Impact of over-pumping and sea level rise on seawater intrusion in Gaza aquifer (Palestine)
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ABSTRACT

Seawater intrusion is considered as one of the main processes that degrade water quality by raising salinity to levels exceeding acceptable drinking water standards. Over-abstraction is the main cause of seawater intrusion. Moreover, climate change and sea level rise speed up seawater intrusion. This paper presents the development of a coupled transient finite element model for simulation of fluid flow and solute transport in soils and its application to study seawater intrusion in Gaza aquifer. The effects of likely sea level rise due to climate change and over-pumping on seawater intrusion in Gaza aquifer are studied using three scenarios: rise in sea level due to climate change; decrease in piezometric head on the land side due to over-pumping; and a combination of sea level rise and over-pumping. The results show that a rise of 1 m in sea level has a significant effect on the position of the transition zone and can result in a further 0.5 km seawater intrusion in Gaza aquifer. However, the combination of sea level rise and over-pumping results in movement of the transition zone further inland (nearly 1.0 km). The results show that Gaza aquifer is subjected to severe seawater intrusion from the Mediterranean Sea and there is an urgent need to protect the aquifer from seawater intrusion.

Key words | climate change, finite element, Gaza aquifer, sea level rise, SEAWAT, seawater intrusion

INTRODUCTION

Many coastal areas are heavily urbanized, which increases the need for freshwater. The increased extraction of freshwater from coastal aquifers to meet growing demands decreases the freshwater spilled out to the sea. Consequently, seawater intrusion may reach several kilometers inland and wells may become contaminated and unsuitable for human use due to salinity increase. The problem is more severe in arid regions where groundwater pumping rates exceed the natural recharge. The problem of seawater intrusion is influenced by a number of parameters including, among others, the geometry of the aquifer, geological setting of the system, hydrogeological parameters and pumping and recharge rates. Under normal conditions, without any anthropogenic activity, the freshwater flows into the sea. However, increase in abstraction from aquifers may result in inversion of the flow from the sea toward the inland causing saltwater intrusion. Salinization of groundwater is considered a special category of pollution that threatens groundwater resources, because mixing a small quantity (2–5%) of seawater with groundwater makes freshwater inadequate for human uses and can result in abandonment of the freshwater resource. The risk of saline intrusion clearly limits the extent to which coastal aquifers can be developed for water supply.

There is a complex interaction between freshwater and saline water in coastal aquifers. Freshwater and saltwater are miscible fluids, and a transition zone always exists between them (Bear 1979). A number of mathematical and numerical models have been developed to predict the location and movement of the interface between saline water and freshwater. Depending on the method of treating the interface for simulation, these models can be grouped into two categories: sharp interface and diffusive interface models, where a wide interface zone separates the two
fluctuations. The sharp interface assumption can be applied only under certain conditions when the width of the transition zone is relatively small compared with the thickness of the aquifer (Abd-Elhamid & Javadi 201b). The diffusive interface model, which accounts for the effects of hydrodynamic dispersion, may be more practical because it provides more details concerning the transition zone.

The first attempts to predict the location and movement of a saltwater interface were made by Ghyben (1889) and Herzberg (1901). Over the last few decades a number of models have been developed. The majority of existing models consider a limited number of mechanisms controlling solute transport in seawater intrusion. Some of these models consider a sharp interface (e.g. Hubbert 1940; Glover 1959; Henry 1959) while others assume a diffusive interface (e.g. Lee & Cheng 1974; Segol et al. 1975; Frind 1982; Huyakorn et al. 1987). Some consider only steady-state flow conditions (e.g. Sherif et al. 1988; Bixio et al. 1998; Rastogi et al. 2004) and some consider transient analysis (e.g. Sbai et al. 1998; Sakr 1999; Canot et al. 2006). Many of the previous numerical models consider fluid flow and solute transport in saturated soil. However, there are only a limited number of models that consider fluid flow and solute transport in unsaturated soil (e.g. Voss 1984; Cheng et al. 1998; Paniconi et al. 2001; Jung et al. 2002). This study presents the development and application of a finite element model for simulating seawater intrusion in coastal aquifers. The model accounts for transient density-dependent flow and solute transport in saturated and unsaturated soils. The effects of various mechanisms that govern solute transport processes such as advection, diffusion, dispersion, adsorption, chemical reaction and biological degradation are incorporated in the model. The governing differential equations of water flow, air flow and solute transport are solved using a finite element method in the space domain and a finite difference scheme in the time domain. The model is validated and then applied to simulate seawater intrusion for a real case study in Gaza, Palestine.

One of the future challenges in management of water resources is sea level rise due to climatic change and its impact on saltwater intrusion. Climate change has caused changes in sea levels primarily due to expansion of seawater and melting of ice caps resulting from the rise in temperature. The study of the impact of climate change and sea level rise on saltwater intrusion in the long term is very important in the management of groundwater resources. A limited number of models were developed to study the impact of climate change and sea level rise on seawater intrusion. Sherif & Singh (1999) investigated the effects of likely climate change on seawater intrusion in the Nile Delta aquifer in Egypt and the Madras aquifer in India. El Raey et al. (1999) carried out an assessment of the vulnerability and expected socio-economic losses over the Nile Delta coasts to determine the impact of sea level rise in Alexandria and Port Said, Egypt. Canning (2001) presented the certainties and uncertainties of climate variability for Washington’s marine water. He also presented a review of the historical sea level rise due to climate changes in Puget Sound. Essink & Schaars (2002) developed a model to simulate groundwater flow, heat and salinity distribution, and seepage and salt load flux to the surface water system. The model was used to assess the effect of future developments such as climate changes, sea level rise, and land submergence as well as human activities on qualitative and quantitative aspects of the groundwater system. Tiruneh & Motz (2004) investigated the effect of sea level rise on the freshwater–saltwater interface, using SEAWAT, considering the impact of pumping and recharge. All these studies have shown that numerical modelling tools play an important role in the monitoring and effective management of coastal aquifers. Also, due to site-specific features of individual aquifers, the application of numerical models in different case studies poses different challenges.

Gaza aquifer is one of the aquifers which is subjected to severe seawater intrusion from the Mediterranean Sea. Investigations of Gaza aquifer have shown that saltwater intrusion has been extended to a distance of more than 3.0 km from the Mediterranean coast. A number of studies were conducted to simulate the seawater intrusion in Gaza aquifer using different numerical techniques. Examples of these studies include: Yakirevich et al. (1998); Qahman & Zhou (2001); Moe et al. (2001); and Qahman & Larabi (2003a, 2003b, 2006). Yakirevich et al. (1998) used SUTRA code and Qahman & Larabi (2003b) used SEAWAT to simulate saltwater intrusion in the Gaza aquifer. Numerical simulations predicted the rate of seawater intrusion in the Gaza aquifer to be 20–45 m/year during 1997–2003. Climate...
change and sea level rise would speed up saltwater intrusion in Gaza aquifer, which was not considered in the previous studies.

This paper presents numerical simulation of seawater intrusion in Gaza aquifer using the coupled transient finite element model for seawater intrusion (2D-FEST), developed by the authors. The results of this model are compared with those of the SEAWAT code carried out by Qahman & Larabi (2006) and a good agreement is obtained. SEAWAT is a generic MODFLOW/MT3DMS-based computer program designed to simulate variable-density groundwater flow coupled with multi-species solute and heat transport. Essentially, SEAWAT solves the same governing equations (as those presented in this paper) using the finite difference method. The developed model is also applied to investigate the position and movement of the transition zone in response to sea level rise and over-pumping according to the expected climate changes. Different scenarios of sea level rise and over-pumping are considered in the current case study.

NUMERICAL MODELLING

In this study, a finite element model is developed to simulate seawater intrusion in coastal aquifers. The governing differential equations describing transient fluid flow, heat transfer and solute transport in saturated/unsaturated soil are presented in terms of four primary variables: pore-water pressure \( (u_w) \), pore air pressure \( (u_a) \), absolute temperature \( (T) \) and solute concentration \( (c) \). The governing equations can be expressed as follows:

Water flow equation

\[
C_{uw} \frac{\partial u_w}{\partial t} + C_{uw} \frac{\partial T}{\partial t} + C_{uw} \frac{\partial u_a}{\partial t} = \nabla [K_{uw} \nabla u_w] + \nabla [K_{uw} \nabla T] + \nabla [K_{uw} \nabla u_a]
+ \rho_w \nabla (K_w \nabla z)
\] (1)

Air flow equation

\[
C_{aw} \frac{\partial u_w}{\partial t} + C_{at} \frac{\partial T}{\partial t} + C_{aw} \frac{\partial u_a}{\partial t} = \nabla [K_{aw} \nabla u_w] + \nabla (K_{aw} \nabla u_a) + H_{aw} \rho_{aw} \nabla (K_w \nabla z)
\] (2)

Heat flow equation

\[
C_{Tw} \frac{\partial u_w}{\partial t} + C_{TT} \frac{\partial T}{\partial t} + C_{Ta} \frac{\partial u_a}{\partial t} = \nabla (K_{Tw} \nabla u_w) + \nabla (K_{TT} \nabla T)
+ \nabla (K_{Ta} \nabla u_a) + V_{Tw} \nabla u_w
+ V_{TT} \nabla T + V_{Ta} \nabla u_a + (T - T_r)\rho_w \nabla (K_w \nabla z)
\] (3)

Solute transport equation

\[
\frac{\partial ((\theta_w + H\theta_a)c)}{\partial t} = - \left( \left( \frac{\partial}{\partial x} (u_w, c) + \frac{\partial}{\partial y} (v_w, c) \right) + \left( \frac{\partial}{\partial x} (u_a, c) + \frac{\partial}{\partial y} (v_a, c) \right) \right)
+ \left[ \left( \frac{\partial}{\partial x} \left( D_{aw} \frac{\partial}{\partial x} (\theta_w c) \right) + D_{aw} \frac{\partial}{\partial y} (\theta_w c) \right) \right]
+ \left[ \left( \frac{\partial}{\partial y} \left( D_{aw} \frac{\partial}{\partial x} (\theta_a c) \right) + D_{aw} \frac{\partial}{\partial y} (\theta_a c) \right) \right]
+ \left[ \left( \frac{\partial}{\partial x} \left( D_{sd} \frac{\partial}{\partial x} (\theta_a c) \right) + D_{sd} \frac{\partial}{\partial y} (\theta_a c) \right) \right]
+ \left[ \left( \frac{\partial}{\partial y} \left( D_{sd} \frac{\partial}{\partial x} (\theta_a c) \right) + D_{sd} \frac{\partial}{\partial y} (\theta_a c) \right) \right]
+ \frac{\partial}{\partial t} \left( \rho_d K_d c \right) - (\lambda_w \theta_w + H\lambda_a \theta_a) (1 + \rho_d K_d / \theta_w) c = 0
\] (4)

The governing equations, numerical solution of coupled fluid flow and solute transport equations, and calibration and validation of the numerical model can be found in Abd-Elhamid & Javadi (2011a, 2011b) and Javadi et al. (2012).

BACKGROUND OF SEAWATER INTRUSION IN GAZA AQUIFER

Gaza Strip has a coastline of about 45 km and a total area of about 365 km². Gaza Strip is home to about 1.5 million Palestinians. The aquifer is the only source of fresh water in Gaza, and provides more than 95% of the water consumed in the Gaza Strip for agriculture, domestic and industrial uses. Water is obtained by pumping from more than 3,000 wells, with a total estimated annual yield of about 140 million cubic meters (Qahman & Larabi 2006). Gaza aquifer is a part of the shallow sandy coastal aquifer which stretches from Israel through Gaza into the Sinai Peninsula in Egypt as shown in Figure 1. A critical and rapidly worsening component of the humanitarian crisis in Gaza Strip is the water crisis. Over-abstraction of water from the aquifer over several decades has caused severe depletion and saltwater intrusion from the

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Mediterranean Sea. The flow of water in the aquifer is naturally toward the sea, though in many places the flow has been reversed. Another major problem for Gaza aquifer is pollution. Contamination consists of fertilizers, pesticides and untreated sewage. The pollution, exacerbated by the conflict’s impact on Gaza’s waste treatment facilities, has resulted in widespread contamination of the aquifer.

Moreover, climate change predictions suggest an imminent catastrophe; as temperature rises, droughts would be exacerbated, and as the sea level rises, saltwater intrusion would speed up. Rising sea level poses another challenge to the Gaza population, as it might lead to the submergence of much of Gaza’s territory. Saltwater intrusion and pollution of the aquifer adversely affect both the human population of the Gaza Strip and its environment. High salinity has been directly linked to a skyrocketing rate of kidney diseases in Gaza. Saltwater intrusion poses a great threat to the municipal supply and industrial growth in the Strip (Qahman 2004).

In this study, the developed model considering coupled flow and solute transport with variable density effects on groundwater flow is applied to simulate groundwater flow and saltwater intrusion in Gaza aquifer. Coupling flow and transport computations allows the effects of fluid density gradients associated with solute concentration gradients to be incorporated into groundwater flow simulations.

SIMULATION OF SEAWATER INTRUSION IN GAZA AQUIFER

Arid and semi-arid regions are vulnerable to water shortage problems due to the scarcity of rainfall and natural recharge...
processes. Gaza is one of the countries that are suffering from a shortage of renewable freshwater resources. Also, the increase in water consumption by different sectors has led to excessive pumping of groundwater in the coastal regions. Over the last decades, over-pumping has accelerated the seawater intrusion process and caused significant deterioration of the groundwater quality in Gaza aquifer. Therefore, this aquifer should be carefully studied to assess the current situation of seawater intrusion and predict any further intrusion considering different scenarios of pumping and climate change. In this paper, Gaza aquifer is selected to predict the current and future intrusion of seawater using the 2D-FEST model. The results of the current model are compared with the results published in the literature. The results are presented and discussed in the following sections.

Site description

Gaza Strip is a part of the Mediterranean coastal plain between Egypt and Israel. It forms a long and narrow rectangular shape 45 km long and 5–10 km wide. Gaza Strip is a foreshore plain gradually sloping westward. The groundwater flow is mainly westward toward the Mediterranean Sea, and the maximum thickness of the saturated zone is 120 m near the sea. Three vertical cross-sections have been selected to study the intrusion of seawater in the aquifer at Jabalya, Wadi Gaza and Khan Younis (Figure 1). The first section at Jabalya is located in the north of Gaza Strip with a length of 5,000 m and average depth of 100 m. The second section at Wadi Gaza is located in the middle of Gaza Strip with a length of 2,000 m and average depth of 100 m. The third section at Khan Younis is located in the south of Gaza Strip with a length of 5,000 m and average depth of 100 m with inclined top and bottom.

Hydraulic parameters

The aquifer is considered to be confined, homogeneous and isotropic with respect to freshwater hydraulic conductivities, molecular diffusion, and longitudinal and transverse dispersivities. The aquifer is subjected to seawater intrusion along the sea boundary, and a uniformly distributed lateral flow along the inland face, with a constant head of 1 m, is considered. The hydraulic conductivities $K_x$ and $K_y$ are 0.2 m/day and 0.1 m/day, respectively. The effective porosity is 0.35 and the longitudinal and transverse dispersivities $\alpha_L$ and $\alpha_T$ are 50 m and 0.1 m, respectively. The densities of fresh water $\rho_f$ and seawater $\rho_s$ are 1.0 t/m$^3$ and 1.025 t/m$^3$, respectively (Qahman 2004).

Boundary conditions

The flow boundary conditions consist of impermeable boundaries along the top and the bottom of the aquifer. Constant head and concentration are specified to the model along the coast. Hydrostatic pressure is assumed along the vertical boundary of the sea side. The aquifer is charged with freshwater at constant flux from the inland side. A prescribed concentration (total dissolved solids, TDS) of 35 kg/m$^3$ is considered on the sea side boundary (Qahman 2004).

Results

The developed model 2D-FEST is applied to simulate saltwater intrusion in the selected three vertical cross-sections in order to predict the intrusion of seawater in different locations in Gaza aquifer. The concentration distributions for the three cross-sections are presented in Figures 2–4. The results of the present model show that the aquifer is subject to a severe seawater intrusion problem and groundwater is unsuitable for human use. At Khan Younis, isoline 2 (2,000 ppm) intruded inland to a distance of about 2.0 km measured along the bottom boundary (Figure 4). On the other hand, at Jabalya, the same isoline intruded inland to a distance of about 3.0 km (Figure 2). The intrusion reduction at Khan Younis might be attributed to the upward slope toward the inland side at this section. At Wadi Gaza, isoline 2 (2,000 ppm) intruded inland to a distance of about 1.2 km, measured along the bottom boundary (Figure 3).

The results of the geophysical survey obtained by PWA/CAMP (2000) indicated that the extent of saltwater intrusion ranged between 1 and 2 km at Khan Younis cross-section. Qahman & Larabi (2006) used the SEAWAT code to simulate saltwater intrusion in Gaza aquifer. The estimated extent of the seawater wedge from seawater intrusion up to 2003 along Khan Younis ranged between 1 and 2 km.
Figure 2 | Isolines of TDS concentration (kg/m³) calculated by 2D-FEST along Jabalya.

Figure 3 | Isolines of TDS concentration (kg/m³) calculated by 2D-FEST along Wadi Gaza.

Figure 4 | Isolines of TDS concentration (kg/m³) calculated by 2D-FEST along Khan Younis.
which is consistent with the results obtained by the geophysical survey (see Figure 5). Also, the results of the present model indicated that the intrusion of seawater at this section is about 2 km (Figure 4). Qahman & Larabi (2006) also used SEAWAT to simulate saltwater intrusion along Jabalya and the estimated extent of the seawater wedge was about 3 km by 2003 (see Figure 6) which is consistent with the results obtained by the present model (Figure 2).

The results of the developed model show good agreement with the results of previous models applied to Gaza aquifer (e.g. Qahman & Zhou 2001; Qahman & Larabi 2003a, 2003b, 2006) and results of the geophysical survey obtained by PWA/CAMP (2000). The discrepancy between results of the current model and the work of Qahman & Larabi (2006) is due to the fact that those authors considered the aquifer to be divided into three sub-aquifers overlying each other and separated by impervious or semi-pervious clay layers. For simplicity the aquifer has been considered homogeneous in the current study. However, the results generally match those of Qahman and Larabi, with the difference being in the shape of the contour lines. Qahman & Larabi (2006) also used the SEAWAT code to simulate saltwater intrusion in Gaza aquifer in the horizontal plane using two different scenarios of pumping. The special distribution of TDS concentration predicted by SEAWAT is shown in Figure 7. It is shown that the intrusion of seawater is about 2 km in Khan Younis, 3 km in Jabalya and 1.2 km in Wadi Gaza, which is consistent with the results of the present model. The results of the present model in vertical view have been compared with SEAWAT results in horizontal view. The comparison between the results of the two models shows good agreement in terms of concentration distribution in vertical sections obtained by the current model and horizontal sections obtained by SEAWAT. The construction of 2D horizontal and vertical sections can be used to obtain a 3D picture of seawater intrusion in coastal aquifers.
The developed model (2D-FEST) is applied to simulate saltwater intrusion in Gaza aquifer, considering the effect of sea level rise and lowering water table due to over-abstraction. Three cross-sections at Jabalya, Wadi Gaza and Khan Younis were simulated to assess the current situation of seawater intrusion in the aquifer, and the results are compared with the results obtained by Qahman & Larabi (2006). The cross-section at Jabalya in the north of Gaza Strip is selected to study the impact of climate change on the aquifer, as it is subjected to the highest intrusion of seawater (3.0 km) inland. The domain is discretized using a two-dimensional grid (ΔX = 50 m and ΔY = 20 m). The mesh consists of 500 elements and 606 nodes. The boundary conditions applied in this case and model parameters were presented in the previous section.

The results of the simulation without changes in sea level are shown in Figure 2. As discussed above, the extent of the seawater wedge along Jabalya is about 3 km presented by isoline 2 (2,000 ppm) (see Figure 2). In this case, the effects of sea level rise and lowering of the water table, due to over-pumping, on the position of the freshwater/saltwater interface are investigated considering three scenarios. In these scenarios, the shore line is maintained at its current location and the effect of submergence of low lands by seawater is not considered.

- Scenario 1, the water level in the sea is raised by 100 cm, the free water table is kept unchanged and all other parameters are kept to their original values.
• Scenario 2, the piezometric head on the land side is lowered by 50 cm to investigate the effect of additional pumping from the aquifer; the water level in the sea is kept unchanged and all other parameters are kept to their basic values.

• Scenario 3, the water level in the sea is raised by 100 cm, the piezometric head on the land side is lowered by 50 cm and all other parameters are kept to their basic values. The results of the three scenarios are shown in Figures 8–10.

In the first scenario (±1 m SLR), isoline 2 intruded inland to a distance of about 3.5 km measured at the bottom boundary from the sea side. In the second scenario (−0.5 m water table), isoline 2 intruded inland to a distance of about 3.25 km. However, isoline 2 in the third scenario intruded...
inland to a distance of about 4.0 km, due to the combination of both sea level rise and lowering water table.

The results of the simulation model indicate that the change of water level on the sea side has a significant effect on the position of the transition zone especially if the effect of sea level rise is combined with the effect of increased abstraction from the aquifer, as is the case in scenario 3. In this case, the transition zone is shifted further inland. Gaza aquifer is contaminated by saline water and urgent actions are needed to prevent such intrusion because the groundwater is the only source of water for about 1.5 million Palestinians living in Gaza Strip.

CONCLUSIONS

Gaza aquifer is subjected to severe seawater intrusion from the Mediterranean Sea, causing serious environmental impacts. The intrusion of seawater into Gaza aquifer is simulated using the developed model at different vertical cross-sections. The results showed that the aquifer is subject to a severe seawater intrusion problem and the groundwater is currently unsuitable for human use. The seawater has intruded inland to distances of about 2 km in the south (Khan Younis), 1.2 km in the middle (Wadi Gaza) and 3 km in the north (Jabalya). The model results were compared with those of SEAWAT, which was applied in the horizontal section. The comparison between the two models showed good agreement in terms of concentration distribution in the vertical domain obtained by the current model and the horizontal domain obtained by SEAWAT. The construction of 2D concentration distributions in horizontal and vertical sections can be used to obtain a 3D picture of seawater intrusion in coastal aquifers.

This study also investigated the possible effects of climate change and sea level rise on seawater intrusion in Gaza aquifer. The rise in seawater levels will impose additional saline water heads on the sea side and therefore more seawater intrusion is anticipated. A 100 cm rise in the Mediterranean Sea level will cause additional intrusion of 500 m in Gaza aquifer. Reduction in the water table (0.5 m) due to over-pumping will cause additional intrusion of 250 m. However, a combination of the two scenarios will cause additional intrusion of 1.0 km in the aquifer. To control or prevent the intrusion of seawater into Gaza aquifer, a steep slope for the piezometric head should be kept as much as possible towards the sea side. Therefore different scenarios, either for pumping activities or land use, should be examined and locations of pumping activities which may not cause significant intrusion can be identified. Redistribution of the pumping fields and land use for agricultural practices (with specific reference to crops with high water
demand) may help to mitigate the seawater intrusion. Techniques such as the use of scavenger wells, artificial recharge either through open basins or recharge wells and others can also be considered.

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