Simulation of seawater intrusion into the Khan Yunis area of the Gaza Strip coastal aquifer

A. Yakirevich · A. Melloul · S. Sorek · S. Shaath
V. Borisov

Abstract The Gaza Strip coastal aquifer is under severe hydrological stress due to over-exploitation. Excessive pumping during the past decades in the Gaza region has caused a significant lowering of groundwater levels, altering in some regions the normal transport of salts into the sea and reversing the gradient of groundwater flow. The sharp increase in chloride concentrations in groundwater indicates intrusion of seawater and/or brines from the western part of the aquifer near the sea.

Simulations of salt-water intrusion were carried out 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. Simulations were done under an assumption that pumping rates increase according to the rate of population growth, or about 3.8% a year. Model parameters were estimated using available field observations. Numerical simulations show that the rate of seawater intrusion during 1997–2006 is expected to be 20–45 m/yr. The results lead to a better understanding of aquifer salinization due to seawater intrusion and give some estimate of the rate of deterioration of groundwater.

Résumé L'aquifère côtier de la bande de Gaza est soumis à une très forte pression hydrologique du fait de sa surexploitation. Les pompages excessifs au cours des dernières décennies dans la région de Gaza a provoqué un abaissement significatif des niveaux de la nappe, en modifiant dans certains secteurs le transport normal de sels vers la mer et en inversant le gradient d'écoulement souterrain. La très forte augmentation des teneurs en chlorures dans la nappe doit être attribuée à une intrusion d'eau de mer et/ou de saumures depuis la partie occidentale de l'aquifère proche de la mer.

Des simulations d'intrusion marine ont été réalisées en utilisant un modèle SUTRA en deux dimensions à écoulement et transport dépendant de la densité (Voss, 1984). Ce modèle a été appliqué au secteur de Khan Yunis de l'aquifère de la bande de Gaza. Les simulations ont été faites en supposant que les débits pompés augmentent au même rythme que la population, soit 3,8% par an. Les paramètres du modèle ont été estimés à partir des observations de terrain disponibles. Les simulations numériques montrent qu'il faut s'attendre à une progression de l'intrusion marine pour la période 1997–2006 de l'ordre de 20 à 45 m/an. Ces résultats permettent de mieux comprendre la salinisation de l'aquifère par l'intrusion marine et fournissent une estimation du taux de dégradation de la qualité de l'eau souterraine.

Resumen El acuífero costero de la Franja de Gaza se encuentra en sobreexplotación. El bombeo excesivo en la región de Gaza durante las últimas décadas ha causado un importante descenso de los niveles piezométricos, alterando la situación natural de transporte de sales hacia el mar e invirtiendo el gradiente de niveles de agua subterránea. El brusco incremento en las concentraciones de cloruros en el agua subterránea indican intrusión de agua marina y/o de salmueras de la parte oeste del acuífero, cercana al mar.

Se llevaron a cabo simulaciones de la intrusión salina usando el modelo bidimensional de flujo y transporte con densidad variable SUTRA (Voss 1984). Este modelo se aplicó al sector de Khan Yunis, en el acuífero de la Franja de Gaza. Las simulaciones se llevaron a cabo bajo la hipótesis que los bombeos se incrementarán de acuerdo con el ritmo de crecimiento de la población, que es del 3.8% anual. Los parámetros del modelo se estimaron a partir de las observaciones de campo. Las simulaciones numéricas muestran que el avance esperado de la intrusión durante 1997-2006 será de 20-45 m/año. Los resultados conducen a un mejor conocimiento de la salinización del acuífero por intrusión

Received, September 1997
Revised, January 1998, July 1998
Accepted, August 1998

A. Yakirevich (✉) · S. Sorek · V. Borisov
Water Resources Research Center, J. Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede Boker Campus, 84990, Israel
Fax: +972-7-6596909
e-mail: alexy@bgumail.bgu.ac.il

A. Melloul
Water Commission, Hydrological Service, P.O. Box 6381, IL-91063 Jerusalem, Israel

S. Shaath
P.O. Box 1357, Gaza City, Gaza Strip

marina y proporcionan estimaciones sobre la velocidad de degradación del mismo.

Key words Gaza Strip · numerical modeling · overexploitation · salt-water/fresh-water relations · groundwater management

Introduction

In arid and semi-arid regions, such as the Middle East, water resources are under escalating stresses due to anthropogenic activities. This trend is significant especially along the Mediterranean coast, where development of the resource has been based upon extensive use of groundwater reservoirs. Modern technology has enabled greater utilization of both shallow and deep groundwater reservoirs, especially near the sea, where parallel growth of population, agriculture, and industry has occurred. Long-term aquifer overexploitation near the sea shore creates an ever-increasing gap between available supply and demand for water, which leads to deterioration in the quality of this resource (US EPA 1990; Ford et al. 1992; Heatwole et al. 1992; Hrkal 1992).

Near the sea shore, the main source of salinization of groundwater is recent seawater intrusion (as much as 35 g/kg TDS, or 20 g/kg Cl) as, e.g., in the Israel coastal plain aquifer (Melloul and Azmon 1997) and in the Suani well field at Tripoli, Libya (Suleiman and El-Baruni 1995). Additional sources of Cl, such as very salty water or brines with more than 20 g/kg Cl, occur as lenses in the deeper aquifer in the southern part of the Gaza Strip coastal aquifer (Fink 1970). In the Gaza Strip coastal aquifer, the presence of brines has been observed in deep zones in some observation wells in different areas (Fink 1970). Seawater and brine sources may be altered due to intensive exploitation of the aquifer. Since the beginning of the 1970s, many studies have described the hydrological situation of the Gaza strip (Fink 1970, 1986; Melloul and Bachmat 1975; Melloul and Bibas 1992; Juanico et al. 1992; Melloul and Collin 1994). Another previous work deals also with the prediction of groundwater and chloride concentrations using extrapolation of graphs based on field data (Chetboun and Melloul 1973), but it did not evaluate the effect of seawater intrusion into the aquifer.

The Gaza Strip coastal aquifer is composed of layers of dune sand, sandstone, calcareous sandstone, and silt, with intercalations of clay and loam of different permeabilities. Near the sea shore, the effects of existing salinization sources may differ from place to place due to the variability in hydraulic conductivity and flow velocities. These differing effects are explained by pollutant characteristics, the heterogeneity of the aquifer media, the geological structure, and the changes in groundwater gradients that result from management procedures, as explained by the laboratory experiments done by Goldenberg et al. (1986, 1993). These studies indicate that the heterogeneity of the aquifer is a practical issue when dealing with groundwater reservoirs. The scale of such variability depends only upon the observation scale (Fayers and Hewett 1994).

Considering these problems, a significant question is how to assess the dynamics of groundwater and of solute during a period of massive exploitation of the aquifer. Computer simulations using an adequate mathematical model can yield plausible explanations. In this study, the SUTRA code (Voss 1984) was used to simulate the cross-sectional density-dependent water flow and solute transport in the Khan Yunis portion of the Gaza Strip coastal aquifer. The model was calibrated on the available field data and used to predict seawater intrusion until the year 2006. Locations are shown in *Figure 1.*

Hydrogeological Background

Figure 1a shows the location and general map of the Gaza Strip. The coastal aquifer of the Gaza Strip region is a Pleistocene-age granular aquifer. It extends from Ashqelon in the north to Rafah in the south, and from the seashore on the west to the Israeli settlements Erez, Kissufim, Nirim, and Nahal Oz on the east (*Figure 1a*). For management purposes, the aquifer of the Gaza Strip is subdivided into four regions: Gaza, Nuseirat, Deir el Balah, and Khan Yunis/Rafah. Each of these regions is subdivided into cells, hydrologic strips, and columns (*Figure 1a*).

This study concerns the Khan Yunis section. A typical hydrogeological section is shown in *Figure 1b*. In most of this area, the coastal aquifer is composed of layers of dune sand, sandstone, calcareous sandstone, and silt, with intercalations of clay and loam. Some of them are lenses; others begin at the coast and separate the aquifer into various subaquifers, designated as A, B1, B2, and C (*Figure 1b*). Subaquifer A is phreatic, whereas B1, B2, and C become confined toward the sea. The aquifer overlies marine clay of Neogene age, known as the Saqiye Clay aquiclude (Fink 1970; Melloul and Bachmat 1975).

In the eastern and southern portions of the Gaza Strip, the aquifer is relatively thin; its thickness is about 30 m at 11 km from the sea shore (*Figure 1b*), and there are no discernible subaquifers. The existing connection between the coastal aquifer and the Eocene aquifer (the latter appears only at a distance more than 30 km from the sea shore) results in highly saline groundwater in the eastern portion of the coastal aquifer; therefore, the level of exploitation there is low (Melloul and Collin 1994).

The amount of exploitation of the coastal aquifer in all the Gaza region is based on data from approximately 2000 wells; average density is about 5 wells per km^2. In the area of study, the density of wells is less than 4 wells per km^2. This lower value reflects a lower population density and less exploitation of the aquifer than in

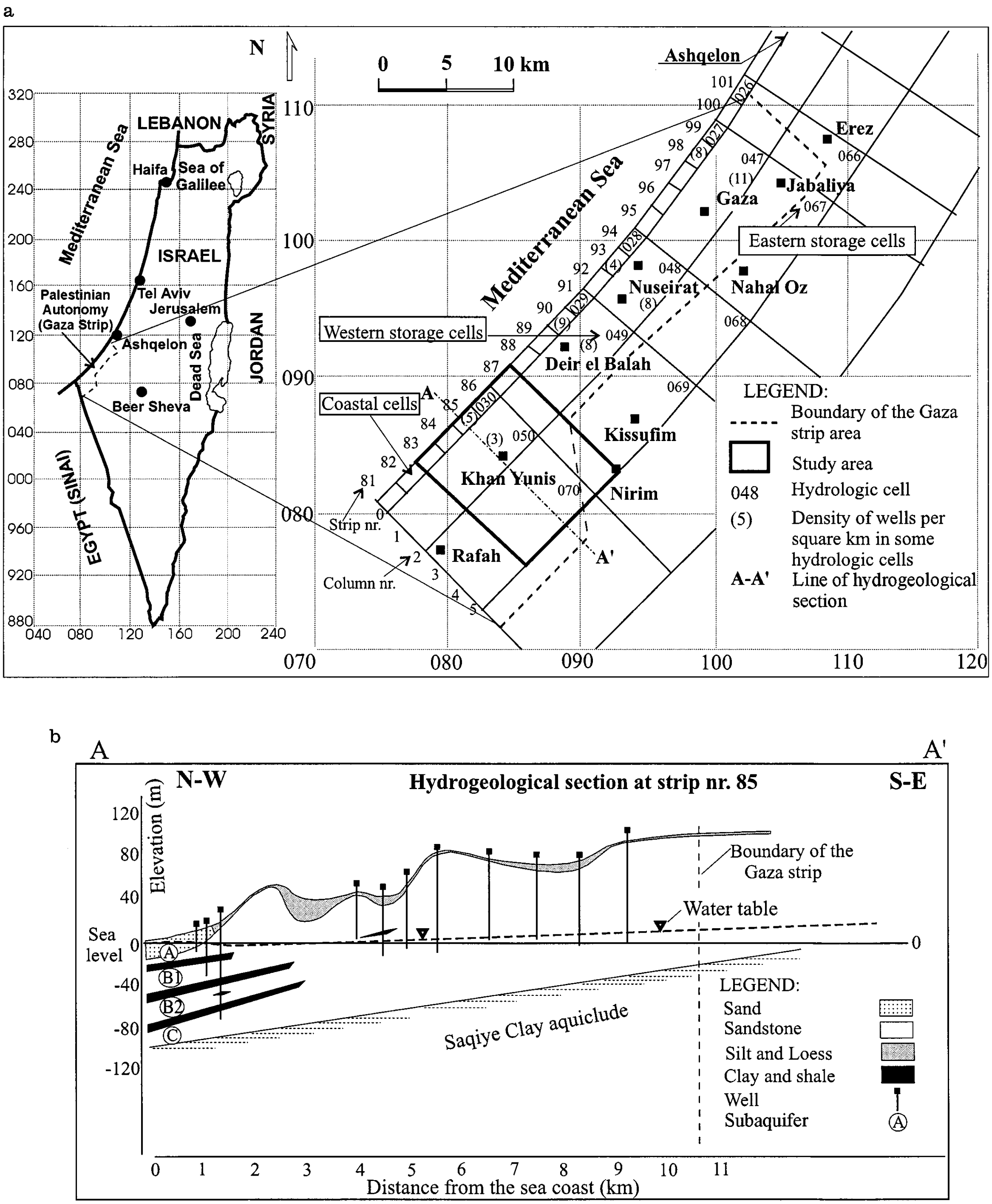

Figure 1 a Location and general map of the Gaza Strip showing study area and **b** section A–A'

the northern portion. In the western side of the area, between Rafah and Khan Yunis, the presence of sand dunes with high sand permeability results in high recharge of the aquifer. In most of this area, exact data about the depths of the wells are absent. Depth of most of the pumping wells is 5–10 m below the groundwater level. Therefore, the depth of wells was estimated on the basis of topography and mean groundwater-level data.

Up to 5 km inland from the seashore, the exploitation of the aquifer is mainly limited to the upper subaquifers A, B1, and the eastern portion of B2. There, the groundwater is fresh and has a relatively low rate of salinity increase. Exploitation from deeper subaquifers (mainly in the western portion of subaquifer C) is limited because the water samples have a salinity that is greater than that of seawater. It is assumed that in the study area the deepest subaquifer is sealed from the sea by impervious formations (Fink 1970; Melloul and Bachmat 1975).

A relatively recent hydrological assessment of the Gaza Strip aquifer was done by Melloul and Collin

(1994) on the basis of estimates of components of the water balance. Estimated pumping in all the Gaza Strip region during 1970–90 was 70–100 MCM/yr (Million Cubic Meters per year). The recommended pumping, as noted in Melloul and Bachmat (1975), is about 55 MCM/yr. Thus, an over-pumping of 15–45 MCM/yr is occurring. This overdraft resulted in a decline of groundwater levels in the Gaza Strip, as shown in the hydrographs of *Figure 2.* This figure depicts the average water-table levels between 1970 and 1993, based on representative wells located along the sea coast, in the western and eastern portions of the aquifer. A general decline in groundwater levels occurred up to 1986, moderate decline occurred between 1986 and 1990, and an increase of 0.5–1.0 m occurred after the rainy season of 1991/92, when the amount of rainfall exceeded the average (about 260 mm in the study area) by 200%. After these years, it is assumed that the hydrological overdraft was significantly smaller than during the preceding years. The reasons for this assumption are: (1) the increase of natural recharge due to heavy rainfall during 1991/92; (2) evaporation was reduced due to new methods of irrigation (changes from furrow irrigation to drip and sprinkler irrigation); (3) due to the increase of groundwater salinity, some wells were shut off and thus the pumping rate was reduced; and (4) management decisions encouraged the use of groundwater for drinking purposes at the expense of irrigation. However, when considering the growth of population and the development that has characterized this area during recent years, the pumping rate may actually have increased. Near the sea, where relatively low groundwater levels already exist, this increase would cause the continuation of the intrusion of seawater and brines that are known to exist in the lower subaquifer (Melloul and Collin 1994).

Additional sources of groundwater salinity in this area are: (1) the flux of saline water coming from the Eocene aquifer in the east; and (2) pollution sources on the ground surface, such as effluent irrigation, domestic land-use effluents, solid waste, etc. (Juanico et al. 1992). As a result, the quality of drinking water in the Gaza Strip has deteriorated significantly. This deterioration is expressed by changes in chloride levels between 1970 and 1993. The aquifer-wide salinity increase is about 6 mg/kg yr^{-1} in inland regions of the Gaza Strip, resulting mostly from anthropogenic activity. For example, in some parts of the Nuseirat and Deir el Balah regions (*Figure 1a*), the groundwater has high chloride concentrations (greater than 0.6 g/kg), and therefore is not recommended for normal agricultural irrigation purposes. Relatively fresh water (with Cl less than 0.25 g/kg) occurs in the northwestern and in western portions of the study area, and in its southwestern portion along the seashore.

Some portions of the Gaza Strip aquifer have shown sharp increases in chloride concentration that are probably due to seawater intrusion or brines (Fink 1986; Melloul and Bibas 1992). High salinity already occurs in areas where groundwater chlorographs indicate Cl concentrations greater than 1 g/kg, with a rate of increase that is more than 20 mg/kg yr^{-1} (Melloul and Azmon 1997). *Figure 3* demonstrates the observed changes of Cl concentration in groundwater from two wells in the study area at distances of 300 and 325 m from the sea. These chlorographs display a low concentration of Cl until 1980, indicating no effects of seawater intrusion. From that year onward, the Cl concentration increased at a much greater rate. Only a massive and continuous salinity flux, such as seawater or brines, could account for such increases of groundwater salinity (Melloul and Azmon 1997). Observations at a few observation wells (most of them now destroyed), indicated that the extent of seawater intrusion varies among subaquifers (Fink 1970). In hydrological strips 81 to 85 (*Figure 1a*), seawater intrusion into the upper subaquifers (A, B1, and B2) is estimated to occur

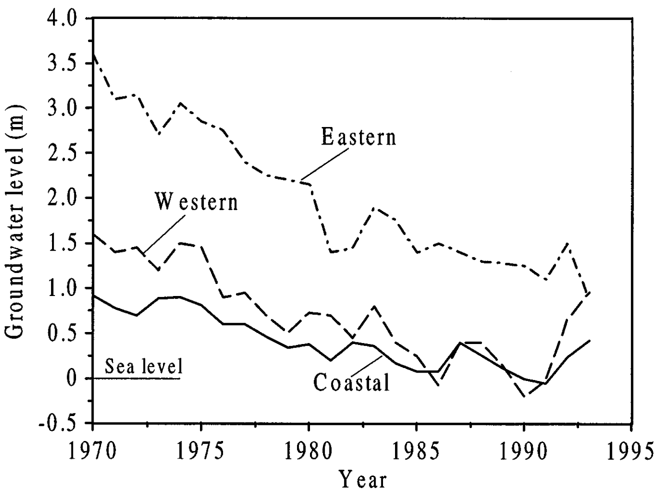

Figure 2 Average groundwater levels in storage cells, 1970–93

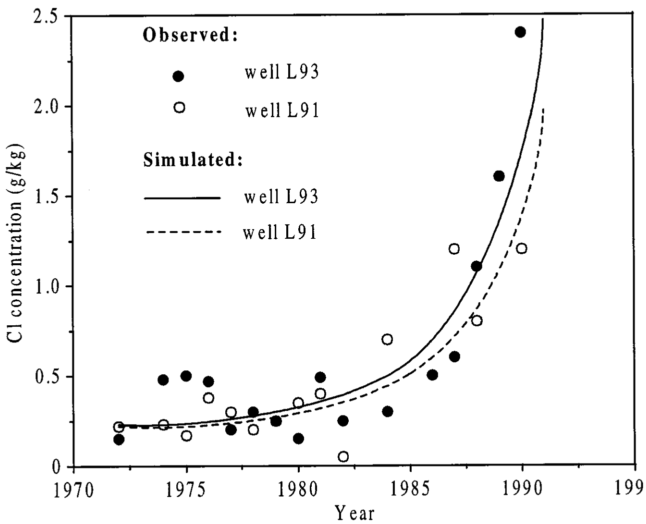

Figure 3 Observed and simulated Cl concentrations in two wells: well L91, 325 m from the sea coast, 10 m below the sea level; well L93, 300 m from the sea coast, 10 m below the sea level

500–1000 m inland from the sea coast (Melloul and Bibas 1992). In this area, relatively fresh groundwater still occurs in the upper subaquifers, whereas in the deepest subaquifer at about 1000 m from the sea coast, groundwater salinity is 40–60 g/kg TDS (a concentration greater than that of the seawater). The high salinity may indicate lenses of brine trapped at the bottom of the subaquifer C. Lowering the water pressure in the upper subaquifers by pumping could induce their salinization by leakage of saline water from the deepest subaquifer. The general pattern to be expected upon the onset of groundwater deterioration by intrusion of seawater and brines is influenced by aquifer characteristics and anthropogenic factors. Thus, to aid in any further operational activity, the use of a mathematical model is valuable in helping to understand and predict the dynamics of solute migration.

Methodology

Data Collection

Data were collected under the guidance of the Israel Hydrological Service (IHS) during 1970–90. Some data are from more recent monitoring. Water samples were taken from the aquifer at locations less than 1500 m from the sea coast. The data also include a period of time preceding the onset of significant anthropogenic degradation of the environment that has occurred in recent years. The relevant field measurements were taken between the coast and the salt-water/fresh-water interface using a network of observation wells that monitored electrical resistivity and water-table levels. These existed only for the year 1970. During other years, chemical data were obtained only from pumping wells. Water levels and chloride-concentration data were routinely incorporated into the coastal aquifer database of the IHS (Hydrological Service Situation Report 1994). In this study, the Cl ion was chosen as a tracer to characterize the processes of groundwater salinization. This choice is based on the fact that Cl concentrations may be determined accurately at low concentrations and that Cl does not react with the aquifer matrix material (White 1977; Konikow and Rodriguez 1993).

Mathematical Model

The SUTRA computer code (Voss 1984) was used for simulations of seawater intrusion into the coastal aquifer of the Khan Yunis region. The mathematical model is based on two-dimensional vertical cross-section equations of fluid density-dependent flow and a single-solute transport in the unsaturated and saturated zones (Voss 1984; Souza and Voss 1987). The two primary variables are fluid pressure (p) and solute concentration (c), expressed as a mass fraction. The porous medium above the groundwater level is partially filled with water and a negative pressure is defined in that zone. To introduce the soil-water retention curve and the unsaturated hydraulic conductivity, the following relations were used (Van Genuchten 1980), respectively

$$S_e = [1 + (-\alpha\psi)^n]^m \tag{1}$$

$$K = K_s S_e^{0.5}[1 - (1 - S_e^{1/m})^m]^2 \tag{2}$$

where $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$, θ_r is irreducible water content, θ_s is the water content at saturation, $\psi(\equiv p/\rho g)$ is the matric pressure head, ρ is fluid density, g is the gravity acceleration, K_s is the saturated hydraulic conductivity of the soil, α and n are Van Genuchten model parameters, and $m = 1 - 1/n$.

The coupled water-flow and solute-transport equations are solved simultaneously by the finite-element method for a two-dimensional vertical cross section.

Finite-Element Mesh

The present study focuses on the seawater intrusion along hydrologic strip 85 crossing Khan Yunis (*Figure 1a*). A schematized cross section with finite-element mesh and assigned boundary conditions is illustrated in *Figure 4*. The nonuniform finite-element mesh for simulations with SUTRA is composed of 8064 quadrilateral finite elements (8281 nodes; not all of them are shown in *Figure 4*). The left and right boundaries of the simulated region are assigned at the seashore and 11 km inland from it, respectively. The upper boundary is at the land surface, and the lower boundary corresponds to the aquifer bottom. The horizontal size of the mesh changes from 10 to 25 m in the 3-km zone near the sea, increases to 200 m between 3 to 7.5 km, and decreases to 50 m at the distance of 7.5 to 11 km. The vertical size of the grid increases from 0.2 m at the land surface to 4 m at the aquifer bottom.

Parameters

In order to make a reliable prediction with the model, estimates of parameters are needed for each aquifer layer. One approach is to use experimentally based parameter values and history fitting between simulated and observed groundwater levels and solute concentrations. However, this procedure does not guarantee a unique set of model parameters, especially in the case of a highly heterogeneous hydrogeological system like the Gaza Strip coastal aquifer. In such a case, a sensitivity analysis can be performed to estimate the effect of parameters on model prediction and to obtain certain bounds for the latter. The ranges of aquifer parameters used in the simulations are presented in *Table 1*. The values of saturated hydraulic conductivities were estimated from pumping and laboratory tests. The water-content saturation (θ_s) is considered to be equal to the porosity. Parameters θ_r, α, and n for the Van Genuchten's relations (1) and (2) are from Yates et al. (1992).

The estimate of a range for the transport equation parameters, i.e., the longitudinal (a_L) and vertical trans-

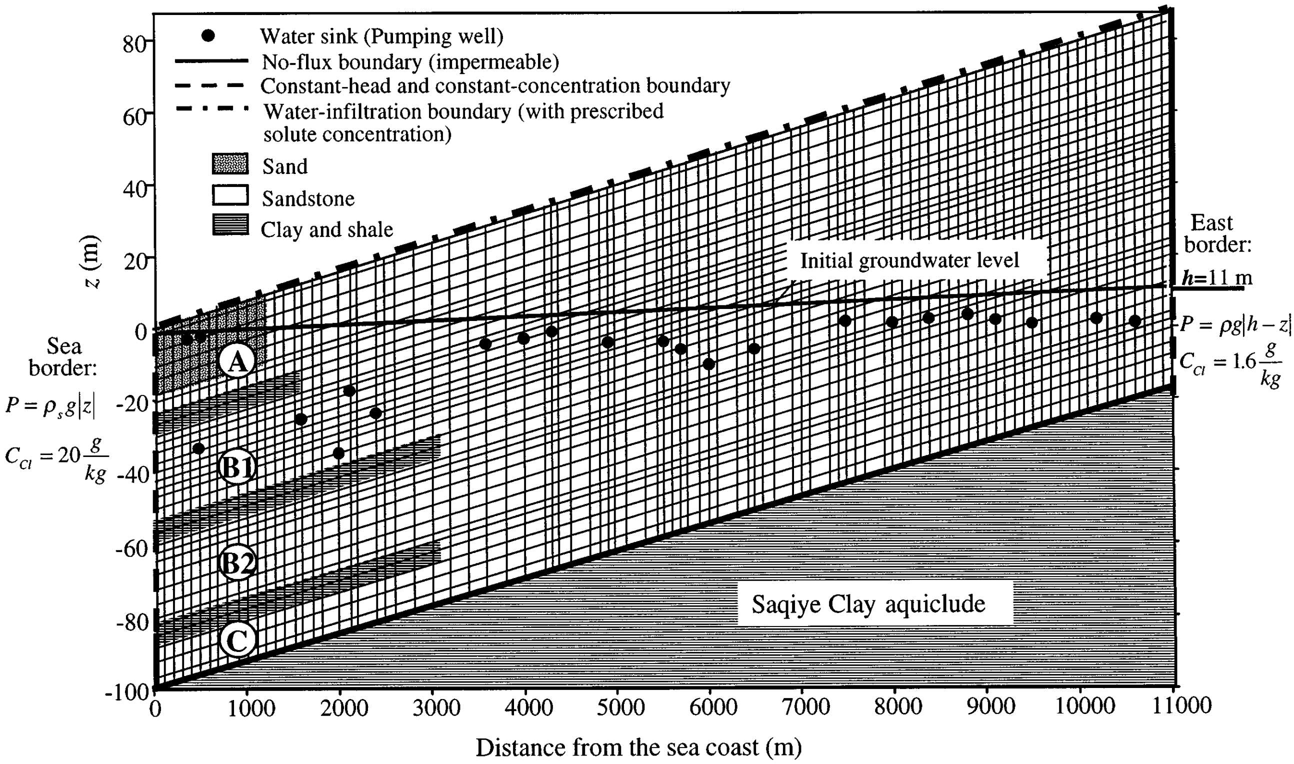

Figure 4 Finite-element grid and boundary conditions for the cross-sectional problem of salt-water intrusion in the Gaza Strip

verse (a_T) dispersivities, are based on published data (Gelhar et al. 1992). At a given scale, the longitudinal dispersivities may be 1–3 orders higher than the vertical transverse dispersivities. In the area of sand dunes of the Gaza Strip, thin lenses of very fresh water (thickness of 50–100 cm) occur very close to the sea on top of the saline water (Melloul and Collin 1994). To simulate such a narrow transition zone, very small dispersivity values are needed (smaller than presented in the *Table 1*). However, the a_L and a_T values should also be associated with the finite-element cell size to decrease the numerical dispersion and spurious oscillations (Voss 1984). Yet, decreasing the cell size and increasing the number of mesh nodes leads to a sharp increase in computer time consumption. Therefore, these narrow lenses of fresh water were not simulated.

Boundary Conditions and Internal Sinks

The boundary conditions for both flow and transport problems are shown in *Figure 4*.

A Neumann-type of no-flux boundary condition was assigned to the bottom of the aquifer (impermeable aquiclude); the part of the left boundary corresponding to the subaquifer C (since it is assumed that this subaquifer is sealed from the sea); and the part of the right boundary above the groundwater level (unsaturated zone).

A Dirichlet-type of boundary condition was assigned to the residual parts of the left (subaquifers A, B1, and B2) and the right (below the groundwater level) boundaries. For the flow problem, a constant pressure was prescribed at these boundaries as $p(z)=\rho_i(z-z_{0i})g$, where ρ_i is the water density (1025 and 1000 kg/m^3 for left and right boundaries, respectively), z is the vertical coordinate, and z_{0i} is its value at the aquifer bottom. For the transport problem, a constant concentration of

Table 1 Aquifer parameters used in the simulations[a]

Parameters	Sand	Sandstone	Clay
Hydraulic conductivity, K_s (m/d)	10–150 (30)	5–75 (15)	0.001–0.05 (0.01)
Water content at saturation, θ_s	0.40	0.35	0.45
Irreducible water content, θ_r	0	0.06	0.1
Parameter in Eq. (1), α (m^{-1})	1.73	0.562	0.156
Parameter in Eqs. (1) and (2), n	7.80	3.27	1.17
Longitudinal dispersivity, a_L (m)	2.5–25 (12.5)	2.5–50 (25)	5–100 (50)
Transverse dispersivity, a_T (m)	0.1–1.2 (0.25)	0.1–2.5 (0.5)	0.2–5 (1.0)

[a] Values in parentheses indicate the best-fitted values of parameters

chloride equal to 20 g/kg and 1.6 g/kg was assigned below the groundwater level at the left and right boundaries, respectively.

A Neumann influx-boundary condition was assigned at the land surface. The averaged water-flux values through the land surface include net infiltration due to rainfall and return flow. Infiltration ranged from 13–156 mm/yr, depending on the distance from the sea coast, as shown in *Figure 5*. The return flow was estimated as 20% of the total pumping in the year 1988/89 (Melloul and Collin 1994) and was kept constant throughout the entire simulation period. The chloride concentration of the infiltrated water was taken as 0.05 g/kg. In this study, the process of salinization due to infiltration of contaminated water from the land surface is ignored, because its effect is small compared to salt-water intrusion near the coast. An estimate of groundwater contamination in the Gaza Strip by anthropogenic chlorides, organic surfactants, and nitrates, which results in flow of surface water through the vadose zone, is given by Zoller et al. (1998).

To simulate the effect of pumping stress on the aquifer throughout strip 85, several internal sinks were assigned (*Figure 4*). The total value of the temporal pumping (P_{mt}) within strip 85 for each year was extrapolated from the actual pumping value (3.77 MCM) in 1988/89, as shown in *Figure 6*. The extrapolation was done under the assumption that the pumping rate increases 3.8% per year, the annual growth of population. Specific sinks were assigned to represent pumping wells. Their flux values account for the accumulation of the actual pumping in their vicinity during 1988/89. Each nodal value of flux was then evaluated as a percentage of the total P_{mt} pumping for that year. This percentage was assumed to be constant throughout the simulation period from 1949–2006. The percentage of pumping as a function of distance from the sea coast is shown in *Figure 7*.

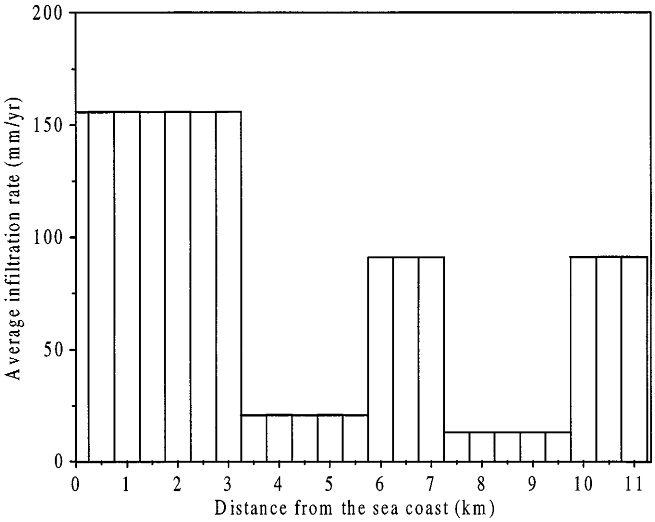

Figure 5 Relation between infiltration rate through the land surface and distance from the sea coast

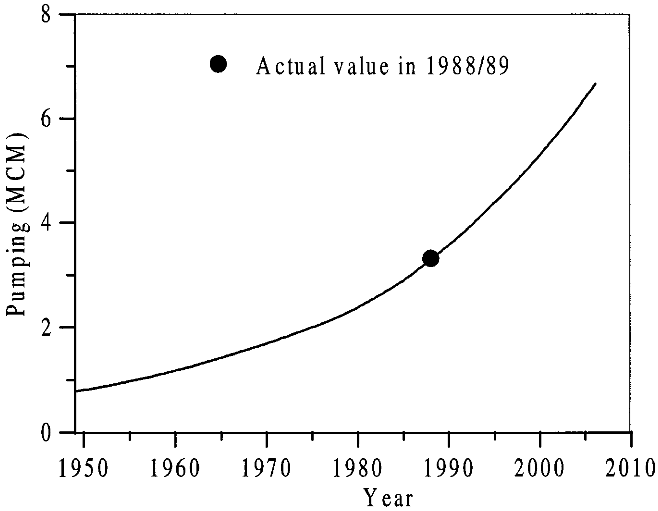

Figure 6 Stipulated pumping values, strip 85

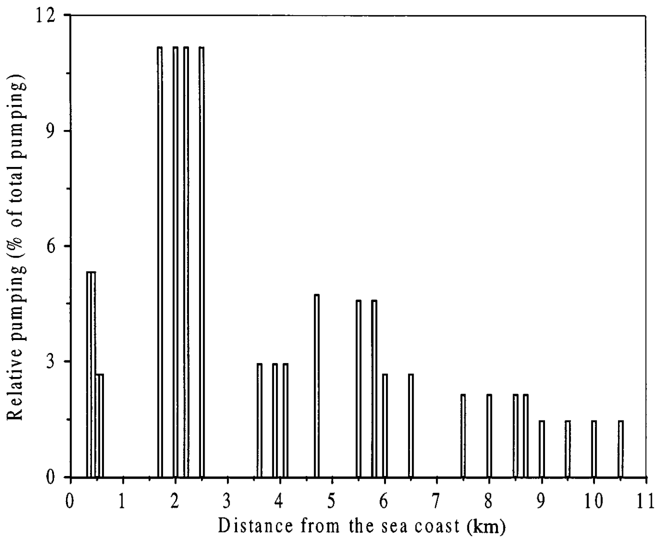

Figure 7 Relation between relative pumping and distance from the sea coast

Initial Conditions

The steady state of the hydrogeological system was identified by long-term transient simulations from arbitrary initial conditions until the system stabilized (Souza and Voss 1987). The initial water level is assumed to change linearly from 0 to 11 m above sea level at the left and the right borders, respectively. The initial chloride concentration was taken as 0.1 g/kg everywhere except in the lower subaquifer C, where it was assigned as 40 g/kg to a distance of 1 km from the sea coast. The initial distribution of the pressure was calculated using this information, according to hydrostatic equilibrium. The computations began with the above-mentioned boundary and initial conditions to simulate a steady-state distribution of heads and concentrations. No pumping was assigned. The simulations were carried out for the periods of 50, 100, and 200 yr. The results at 100 and the 200 yr were similar, i.e., the system stabilized after about 100 yr. Water with a Cl concentration of 10 g/kg (which is half the relative concentration of seawater) penetrated (not shown) to distances of about 25, 35, and 60 m from the sea coast in the subaquifers A, B1, and B2, respectively. Using the obtained results as initial conditions, pumping values equal to the half of the pumping for 1949 (based on the extrapolation shown in *Figure 6*) were prescribed, and another simulation was run to reach a new steady state. Once again, 100 yr was the period required to stabilize the system. The results of the second simulation were then used as the initial conditions for the transient problem of stressing the aquifer by pumping during 1949–2006. The steady-state behavior was sensitive to hydraulic conductivities and had low sensitivity to dispersion parameters.

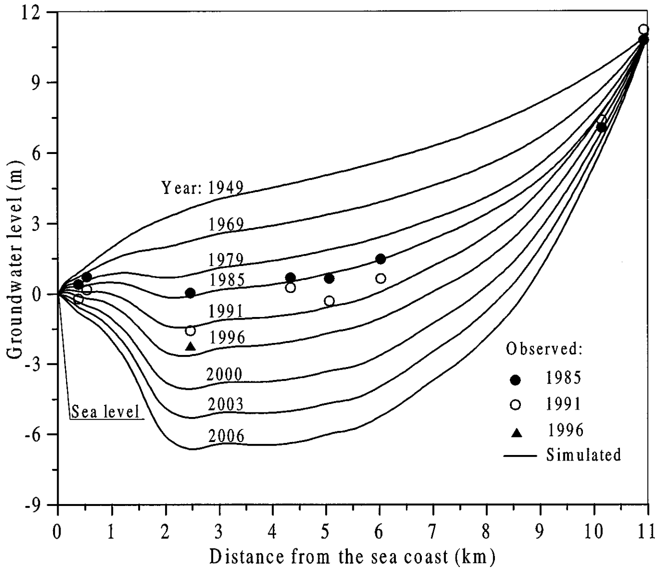

Figure 8 Observed and simulated groundwater levels, strip 85, 1949–2006

Simulation Results and Discussion

Simulations of the transient regime were carried out for a wide range of the aquifer parameters listed in *Table 1*. A sensitivity study was carried out in order to assess the effect of the hydraulic conductivities (K_s) and dispersivities (a_L and a_T) on the simulated groundwater level and on the Cl distribution. The model is more sensitive to the hydraulic conductivities than to the dispersion parameters. Calibration of the model was based on the sensitivity runs; results had to be consistent with the available observations of groundwater levels and chloride concentrations. Estimates of the flow and transport parameters are given in *Table 1* in parentheses. Also checked was the sensitivity of the model to the unsaturated flow parameters θ_r, α, and n, appearing in *Table 1*. Groundwater level and salinity were insensitive to θ_r, α, and n values for sand and sandstone. This is because a boundary-flux condition (with annual average infiltration) was applied at the land surface, which created a low rate water flow in the unsaturated zone. The values of the parameters θ_r, α, and n for clay do not affect simulation results, because the clay layers are totally saturated.

On the basis of the calibrated model and the assumed temporal pumping stress, the transient changes in groundwater levels and of the Cl migration were simulated. *Figure 8* compares the simulated and the observed groundwater levels along strip 85. Consistent agreement was obtained for 1985–96. Based on this, some predictions of the groundwater levels were made until the year 2006 (*Figure 8*). A considerable decline of groundwater levels occurs due to pumping. Water levels at 2.5 km from the sea coast are 2.3 m and 6.6 m below the sea level in 1996 and 2006, respectively. *Figure 3* compares the observed and the simulated Cl concentrations for two wells; good and consistent agreement was obtained.

Figure 9 shows the results of transient prediction for Cl propagation into the part of the aquifer close to the sea, resulting in seawater intrusion as a consequence of the pumping pattern. The extent of seawater intrusion varies in subaquifers A, B1, and B2. Because the subaquifers are separated by clay aquitards with low hydraulic conductivities, *Figure 9* shows the development and propagation of salt-water "fingers," corresponding to the multi-layer configuration, during 1949–2006. Because a no-flux boundary condition was imposed along the bottom and at the sea inlet to subaquifer C, a relatively stable salt-water body occurs, corresponding to the initial brine concentration in this subaquifer.

The graph in *Figure 9* for 1949 demonstrates the results of the second 'steady-state' simulation (with half of the 1949 pumping flux). In subaquifer B2, the isochlor 0.5 g/kg reaches a distance of 1000 m from the sea coast, much farther than in the two upper subaquifers, A and B1. The isochlor 10 g/kg (half of the relative concentration of the seawater) propagates to distances of 40, 50, and 75 m in the subaquifers A, B1, and B2, respectively. Thus, the transition zone between saline and fresh water in subaquifer B2 is much broader than those in subaquifers A and B1. Yet, the prescribed dispersion parameters were the same in all of these subaquifers. Following the previous assumption about the existence of brine sources in subaquifer C (to a distance of 1000 m), the appearance of a long plume with salinity more than 0.5 g/kg in subaquifer B2 is explained by the penetration of salt through the lower aquitard. This process is enhanced by the lowering of pressure resulting from pumping in the upper subaquifers. The plume propagates inland due to seawater intrusion (*Figure 9*).

No seawater intrudes into subaquifer C, because it was assumed that it is sealed at the sea border. A salinity greater than 0.5 g/kg in steady state extends 1430 m from the sea (*Figure 9*, year 1949). This remains practi-

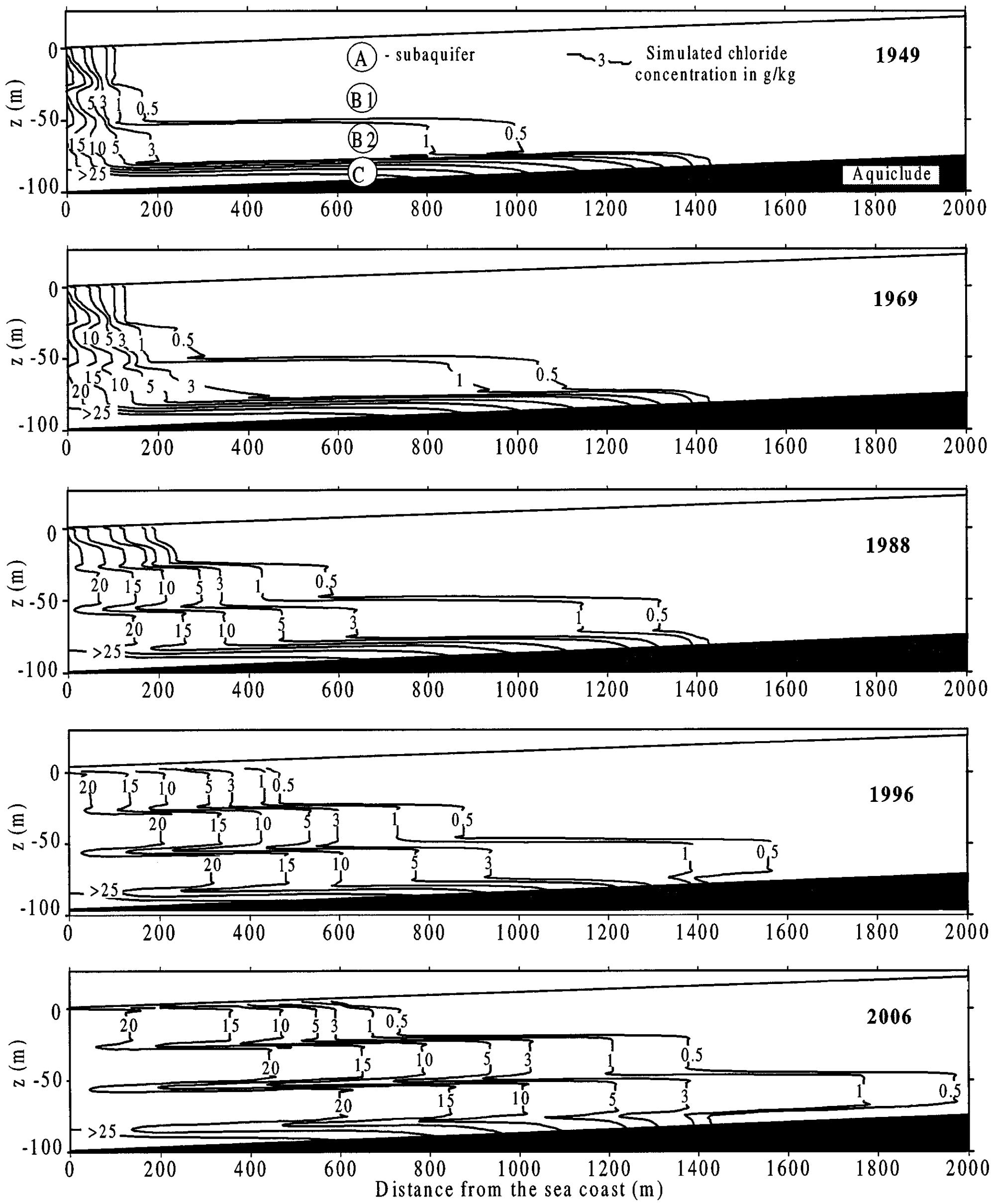

Figure 9 Simulated Cl concentration for strip 85, 1949–2006

cally constant during transient simulations. Hence transport in this subaquifer is probably controlled mainly by diffusion.

Figure 10 demonstrates the propagation with time of different isochlors in subaquifers A, B1, and B2. The results of the simulations indicate that the expected extent of intrusion of water with Cl salinity greater than 1 g/L is as given in *Table 2*. The rate of seawater intrusion during next decade is expected to be 20–25 m in subaquifer A, 40–45 m in subaquifer B1, and 35–40 m in subaquifer B2. These values are consistent with those estimated for the northern part of the Israeli coastal aquifer, which is also stressed by high pumping rates (Melloul and Goldenberg 1997).

In addition, seawater intrusion was simulated for a pumping scenario, following the same rate as in 1997, until 2006. The results indicate that seawater intrusion in 2006 for this scenario would be less (compared to the previous simulations) by 50, 65, and 75 m in subaquifers A, B1, and B2, respectively.

Table 2 Expected extent of intrusion of water with Cl salinity greater than 1 g/L, as indicated by the simulations

Subaquifer	Distance, m	
	1997	2006
A	450	650
B1	750	1200
B2	1350	1750

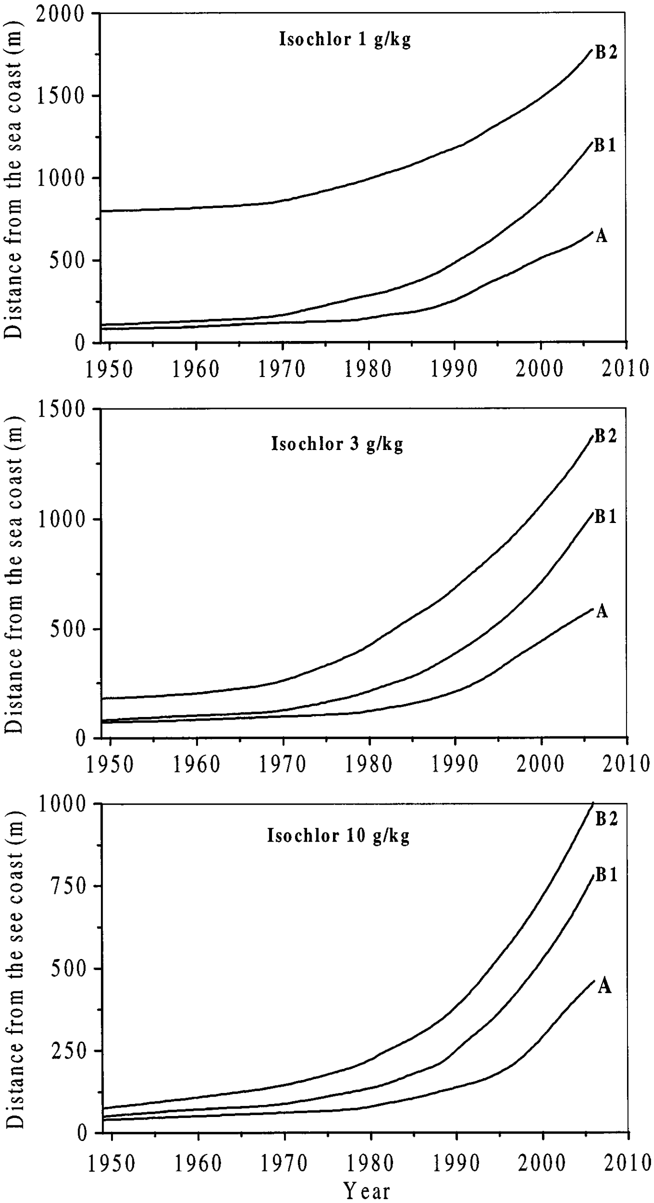

Figure 10 Relation between distance from the sea coast and time, for isochlors of 1, 3, and 10 g/kg in subaquifers A, B1, and B2

Conclusions

This study focuses on seawater intrusion in the Khan Yunis section of the Gaza Strip coastal aquifer. Numerical simulations were carried out with the SUTRA code (Voss 1984), which is based on a 2-D cross-sectional density-dependent flow and transport model. Transient simulations were performed along a typical section of a multi-layered groundwater system that is subject to high pumping stresses. The results show significant declines of groundwater levels (to as much as 2.3 m and 6.6 m below sea level in 1996 and 2006, respectively) due to pumping. This process enhances seawater intrusion and deterioration of water quality in the aquifer.

Numerical simulations under the assumption of an annual increase of pumping rate of 3.8% indicate that in 1997, the expected extent of water with Cl salinity greater than 1 g/kg is as much as 450, 750, and 1350 m in subaquifers A, B1, and B2, respectively. The expected rate of seawater intrusion during 1997–2006 is 20–45 m/yr.

It had been assumed that at the deepest subaquifer C, water of very high salinity is trapped under a clay layer with low permeability. However, simulations indicate that seawater intrusion overrides the salinization processes of the upper subaquifers by brine from the deepest subaquifer. An increase in the pumping rate may lead to a decrease of hydraulic heads in the two upper subaquifers. As a result, the exchange by water and salts with the lower subaquifer could be more intensive at present.

Acknowledgment This research was supported under Grant No HNE-0158-G-00-4060-00, The Middle East Regional Cooperation Program, Office of the Science Advisor, US Agency for International Development, and the AVICENNE program, Grant No CT93AVI2073 of the European Community.

References

Chetboun G, Melloul A (1973) Forecast of salinity and water levels in the Coastal Plain aquifer of the Gaza Strip. Hydrological Service Hydro-report, Jerusalem (in Hebrew)

El-Baruni SS (1995) Deterioration of quality of groundwater from Suani Wellfield, Tripoli, Libya 1976–93. Hydrogeol J 3:58–64

Fayers FJ, Hewett TA (1994) A review of current trends in petroleum reservoir description and assessment of the impacts on oil recovery. Adv Water Resour 15:341–365

Fink M (1970) The hydrogeology of the Gaza Strip. TAHAL report 3, Tel-Aviv (in Hebrew)

Fink M (1986) Hydrogeological survey of the Pleistocene aquifer of the Gaza Strip: salinity trend analysis. TAHAL report, Tel Aviv

Ford M, Tellman JH, Hughes M (1992) Pollution-related acidification in the urban aquifer Birmingham, UK. J Hydrol 140:297–312

Gelhar LW, Claire W, Rehfeldt KR (1992) A critical review of data on field-scale dispersion in aquifers. Water Resour Res 28:1955–1974

Goldenberg LC, Mandel S, Magaritz M (1986) Fluctuating nonhomogeneous changes of hydraulic conductivity in porous media. Q. J. Eng. Geol 19:183–190

Goldenberg LC, Hutcheon I, Waldlaw N, Melloul A (1993) Rearrangement of fine particles in porous media causing reduction of permeability and formation of preferred pathways of flow: experimental findings and a conceptual model. Transport in Porous Media 13:221–237

Heatwole CD, Zacharias S, Mostaghimi S, Dillaha TA, Young RW (1992) Fate and transport of pesticides in a Virginia Coastal Plain soil. Virginia Water Resour Center Bull 175:1–21

Hrkal Z (1992) Les nitrates dans les eaux souterraines de la boheme du nord. Hydrogeologie 3:137–143

Hydrological Service Situation Report (1994) Development of groundwater resources in Israel up to Autumn 1993. Report 93-1093 (in Hebrew)

Juanico M, Amiel A, El-Wahidi A, Ronen D (1992) Survey of sewage pollution and resultant influence upon groundwater in the Gaza Strip. Technion Research and Development Foundation, Ltd, and Water Commission, Haifa (in Hebrew)

Konikow LF, Rodriguez AJ (1993) Advection and diffusion in a variable-salinity confining layer. Water Resour Res 29:2747–2761

Melloul A, Azmon B (1997) Graphic expression of salinization and pollution of groundwater: The case of Israel's groundwater. Environ Geol 30:126–136

Melloul A, Bachmat Y (1975) Assessment of the hydrological situation in the Gaza Strip as a basis for the management of the Coastal Plain aquifer in that region. Hydrological Service Report no. 3, Jerusalem (in Hebrew)

Melloul A, Bibas M (1992) Description of the hydrological situation in Gaza Strip between the years 1985 and 1990, Hydrological Service Report no. 92/7, Jerusalem (in Hebrew)

Melloul AJ, Collin M (1994) The hydrological malaise of the Gaza strip. Israel J Earth Sci 4:105–116

Melloul AJ, Goldenberg AC (1997) Monitoring of seawater intrusion in coastal aquifers: Basics and local concerns. J Environ Management 51:73–86

Souza WR, Voss CI (1987) Analysis of an anisotropic coastal aquifer system using variable-density flow and solute transport simulation, J Hydrol 92:17–41

US EPA (1990) Progress in groundwater protection and restoration. Report no. 440/6-90-001

Van Genuchten MTh (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soil. Soil Sci Soc Am J 44:892–898

Voss CI (1984) A finite element simulation model for saturated-unsaturated, fluid-density-dependent groundwater flow with energy transport or chemically-reactive single species solute transport. Water Resources Investigation Report 84-4369, US Geological Survey

White KE (1977) Tracer methods for the determination of groundwater residence-time distributions. In: Groundwater quality-measurement, prediction and protection. Water Research Center, Medmenham, England, pp 246–273

Yates SR, Van Genuchten MTh, Leij FJ (1992) Analysis of predicted hydraulic conductivities using RECT. In: Van Genuchten MTh, Leij FJ, Lund LD (eds) Proc Int Workshop, Riverside, California, October 11–13, 1989, pp 273–283

Zoller U, Goldenberg LC, Melloul AJ (1998) The "short-cut" enhanced contamination of the Gaza Strip coastal aquifer. Water Resour 32:1779–1788

