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Numerical Simulation of the Movement of Saltwater under Skimming and Scavenger Pumping in the Pleistocene Aquifer of Gaza and Jericho Areas, Palestine

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Abstract. The Pleistocene aquifers are important sources of water supply in both the Gaza and Jericho areas of Palestine. The aquifers are saline with freshwater lenses floating on saline bodies of water. It is important to investigate how to exploit these freshwater lenses without causing unnecessary mixing of the fresh and saline waters. The objective of this research is to investigate the feasibility of applying skimming and scavenger pumping as a means to exploit the freshwater lenses and to control saline water upconing in the aquifers. This study is the first to examine the movement of fresh and saline waters underneath skimming and scavenger wells in the aquifers of Gaza and Jericho. Two simulation models that couple density-dependent fluid flow and solute transport have been used to simulate and predict the movement of saltwater under different hydrogeological and operational conditions of skimming and scavenger wells in the two aquifers. The results show (for the Jericho Aquifer) that: the location of well screen has a strong control on the steady-state position of the fresh/saline water transition zone; the upconing mechanism appears to continue under skimming pumping until saline water enters the well screen even when the pumping rate is reduced; and for better salinity control it is necessary to place well screen against the gravel layers only and locate one screen segment in the saline water zone. The study shows (for the Gaza coastal aquifer) that the most important parameters affecting the movement of saline water under scavenger pumping are the relationship between recharge and pumping rates, the location of the well screen within the saturated thickness, the vertical permeability; and the transverse dispersivity. This study shows that saltwater upconing in Gaza aquifer can be controlled by operating a second well in the saline water zone so that the optimal ratio between saline water and freshwater pumping is 1:2 respectively.

Key words: Scavenger wells, skimming wells, saltwater intrusion, fresh/saline transition zone.

1. Introduction

Groundwater is the main source of water supply for the Palestinians in both Gaza and Jericho areas. The aquifers in both areas are of Pleistocene age. Lithological differences exist between the aquifers. In Gaza, the aquifer comprises of sandstone with interbedded impure clays (of low permeability) while in Jericho the aquifer

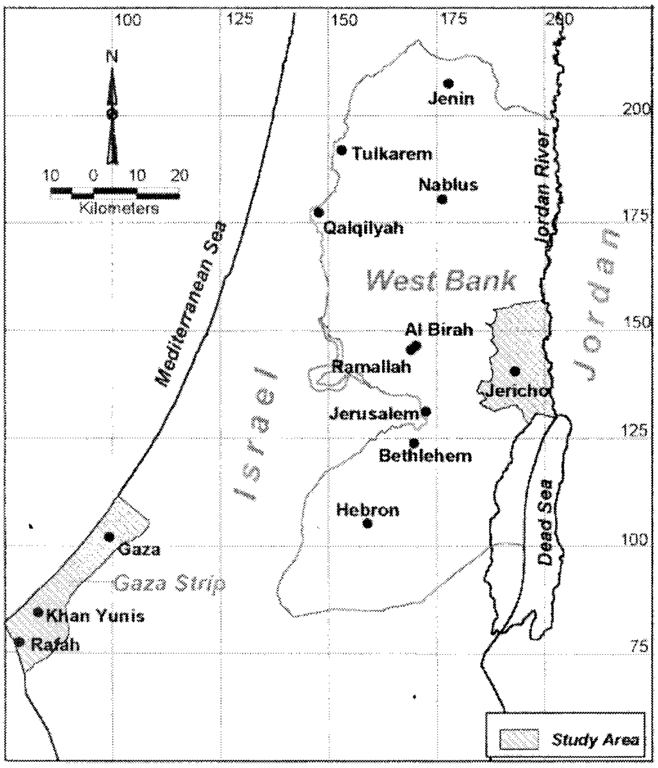

Figure 1. Locatio map of study areas.

is composed mainly of marl with bands of gravel. The reasons for studying both the Pleistocene aquifers in Gaza and Jericho, even though Jericho and Gaza are geographically not connected (see Figure 1) are twofold. First, the Palestinian population uses both aquifers heavily for domestic and agricultural purposes and this is causing severe salinity problems. Second, the hydrogeology of the aquifers in both Gaza and Jericho present many similarities where the aquifers are saline with freshwater lenses floating on saline bodies of water. The objective of the research is to investigate the feasibility of applying skimming and scavenger pumping as a means to exploit freshwater lenses and to control saline water upconing in the Pleistocene aquifer in both Gaza and Jericho areas. This is the first study in the region (Palestine and Israel) that is aimed at explaining, using numerical modelling, the movement of fresh and saline waters around skimming and scavenger wells in the Pleistocene aquifers of Gaza and Jericho. Other studies have addressed the Pleistocene aquifers and the problems in the context of regional assessment, but these are largely descriptive and have not provided solutions to the problem of salinity control. This study specifically addresses how to control further saline water mixing with freshwater during aquifer pumping. The field programmes carried out during the course of the study were aimed at determining the hydrogeological settings and the problems of the aquifers in Gaza and Jericho. Two modelling codes (RASIM and SUTRA-ANE) that couple density-dependent fluid flow and solute transport in a multilayer confined/phreatic aquifer system with isotropic/anisotropic properties were used for the Jericho and Gaza case studies. The two codes were used to predict the movement of saltwater under different hydrogeological and operational conditions for both skimming and scavenger wells. The adoption of two different models reflects the fact that this study represents the integration efforts from two separate research projects, one in Gaza and the other in Jericho. The authors have previously shown that the two codes generate essentially identical results (see Aliewi, 1993 about the Sind case study). Models using both SUTRA-ANE and RASIM have been previously verified and validated. In this study the simulations show (for the Jericho Aquifer) that:

(1) the location of well screen (installed in one or more sections) has a strong control on the steady state position of the fresh/saline water transition zone;
(2) upconing seems to continue under skimming pumping until saline water enters the well screen even when the pumping rate is reduced;
(3) salinity control is improved of the well screen segments are placed against the gravel layers only and one screen segment is located in the saline water zone, which is the idea of scavenger pumping.

The study shows (for the Gaza coastal aquifer) that the most important and sensitive parameters affecting the movement of saline water under scavenger pumping are:

(1) the relationship between recharge and pumping rates;
(2) the location of the well screen within the saturated thickness;
(3) the vertical permeability of the aquifer; and
(4) the transverse dispersivity.

This study demonstrates clearly that saltwater upconing in Gaza coastal aquifer can be controlled by installing and operating a second well in the saline water zone so that the optimal ratio between saline water and freshwater pumping is 1:2 respectively.

2. Salinity Problems in Jericho and Gaza Aquifers

2.1. JERICHO PLEISTOCENE AQUIFER AND ITS SALINITY PROBLEMS

The Pleistocene aquifer in the Jericho area (Figure 1) is the main source of water for agriculture in the Jordan Valley. The aquifer is comprised of alluvial fan deposits (up to 120 m thickness) that were formed along the outlets of the major wadis on the eastern flanks of the mountains of the West Bank. The area of the aquifer is several hundred square kilometres. The lithology encountered by a typical well located in the Pleistocene aquifer is shown in Figure 2. The data in this figure are compiled from the database of the Palestinian Water Authority. It shows that the aquifer comprises mainly of marine marls intercalated by gravel bands. The yield

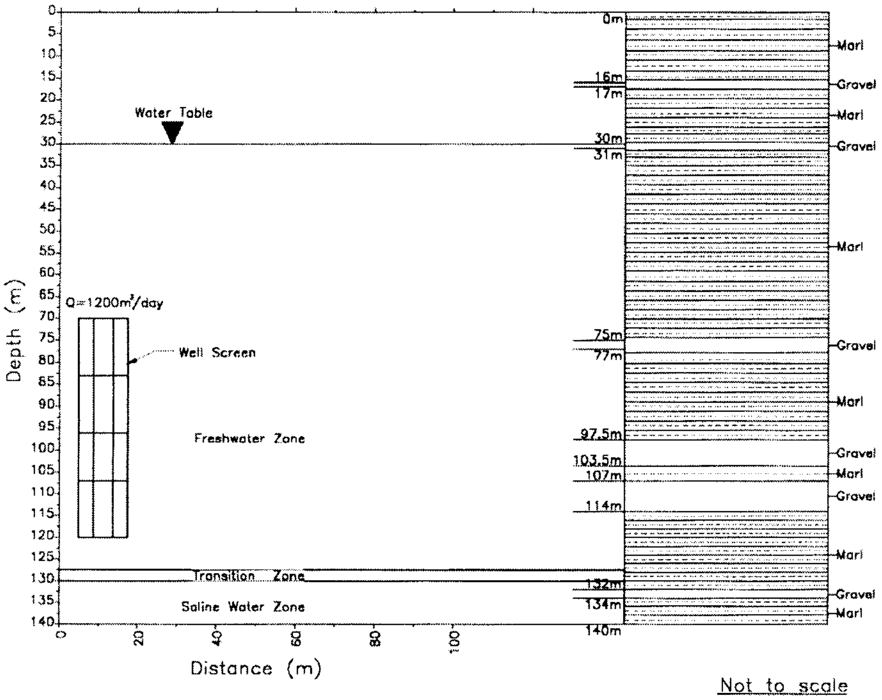

Figure 2. Hydrogeological setting of Jericho Aquifer (Data of this figure compiled from the database of the Palestinian Water Authority).

of the wells in the Pleistocene aquifer is about 20–100 m^3/hr. The water quality is variable (from 100 mg/1 to more than 2000 mg/1). Estimates of transmission properties show that the aquifer varies from low potential (less than 10 m^2/day) to fair potential (between 10 and 50 m^2/day). The steep dip of the aquifers along the Jordan Valley has caused deep circulation of the recharging groundwater bringing it into contact with the contaminated salty formations at depth. Recent drilling in the Pleistocene aquifer has shown that salinity increases with depth. Salinity data obtained from one well in Jericho shows that the chloride content increases from 380 mg/l at 30 m depth to over 2000 mg/l at 162 m depth. A component of the salinity may be the result of flushing of soluble salts from the soil zone by excess of irrigation water.

The water quality of the Pleistocene aquifer has deteriorated due to the encroachment of saline water from the fringes of the alluvial fans into the heavily pumped areas and this has led eventually to the abandonment of several wells in the Jordan Valley. Owing to the heavy pumping in the Jordan Valley a considerable decline of water table levels has been observed. The principle result is an increase of groundwater salinity. It has been observed that high chloride concentrations prevail in the heavy pumping areas (1000–2000 mg/l); and much lower chloride concentrations are seen in the areas near wadis. The wadis are considered as sources of groundwater recharge. At distance from the heavy pumping areas the salinity was measured at 500–1000 mg/l.

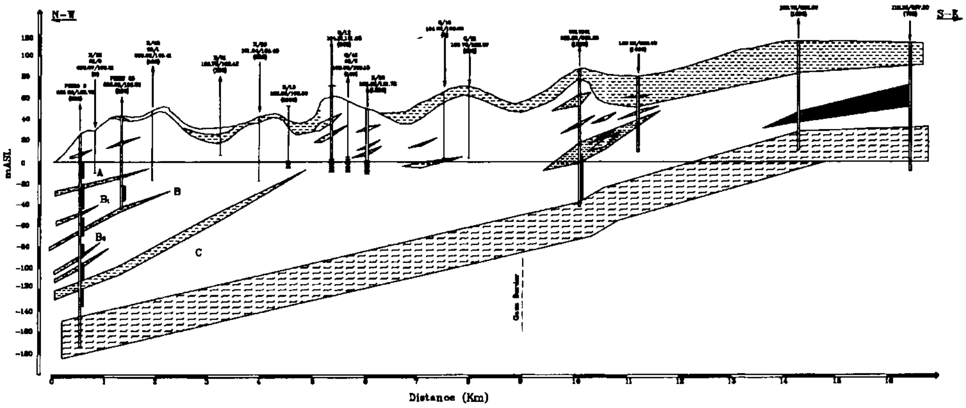

Figure 3. Typical cross section of the Gaza Aquifer (after Greitzer and Dan, 1967. The numbers are wells names; lower permeability clay lenses are presented as scattered dark marks in the figure).

2.2. GAZA PLEISTOCENE COASTAL AQUIFER AND ITS SALINITY PROBLEMS

Gaza strip is a coastal area along the eastern Mediterranean Sea (Figure 1). The total area of the Gaza Strip is about 365 km^2. Groundwater is probably the only water resource in the Gaza Strip. The Gaza aquifer is a saline coastal aquifer with freshwater lenses floating on the main saline water body. This phenomenon has been observed both near the coast and inland. The saturated thickness of the aquifer does not exceed 180 m. The general groundwater flow pattern is from east to west towards the Sea. The Gaza aquifer is classified as an unconfined aquifer in the east. In some areas near the coast lower permeability clay lenses create a confining layer as seen in Figure 3 (Greitzer and Dan, 1967). The aquifer is comprised of tertiary and quaternary age formations. The bottom of the aquifer has a contact with Saqya formation, which is comprised of shallow marine clays, shales and marls. The aquifer itself is comprised of consolidated quartz sands with calcareous material. The aquifer has both high permeability and porosity.

There are more than 3000 wells in the Gaza Strip. The area of Gaza Strip is 365 km^2, which means that there are on average 8 wells in each 1 km^2. This dense network of wells extract volumes of water much greater than the recharge volumes of the aquifer resulting in a severe reduction in the freshwater levels and significant leaching of the irrigated soils. As a result, three processes take place:

(1) seawater intrusion along the Mediterranean coast;
(2) upconing of saline water in the inland region of the aquifer; and
(3) rapid infiltration of agro-chemicals.

The water supplies tend to be saline and rich in nitrates. Salinity levels approach 1300 mg/l in the eastern part of the study area rendering this water unsuitable for most agricultural uses in Gaza. The high levels of nitrates (which sometimes exceed

500 mg/l) indicate the groundwater is being contaminated by irrigation return flows and raw wastewater generated in populated areas.

There is a need to find effective and economic measures that control the salt and agrochemical pollution in Gaza. This study addresses only the problem of salt pollution.

3. Previous Studies and Importance of this Study

This study is concerned only with the application of the principles of skimming and scavenger pumping at the local scale (i.e., in the vicinity of the pumping area around a well) in the Pleistocene aquifers of both. It does not deal with regional groundwater movements or the distribution of water quality in these aquifers. A review of the available literature indicates that there are no previous publications about the use of scavenger wells in the area of Palestine and Israel. However, many publications have been produced concerning the regional description and assessment of the aquifers. A brief summary of some of these regional studies is included here for completeness.

In the area of Israel and Palestine, most studies concentrate on the assessment of the regional groundwater movement of fresh and saline waters and their chemical compositions. Greitzer and Dan (1967) have attempted to explain the distribution of fresh and saline waters in the coastal aquifer of Israel. Vengosh and Rosenthal (1994) studied the chemical composition of the groundwater of Gaza Aquifer. They showed that, in many deep wells in Gaza, the chloride content is higher than that in seawater. They present the ionic composition of the water of these deep wells and show deficiencies in sodium, magnesium, potassium, and sulphate, and enrichment of calcium, relative to seawater or seawater diluted by freshwater at the coast. In a similar study of this type Vengosh and Ben-Zvi (1994) showed that the chemical composition of the brackish water near Gaza is indicative of two types of Ca–Cl brines. The first resembles Ca–Cl water that would have formed in coastal sabkhas, while the second type is identical to the deep-water brine found in the south west of Gaza. They concluded that such saline water may be found in localized areas throughout the coastal plain (and hence throughout the Gaza Strip). They also indicated that deep saline ‘pockets’ in the coastal aquifer may originate in deeper formations, and may be hydraulically connected to the coastal aquifer through faults or other structural complexities. Rosenthal *et al.* (1992) studied the origin of saline water in the Gaza Aquifer. They suggested that the high salinity was caused by dissolution of soluble salts in the Eocene rocks. Moe *et al.* (2001a,b) studied the regional movement of freshwater and saltwater in the coastal aquifer of Gaza. They developed a three-dimensional model to assess the sustainable yield of the aquifer and salt water intrusion due to the heavy pumping in the Gaza Strip aquifer.

This study differs from the above studies in the following manner:

(a) It is the first in the region that explains what happens locally underneath skimming and scavenger pumping wells in terms of the movement of fresh and saline waters in the Pleistocene aquifers of Gaza and Jericho. While Schmorak and Mercado (1969) considered (using general field observations) the design and operation criteria for skimming wells only in the coastal aquifer of Israel, their study did not take into consideration the different operational and field conditions provided by this study. Moreover, their study did not adopt numerical simulations to determine the maximum pumping rate coupled to the optimal screen interval so that the fresh/saline water interface does not rise above the base of the screened section.

(b) The study provides design parameter values for skimming and scavenger pumping in Jericho and Gaza aquifers.

The concepts of skimming and scavenger wells are not new and some of the literature addressing previous applications outside Palestine and Israel are presented below.

Skimming wells pump only freshwater from saline aquifers such that the saline water does not rise above the base of the well screen. The design of skimming wells in areas other than Palestine and Israel can be found in Wang (1965), Sahni (1973) and Reilly and Goodman (1987). Birch and van Wonderen (1990) showed that skimming wells in Pakistan are not the most economical method to abstract freshwater lenses of less than 90 m thickness. They suggest scavenger wells where freshwater lenses are less than 90 m thickness.

Scavenger wells pump both the fresh and saline groundwaters to extract water from thin fresh groundwater lenses overlying saline water. They are screened in both fresh and saline zones of the aquifer. Standard configurations are either twinned boreholes or a single well with two pumps. The inlet of one well/pump is located in the freshwater zone while the inlet of the other well/pump is positioned in the saline water zone. The concept of a scavenger well relies on the fact that interface upconing is the result of pumping in the freshwater zone while interface downconing is caused by pumping saline water. These two processes can be balanced by varying the pumping rates from the two zones. Scavenger wells are economically more effective than skimming wells where the thickness of freshwater lenses is less than 90 m. Scavenger wells should not be used if there is no place to dispose safely saline water. The study aims at demonstrating that operating both freshwater and saline water pumps under controlled operational conditions in the Gaza and Jericho aquifers will be effective at stopping the fresh and saline waters from mixing.

In order to recover freshwater overlying saline water in the Chicot aquifer of southwestern Louisiana (USA), Fader (1957) described a two-well system in which a scavenger well is screened in the lower part of the aquifer to draw off only saline water and a nearby supply well is screened in the freshwater section of the aquifer. In the same state of Louisiana, Long (1965) field tested the feasibility of the two-well scavenging system suggested by Fader (1957) and concluded that this system could be effective to recover fresh groundwater overlying saline water under controlled conditions. The work of Mott Macdonald Group and the British Geological

Survey on the saline aquifers of the Sind Province of Pakistan is reported in Birch and van Wonderen (1990). In the Pakistan study it is concluded that scavenger wells are the most economical method to optimise the freshwater recovery in saline aquifers. Zack and Munoz-Candelario (1984) and Zack (1988) carried out field studies to demonstrate that screening a pumping well in both fresh and saline water will provide an effective method for extracting potable water from a thin freshwater layer in the coastal aquifers of Puerto Rico of the United States. From their results, they established a hydraulic approach to estimate optimal withdrawals of freshwater based on pumping rates and the level of solute concentrations.

4. Objective and Approach

The objectives of this research are twofold: (1) to predict the movement of saltwater under skimming and scavenger pumping; (2) to investigate the feasibility of applying scavenger pumping as a means to control saline water upconing in the coastal aquifer of Gaza and the Pleistocene aquifer of Jericho. A field programme and numerical simulations were carried out. In the Jericho area the field programme comprised the drilling of two wells using a design that would allow different pumping schemes as well as determine the hydrogeological setting of the problem of Jericho study area. In Gaza, field data were gathered only to determine the hydrogeological setting of the problems of the coastal aquifer. A finite-difference simulation model (RASIM) that couples density-dependent fluid flow and solute transport in a multilayer confined/phreatic aquifer system with isotropic/anisotropic properties was used for the case study of Jericho. RASIM was developed specifically to study Scavenger well design and operation by Aliewi (1993). The finite element software package, SUTRA-ANE (Voss, 1984a, b), was used for the case study of Gaza. Further details about RASIM (RAdial SIMulation) and SUTRA-ANE (Saturated-Unsaturated fluid flow and solute TRAnsport) can be found in Aliewi (1993) and Voss (1984a,b) respectively. The reason for using two different models has been previously explained.

5. Governing Equations

Both codes solve for density-dependent fluid flow and solute transport in non-homogeneous formations. This is required because the Pleistocene aquifer is strongly heterogeneous and anisotropic. The density-dependant fluid flow and solute transport equations (Voss, 1984b) are:

$$\rho S_{OP}\frac{\partial P}{\partial t} + \left(\varepsilon\frac{\partial \rho}{\partial C}\right)\frac{\partial C}{\partial t} - \nabla \cdot \left[\left(\frac{\rho \underline{\underline{k}}}{\mu}\right) \cdot (\nabla P - \rho \mathbf{g})\right] = Q_p, \tag{1}$$

$$\frac{\partial}{\partial t}[(\varepsilon\rho)C] + \nabla \cdot [(\varepsilon\rho\underline{V})C] - \nabla \cdot [(\varepsilon\rho\underline{\underline{D}}) \cdot \nabla C] = Q_p C^{*}. \tag{2}$$

P: fluid pressure [M/LT^2]; C: solute-mass fraction [Ms/M]; ρ: fluid density [M/L^3] as:

$$\rho(C) = \rho_0 + \frac{\partial \rho}{\partial C}(C - C_0) \tag{3}$$

$\partial\rho/\partial C$ density change with concentration [M/L^3].
C_0 is background concentration [1], ρ_0: background density [M/L^3].
μ: fluid viscosity [M/(LT)]; S_{OP}: specific pressure storativity [M/(LT^2)]$^{-1}$ as:

$$S_{OP} = (1-\varepsilon)\alpha_P + \varepsilon\beta \tag{4}$$

ε: porosity [1]; β: fluid compressibility [M/(LT^2)]$^{-1}$; α_P: aquifer compressibility [M/(LT^2)]$^{-1}$; $\underline{\underline{k}}$: Intrinsic permeability tensor [L^2]; Q_P: fluid-mass source [M/L^{3}T].

The average pore velocity [L/T] is:

$$\underline{V} = -\left(\frac{\underline{\underline{k}}}{\varepsilon\mu}\right)\cdot[\nabla P - \rho\mathbf{g}] \tag{5}$$

$\mathbf{g}$: gravity vector [L/T^2].
$\partial(\rho\varepsilon C)/\partial t$ total change in solute mass per unit aquifer volume [M/(L^{3}T)]; $\nabla\cdot(\varepsilon\rho V C)$ solute advection [M/L^{3}T]; $\nabla\cdot(\varepsilon\rho\underline{\underline{D}}\cdot\nabla C)$ solute dispersion [M/L^{3}T]; $\underline{\underline{D}}$ hydrodynamic dispersion tensor [L^2/T]; $Q_P C^*$: [M/(L^{3}T)] fluid source with concentration, C*.

The symmetric hydrodynamics dispersion tensor in (r-z) coordinates can be written as:

$$\underline{\underline{D}} = \begin{bmatrix} D_{rr} & D_{rz} \\ D_{zr} & D_{zz} \end{bmatrix}, \tag{6}$$

$$D_{rr} = \alpha_{\mathrm{L}}\frac{V_r^2}{|\underline{V}|} + \alpha_T\frac{V_z^2}{|\underline{V}|} + D_m, \tag{7}$$

$$D_{rz} = D_{zr} = (\alpha_{\mathrm{L}} - \alpha_{\mathrm{T}})\frac{V_r V_z}{|\underline{V}|}, \tag{8}$$

$$D_{zz} = \alpha_{\mathrm{L}}\frac{V_z^2}{|\underline{V}|} + \alpha_{\mathrm{T}}\frac{V_r^2}{|\underline{V}|} + D_m, \tag{9}$$

$$|\underline{V}| = \sqrt{V_r^2 + V_z^2}, \tag{10}$$

$$\alpha_{\mathrm{T}} = \frac{\alpha_{\mathrm{T\,max}}\alpha_{\mathrm{T\,min}}}{\alpha_{\mathrm{T\,min}}\cos^2\theta + \alpha_{\mathrm{T\,max}}\sin^2\theta}, \tag{11}$$

$$\alpha_{\mathrm{L}} = \frac{\alpha_{\mathrm{L\,max}}\alpha_{\mathrm{L\,min}}}{\alpha_{\mathrm{L\,min}}\cos^2\theta + \alpha_{\mathrm{L\,max}}\sin^2\theta}. \tag{12}$$

α_L and α_T: longitudinal and transverse dispersivity [L]; V_r and V_z: radial and vertical velocity [L/T]; θ: angle between flow direction and direction of maximum permeability.

For the two case studies, dispersivity is assumed dependent on travel distance from the solute source. The following model (Aliewi, 1993) for heterogeneous dispersivity is used:

$$\alpha_{\mathrm{L\,max}} = (\alpha_{\mathrm{L\,high}} - \alpha_{\mathrm{L\,low}}) \times \left[1 - \frac{A_\alpha}{r_s + A_\alpha}\right] + \alpha_{\mathrm{L\,low}}. \tag{13}$$

r_s: is the travel distance from solute source [L]; A_α: constants (values used 0–100 m); $\alpha_{\mathrm{L\,low}}$ and $\alpha_{\mathrm{L\,high}}$ are the possible minimum and maximum field values of longitudinal dispersivity [L].

The coupled equations above are solved iteratively by solving first the flow equation to find values for fluid velocity and then the solute transport equations are solved after updating the dispersion and advection terms. The flow solution is then updated for the altered density values and the iteration is repeated until convergence is achieved. This process is repeated for all time steps of the numerical solution.

6. The Conceptual Models of Jericho and Gaza Aquifers

Figures 2 and 4 represent the conceptual hydrogeological models used for the Jericho and Gaza aquifers respectively. Table I presents the values of the parameters used in the simulation runs. The well abstractions were 1200 and 5000 m^3/d in the freshwater zones for Jericho and Gaza Aquifers, respectively. No flux boundary is assigned to the bottom and sides of the aquifer or a hydrostatics lateral boundary condition is adopted; the recharge is applied to the top of the model. A

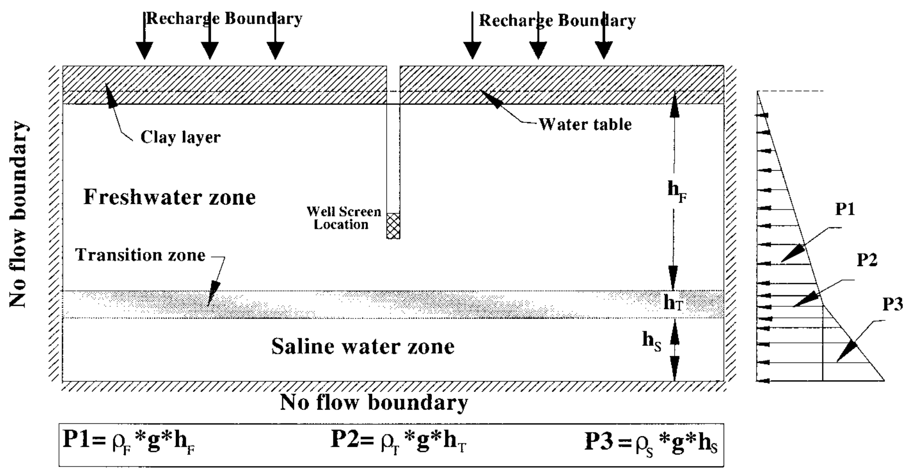

Figure 4. Conceptual model for Gaza Aquifer.

Table I. Parameters** used in the models

Parameter	Gaza aquifer	Jericho aquifer
K_H for lower permeability layer	2 m/d	1.2 m/d
K_H for aquifer	30 m/d	12 m/d
K_V for lower permeability layer	0.1 m/d	0.2 m/d
K_V for aquifer	2 m/d	2 m/d
Initial depth of water table	20 m bgl*	30 m bgl
Lateral dispersivity (α_L)	5 m	10 m
Transverse dispersivity (α_T)	0.33 m	0.1 m
Porosity	0.30	0.35
Density change with concentration	700 kg/m^3	For both aquifers
Viscosity	0.001 kg/m s	For both aquifers
Gravity acceleration	9.8 m/s^2	For both aquifers
Fluid compressibility	4.5E-10 m s^2/kg	For both aquifers
Fluid diffusivity	1.0E-9 m^2/s	For both aquifers
Solid matrix compressibility	1.0E-8 m s^2/kg	For both aquifers

*:m bgl is meter below ground level.
**:Values used are obtained from the database of the Palestinian Water Authority. Some parameter values such as solid matrix compressibility were assumed close to theoretical values in the literature.

laterally uniform hydrostatic pressure distribution is specified for the initial conditions. The fresh and seawater densities are taken to be 1000 kg/m^3 and 1025 kg/m^3 respectively. The groundwater salinity varies gradually over the aquifer vertical dimension. For analysis it is convenient to define the top of the transition zone by a particular salinity value. The salinity level at the top of transition zone (TOTZ) has been chosen (depending on the purpose to use water) to reflect the salinity of 250 mg/l (for Gaza for drinking purposes) and 1500 mg/l (for Jericho for some irrigation purposes) (0 isochlor), and the bottom of the transition zone (top of the saline water) has a chloride concentration equal to 20,000 mg/l (1 isochlor).

7. Simulation Results and Discussion

7.1. JERICHO AQUIFER

Running the model for the Jericho aquifer problem under normal skimming pumping (discharge = 1200 m^3/d) results in a sharp rise of the top of the transition zone (TOTZ) until saline water reaches the bottom of the screen of the skimming well (Figure 5) after which the movement of TOTZ gradually slows down to achieve eventually a state of equilibrium after nearly 1530 days. This explains why most of the agricultural skimming wells in the Jericho area have produced saline water after only a few years since pumping began and which has resulted in the abandoning

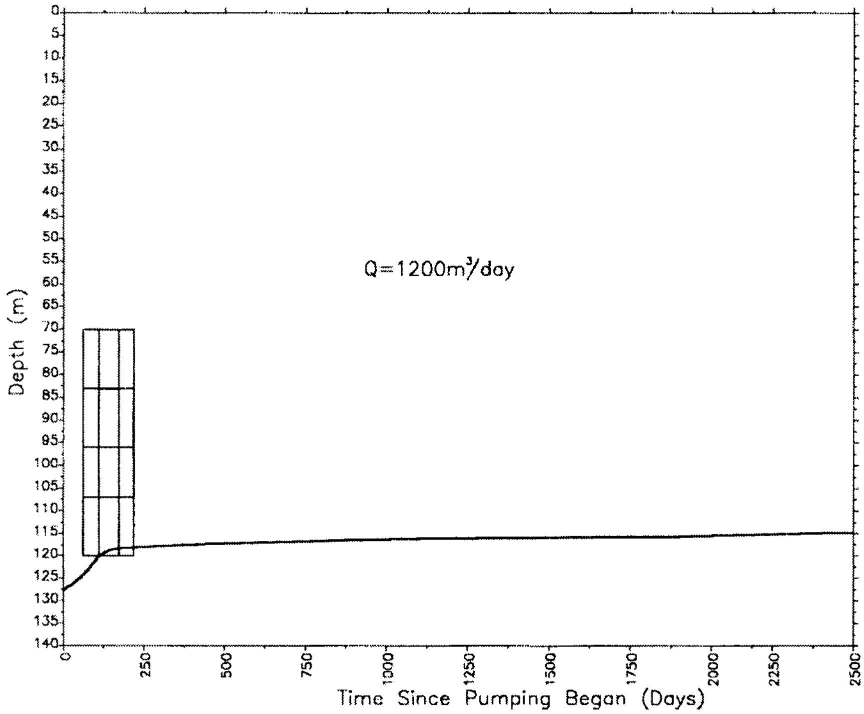

Figure 5. Movement of top of fresh/saline water transition zone over time under normal skimming pumping.

of nearly 30 wells of this type. To solve the problem, the pumping rate of the skimming well was reduced to 900 m^3/d. The simulation results show that the rate of the vertical movement of TOTZ was almost constant over the entire simulation period (Figure 6) at nearly 0.5 cm per day.

It can be shown that if the simulation period is increased the TOTZ eventually reaches the well screen, which effectively means that the problem is delayed but not solved. It seems that regulating the well capacity to produce lower values will not stop or suppress the vertical movement of saline water given the hydrogeological conditions of Jericho aquifer.

A possible solution to the above problem is to deal with the well screen as sections with each section designed to extract water from a gravel section within the aquifer (Figure 7). This configuration was applied in the field where a well was drilled and the casing was screened only against gravel sections. For this particular well, the screen sections were set at the following depth intervals: 75–77, 97.5–103.5, 107–114, 132–134 m bgl. The last section is located in the saline water zone. The simulation results show that saline water upconing reaches equilibrium after 14 days only because the last screen section (132–134 m bgl) was located initially in the saline water zone which meant that saline water was pumped from the beginning creating a low pressure zone around this screen section which helped

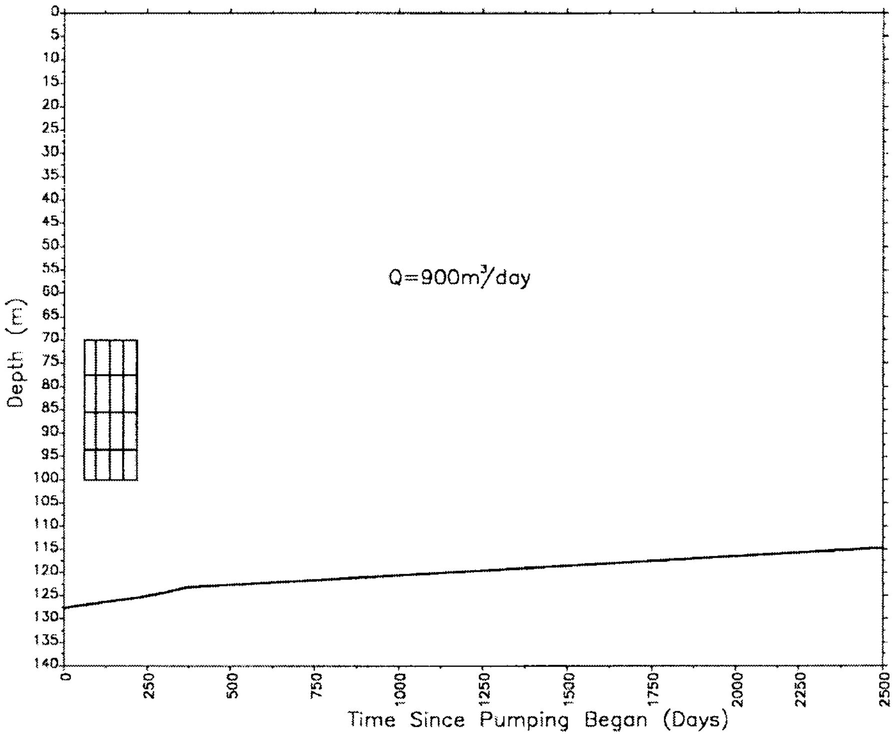

Figure 6. Movement of top of fresh/saline water transition zone over time under low skimming pumping.

reduce the saline water potential from considerable vertical movement towards the well screen (Figure 7). This is an illustration of scavenger pumping which shows that by pumping saline and freshwater simultaneously, it is possible to suppress the vertical movement of saline water and prevent saline and fresh waters from mixing.

7.2. GAZA AQUIFER

Running the model for 20 years of continuous pumping without operating the saline water pump resulted in a continuous movement of saline water until it reached the freshwater pump (Figure 8). In the first year, the average rate of upconing of TOTZ was 1 cm/day, and decreased gradually to 0.5 cm/day over the next 3 years. Almost constant upward movement of 0.2 cm/day was simulated till year 10 and then a gradual decrease to 0.1 cm/day up to year 16 after which the movement of TOTZ reached steady state (Figure 9). When the saline pump was operated simultaneously with the freshwater pump, a capture zone of both high salinity and freshwater was created showing that the salinity of the abstracted water from the freshwater pump did not increase considerably (Figure 10). The disadvantage of this is that freshwater entered the saline water pump.

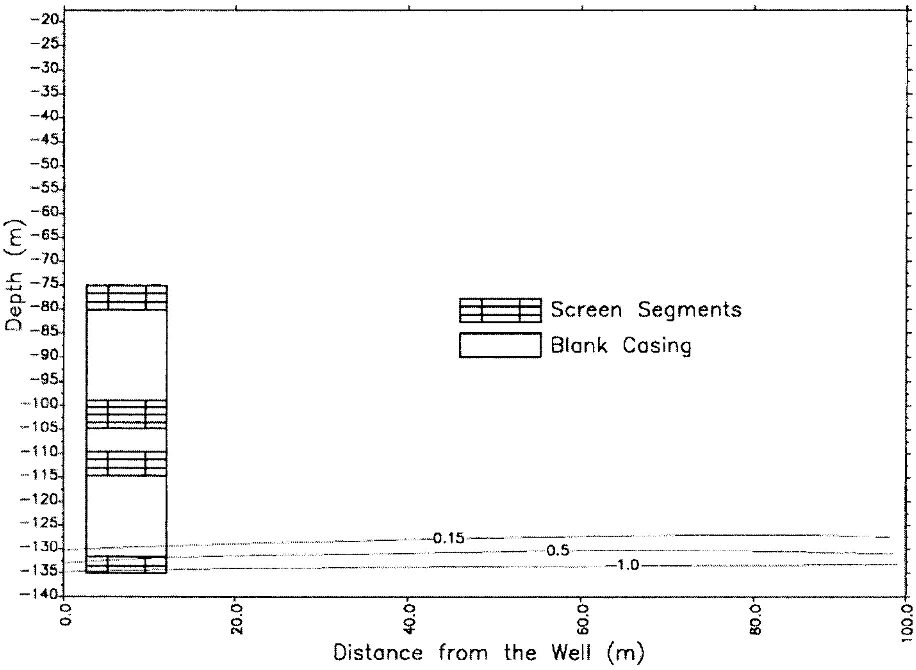

Figure 7. Isochlor distribution for segmented screen at equilibrium.

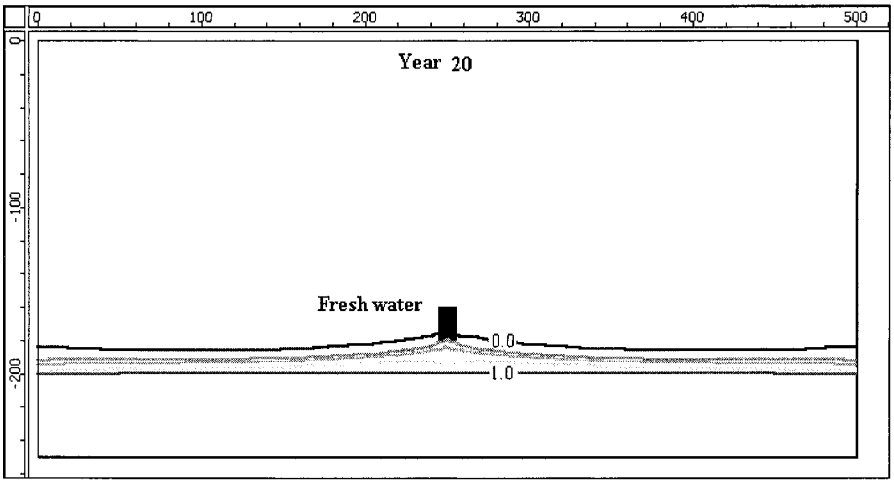

Figure 8. Isochlor distribution beneath the pumping well by year 20.

When only the freshwater pump was in operation (Figure 8), saline water entered this pump. The pumping rate of the saline water pump was altered in relation to the pumping rate of the freshwater pump. Several different ratios of fresh to saline discharges were examined. The simulation results are shown in Figures 10 to 13. The results show clearly that it is feasible to control the vertical movement of

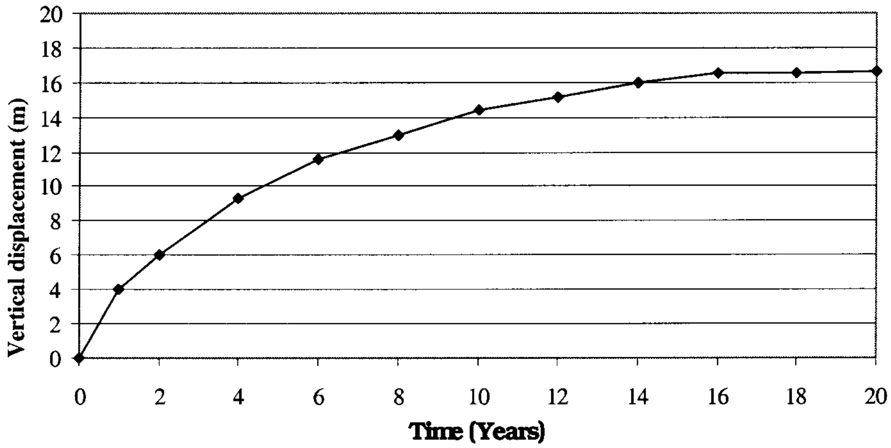

Figure 9. Movement of the top of transition zone over time for field conditions.

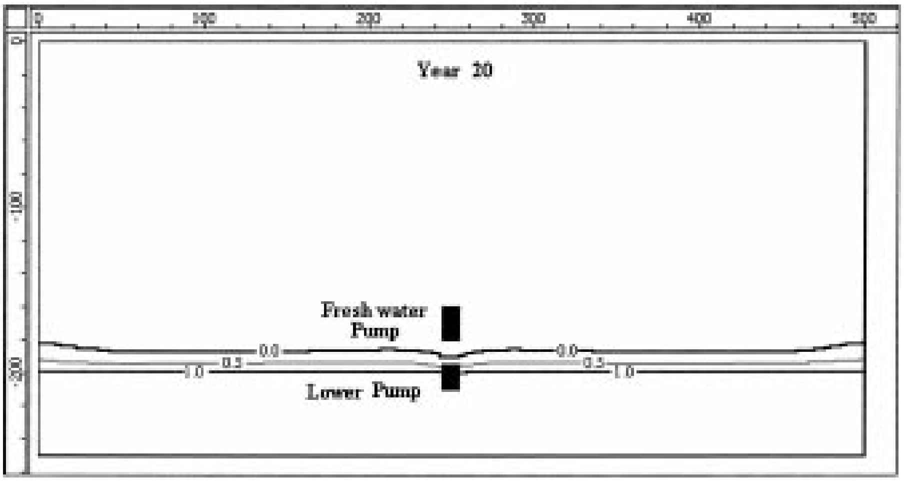

Figure 10. Isochlor distribution around the well with two pumps, $Q_s = Q_f$.

the saline water by increasing the saline water abstraction but care must be taken so that freshwater is not lost to saline water pump (Figures 10 and 13). This is simply because the saline water pump will create a low-pressure zone around it and water will move to it instead of advancing upwards. It is important to find the best ratio between freshwater abstraction and saline water abstraction. This study shows (Figure 12) the best ratio is $Q_s = 0.5\, Q_f$.

Sensitivity analysis was carried out to identify the most sensitive parameters that control the separation process between fresh and saline waters in Gaza saline aquifer. Simulation results show that these parameters are:

(1) The ratio of recharge rate to freshwater abstraction provided that saline water pump is not operational. This ratio plays a big role in determining the de-

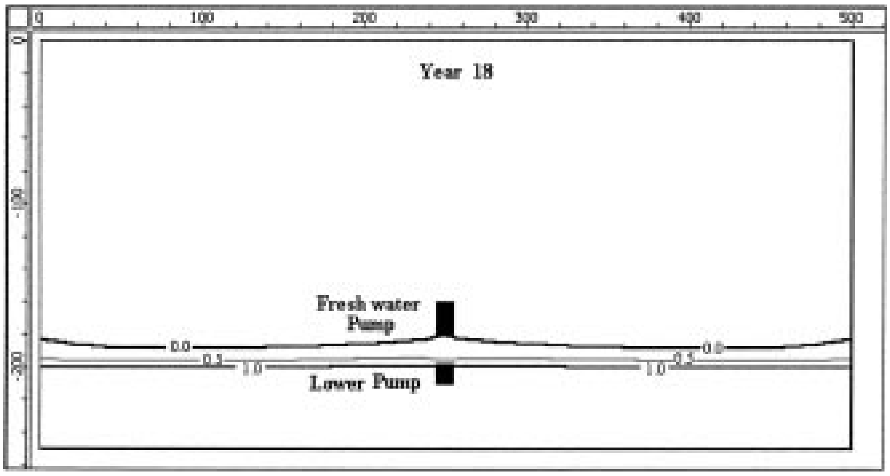

Figure 11. Isochlor distribution around the well $Q_s = 0.25\,Q_f$.

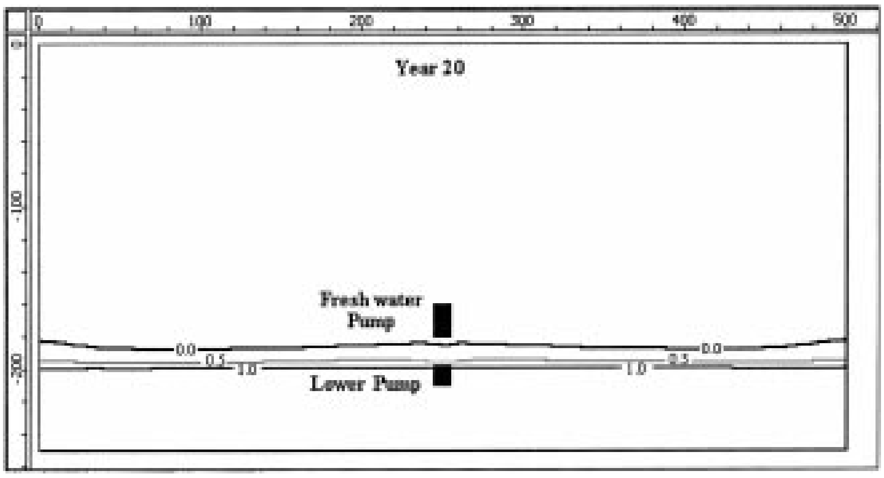

Figure 12. Isochlor distribution around the well with $Q_s = 0.5\,Q_f$.

ficit that may come from deep saltwater when the recharge rate is less than freshwater abstractions;

(2) The location of the well screen with respect to the initial position of the fresh/saline water interface. It is shown that if the freshwater well screen is closer to the initial position of the fresh/saline water interface, then the mixing process will happen sooner and the overall abstracted water will have relatively higher values of salinity;

(3) The aquifer vertical permeability (K_v). Higher values of K_v means more mixing between saline and fresh waters;

(4) The transverse dispersivity. Increasing the value of transverse dispersivity means more mixing and faster movement of TOTZ.

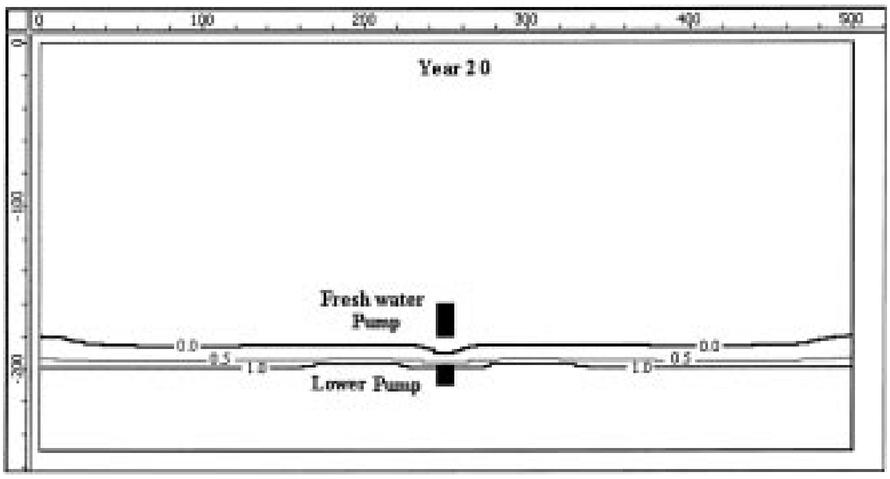

Figure 13. Isochlor distribution around the well with $Q_S = 1.25\ Q_f$.

It was also shown in this study that the following parameters did not play a significant role in the process of vertical mixing between fresh and saline waters under different operational conditions: lateral flow; horizontal permeability; longitudinal dispersivity; well screen length (although its position is important).

8. Conclusions

The current operational conditions of the agricultural skimming wells in the Jericho area have led to fast arrival of the TOTZ to the bottom of the well screen. This has resulted in the abandonment of nearly 30 wells of this type in the Jericho area. In order to try to solve the problem, the pumping rate of the skimming well was reduced but the problem was only delayed not solved. A possible solution to this problem was to deal with the well screen as sections each section is designed to extract water from the gravel layer within the aquifer. The simulation results show that saline water upconing reaches equilibrium after 14 days only (Figure 7). This is an illustration of scavenger pumping which shows that by pumping saline and freshwater simultaneously, it is possible to suppress the vertical movement of saline water and prevent saline and fresh waters from mixing. Groundwater is the only reliable source of water supply for Gaza. As time passes, this source of water is becoming increasingly vulnerable to contamination by wastewater, irrigation return flows and salinisation. Gaza aquifer is shallow with high permeability sandstone. Over-pumping from more than 3000 wells has caused severe groundwater salinisation problems. The results presented here illustrate that scavenger wells can be used to control groundwater salinisation in the polluted coastal aquifer of Gaza. It is shown by simulation using a simplified cross section model that saltwater upconing continues, as a result of operating a single pump alone until saline water abstraction occurs. The only way to stop the upconing is to operate a second saline water pump. The saltwater upconing can be greatly reduced if the screen of the freshwater well is located in the upper part of the aquifer and if the saline water pump extracts water with rates higher than half the freshwater pumping rate.

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