THREE DIMENSIONAL NUMERICAL MODELS OF SEAWATER INTRUSION IN THE GAZA AQUIFER, PALESTINE

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Abstract

The Gaza coastal aquifer is historically the only natural source of water supply in the Gaza Strip. Water is presently accessed through pumping of more than 3000 wells, with a total estimated annual production in 1999 of about 140 million cubic meters (Mm^3). Current rates of aquifer abstraction are unsustainable, and deterioration of groundwater quality is documented in many parts of the Gaza Strip due to seawater intrusion. The SEAWAT computer code was used for simulating the spatial and temporal evolution of the hydraulic heads and solute concentration in groundwater. A regular finite difference grid with 400 m square-cells in the horizontal plane, in addition to a 12-layer model was chosen. The extent of the saltwater intrusion toe was simulated for more than 3000, 2000, 2500 m in the lower sub-aquifer in the northern, the middle, and the southern parts of the Gaza strip in the year 2003, respectively. Two management scenarios were presented to predict the extent of seawater intrusion in the aquifer and also the water level. The first scenario is the worst, which assumes that pumping from the aquifer will reach 200 Mm^3 by the year 2020, and the second scenario assumes that the abstraction will be decreased to keep a considerable discharge to the sea in the order of 11 Mm^3/yr. The result of the simulation shows that the second scenario can improve the aquifer situation and recover groundwater levels in the aquifer.

Keywords: Seawater intrusion; upconing; groundwater flow; transport; modeling.

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 delicate issue, and a careful management is required if water quality degradation due to encroachment of seawater is to be avoided. In many cases,

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difficulties arise when aquifers are pumped beyond their natural rate of replenishment and seawater is drawn into the system to maintain the regional groundwater balance. Problems can also occur when excessive pumping at individual wells lowers the potentiometric surface on a localized scale and causes upconing of the natural interface between freshwater and saline water.

In the last twenty years, many models have been developed to represent and study the problem of seawater intrusion. They range from relatively simple analytical solutions to complex numerical models. This paper presents a case study conducted on the Gaza Strip aquifer, in which the numerical model, SEAWAT (Guo and Bennett, 1998) was used for the simulation of seawater intrusion using the 3-D finite difference discretization. The main objective of the paper is to estimate the extent of solute migration in depth and time in the Gaza aquifer, to clarify when and where most of the seawater intrusion occurred, and to predict its future behavior along the Gaza Strip in response to the proposed management scenarios.

Description of the Gaza aquifer

Geographical setting

Geographically, the Gaza Strip is part of the Palestinian coastal plain in the south west of Palestine, where it forms a long and narrow rectangle. Its area is about 365 km^2 and its length is approximately 45 km. The location of the Gaza Strip is shown in Figure 1. 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. The Palestinian Bureau of Statistics estimates that the population of Gaza Strip was about 1,025 million in 1997 (PCBS, 1998).

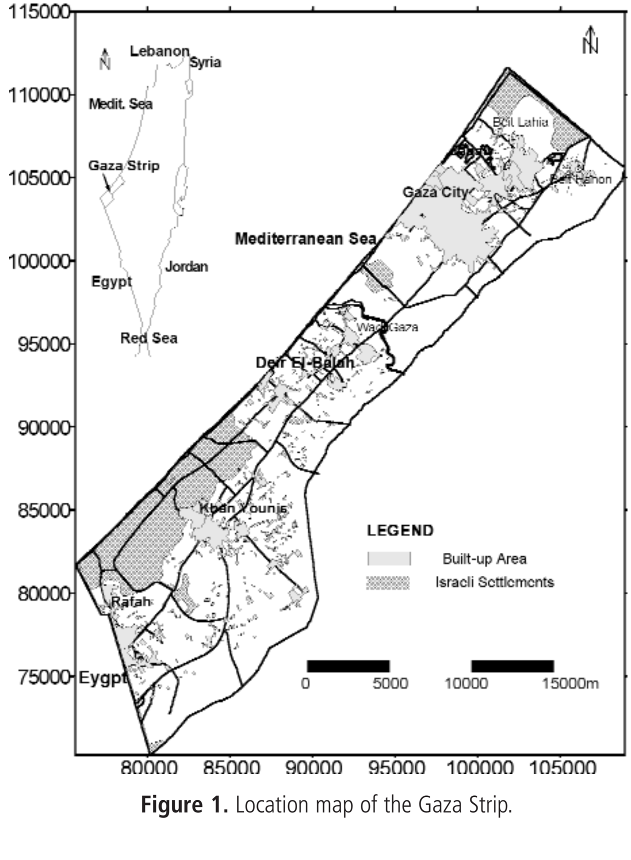

Figure 1. Location map of the Gaza Strip.

The average daily mean temperature ranges from 25 °C in summer to 13°C in winter. Average daily maximum temperatures range from 29°C to 17°C and minimum temperatures from 21 °C 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 amounts to 2200 J/cm^2/day (EPD/IWACO-EUROCONSULT, 1994). The average annual rainfall varies from 450 mm/yr in the north to 200 mm/yr 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 aerial 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 1300 mm/yr. 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 December to January.

The Gaza aquifer system

The Gaza Strip is essentially a foreshore plain gradually sloping westwards and underlie by a series of geological formations from the Mesozoic to the Quaternary. The hydrogeology of the coastal aquifer consists of one sedimentary basin, the post-Eocene marine clay (Saqiya), which forms the bottom of the aquifer. Pleistocene sedimentary deposits of alluvial sands, graded gravels, 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 sub-aquifers (A, B, C). These sub-aquifers overlay each other and are separated by semi-pervious clayey layers. Schematization of hydrogeological cross section of the Gaza Strip aquifer is shown in Figure 2. It is implied that sub-aquifer A is phreatic, whereas sub-aquifers B and C become increasingly confined towards the sea.

The regional groundwater flow is mainly westward towards the Mediterranean Sea. Most of the recharge is from dune areas near the west coast. 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 low land area along the shoreline and about 70 m below topography along the eastern border.

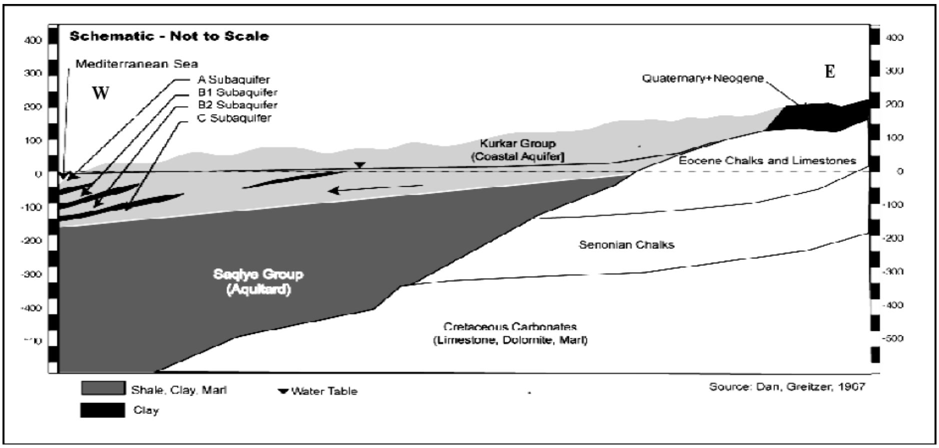

Figure 2. Schematization of a hydrogeological cross-section of the Gaza Strip aquifer (source: PWA/USAID, 2000).

The major source of renewable groundwater in the aquifer is rainfall. The total rainfall recharge to the aquifer is estimated to be approximately 45 Mm^3/yr. The remaining rainwater evaporates or dissipates as run-off during the short periods of heavy rainstorms. The lateral inflow to the aquifer is estimated between 10 and 15 Mm^3/yr. 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 to, at its best, 2 Mm^3 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 Mm^3/yr.

The coastal aquifer holds approximately 5000 Mm^3 of groundwater of different quality. However, only 1400 Mm^3 groundwater is considered freshwater, with a chloride content of less than 500 mg/L. This fresh groundwater typically occurs in the form of lenses that float on the top of the brackish and/or saline ground water. This means that approximately 70 % of the aquifer is brackish or saline water and only 30% is freshwater.

Simulation of seawater intrusion in the Gaza aquifer

Model development

The regional scale model simulates transient groundwater flow for a period from 1935 to 2003. The model was developed using the conceptual typical hydrologeologic model shown in Figure 2.

Simulation code

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 ground water flow equation and MT3D (Zheng and Wang, 1998) to solve the solute-transport equation. SEAWAT code uses a one-step lag between solutions of flow and transport. This means that MT3D runs for a time step, and then MODFLOW runs for the same time step using the last concentrations from MT3D to calculate the density terms in the flow equation. For the next time step, velocities from the current MODFLOW solution are used by MT3D to solve the transport equation. For most simulations, the one-step lag does not introduce significant error, and the error can be reduced or evaluated by decreasing the length of the time step.

Spatial and temporal discretization

A regularly spaced, finite-difference model grid was constructed and rotated so that the *y*-axis would roughly parallel the coast (Figure 3). Each cell is 400 m x 400 m in the horizontal plane. The grid consists of 115 rows and 35 columns, and the rotation angle from true north is clockwise 40 degrees. The purpose for rotating the grid is to align model rows with the principal direction of groundwater flow, which is primarily toward the sea under natural conditions. When groundwater flow is not parallel to one of the primary model axes, some numerical schemes can experience accuracy problems in the solution of the transport equation. Another reason for rotating the model grid is that future modifications of the model may require a higher level of discretization in the coastal area. A rotated model grid allows the resolution along a flow line to be increased by dividing columns near the coast (Langevin, 2003).

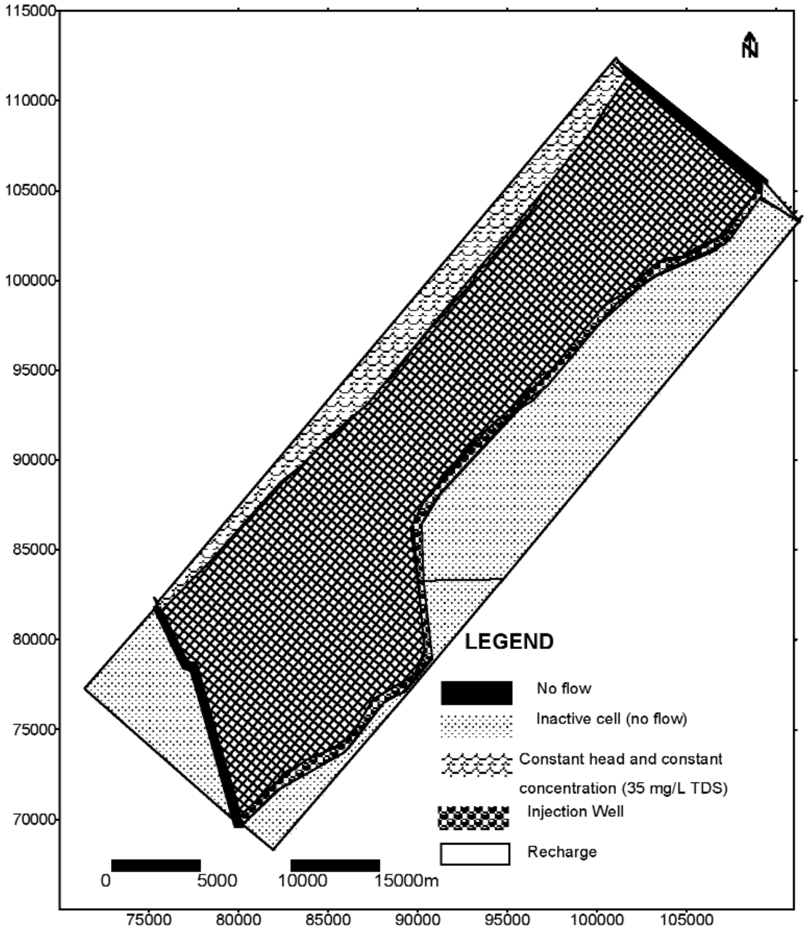

Figure 3. Finite-difference grid and boundary conditions for the Gaza regional model.

Accurate simulation of variable density flow systems requires a finer vertical resolution compared to that required for simulating constant density flow systems. This increased resolution is necessary because of transport considerations and because vertical density gradients must be resolved in order to calculate accurate flow velocities. Accordingly, the model grid, which represents the Gaza aquifer, consists of 12 layers. The top elevation of layer 1 is spatially variable and corresponds with land surface elevation, based on a compiled topographic contour map. The bottom of layer 1 is set at an elevation of 5.0 m below sea level. The nearly 70-year simulation period is divided into 9 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 flow time steps was in the range of 10-30 days and the transport time step was assigned to start with 1 day and increased by a multiplier factor of 1.2.

Assignment of 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 for tests carried out in the Gaza Strip show that values were from 20-80 m/d.

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

The estimate range for the transport equation parameters, i.e., the longitudinal and vertical transverse dispersivities, are obtained from published data from literature studies related to the Gaza aquifer (EC, 2000; Bear et al., 2001). Bear et al. (2001) choose the values of 10 m and 1 m for longitudinal and transversal dispersivities respectively.

Accordingly, the approach for assigning aquifer parameters that pertain to groundwater flow and solute transport was to use the simplest distribution that would result in the 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 specified concentration was applied to the model cells along the coast. The specified constant concentration of salinity is 35 kg/m^3. The head for each cell was converted to freshwater head using the specified salt concentration of 35 kg/m^3 and the center elevation of the cell. A reference density of 1025 kg/m^3 was used 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.

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. The rate of injection was calculated from the available water levels contour maps. 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. A Neumann-influx boundary condition was assigned at the land surface, and the recharge package was used to represent the recharge of the aquifer. The northern and the southern boundaries are assumed to be no-flow boundaries, since the flow lines are parallel to them.

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, 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 an infiltration coefficient. The infiltration coefficient was estimated according to the soil type, the land use and the 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.

Municipal and agricultural well fields

More than 3000 pumping wells were inventoried and represented in the model domain. The applied groundwater abstraction from the model domain is summarized in Table 1. The estimation was done according to the available data of population, population growth, number of wells, and groundwater abstraction in the period between the years 1987 to 1993.

Table 1. Estimated ground water abstraction from the Gaza aquifer.

Abstraction period	Period	Abstraction (Mm^3/yr)
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

Initial conditions

The initial water level for the transient model was specified from the calibrated results of a steady state flow model for year 1935. The initial concentration in the aquifer was assumed to be 0 kg/m^3, since the initial concentration is not known. The steady state of the hydrological system was identified by long-term transient simulations from arbitrary conditions until the system stabilized (Souza and Voss, 1987). The calculation began with the above-mentioned initial conditions and no pumping quantities were assigned.

The simulation was carried out for 10 years. Using the obtained results as initial conditions, low pumping was prescribed, and another simulation was run to reach a new steady state. The results of the second run were used as initial conditions for transient simulation of stressing aquifer by pumping during 1935-2003.

Calibration and model results

The numerical model was calibrated and tested against both steady state and transient head data. Two sets of target conditions were selected for calibration purposes, steady state conditions in the year 1935 and time-varying conditions between the years 1935 and 1969. Verification of the model was done based on the average water level of the year 2002.

During calibration, the measured and model-computed heads (water levels) are compared, and the difference is referred to as the residual. Figure 4a shows the calibrated, simulated flow field in the Gaza Strip for the conditions in 1935, and the spatial distribution of residuals. Average water levels for 50 wells in the year 1935 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 m 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 m to 1.25 m.

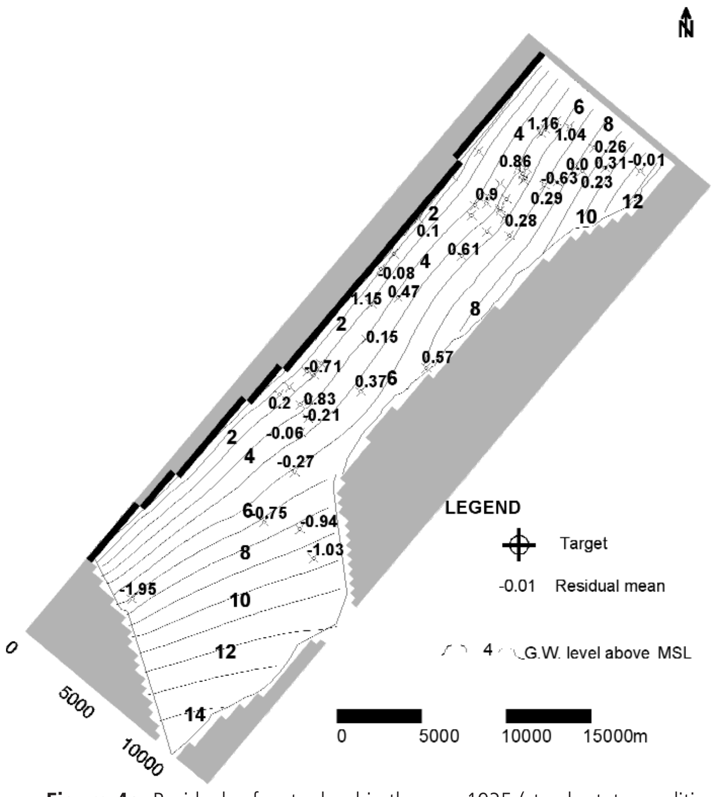

Figure 4a. Residuals of water level in the year 1935 (steady state conditions).

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

The 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, the adjustment was made by changing the values of the storage coefficients. The verification of the model was done using groundwater level data of the year 2002. The results of calibration and verification are presented in Table 2. For the year 1969, the calculated residual mean error and the absolute mean error are about -0.15 m and 0.82 m, respectively, with a standard deviation for the model domain, of 0.98 m. For the year 2002, the calculated residual mean error and the absolute mean error are about -0.01 m and 0.82 m, respectively, with a standard deviation for the model domain of 1.09 m. The simulated water level for the year 2002, after calibration, is shown in Figure 4b. The results of the transient calibration and verification are considered as acceptable for the purpose of this study.

As a preliminary check of the model results, comparison is made with the results of a geophysical survey carried out in the southern sector of the Gaza Strip, which was conducted by the Italian co-operation (CISS/WRC 1997).

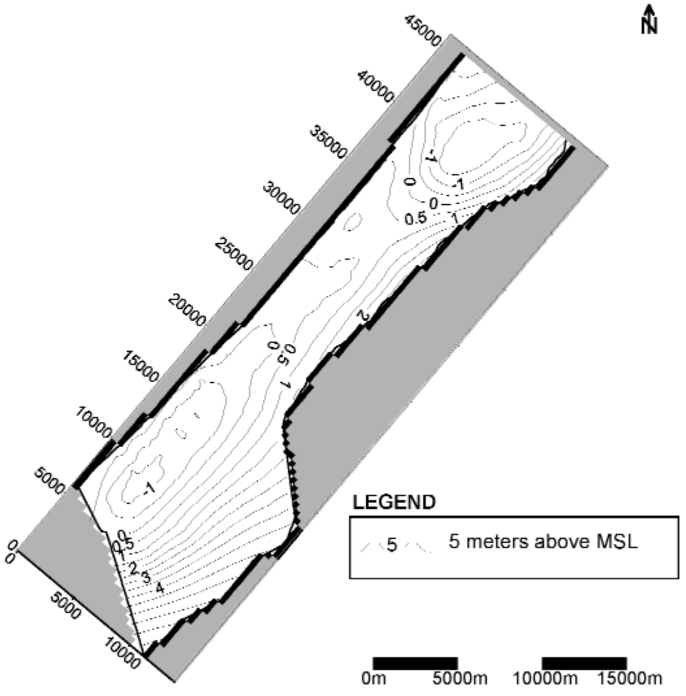

Figure 4b. Simulated water level in the year 2002 after calibration and verification.

Table 2. Statistical results of the calibration and verification 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

The geoelectrical section executed in the Deir El Balah area (Figure 5a) which is composed of ten vertical electrical sounding (VES) and extends from the borderline to the sea in a SE-NW direction. From VES number 64 to number 66 the interpretative model is composed by a more conductive top layer (3 Ohm·m) over a much less resistive middle layer (10 Ohm·m) overlapping the high conductive bottom layer (0.1–10 hm·m). It was concluded that, the general relative lowering of the resistivity is due to seawater intrusion inside the aquifer formation upper conductive (clay) and resistive (sandstone and pebble) layers. The results of the geophysical survey indicate that the extent of seawater intrusion along the Deir El Balah profile in the sub-aquifer A may reach 1000 m, which agrees, in general, with the simulation results as illustrated in Figure 5b.

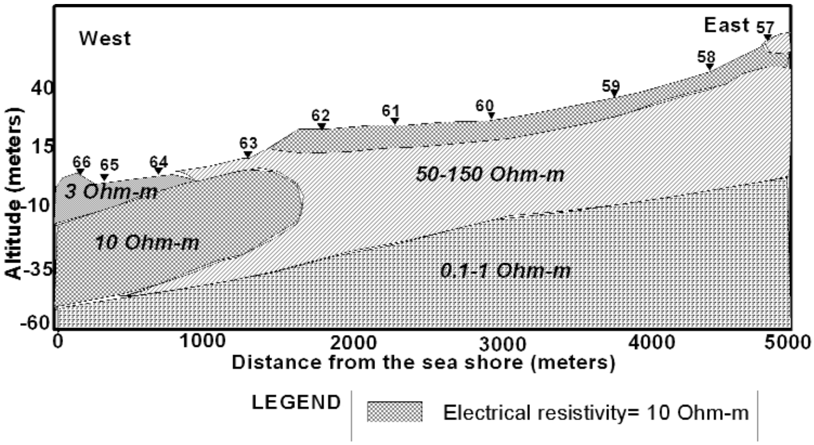

Figure 5a. Deir El Balah geoelectrical section.

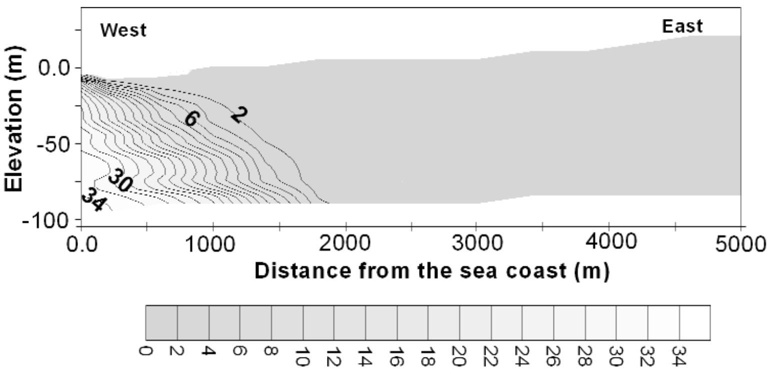

Figure 5b. Isolines of calculated TDS concentration (kg/m^3) by SEAWAT in the year 1996 along the Deir El Balah geoelectrical cross-section.

In addition to the above, the model results for the year 2000 were compared with the geophysical survey results obtained from PWA/USAID (2000). In particular, the results of the time-domain electromagnetic method (TDEM) survey were used. The results of this comparison show that the simulated extent of the seawater wedge in the year 2000 gave a reasonable agreement with the TDEM measurements at two cross-section locations near the coast in Rafah and Deir El Balah also. Most values of the TDEM records within the intruded area identified by the simulation model have values lower than 2.0 ohm·m of apparent resistivity, which is considered an indication of seawater intrusion in coastal areas.

A summary of the aquifer hydraulic and transport properties that better describe the aquifer behavior after model calibration, are presented in Table 3.

Table 3. Aquifer parameters after calibration.

Strati-graphic unit	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)	Specific yield	Specific storage (m^{-1})	Porosity	Longitudinal dispersivity (m)	Vertical 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

Simulation results and discussion

The saltwater-freshwater transition zone

The estimated extent of the seawater wedge from seawater intrusion modeling until the year 2003 is presented in two cross-sections in Figure 6a and Figure 6b (Jabalya and Khan Younis, respectively). For the purpose of presentation, it is considered that the extent (wedge) of the seawater intrusion is represented by the isoline 2.0 kg/m^3 of TDS contents.

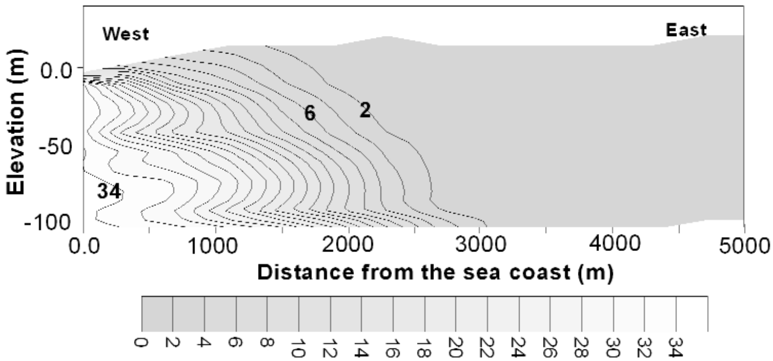

Figure 6a. Isolines of calculated TDS concentration (kg/m^3) by SEAWAT for the year 2003 along the Jabalya cross-section.

From Figure 6a it is estimated that seawater intrusion near Jabalya may extend about 1.5 km and 2 km inland in sub-aquifers A and B respectively, and up to 3 km in the sub-aquifer C. In Khan Younis (Figure 6b), seawater intrusion is about 2 km in the sub-aquifer B2 and about 1.5 km in the sub-aquifer B1. Figure

7 shows a plan view of the simulated current (2003) intrusion in the A and C sub-aquifers in the Gaza aquifer.

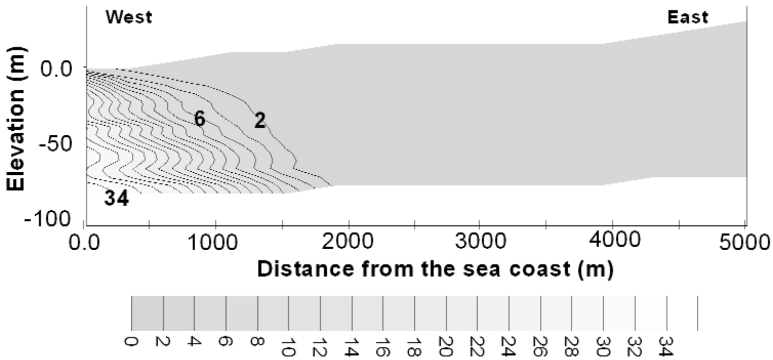

Figure 6b. Isolines of calculated TDS concentration (kg/m^3) by SEAWAT for the year 2003 along the Khan Younis cross-section.

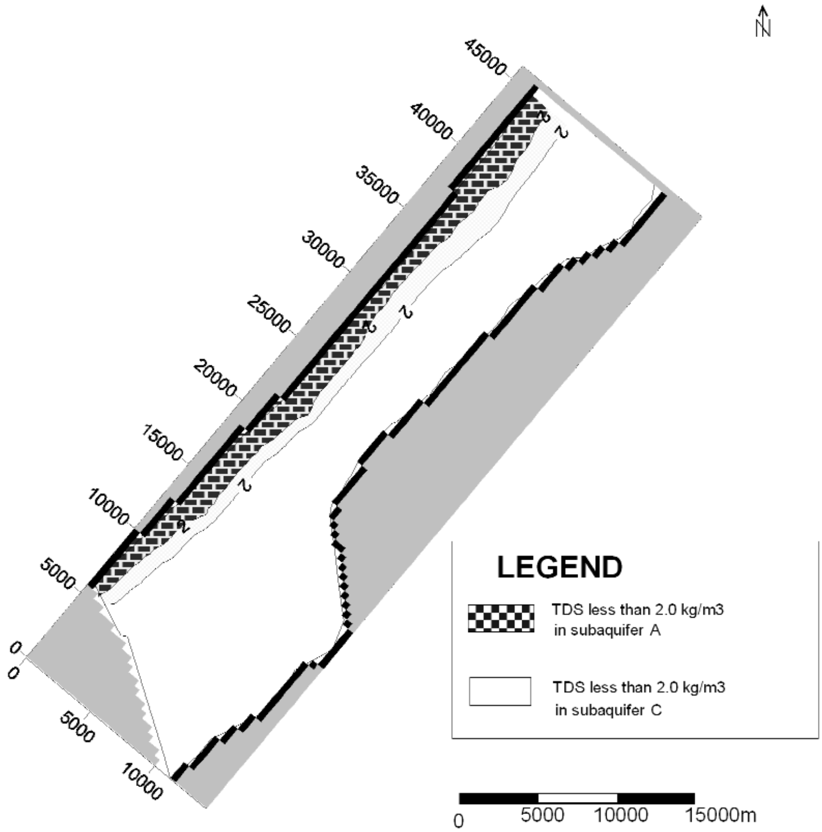

Figure 7. Simulated extent of TDS concentration (less than 2.0 kg/m^3) in sub-aquifers A and C for the year 2003.

It is clear from the above results that most of the area affected by seawater intrusion is located in the north of the Gaza Strip, to the north of Gaza city, and in the south, near Khan-Younis city.

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, the decrease in groundwater withdrawal is a very important aspect to be considered in the future to prevent further seawater intrusion into the inland aquifer. In order to demonstrate the effect of future scenarios of groundwater pumpage on seawater intrusion, two pumpage schemes were designed to use the calibrated model for calculations of future changes in water levels and salinity concentrations for a period of another 17 years. The two management scenarios are presented as follow:

1. The first (worst) scenario, where 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 the Gaza Strip, such as desalination of seawater, import water from outside the Gaza Strip and reuse of treated wastewater in agricultural irrigation.

Table 4 shows the amount of abstracted water from the aquifer for both scenarios. Figures 8a and 8b show the future changes in water levels in the year 2020 of the two predictive scheme simulations. Obviously, water levels in Figure 8a dropped to reach altitudes below MSL in most of the Gaza Strip area if it is compared with Figure 4b. On the other hand, Figure 8b shows that in all the Gaza Strip water level is AMSL, which means that there is improvement in groundwater balance.

Table 4. Abstraction amounts for management scenarios.

Number of stress period	Period length	First scenario abstraction (Mm^3/yr)	Second scenario abstraction (Mm^3/yr)
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

It is predicted that between the 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 = 2.0 kg/m^3, at the base of the sub-aquifer A, will move about an additional 1.5 km in the northern part. On the other hand, the results of the comparison indicate that the second scenario prevent any further seawater intrusion after the year 2003. In the year 2020, the total inflow from the sea is estimated to be 72 Mm^3/yr and 32 Mm^3/yr for the first scenario and second scenario respectively, where the discharge to the sea for the same year is estimated to be about 3 Mm^3/yr and 18 Mm^3/yr for the first and second scenarios.

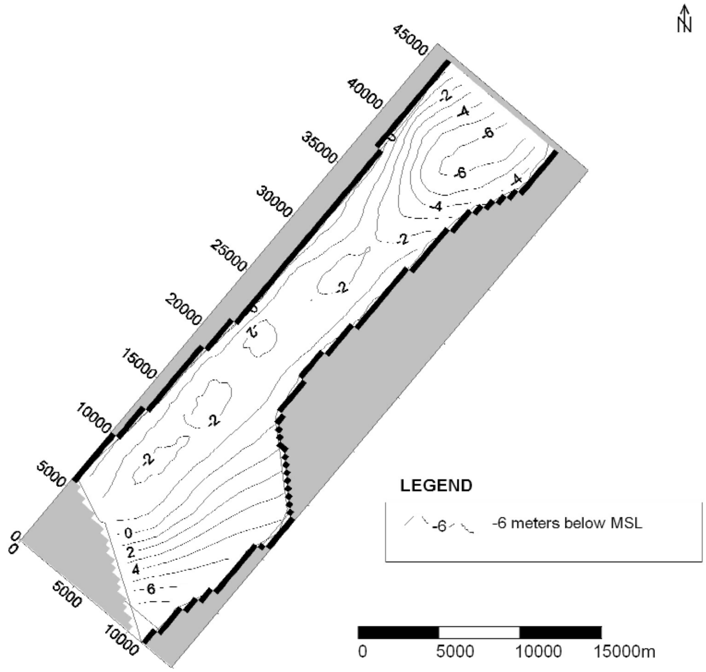

Figure 8a. Predicted contour lines of groundwater levels for the first scenario in the year 2020.

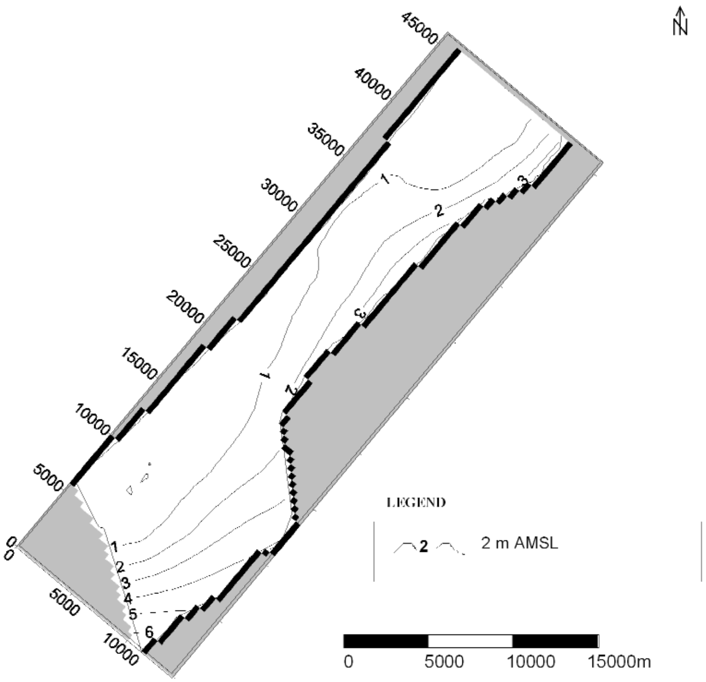

Figure 8b. Predicted contour lines of groundwater levels for the second scenario in the year 2020.

Conclusions

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

The numerical model is applied to test the overall regional impact on the aquifer with two future pumping scenarios. The first scenario is pumping from the aquifer continuously until the year 2020 to reach 200 Mm^3/yr; and the second scenario is to decrease the pumping rate from the aquifer, to reach 110 Mm^3/yr from the existing pumping wells in the year 2020. It is predicted that between the 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 = 2.0 kg/m^3, at the base of the sub-aquifer A, will move about an additional 1.5 km in the northern part. On the other hand, the results of the comparison indicate that the second scenario will prevent any further seawater intrusion after the year 2003. In year 2020 the total inflow from the sea is estimated to be 72 Mm^3/yr and 32 Mm^3/yr for the first scenario and second scenario respectively, where the discharge to the sea for the same year is estimated to be about 3 Mm^3/yr and 18 Mm^3/yr for the first and second scenarios.

Given the uncertainties in the available data, additional refinement of the model grid at this stage does not provide more accuracy. However, 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 future, as new data become available, the model should be periodically updated to refine estimates of input parameters and simulate new management options.

Acknowledgments

This work was carried out at LIMEN, Ecole Mohammadia d’Ingénieurs (EMI) and supported primarily with research funds from the UNESCO/KEIZO OBUCHI fellowship Program. Additional support was made available from the SWIMED project under contract number ICA3-CT2002-10004 funded by EU, and it is conducted on behalf of Gaza Islamic University partner-Palestine.

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