Evaluation and numerical modeling of seawater intrusion in the Gaza aquifer (Palestine)

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Abstract A numerical assessment of seawater intrusion in Gaza, Palestine, has been achieved applying a 3-D variable density groundwater flow model. A two-stage finite difference simulation algorithm was used in steady state and transient models. SEAWAT computer code was used for simulating the spatial and temporal evolution of hydraulic heads and solute concentrations of groundwater. A regular finite difference grid with a 400 m^2 cell in the horizontal plane, in addition to a 12-layer model were chosen. The model has been calibrated under steady state and transient conditions. Simulation results indicate that the proposed schemes successfully simulate the intrusion mechanism. Two pumpage schemes were designed to use the calibrated model for prediction of future changes in water levels and solute concentrations in the groundwater for a planning period of 17 years. The results show that seawater intrusion would worsen in the aquifer if the current rates of groundwater pumpage continue. The alternative, to eliminate pumpage in the intruded area, to moderate pumpage rates from water supply wells far from the seashore and to increase the aquifer replenishment by encouraging the implementation of suitable solutions like artificial recharge, may limit significantly seawater intrusion and reduce the current rate of decline of the water levels.

Résumé Un bilan numérique de l'intrusion de l'eau souterraine à Gaza, Palestine, a été réalisé au moyen d'un modèle 3D d'écoulement des eaux souterraines à densité variable. Une simulation par différences finies à deux niveaux a été utilisée en régime permanent et transitoire. Le code SEAWAT a été utilisé pour simuler l'évolution spatiale et temporelle des hauteurs piézométriques ainsi que les concentrations en solutés dans l'eau souterraine. Une grille régulière aux différences finies et des cellules de 400 m^2, et douze couches horizontales constituent le modèle. Ce dernier a été calibré en condition de régime permanent et régime transitoire. Les résultats de la simulation indiquent que les schémas proposés simulés simulent avec succès les mécanismes d'intrusion. Deux schémas de pompages ont été définis pour prédire, grâce au modèle calibré, à prédire les changements des niveaux d'eau et des concentrations dans l'eau souterraine, sur une période de 17 ans. Les résultats montrent que l'intrusion de l'eau de mer pourrait s'aggraver dans l'aquifère, si les pompages actuels se poursuivent à ce niveau. L'alternative, éliminer le pompage dans la zone d'intrusion, serait de modérer les taux de pompages des puits de production éloignés de la cote et d'accroître le réapprovisionnement de l'aquifère en encourageant l'application de solutions telles que la recharge artificielle, qui limiteraient significativement l'intrusion des eaux souterraines et déduiraient le taux actuel de déclin des niveaux d'eau.

Resumen Se ha logrado una evaluación numérica de la intrusión de agua salada en Gaza, Palestina aplicando un modelo de flujo 3-D de densidad variable de agua subterránea. Se utilizó un algoritmo de simulación de diferencia finita de dos etapas en modelos de régimen permanente y transitorio. Se utilizó el código de computación SEAWAT para simular la evolución espacial y temporal de presiones hidráulicas y concentraciones de soluto de agua subterránea. Se eligió una malla regular de diferencia finita con una celda de 400 m^2 en el plano horizontal en adición a un modelo de 12 capas. El modelo se ha calibrado bajo condiciones de régimen permanente y transitorio. Los resultados de la simulación indican que los esquemas propuestos simulan exitosamente el mecanismo de intrusión. Se diseñaron dos esquemas de bombeo para utilizar el modelo calibrado para predecir los cambios futuros en niveles de agua y concentraciones de soluto en el agua subterránea para un periodo de planificación de 17 años. Los resultados muestran que la intrusión de agua de mar empeoraría en el acuífero si los ritmos actuales de bombeo de agua subterránea continúan. La alternativa de eliminar el bombeo en el área de intrusión, a ritmos de bombeo moderado de pozos de abastecimiento de agua alejados de la costa,

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a incrementar el reabastecimiento mediante el estímulo de implementar soluciones disponibles como recarga artificial puede limitar significativamente la intrusión de agua de mar y reducir el ritmo actual de descenso de niveles de agua.

Introduction

Water is the most precious and valuable natural resource in the Middle East in general and in Palestine (Gaza Strip) in particular. It is vital for socio-economic growth and sustainability of the environment. The development of groundwater resources in coastal areas is a sensitive issue, and careful management is required if water quality degradation, due to the encroachment of seawater, is to be avoided. In many cases, difficulties arise when aquifers are pumped at rates exceeding their natural capacity to transmit water, thus inducing seawater to be drawn into the system to maintain the regional groundwater balance. Problems can also occur when excessive pumping at individual wells lowers the potentiometric surface locally and causes upconing of the natural interface between fresh water and saline water.

The Gaza coastal aquifer, underlying an area of 365 km^2, is the only natural source for domestic, agricultural, and industrial purposes in the Gaza Strip with a population of about 1.2 million. Water is presently obtained by pumping more than 3000 wells, with a total estimated annual yield of about 140 million cubic meters (MCM). The total production presently exceeds natural recharge, and there is a net deficit in the aquifer water balance (PWA/USAID 2000). Current rates of aquifer abstraction are unsustainable and deterioration of groundwater quality is documented in many parts of the Gaza Strip. Saltwater intrusion presently poses the greatest threat to the municipal supply and continuous urban and industrial growth is expected to further impact the water quality.

The understanding of processes and chemical reactions related to seawater intrusion, and refreshening of water in coastal aquifers has been investigated by several authors, for instance, Giménez and Morell (1997), using hydrogeochemical analyses, studied a coastal aquifer affected by salinization in Spain; Petalas and Diamantis (1999) identified different sources of saline water with hydrochemical techniques in a coastal aquifer of northeastern Greece; and Stuyfzand (1999) showed chemical changes related to seawater intrusion and refreshening of water in Dutch coastal dunes. A modeling approach to the multicomponent ion-exchange process in a coastal aquifer of Argentina was presented by Martínez and Bocanegra (2002). Lambrakis and Kallergis (2001), with a similar methodology, defined an estimate of the rate of water refreshening, under natural recharge conditions, for three coastal aquifers in Greece.

In many cases, understanding of the mechanics of seawater intrusion has been incorporated into numerical models. Quantitative studies of modeling the seawater intrusion in coastal regions have been conducted by numerous authors worldwide (Andersen et al. 1988; Rivera et al. 1990; Ghassemi et al. 1993, 1996; Calvache and Pulido-Bosch 1994; Gangopadhyay and Gupta 1995; Xue et al. 1995; Zhou et al. 2000; Sadeg and Karahonglu 2001; Langevin 2003). Two general approaches, the sharp interface approach and the transition zone (dispersion) approach, have been used to analyze seawater intrusion in coastal aquifers. Two-dimensional and three-dimensional models have been developed in both approaches to simulate the steady state or unsteady state problem of seawater intrusion. Numerical models based on the sharp interface approximation assumption are reported in Mercer et al. (1980), Polo and Ramis (1983), Essaid (1990), and Larabi and De Smedt (1994, 1997). Numerical models based on the second approach which is considering the transition zone between seawater and freshwater are reported in Huyakorn et al. (1987), Galeati et al. (1992), Das and Datta (1995), Putti and Paniconi (1995), Guo and Langevin (2002), and Aharmouch and Larabi (2004).

The seawater intrusion problem in the Gaza Strip has been the subject of a number of studies (Yakirevich et al. 1998; Qahman and Zhou 2001; Moe et al. 2001; Qahman and Larabi 2003a,b). Yakirevich et al. (1998), carried out simulations of saltwater intrusion using a two-dimensional density-dependent flow and transport model SUTRA (Voss 1984). This model was applied to the Khan Yunis section of the Gaza Strip aquifer (Fig. 1).

Numerical simulations show that the rate of seawater intrusion during 1997–2006 is expected to be 20–45 m/year. Qahman and Zhou (2001), carried out a simulation of seawater intrusion along a cross-section in the northern part of the Gaza Strip using the SUTRA code. The results of the simulation were used for identifying the number and locations of monitoring sites along the northern cross-section. Moe et al. (2001), presented a 3-D coupled flow and transport model for simulating the effects of a proposed management plan for the aquifer. DYNCFT finite element computer code (Fitzgerald et al. 2001) was used for the calculation. Modeling results demonstrate that implementation of the proposed management plan will have an overall beneficial impact on the aquifer. In this work the period before year 1969, when most of the water level-drop occurred, was not given enough importance in the northern area and, accordingly, the seawater intrusion results in that period were not presented. Qahman and Larabi (2003a), showed chemical changes related to seawater intrusion and refreshening of water in the Gaza aquifer using the Stuyfzand (1999) method and the groundwater flow patterns were also studied. The results indicated that about 10 coastal wells are affected by seawater intrusion showing a deficit in the cation exchange and a considerable high chloride concentration (>250 mg/l). Qahman and Larabi (2003b) carried out a simulation of seawater intrusion along a cross-section of the Gaza Strip at Khan Younis using SEAWAT computer code. The objective of the simulation was to compare the SEAWAT results with the previous results of SUTRA for the same cross-section using the same input data. The re-

Fig. 1 Location map of the Gaza Strip (source: EPD/IWACO-EUROCONSULT 1996)
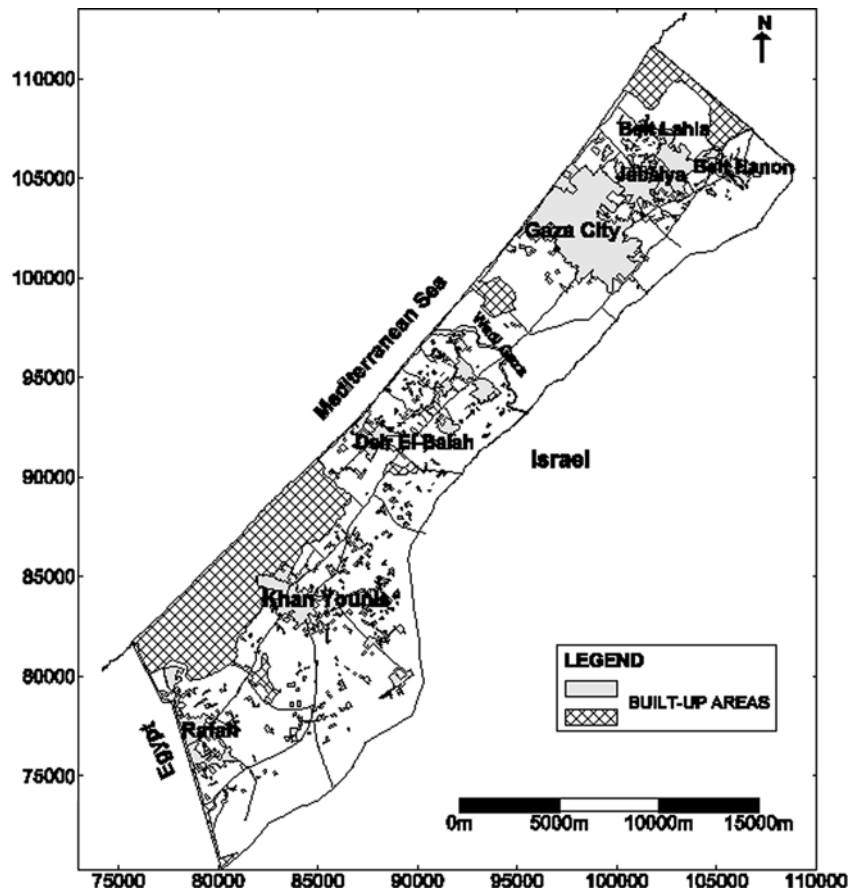
sults of this work indicated that the SEAWAT code gave very good results compared with the SUTRA code and it was recommended to extend the work by making a 3-D model using the SEAWAT code.

In the view of the previous studies, the present work was initiated to investigate the current status of the seawater intrusion in the Gaza aquifer using the available data. It was aimed at defining the hydrodynamics and hydrochemical behavior of the intrusion in the region and to assess its evolution, by applying the variable-density SEAWAT code using the 3-D finite difference discretization. In this way it was planned to clarify when and where most of seawater intrusion occurred and to predict its future behavior along the Gaza Strip.

Description of the study area

The Gaza Strip is a part of the Mediterranean coastal plain between Egypt and Israel, where it forms a long and narrow rectangle (Fig. 1). Its area is about 365 km^2 and its length is approximately 45 km. The population characteristics of the Gaza Strip are strongly influenced by political developments which have played a significant role in the growth and population distribution of the Gaza Strip. In 1997 the Palestinian Bureau of Statistics estimated the population to be about 1 million (PCBS 1998).

The average daily mean temperature ranges from 25°C in summer to 13°C in winter. Average daily maximum temperatures range from 29 to 17°C and minimum temperatures from 21 to 9°C in the summer and winter respectively. The daily relative humidity fluctuates between 65% in the daytime and 85% at night in the summer, and between 60 and 80%, respectively in winter. The mean annual solar radiation is 2,200 J/cm^2/day (EPD/IWACO-EUROCONSULT 1994). The average annual rainfall varies from 450 mm/year in the north to 200 mm/year in the south. Most of the rainfall occurs in the period from October to March, the rest of the year being completely dry. Precipitation patterns include thunderstorms and rain showers, but only a few days of the wet months are rainy days. There is less areal variation in evaporation than in rainfall in the Gaza Strip. Evaporation measurements have clearly shown that the long term average open water evaporation for the Gaza Strip is in the order of 1,300 mm/year. Maximum values in the order of 140 mm/month are quoted for summer, while relatively low pan-evaporation values of around 70 mm/month were measured during the months of December and January.

Geological and hydrogeological setting

The Gaza Strip is essentially a foreshore plain gradually sloping westward and is underlain by a series of Mesozoic

Fig. 2 Schematization of the hydrogeological cross-section of the Gaza Strip aquifer (from: PWA/USAID 2000); vertical scale in meters
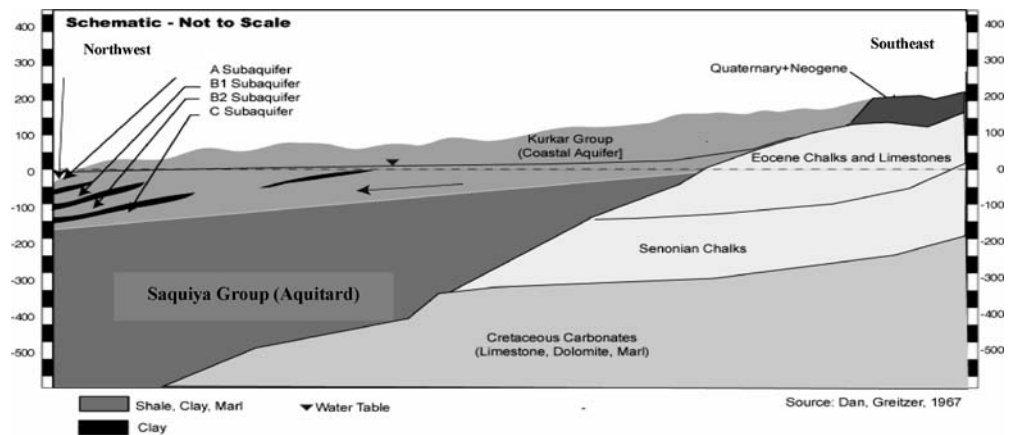
to the Quaternary geological formations. The hydrogeology of the coastal aquifer consists of one sedimentary basin; the post-Eocene marine clay (Saqiya Group), forms the bottom of the aquifer. Pleistocene sedimentary deposits of alluvial sands, graded gravel, conglomerates, pebbles and mixed soils constitute the regional hydrological system. Intercalated clay deposits of marine origin separate these deposits, and are randomly distributed in the area. The Gaza aquifer can be divided into three subaquifers (A, B, C). Schematization of the hydrogeological cross section of the Gaza Strip aquifer is shown in Fig. 2. It is implied that subaquifer A is phreatic, whereas subaquifers B and C become increasingly confined towards the sea.

The regional groundwater flow is mainly westward towards the Mediterranean Sea. The maximum saturated thickness of the aquifer ranges from 120 m near the sea to a few meters near the eastern aquifer boundary. Natural average groundwater heads decline sharply east of the Gaza strip and then gradually decline towards the Sea. Depth to water level of the coastal aquifer varies between a few meters in the lowland area along the shoreline and about 70 m below the surface along the eastern border.

The major source of renewable groundwater in the aquifer is rainfall. The total rainfall recharge to the aquifer is estimated to be approximately 45 MCM/year. The remaining rainwater evaporates or dissipates as runoff during the short periods of heavy rainstorms. The lateral inflow to the aquifer is estimated at between 10 and 15 MCM/year. Some recharge is available from the major surface flow (Wadi Gaza). But because of the extensive extraction from Wadi Gaza by Israel, this recharge is limited at its best to 2 MCM during the ten days the wadi actually flows in a normal year. As a result, the total freshwater recharge at present is limited to approximately 60 MCM/year.

Currently, the Gaza aquifer is monitored by a multipurpose groundwater monitoring network which is used for observing the groundwater levels and the nitrate and chloride content. The existing water level monitoring network includes 135 wells and 39 piezometers (small-diameter pipes) distributed all over Gaza Strip since 1972 (PWA 1997a). The existing groundwater quality monitoring network has 700 wells for chloride monitoring and 450 wells for nitrate monitoring (PWA 1997b).

Seawater intrusion in Gaza aquifer

Under natural conditions, groundwater flow in the Gaza Strip is discharging towards the Mediterranean Sea. However, pumping over 50 years has significantly disturbed natural flow patterns. Large cones of depression were formed in the north and south where water levels are below mean sea level, inducing inflow of seawater towards the major pumping centers.

Surveys of hydrologic characteristics began under the British Government of Palestine (1917–1948), and regular monitoring throughout the region began in the early 1930s. Between October 1934 and September 1935 a survey of chloride concentration and water levels in wells was conducted throughout the region (PWA/USAID 2000).

In order to figure out the extent of groundwater declines and the changes in groundwater quality, historical changes in groundwater levels and chloride concentrations were analyzed for the period 1935 and 2000 (Figs. 3 and 4). The kriging interpolation method was used to estimate the spatial distribution of values depending on available data from measurement points which are located on the figures. Water level contours have declined from east towards the west (Fig. 3a), in a smooth pattern almost parallel to the coastline. This could well be thought of as an initial (natural) condition of the aquifer where only a few wells might be pumping under near-steady-state conditions.

A comparison of Figs. 3a and 4a shows that groundwater levels dropped by as much as 8 meters between 1935 and 1969 in the northern area of the Gaza Strip. This drop is most apparent in the north due to possible extensive exploitation of groundwater at the eastern and northern borders of the Gaza Strip during 1948–1969, in addition to the sudden increase of the Gaza Strip population in 1948 which has increased the water demand in this area. On the other hand, a comparison of Figs. 3b and 4b indicates that there is no considerable difference in the chloride spatial distribution. This could be explained if, during this period, there was enough water in storage and the total amount
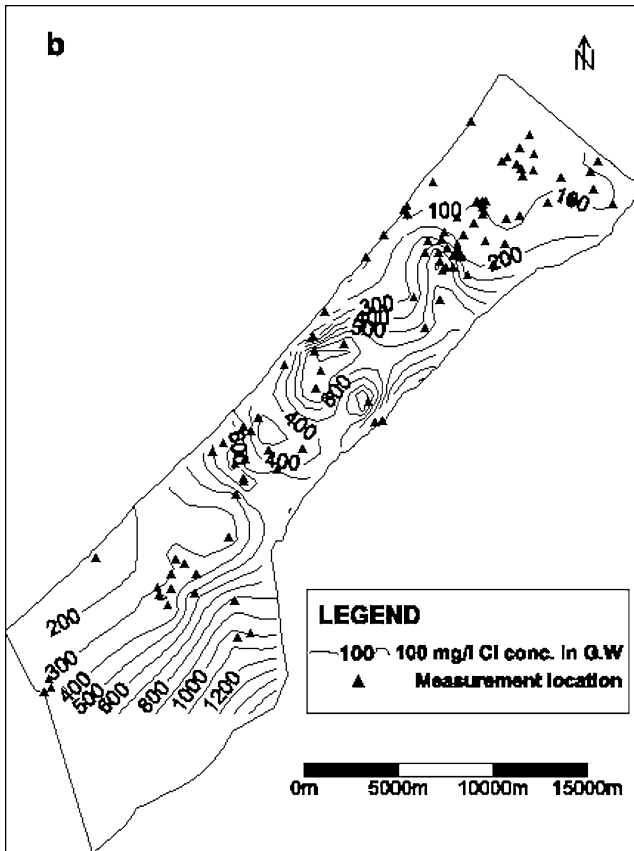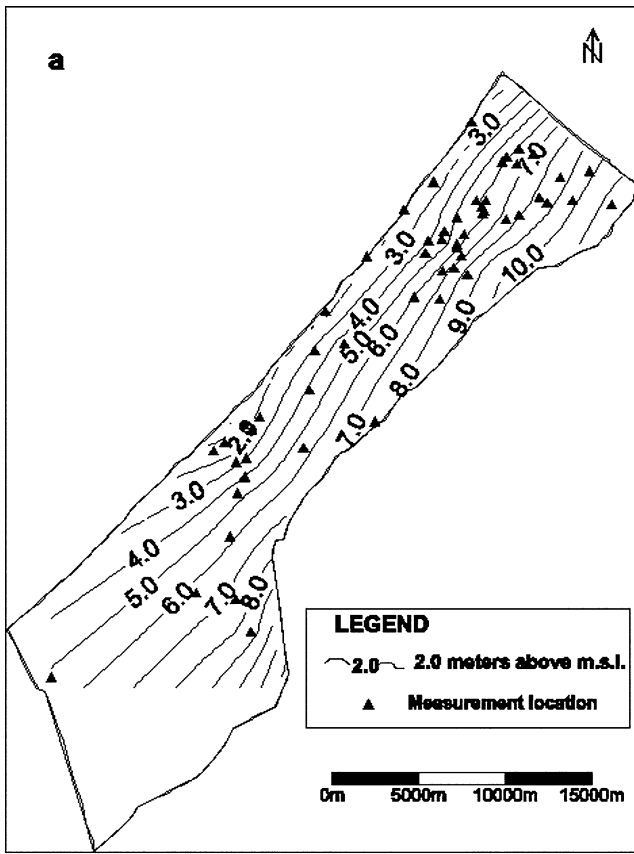
Fig. 3 **a** Groundwater level contours, **b** Chloride concentration isolines in groundwater (year 1935); isoline interval 100 mg/l
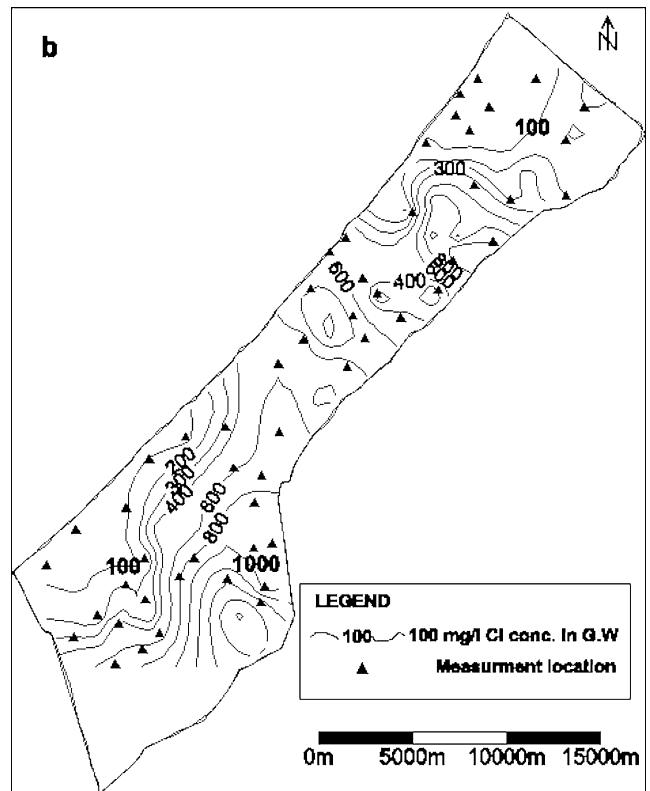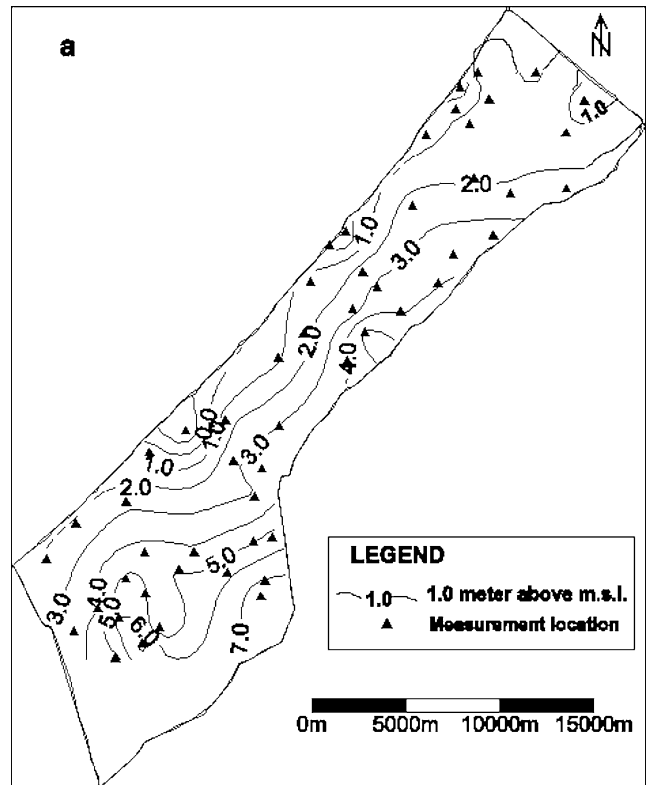

Fig. 4 **a** Groundwater level contours, **b** Chloride concentration isolines in groundwater (year 1969); isoline interval 100 mg/l

abstracted from the aquifer, in general, did not exceed the total natural recharge.

Between 1970 and 2000, groundwater levels dropped by almost 3m on average. This drop is most apparent in the south where there is a lower recharge rate from rainfall. In the north, most wells exhibited a relatively small water level drop in this period due to the higher recharge rate (Figs. 4a and 5a). In addition, water levels often drop below sea level, presumably because of excessive discharge from a nearby well field. From Fig. 5a, it can be estimated that water levels are below mean sea level in area of more than 100 km^2 of the Gaza Strip. Comparison of Figs. 4b and 5b shows that there is a noticeable change in the position of the chloride isolines, especially near the coast, indicating possible landward migration of seawater.

In recent years, the seawater intrusion effect is more evident. High rates of urbanization and increased agricultural and industrial activities require more water to be pumped from the aquifer. This pumping has continually increased the risk of seawater intrusion and deterioration of freshwater quality in the Gaza aquifer.

Figure 6a shows a typical water level time series trend for well number E/32 along the coast of the Gaza Strip about 6 km south of the border. Figure 6b shows a sudden typical breakthrough of salinity for well number E/32. This could be due to either lateral encroachment of saline water (seawater intrusion) and/or vertical upconing in the summer season due to the increase of the abstraction rate from wells.

Numerical simulation of coupled groundwater and solute transport

Model development

The regional scale model simulates transient groundwater flow for the period 1935–2003. The model was developed using the conceptual hydrologic model shown in Fig. 2.

Governing equations

Variable density groundwater flow is described by the following partial differential equation as presented in Langevin (2003).

$$\nabla \rho \, K_f + \left(\nabla h_f + \frac{(\rho - \rho_f)}{\rho_f} \nabla z \right) = \rho \, S_f \frac{\partial h_f}{\partial t}$$
$$+ n \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \overline{\rho q} \tag{1}$$

where z is a coordinate direction aligned with gravity (L). ρ is fluid density (ML^{-3}). K_f is the equivalent fresh water hydraulic conductivity (LT^{-1}). h_f is the equivalent fresh water head (L). ρ_f is the density of fresh water (ML^{-3}). S_f is equivalent fresh water storage coefficient (L^{-1}). t is time (T). n is porosity (L^0). C is the concentration of the dissolved constituent that affects fluid density (ML^{-3}). $\bar{\rho}$ is the fluid density of a source or a sink (ML^{-3}). $\bar{q}$ is the flow rate of the source or sink (T^{-1}).
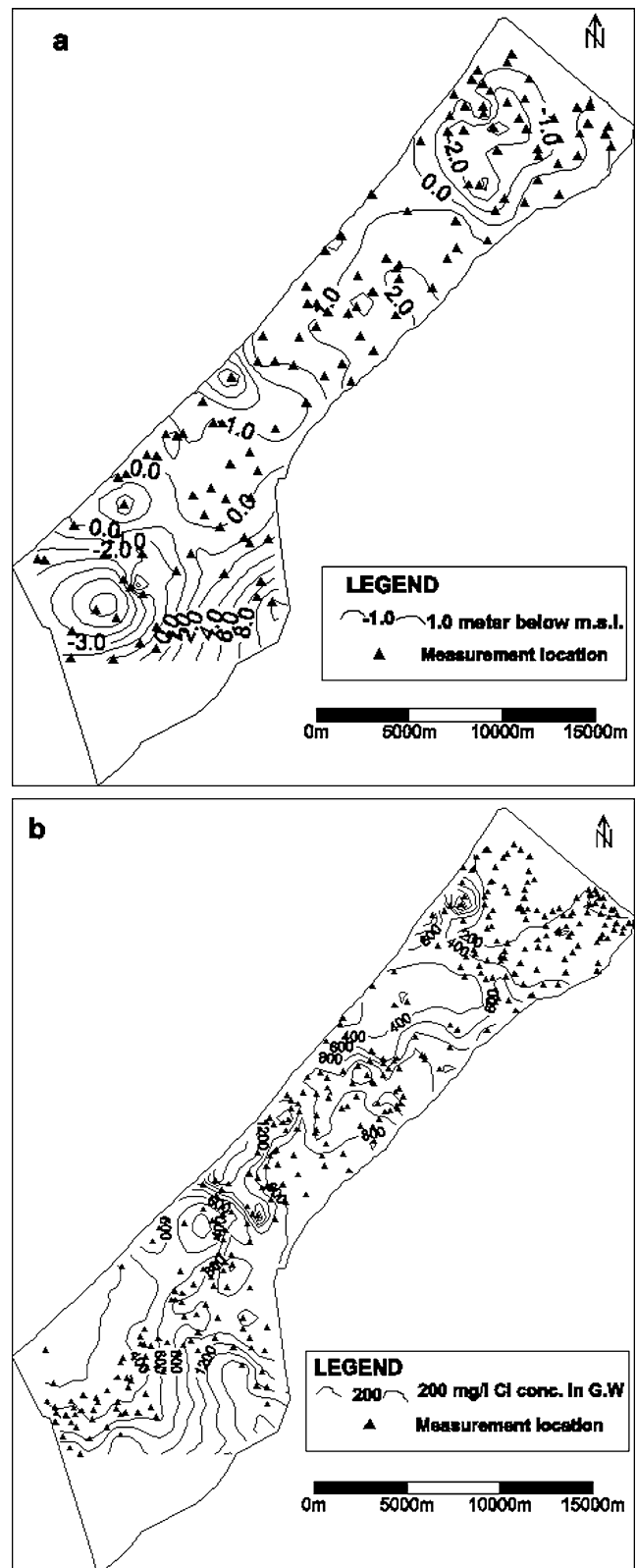

Fig. 5 **a** Groundwater level contours, **b** Chloride concentration isolines in groundwater (year 2000); isoline interval 200 mg/l
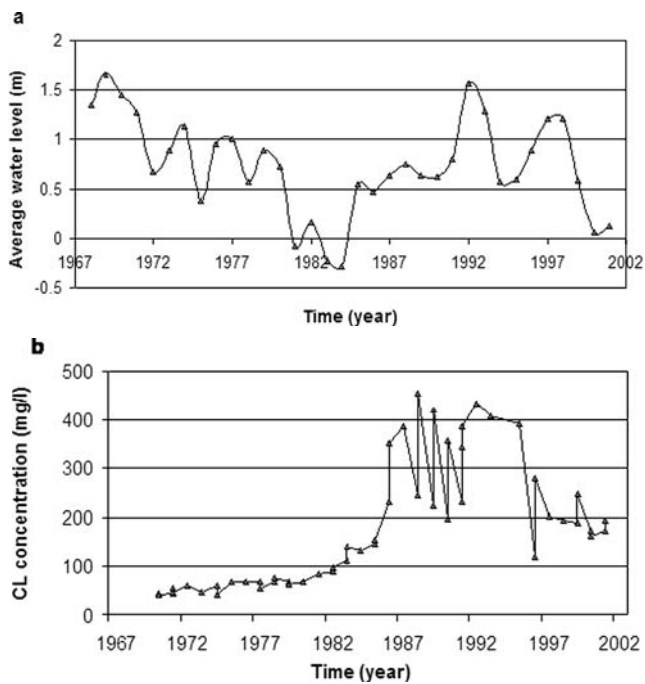
Fig. 6 **a** Water level time series, **b** Chloride time series (well E-32 near the coast in the north of the Gaza Strip)

To solve the variable density ground water flow equation, the solute-transport equation also must be solved because fluid density is a function of solute concentration, and concentration may change in response to the groundwater flow field. For dissolved constituents that are conservative, such as those found in sea water, the solute transport equation is:

$$\frac{\partial C}{\partial t} = \nabla(D\nabla C) - \nabla(\nu C) - \frac{q_s}{n} C_s \qquad (2)$$

where D is the dispersion coefficient (L^2T^{-1}). ν is the groundwater flow velocity (LT^{-1}). q_s is the flux of a source or sink (T^{-1}). C_s is the concentration of the source or sink (ML^{-3}).

Simulation code

To simulate variable density effects on groundwater flow, the coupled flow and transport code SEAWAT was used (Guo and Bennett 1998). Coupling flow and transport computations allows the effects of fluid density gradients associated with solute concentration gradients to be incorporated into groundwater flow simulations (i.e., density-dependent flow). It uses the finite difference method of numerical integration to solve 3-D confined and unconfined groundwater flow under many types of natural and artificial aquifer stresses.

The original SEAWAT code was written by Guo and Bennett (1998) to simulate groundwater flow and salt water intrusion in coastal environments. SEAWAT uses a modified version of MODFLOW (McDonald and Harbaugh 1988) to solve the variable density, groundwater flow Eq. (1) and MT3D (Zheng 1990) to solve the solute-transport Eq. (2).

Spatial and temporal discretization

The model domain and finite difference grid used to simulate groundwater flow within the Gaza coastal aquifer are shown in Fig. 7. The model encompasses an area of about 365km². The grid consists of 115 rows, 35 columns with 4025 regular cells in plan view. Each cell is 400 m 400 m in the horizontal plane.

The model was discretized vertically into 12 layers, this increased resolution is necessary because of transport considerations and because vertical density gradients must be resolved in order to calculate accurate flow velocities. The top elevation of layer 1 is spatially variable and corresponds with land surface elevation, based on a topographic map. The bottom of layer 1 is set at an elevation of 5.0m below sea level. The nearly 70-year simulation period is divided into nine stress periods. For each stress period, the average hydrologic conditions for that period are assumed to remain constant. Further temporal discretization is introduced in the form of time steps within each stress period. The length of the transport time step was assigned to start with 1 day and to be increased by a multiplier factor of 1.2.

Assignment of values to aquifer parameters

The basis for assigning hydraulic properties were the existing data from pumping tests in the Gaza Strip, previous modeling studies by Israeli organizations in the coastal plain, and miscellaneous literature related to transport parameters. The distribution of hydraulic conductivity values for tests carried out in Gaza show that values were 20–80 m/day.

Pumping tests carried out in the Gaza Strip to date have yielded unreliable values of storage coefficient; hence values were obtained from the literature for similar types of sediments, as well as results from previous studies (PWA/CAMP 2000). Specific yield values are estimated to be about 15–30 percent while specific storage is about $10^{-4}m^{-1}$ from tests conducted in Gaza.

Accordingly, the approach for assigning aquifer parameter values that pertain to groundwater flow and solute transport was to use the simplest distribution that would result in adequate representation of the flow system. All parameter values were adjusted during the model calibration process until the model adequately reflected the observed water level distribution and interpreted flow patterns throughout the aquifer.

Boundary conditions

Constant head and concentration were specified to the model cells along the coast. The specified constant concentration of TDS is 35 kg/m³. The head for each cell was converted to freshwater head using the specified TDS concentration of 35 kg/m³ and the center elevation of the cell. A reference density of 1,000 kg/m³ was used for freshwater and 1,025 kg/m³ for seawater. The coupled flow and transport model (SEAWAT) uses this reference value to calculate and adjust fluid densities relative to simulated concentrations of dissolved salts in the model.

Fig. 7 Finite-difference grid
and boundary conditions for the
Gaza regional model
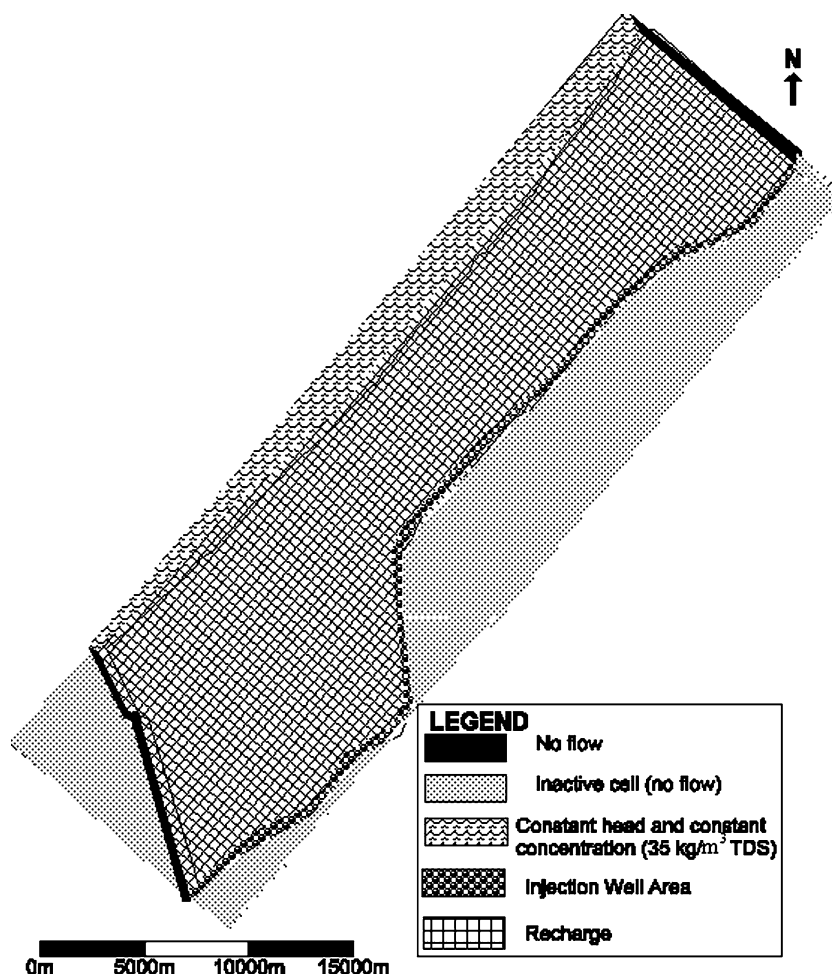
To represent the lateral flow of groundwater from the inland perimeter of the model, injection wells were assigned to the eastern boundary of the model with a specified salt concentration to be within the range of 0.2–3 kg/m^3 from the north to the south of the eastern border. The rate of injection was calculated from the available water level contour maps. For example, the lateral water inflow from the east was estimated to be about 6 MCM/year for the northern part of the Gaza strip (8 km length) according to the water table contours of 1935, considering the hydraulic conductivity as 25 m/day and the aquifer thickness 70 m. The same method can be applied for other years and border sections. The value of lateral flow was adjusted during the model run.

The lower boundary of the model represents the base of the aquifer. A Neumann-type of no-flux boundary conditions was assigned to the bottom of the aquifer (Guo and Langevin 2002).

The northern and the southern boundaries are assumed to be no-flow boundaries, assuming that the flow lines are parallel to them under natural conditions. However, the exact position of this boundary is not known due to the scarcity and uncertainty of data. This assumption could be changed in case the water level data are obtained.

Internal hydrologic stresses

Hydrologic stresses that are internal to the model domain are represented with internal boundary conditions. Internal hydrologic stresses include: recharge from rainfall, return flow, and municipal and agricultural withdrawals.
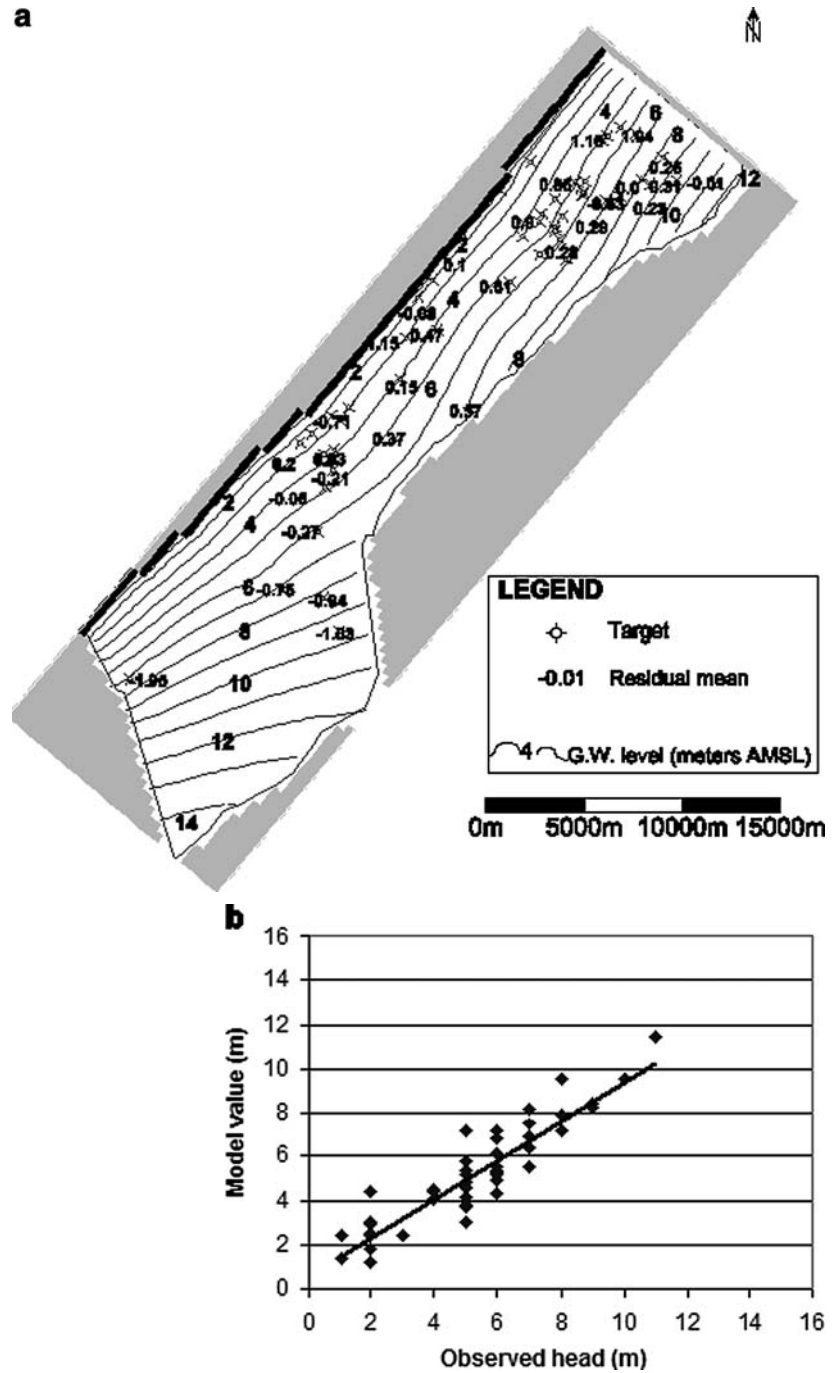
Recharge

The recharge (RCH) package in SEAWAT is used to apply surface recharge from rainfall to the model with a specified low salt concentration of 0.085 kg/m^3. The general procedure for estimating recharge values was to multiply the average annual rainfall quantity in each zone by infiltration coefficient. The infiltration coefficient was estimated according to soil type, land use and evapotranspiration rate. According to the long term annual average of rainfall data within the Gaza Strip area, the average rate of recharge applied on the model was in the range of 0.0002–0.00045 m/day.

Return flow

Agriculture pumping within the Gaza Strip is on the order of 80–100 MCM/year in any given year. A portion of this applied water infiltrates back into the aquifer. The quantities that infiltrate depend on methods of irrigation, crop

Fig. 8 **a** Residuals of water level in year 1935 (steady state). **b** Observed heads versus simulated heads in year 1935 (steady state)

types, soil types, and irrigation schedules. Hence, in the Gaza Strip, 25% of the pumping at individual wells was recharged back to the aquifer (PWA/CAMP 2000).

Municipal and agricultural well fields
More than 3,000 pumping wells are inventoried and represented in the model domain. The applied groundwater abstraction rate from the model domain is summarized in Table 1. The estimation was done according to the available data on population, population growth, number of wells, and groundwater abstraction rates between 1987 and 1993.

Initial conditions
A steady state simulation was performed using 1935 hydrologic conditions. The results (water level and concentrations) from the steady state simulation were used as initial conditions for transient simulation.

Calibration and model results
The numerical model was calibrated and tested against both steady state and transient data. Two sets of target conditions were selected for calibration purposes, steady state conditions in year 1935 and time varying

Table 1 Estimated groundwater abstraction from the Gaza aquifer

Abstraction period	Period	Abstraction rate (MCM/year)
1	1935–1949	16
2	1949–1955	22
3	1955–1960	55
4	1960–1969	78
5	1969–1975	98
6	1975–1982	107
7	1982–1990	116
8	1990–1998	135
9	1998–2003	150

Table 2 Statistical results of calibration processes

	Year 1935	Year 1969	Year 2002
Mean residual (m)	−0.01	−0.15	−0.01
Absolute mean residual (m)	0.69	0.82	0.82
Standard deviation of mean residual	0.96	0.98	1.09

conditions between 1935 and 1969. Verification of the model was done based on the average water level in year 2002.

During calibration, measured and model-computed heads (water levels) are compared, and the difference is referred to as the residual. Figure 8a shows the calibrated, simulated flow field in the Gaza Strip for year 1935 conditions, and the spatial distribution of residuals. Average water levels of year 1935 for 50 wells within the model domain were used as calibration targets. Within the model domain, observed water levels range from 0.5 m above mean sea level (AMSL) to 15 m AMSL. The calculated residual mean error and absolute mean error are about −0.01 and 0.69 m, respectively, with a standard deviation for the model domain of 0.96 m. In general, the residual values range from −1.95 to 1.25 m. Comparison of calculated and measured groundwater levels for year 1935 shows that they are compatible with each other (Fig. 8b).

The results of steady state calibration show that there is no apparent trend related to the spatial distribution of residuals especially in the two-thirds of the model domain to the north of Khan-Younis, where there are a lack of targets and monitoring data. However, this area of the model contains poor water quality. In the southeastern part of the model domain and for very low abstraction rates, the calibration is regarded as acceptable in general.

Transient calibration was conducted for the 1935–1969 target period, using the calibrated 1935 steady state results as an initial condition. For the transient calibration, the major pumping and lateral fluxes were changed for the specified stress periods.

For transient simulations, adjustments were made to the storage coefficients. A further calibration step of the model was done based on groundwater level data of year 2002. The results of calibration are presented in Table 2. For year 1969, the calculated residual mean error and absolute

mean error are about −0.15 and 0.82 m, respectively, with a standard deviation for the model domain of 0.98 m. For year 2002, the calculated residual mean error and absolute mean error are about −0.01 and 0.82 m, respectively, with a standard deviation for the model domain of 1.09 m. The results of transient calibration are considered as acceptable for this study purpose.

Table 3 summarizes the mass balance calculated by the model taking into consideration that amount between 20 and 30% is deducted from the total abstraction to represent the return flow which comes from irrigation, sewage infiltration and leakages from water networks. This means that the amount assigned for abstraction from the wells in the table represents the net abstraction after deducting the return flow from the total abstraction. This was done to simplify the modification of recharge zones assigned for the model and also it decreases the uncertainty coming from assigning the location of return flow which is not known very well. The steady state water balance for year 1935 shows that a large quantity of groundwater is discharged to the sea (about 55 MCM/year) which is enough to counteract seawater intrusion. In years 1969, 1998, and 2003, the discharge quantity to the sea is decreased to about 9.8 MCM/year where the seawater intrusion quantity reaches about 46 MCM/year.

As a preliminary check on the model simulation of seawater intrusion, results were compared with geophysical survey results in the southern sector of the Gaza Strip which was done with Italian cooperation (CISS/WRC 1997). The geoelectrical section executed in the Deir El Balah area (Fig. 9a) which is composed of ten numbered vertical electrical soundings (VES) and extends from the borderline to the sea in a southeast-northwest direction. From VES number 64 to number 66 the interpretative model is composed of a more conductive top layer (3 Ωm) over a much less resistive middle layer (10 Ωm) overlapping the highly conductive bottom layer (0.1–1 Ωm). It was concluded that, the general relative lowering of the resistivity is due to the seawater intrusion inside the aquifer formation upper conductive (clay) and resistive (sandstone and pebble)

Table 3 Summary of the calculated mass balance of the flow model

Year	In (MCM/year)					Out (MCM/year)				In–Out
	Storage	Lateral flow	Sea	Recharge	Total in	Storage	Wells	Sea	Total out	
1935	0.00	26.64	7.15	38.81	73.94	0.00	17.64	55.07	73.94	0.001
1969	9.64	16.59	24.50	38.81	89.53	0.00	61.74	27.79	89.53	0.005
1998	2.65	27.30	42.80	38.81	111.56	0.00	100.27	11.29	111.56	0.001
2003	5.13	27.30	46.16	38.56	117.14	0.00	107.36	9.78	117.14	0.002

Fig. 9 **a** Deir El Balah geoelectrical section in year 1996. **b** Isolines of calculated TDS concentrations (kg/m³) by SEAWAT in year 1996 along Deir El Balah geoelectrical cross section; isoline interval 2kg/m³
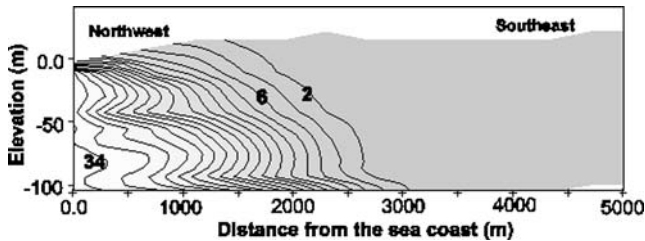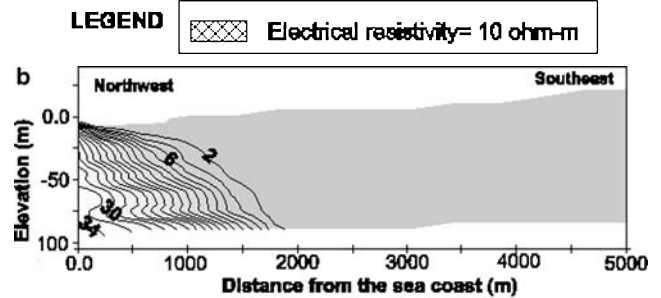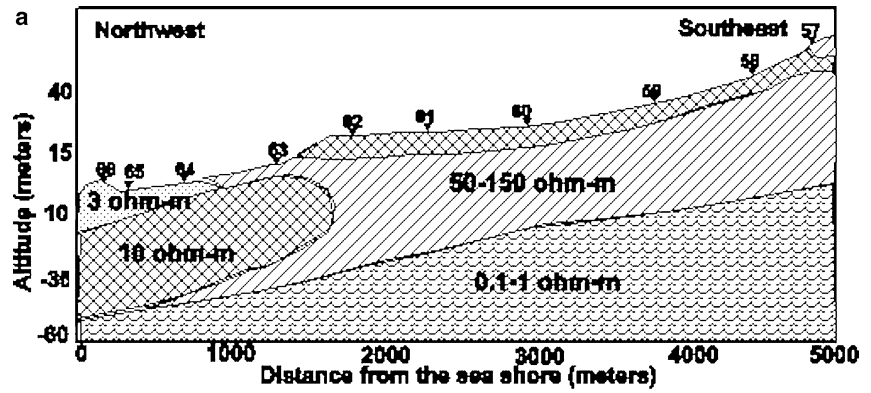

Fig. 10 Isolines of calculated TDS concentration (kg/m³) by SEA-WAT in year 2003 along the Jabalya cross section
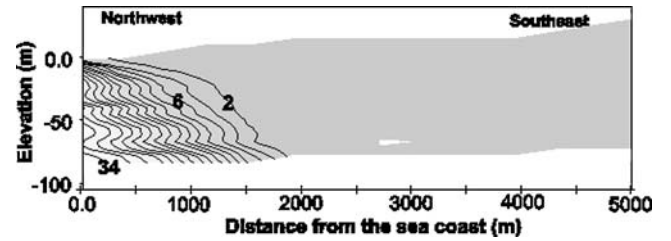
Fig. 11 Isolines of calculated TDS concentration (kg/m³) by SEAWAT in year 2003 along the Khan Younis cross section

layers. The results of the geophysical survey indicate that the extent of seawater intrusion along Deir El Balah profile in the subaquifer A, may reach 1,000 m inland which agrees in general with the simulation results as illustrated in Fig. 9b.

In addition to the above, the model results for year 2000 were compared with geophysical survey results obtained from PWA/CAMP (2000). In particular, the time-domain electromagnetic method (TDEM) survey results were used. The results of comparison show that the simulated extent of the seawater wedge in year 2000 gave a reasonable agreement with the TDEM measurements at two cross section locations near the coast in Rafah and also in Deir

El Balah also. Most values of the TDEM records within the intruded area identified by the simulation model have values less than 2.0 Ωm of apparent resistivity, which is considered an indication for seawater intrusion in coastal areas.

The model gave good agreement with results of previous modeling studies of Gaza aquifer (Yakirevich et al. 1998; Qahman and Zhou 2001; Moe et al. 2001).

A summary of the aquifer hydraulic and transport properties that best describes the aquifer behavior in steady state and transient models after model calibration is presented in Table 4.

Table 4 Aquifer parameter values after calibration

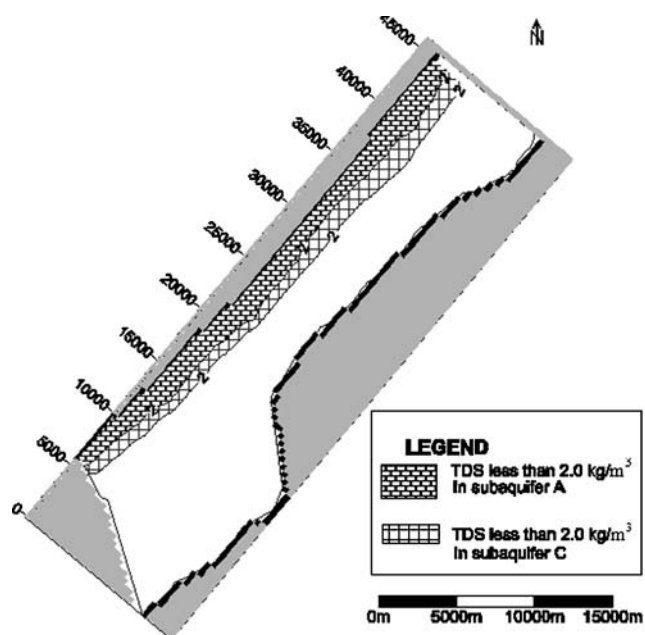| Stratigraphic unit	Horizontal hydraulic conductivity (m/day)	Vertical hydraulic conductivity (m/day)	Specific yield	Specific storage (m⁻¹)	Porosity	Longitudinal dispersivity (m)	Transverse dispersivity (m)
Sandstone	30	3	0.2	0.0001	0.35	10	0.1
Clay	0.2	0.1	0.1	0.0001	0.4	50	0.1

Fig. 12 Simulated inland extent of TDS concentration (more than 2.0kg/m^3) in subaquifers A and C in year 2003

Simulation results and discussions

Saltwater-freshwater transition zone

The estimated extent of the seawater wedge from seawater intrusion modeling until year 2003 is presented in two cross-sections (Figs. 10 and 11; Jabalya and Khan Younis, respectively). For the purpose of presentation, it is considered that the extent (wedge) of seawater intrusion is represented by the 2.0 kg/m^3 isoline of TDS concentrations.

From Fig. 10 it is estimated that seawater intrusion near Jabalya may extend about 2 km inland in subaquifer B, and up to 3 km in subaquifer C. Localized intrusion in subaquifer A is restricted to the coastal area.

In Khan Younis (Fig. 11), seawater intrusion extends inland about 2 km in subaquifer B2 and about 1.5 km in subaquifer B1.

Figure 12 shows a plan view of simulated current (2003) intrusion in the A and C subaquifers in the Gaza aquifer. It is clear from the above results that most of the area affected by seawater intrusion is located in the north coast of the Gaza Strip to the north of Gaza city (from about 35 000 to 45 000N). Extensive seawater intrusion also has occurred in the south from about 10 250 to 25 250N. Other sources of chloride, such as the Eocene age rocks (chalks and limestones) at the eastern model boundary (with chlo-

ride concentrations less than 2,000 mg/l) will not exert notable influences on the water levels and water quality because of their generally low transmissivity.

Predicted results

Because increased withdrawal of groundwater from the water supply wells near the coast is the main cause of seawater intrusion into the aquifer, a future decrease in groundwater withdrawal is a very important consideration to prevent further intrusion of the seawater into the aquifer. In order to demonstrate the effect of future scenarios of groundwater pumpage on seawater intrusion, two pumping schemes were designed to use the calibrated model for calculations of future changes in water levels and salinity concentrations in a period of another 17 years. The two management scenarios are presented as follow:

1. The first (worst) scenario where the pumping from the aquifer continues to increase assuming that there is no new water resources for the Gaza Strip.
2. The second scenario where pumping from the aquifer is assumed to be decreased and the deficit in water demand is covered by developing new water resources in Gaza Strip like desalination of seawater, the import of water from outside the Gaza Strip and reuse of treated wastewater in agricultural irrigation.

Table 5 shows the amounts of abstracted water from the aquifer for both scenarios.

Figures 13a and b show the future changes in water levels in year 2020 for the two predictive scheme simulations. Obviously, water levels in Fig. 13a dropped below MSL in most of the Gaza Strip area. On the other hand, Fig. 13b shows that in all the Gaza Strip, water levels are AMSL, which means that there is improvement in the groundwater balance.

Figures 14a and b show the comparison between the extent of seawater intrusion in subaquifer A in year 2003 and 2020 for both scenarios. It is predicted that between years 2003 and 2020, the first scenario will induce a considerable quantity of seawater intrusion especially in the northern part. Model results indicate that the extent of the isoline (TDS concentration = 2.0 kg/m^3) at the base of subaquifer A will move about an additional 1.5 km in the northern part. On the other hand, the results of comparison indicate that the second scenario prevent any further seawater intrusion after year 2003. In year 2020 the total inflow from the sea is estimated to be 72 MCM/year and 32 MCM/year for the first scenario and second scenario respectively, where the

Table 5 Abstraction amounts for management scenarios

Stress period no	Period length	First scenario Abstraction (MCM/year)	Second scenario Abstraction (MCM/year)
1	2003–2008	160	140
2	2008–2011	170	130
3	2011–2014	180	120
4	2014–2017	190	110
5	2017–2020	200	110

Fig. 13 **a** Predicted
groundwater level contour lines
for first scenario, **b** Predicted
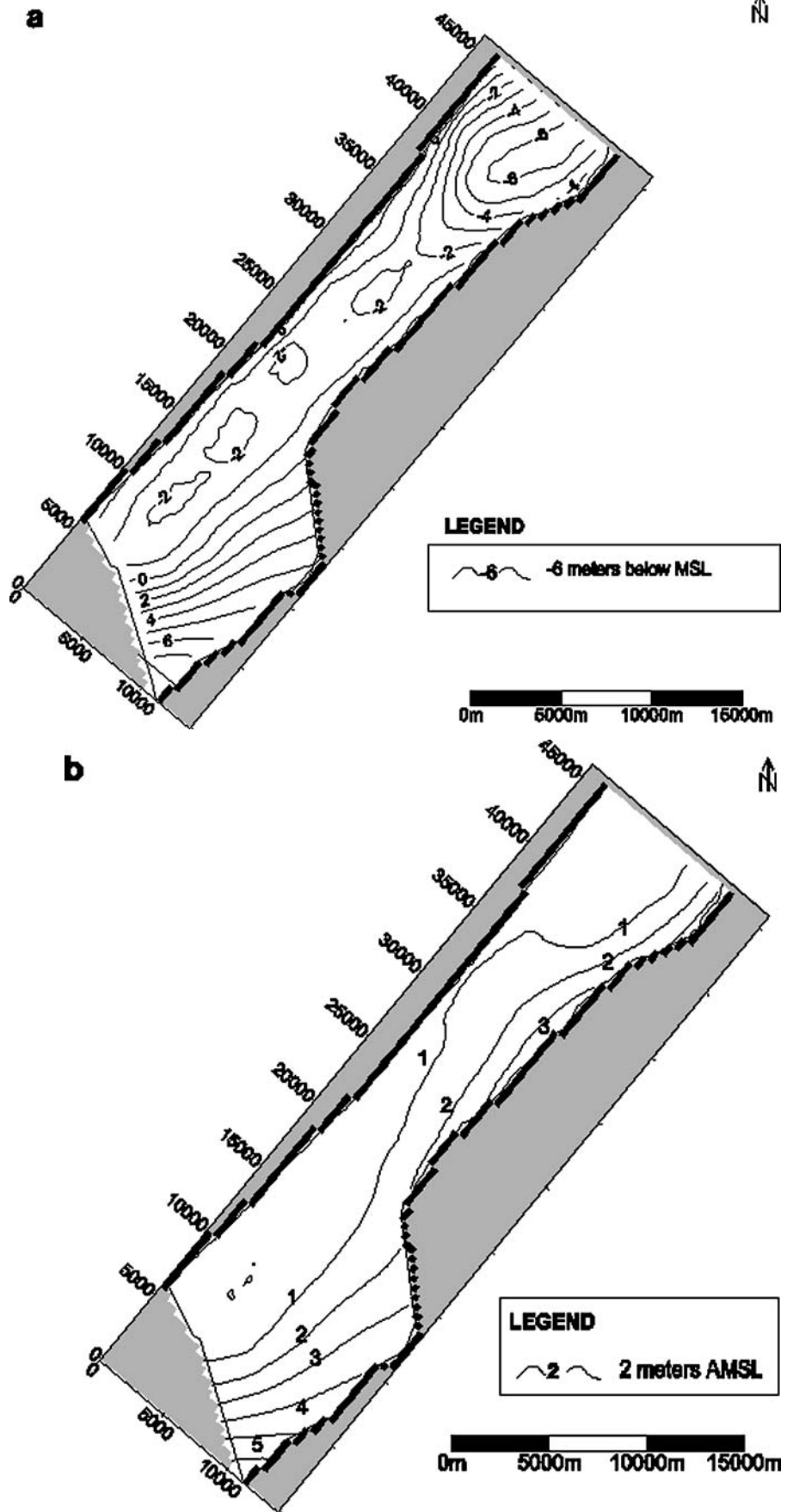groundwater level contour lines
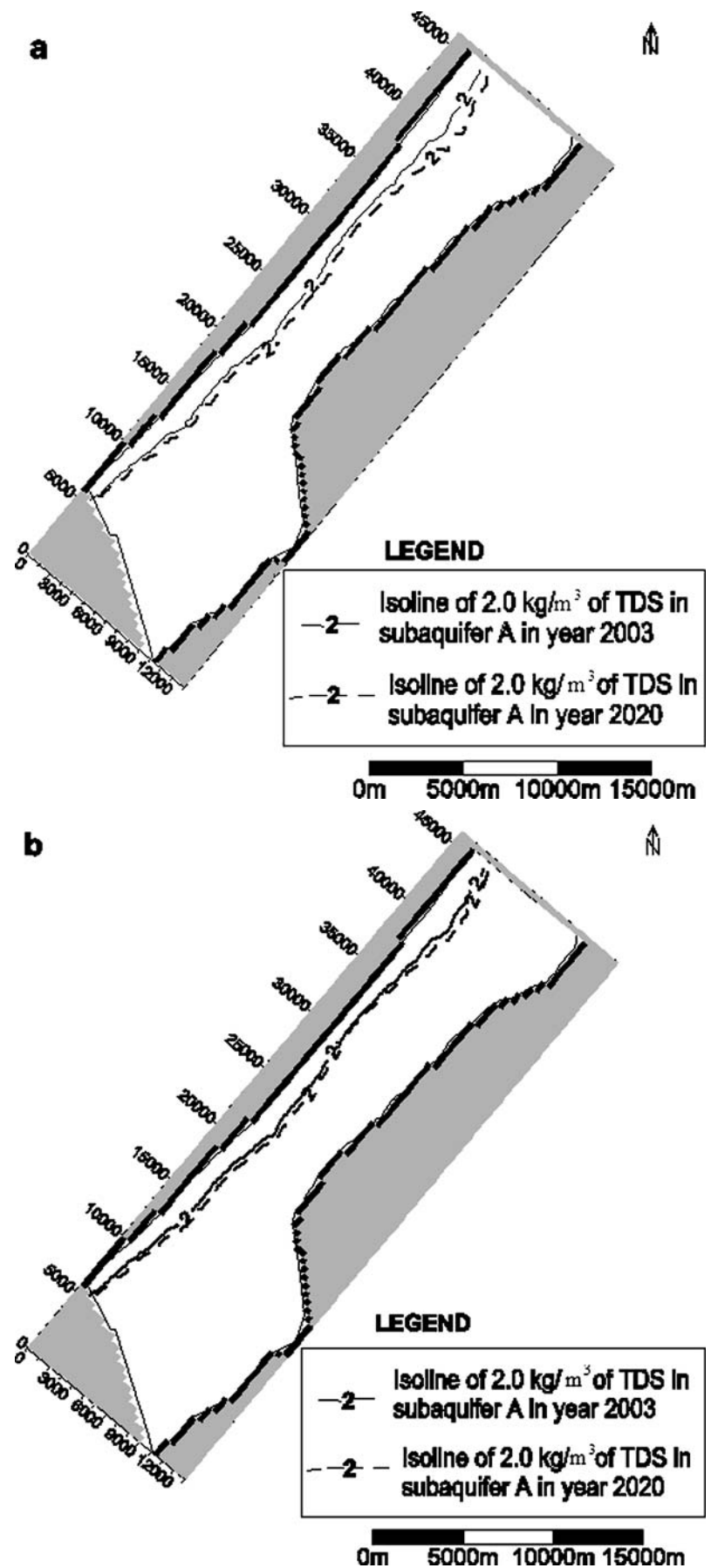for second scenario year (2020)

Fig. 14 Simulated extent of TDS concentration in subaquifers A in years 2003 and 2020. **a** under the first scenario conditions, **b** under the second scenario conditions

discharge to the sea for the same year is estimated to be about 3 and 18 MCM/year for the first and second scenarios.

Conclusions

The Gaza coastal aquifer is a dynamic groundwater system, with continuously changing inflow and outflow conditions. The equilibrium condition that once may have existed between fresh and saline water has been disturbed by large scale pumping. The aquifer has been overexploited for the past 40 years; this has induced seawater flow towards the major pumping centers in the Gaza Strip to the north of the Gaza City and near Khan-Younis City.

The understanding of the three dimensional pattern of groundwater flow and variation of groundwater quality are incomplete. All the wells tested and sampled in the Gaza Strip are located in the shallow portion of the aquifer; the deeper subaquifer was sampled in some deep municipal wells. However, many of these wells receive water from two or more subaquifers, so the water quality in the specific subaquifers could not be determined. Fresh groundwater (based on a TDS concentration of less than 250 mg/l) is only found in the north and in the southwest in sandy dune areas, and in shallow parts of the aquifer where recharge from rainfall is high.

The coupled flow and transport finite difference code (SEAWAT) was applied to examine how far inland the seawater transition zone has moved since intrusion began. The model gave good results for the evolution of salinity in the aquifer. The preliminary model results suggested that the seawater intrusion began in the 1960s which is in agreement with the available information about general pumping and well information. Most of the seawater intrusion has occurred to the north of Gaza City and also near Khan-Younis City in the south.

The numerical model was applied to evaluate the overall regional impact on the aquifer for two future scenarios of pumping. The first scenario is to pump from the aquifer continuously until the year 2020 when the pumping rate reaches 200 MCM/year; and the second scenario is to progressively decrease the pumping rate, starting at 140 MCM/year in the year 2003, to 110 MCM/year from the existing wells. It is predicted that between years 2003 and 2020, the first scenario will induce a considerable quantity of seawater intrusion especially in the northern part. Model results indicate that the extent of the isoline (TDS concentration = 2.0 kg/m^3) at the base of subaquifer A will move about an additional 1.5 km in the northern part. On the other hand, the second scenario would prevent any further seawater intrusion after the year 2003. In the year 2020 the total inflow from the sea is estimated to be 72 and 32 MCM/year respectively for the first and second scenarios. The discharge to the sea for the same year is estimated to be about 3 and 18 MCM/year respectively for the first and second scenarios.

For the regional scale model to accurately simulate the groundwater levels, the model must accurately simulate the three dimensional distribution of groundwater salinity.

Unfortunately, data are lacking to adequately characterize the distribution because most of the monitoring wells are installed in the top layers of the aquifer. In addition, data are lacking on depths of the well screens and, as noted above, the water quality in specific subaquifers could not be determined. Given the uncertainties in the available data, additional refinement of the model grid at this stage does not provide more accuracy. However, in general, the model reasonably simulates the position of the saltwater transition zone, particularly near the coast. The current model is a reasonable representation of the aquifer in an overall regional context. In the future, as new data become available, the model should be updated periodically to refine estimates of input parameter values, and simulate new management options.

Since the Gaza aquifer is the single most important source of water for the Gaza strip, appropriate investments should be made to ensure that each of the major components of the hydrological water budget are adequately quantified, understood, and incorporated into the regional groundwater model. This requires installation of dedicated observation wells (to obtain water levels and to define spatial variations in water quality), implementation of systematic sampling programs, and to carefully study the major factors that influence the groundwater regime in the Gaza Strip.

References

Aharmouch A, Larabi A (2004) 3-D finite element model for seawater intrusion in coastal aquifers. In: Proceedings of 15th international conference computational methods in water resources, North Carolina

Andersen PF, Mercer JW, White HO (1988) Numerical modeling of saltwater intrusion at Hallandale, Florida. Ground Water 26:619–630, 23(2):293–312

Calvache ML, Pulido-Bosch A (1994) Modeling the effects of saltwater intrusion dynamics for a coastal karstified block connected to a detrital aquifer. Ground Water 32(5):767–771

CISS/WRC (1997) Geophysical study of the southern sector of the Gaza Strip (Khan Younis area). Italian cooperation South (CISS-Palermo) and Water Research Center (WRC Alazhar University-Gaza), Palestine

Dan J, Greitzer Y (1967) The effect of soil landscape and Quaternary geology on the distribution of saline and fresh water aquifers in the Coastal Plain of Israel: Tahal Water Planning for Israel, Publ. 670, Tel Aviv

Das A, Datta B (1995) Simulation of density dependent 2-D seawater intrusion in coastal aquifers using nonlinear optimization algorithm. In: Proceedings of American Water Resource Association of annual summer symposium on water resource and environmental emphasis on hydrology and cultural insight in Pacific Rim. American Water Association, Herndon, VA, pp 277–286

EPD/IWACO-EUROCONSULT (1994) Gaza environmental profile, part one: inventory of resources. Environmental Planning Directorate (EPD), Ministry of Planning and International Cooperation (MOPIC), Palestine

Essaid HI (1990) A multi-layered sharp interface model of coupled freshwater and saltwater in coastal systems: model development and application. Water Resour Res 27(7):1431–1454

Fitzgerald R, Riordan P, Harely B (2001) An integrated set of modeling codes to support a variety of coastal aquifer modeling approaches. In: Proceedings of first international conference saltwater intrusion in coastal aquifers, Morocco

Galeati G, Gambolati G, Neuman SP (1992) Coupled and partially coupled Eulerian-Lagrangian model of freshwater-seawater mixing. Water Resour Res 28(1):147–165

Gangopadhyay S, Gupta AD (1995) Simulation of salt-water encroachment in a multi-layer ground water system, Bangkok, Thailand. Hydrogeol J 3(4):74–88

Ghassemi F, Chen TH, Jakeman AJ, Jacobson G (1993) Two and three-dimensional simulation of sea water intrusion: Performances of the "SUTRA" and "HST3d" models. AGSO J Austr Geol Geophys 14(2/3):219–226

Ghassemi F, Jakeman AJ, Jacobson G, Howard KWF (1996) Simulation of sea water intrusion with 2D and 3D Models: Nauru Island Case Study. Hydrogeol J 4(3):4–20

Giménez E, Morell I (1997) Hydrogeochemical analysis of salinization processes in the coastal aquifer of Oropesa (Castellón, Spain). Environ Geol 29:118–131

Guo W, Bennett GD (1998). Simulation of saline fresh water flows using MODFLOW. In: Proceedings of MODFLOW '98 conference at the International Ground Water Modeling Center, Golden, Colorado, vol 1, pp 267–274

Guo W, Langevin C (2002) User's Guide to SEAWAT, A computer program for simulation of three-dimensional variable density groundwater flow: techniques of water-resources investigations Book 6. U.S. Geological Survey

Huyakorn PS, Anderson PF, Mercer JW, White JRWO (1987) Saltwater intrusion in aquifers: development and testing of a three dimensional finite element model. Water Resour Res 23(2):293–312

Lambrakis N, Kallergis G (2001) Reaction of subsurface coastal aquifers to climate and land use changes in Greece; modeling of groundwater re-freshening patterns under natural recharge conditions. J Hydrol 245:19–31

Langevin CD (2001). Simulation of ground-water discharge to Biscayne Bay, southeastern Florida. U.S. Geological Survey Water-Resources Investigations Report 00–4251

Langevin CD (2003) Simulation of submarine groundwater discharge to a marine estuary: Biscayne Bay, Florida. Ground Water 41:758–771

Larabi A, De Smedt F (1994) Solving 3-D hexahedral finite elements groundwater models by preconditioned conjugate gradient methods. Water Resour Res 30(2):509–521

Larabi A, De Smedt F (1997) Numerical solution of 3-D groundwater flow involving free boundaries by a fixed finite element method. J Hydrol 201:161–182

Martínez DE, Bocanegra EM (2002) Hydrogeochemistry and cation-exchange processes in the coastal aquifer of Mar Del Plata, Argentina. Hydrogeol J 10(3):393–408

McDonald MG, Harbaugh AW (1988) A modular three dimensional finite-difference ground-water flow model. U.S. Geological Survey techniques of water resources investigations, Book 6

Mercer JW, Larson SP, Paut CR (1980) Simulation saltwater interface motion. Ground Water 18(4):374–385

Moe H, Hossain R, Fitzgerald R, Banna M, Mushtaha A, Yaqubi A (2001) Application of 3-dimensional coupled flow and transport model in the Gaza Strip. In: Proceedings of first international conference on saltwater intrusion in coastal aquifers (SWICA), Morocco

PCBS (1998) Population data for the Gaza Strip. Palestinian Central Bureau of Statistics (PCBS), Palestine

Petalas CP, Diamantis IB (1999) Origin and distribution of saline groundwaters in the upper Miocene aquifer system, coastal Rhodope area, northeastern Greece. Hydrogeol J 7(3):305–316

Polo JF, Ramis FJR (1983) Simulation of salt water-fresh water interface motion. Water Resour Res 19(1):61–68

Putti M, Paniconi C (1995) Finite element modeling of saltwater intrusion problems. In: Springer-Verlag (ed) Advanced Methods for Groundwater Pollution Control. International Centre for Mechanical Sciences, New York, 364, pp 65–84

PWA (1997a) Water level monitoring network review. Palestinian Water Authority (PWA), Palestine

PWA (1997b) Water quality monitoring network review. Palestinian Water Authority (PWA), Palestine

PWA/CAMP (2000) Coastal aquifer management program (CAMP)/final model report (task 7). PWA, Palestine

PWA/USAID (2000) Summary of palestinian hydrologic data 2000—volume 2: Gaza. Palestinian Water Authority (PWA), Palestine

Qahman K, Larabi A (2003a) Identification and modeling of seawater intrusion of the Gaza Strip Aquifer—Palestine. In: Proceedings of TIAC03 international conference, Alicante, Spain, vol 1, pp 245–254

Qahman K, Larabi A (2003b) Simulation of seawater intrusion using SEAWAT code in Khan Younis Area of the Gaza Strip aquifer, Palestine. In: Proceedings of JMP2003 international conference, Toulouse, France

Qahman K, Zhou Y (2001) Monitoring of seawater intrusion in the Gaza Strip, Palestine. In: Proceedings of first International Conference on saltwater intrusion in coastal aquifers, Morocco

Rivera A, Ledoux E, Sauvagnac S (1990) A compatible single-phase/two-phase numerical model: 2. Application to a coastal aquifer in Mexico. Ground Water 28(2):215–223

Sadeg SA, Karahonglu N (2001) Numerical assessment of seawater intrusion in the Tripoli region, Libya. Environ Geol 40:1151–1168

Stuyfzand PJ (1999) Patterns in groundwater chemistry resulting from groundwater flow. Hydrogeol J 7(1):15–27

Voss CI (1984) SUTRA, saturated–unsaturated transport a finite simulation model. USGS, Reston, Virginia, U.S.A

Xue Y, Xie C, Wu J, Liu P, Wang J, Jiang Q (1995) A three dimensional miscible transport model for sea water intrusion in China. Water Resour Res 31(4):903–912

Yakirevich A, Melloul A, Sorek S, Shaat S (1998) Simulation of seawater intrusion into the Khan Yunis area of the Gaza Strip coastal aquifer. Hydrogeol J 6:549–559

Zheng C (1990). MT3D: A modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. Report to the U.S. Environmental Protection Agency, Ada, Oklahoma

Zhou X, Chen M, Wan L, Wang J, Ning X (2000) Numerical simulation of sea water intrusion near Beihai, China. Environ Geol 40:223–233