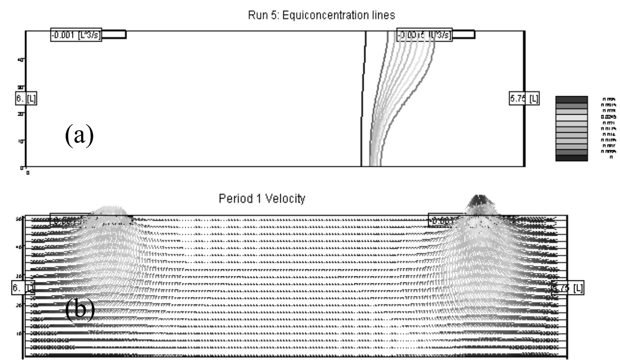

Figure 5. Equiconcentration lines and velocity vectors, run-5.

In run-2, the specified head was reduced to 5.0 m and all other parameters were kept the same. The resulted equi-concentration lines are presented in Fig. 2. The same equi-concentration lines 0.0 and 0.035 (defining the width of the dispersion zone) migrated inland to a distance of 277 m and 196 m, respectively, as measured along the bottom boundary from the seaside. As expected, reducing the hydraulic head at the land side increased the degree of intrusion and the width of the dispersion zone. In run-3, the hydraulic head at the land side was maintained at 6.0. In addition a uniform freshwater pumping of 86.0 m^3/d was introduced at distance 900 m < x < 800 m, from the sea boundary. All other parameters were unchanged. Equi-concentration lines 0.0 and 0.035 moved inland to a distance of 820 m and 754 m, respectively, measured along the bottom boundary from the seaside, Fig. 3.

In run-4, in addition to the freshwater pumping (included in run-3), saline groundwater was also pumped uniformly at a rate of 86.0 m^3/d from a distance 200 m < x < 100 m, measured from the sea boundary. Fig. 4a represents the resulted equi-concentration lines under the steady state conditions. Equi-concentration lines 0.0 and 0.035 retreated toward the seaside and intersected the bottom boundary at a distance of 553 m and 491m, respectively, measured along the bottom boundary. On the other hand, because of the velocity pattern, Fig. 4b, the width of the dispersion zone has increased near the upper boundary. In run-5, the pumping of saline groundwater was increased to 130 m^3/d and all other parameters remained unchanged. Figs. 5a and b present the resulted equi-concentration lines and velocity vectors in the study domain. Equi-concentration lines 0.0 and 0.035 retreated more toward the seaside and the quality of the groundwater was enhanced considerably. The intrusion was mainly limited to the area between the sea boundary and saline groundwater pumping field. Despite the increase of total pumping of (fresh and saline) groundwater in runs 4 and 5, the overall quality of the groundwater in the aquifer has improved. This result is consistent with the findings of Sherif and Hamza (2001) [6]. Pumping of saline groundwater from coastal aquifers would mitigate the migration of seawater deep into the aquifer and would contribute to the enhancement of the groundwater quality.

CONCLUSION

A new methodology for controlling the seawater intrusion and enhancing the quality of the groundwater in the coastal aquifers is proposed. A two-dimensional finite element model, SUTRA, has been employed to verify the proposed methodology. The model is based on the variable density approach which accounts for the change in the fluid density with the change of its concentration. The effect of groundwater pumping from fresh/saline/brackish zone(s) on the equiconcentration lines and velocity fields in the vicinity of the shore line is investigated. It is concluded that seawater intrusion problems could be controlled through proper pumping of fresh/saline/brackish groundwater from the coastal zone.

ACKNOWLEDGEMENT

This research was funded equally by the research sectors of both UAE University and Sultan Qaboos University.

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