Monitoring of Seawater Intrusion in the Gaza Strip, Palestine

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ABSTRACT

The water supply for Gaza strip is provided from the shallow sandy coastal aquifer. Over-exploitation has been causing seawater intrusion. In the coastal margins of the Gaza strip, seawater intrusion is still expanding and the salinity of many wells has increased enormously in the last decades. Monitoring of seawater intrusion is essential to delineate the fresh-saline water interface for the protection of water supply wells.

The modelling approach was applied for designing the seawater intrusion monitoring network. SUTRA-ANE was used for simulating the seawater intrusion along a cross-section in the northern part of the Gaza strip. The extent of saltwater intrusion was predicted to be 2300 m in the upper aquifer and 2800 m in the lower aquifer by the year 2015.

The result of the model was used for identifying the location and the number of monitoring sites. Three alternative monitoring networks were analysed. The first was a combined system for monitoring the transition zone in the upper and lower aquifers. The second alternative was a separate system for monitoring the transition zones for the two aquifers. The third alternative was to monitor 10,000 mg/l chloride concentration contour line.

INTRODUCTION

Gaza is an ancient gateway from the desert whose environment is under enormous strain for thousands of years (figure 1). Gaza has been the well-watered gateway to the fertile lands of Canaan (where rainfall exceeds 400 mm/yr) from the desert of Sinai (where rainfall is less than 200 mm/yr). Today, the Gaza Strip is a land under great pressure. It is extremely densely populated, with its population of more than one million over 10 times higher than in 1948, and a population density of about 2500 persons per square kilometre. The environment in Gaza has been under great strain for sometime and now in crisis one from which its people suffer severely today and its landscape may never fully recover.

Gaza's groundwater resources are of great strategic importance and are being 'overexploited'. The strip is underlain by a shallow sandy aquifer that extends north into Israel as the coastal aquifer, up to Haifa, and south into Sinai coast. The Gaza aquifer is composed of Quaternary deposits that include layer of loess, dune sand, calcareous sandstone, silt, and clay. It forms a seaward sloping plain, which ranges in thickness from about 40-50 m near the
eastern border with Israel to 150-200 m at the shore. Clay layers, which begin at the coast and feather out approximately 4 km from the sea, separate the main aquifer into various sub-aquifers near the shore. The base of the aquifer is the low-permeability Saqiya Formation (Tertiary age), and approximately 1 km thick wedge of marine clay, shale, and marl.

Groundwater flows naturally from east to west. In the northern part of Gaza, water levels range from about 2 meters above mean sea level at the eastern border with Israel to mean sea level along the shore. In the southern part, the water level gradient is steeper, from about 10 meters above sea level near the eastern border to mean sea level along the shore. Municipal and agricultural pumping interrupts seaward flow. In some places, flow directions have been reversed as a result of over-pumping. The total estimated production pumping in 1996 was about 40 million m3/yr from municipal supply wells (domestic use) and about 80 million m3/yr from agricultural supply (irrigation). Extractions by Israeli settlements have been estimated to approach 10 million m3/yr.

Replenishment of the aquifer is mainly from infiltration of rainwater. Average recharge from rainfall is estimated at between 40 and 50 million m3/yr. Present irrigation return flow amount 30 million m3/yr. Through flow from the coastal aquifer in Israel is believed to be less than 10 million m3/yr, and is influenced by extraction from production wells in Israel across the Gaza border. Thus, groundwater extraction is currently estimated to exceed recharge by about 50-70 million m3/yr.

Groundwater quality in the Gaza aquifer is generally poor. Over-exploitation has resulted in saltwater intrusion and upconing. In most areas of Gaza, a slow, continuing decline in groundwater levels has been observed since the mid-1970s. Saltwater intrusion varies with depth, and different sub-aquifers exhibit varying degrees of seawater penetration. In the deepest sub-aquifers, high levels of chloride may be related to different sources of salinity (e.g. seawater of possibly poor quality fossil water).

In fact, in order to get more accuracy when assessing seawater intrusion in the Gaza Strip, only a good monitoring network for seawater intrusion can resolve the problem.

There is a multi-purpose groundwater monitoring network in the Gaza Strip. It is used for observing depth of groundwater and nitrate and chloride contents. It was concluded that the existing network is not really suitable for monitoring the seawater intrusion.

The main objective of this paper is to identify the recommended location for additional data collection and to set-up recommended methodology for designing a monitoring network for seawater intrusion in the Gaza Strip.

**VERTICAL CROSS SECTION SIMULATION**

A general view and a typical hydrogeological cross-section of the Gaza Strip are described in figure 2 and figure 3. The present study will focus on the seawater intrusion simulated in a vertical cross section aligned with strip 99 crossing Jabalia area. The pumpage at the area can grossly be considered as being situated along several strips of well batteries. To estimate the extent of solute migration in depth and time such stress conditions, we simulated the salt dependent transport problem in vertical cross sections. The SUTRA-ANE
computer code was applied for simulation of flow and transport in a vertical cross section.

**Discretization and Boundary Conditions**

As mentioned previously, a vertical cross section along strip 99 was considered. This section, 10000 m long and 160 m deep near the shore with an arbitrary thickness of 1 m, was discretized to 1402 rectangular elements and 1527 nodes. The horizontal spacing was constant at 100 m, and the vertical spacing was also constant at 10 m.

A no-flow boundary condition is specified along the bottom of the mesh, where Saqiya clay is considered to be impervious. Along the left boundaries a hydrostatic pressure is defined by:

\[
P = D_s g d
\]

Here, \(p\) is the hydrostatic pressure (M/L.s\(^2\)), \(g\) is acceleration due to gravity (L/s\(^2\)), \(D_s\) is the seawater density (M/L\(^3\)), and \(d\) is the depth (L) below sea level. Therefore, the pressure at the top of this boundary is zero and increases linearly with depth.

The boundary conditions for the transport simulation are dependent on the flow boundary conditions. The inflow of seawater has a seawater chloride concentration of 20500 mg/kg. Any flow out of the mesh at the specified boundaries occurs at the ambient concentration of the aquifer fluid. Solute may neither disperse nor advect across the no-flow boundary. Chloride concentrations in mg/l were converted to total dissolved solids (salinity) in kg/kg by multiplying by a factor \(1.756 \times 10^{-6}\).depth. The mesh and the boundary conditions are shown in figure 4.

**Selection of Model Parameters**

It should be noted that SUTRA employs only one type of porosity, the total porosity. In some instances there may be a need to distinguish between porosity for pores which take place in fluid flow, and pores which contain stagnant fluid. Modifications may be made to include this process by changing the saturation factor \((s_w)\). The total porosity was set at the average value of 0.35 for the unconsolidated sandstone and 0.45 for the clay. The porosity value of clay was modified by decreasing the saturation factor \((s_w)\) to be about 0.2, accordingly the effective porosity was about 0.09. The specific storage of the aquifer was assigned by defining the values for the fluid compressibility and the solid matrix compressibility: \(4.47 \times 10^{-10}\) m.s\(^2\)/kg and \(10^{-10}\) m.s\(^2\)/kg respectively. Later on, during the calibration dispersivities and intrinsic permeability were assigned. Concerning the specific yield values SUTRA-ANE is asking only about the porosity so the user can modify the porosity values for the above cells to be consistent with the specific yield values (effective porosity) for the sand and gravel.

**Set-up of the Steady-State Flow Model**

According to the available data of groundwater abstraction in the Gaza strip, the beginning of depletion of the aquifer started after the year 1935. The steady-state model was
set up for that year as a necessary initial condition for the transient simulation. The steady-
state simulation for year 1935 was used also for calibrating the flow parameters.

Values of hydrological stresses

Total abstraction rates for the year 1935 was estimated for strip 99 according to the logistic extrapolation curve (figure 5). The amount of abstraction (345 m$^3$/year for unit width) was distributed equally on 16 pumping wells along the cross section. The total recharge was assigned to be as in figure 6, with chloride concentration of 50 mg/l. The lateral flow was assumed to follow the calculated value according to the available water table contour map for 1935. The value of the lateral flow was estimated for the unit width at about 750 m$^3$/year with chloride concentration of 200 mg/l.

Set-up of the Transient Model

The simulation period was 61 years, starting in 1935 and ending in 1996. The period from 1935 to 1974 was used to calibrate the model for the transport parameters. This period was discretised into three abstraction periods. The period from 1974 to 1996 was used for model verification. The time step for the transient model was 15 days.

The initial conditions of the transient model for pressure and concentration was taken from the steady-state output model for year 1935.

Values of hydrological stresses

The gross annual abstraction from the strip 99 was described in figure 5. In addition, the natural recharge was assumed to be constant following the values in figure 6 with a chloride concentration 50 mg/l. The lateral flow was estimated from the water table contour map for year 1969 to be about 300 m$^3$/year for each unit width with a chloride concentration 200 mg/l.

CALIBRATION OF THE MODEL

Approach to calibration

The purpose of calibration was to adjust the aquifer parameters so that the model produces groundwater level conditions and chloride concentrations similar to the field observations.

The field measurements of groundwater levels in 1935 and 1969 were taken as the target of calibration. Another set of data was the chemograph for the chloride concentration of the monitoring wells between 1974 to 1996. Unfortunately, the depth of these monitoring wells was not known exactly, which made the calibration process for the transport parameters rather uncertain. The calibration was approached by following a trial and error method. The model was first calibrated for steady-state flow situation in the year 1935, and for transient transport situation from 1935 to 1974.

The steady state flow model calibration for year 1935
The model was run many times after adjusting the values of the intrinsic permeability to produce the groundwater level for the year 1935 as shown in figure 7. Since the simulation period was one year and there is no data before 1935 for the chloride concentration, it was assumed that there was no considerable seawater inflow into the aquifer, due to lack of chemical data to calibrate the transport model in year 1935. The calibrated value for the intrinsic permeability was converted for hydraulic conductivity for fresh water, and found to be 30 m/day for the unconsolidated sandstone.

**The Transient model Calibration 1935-1974**

In this stage, the calibration was carried out for the transport parameters and verification for the flow model was also conducted. This stage was divided into three abstraction periods.

The transport calibration was carried out for the longitudinal and transverse dispersivity. This was based upon the chloride measurements for a number of the wells along this section. This calibration could be done better if the exact depth of these wells was available. The calibrated values of dispersivities were 25 m and 2.5 m for the longitudinal and transverse dispersivities respectively. Figure 8 shows the calculated chloride concentration compared with the measured values in year 1974.

**MODELLING RESULTS AND DISCUSSION**

The position of the transition zone is time dependent. The variations in the interface depend on the geo-hydrological conditions of the aquifer, in particular the fresh water head and permeability value. The model was run for the period from 1935 to 1996. Figure 9 summarises the position of the transition zone for different years.

It is clear that there are two distinct transition zones due to the existence of the clay layer (two sub-aquifers). Also, it can be concluded that most of the saltwater intrusion along strip 99 happened within the period 1935 to 1969 with intrusion rate of 17 m/year. This can be justified by the large amount of abstraction at the eastern border of the Gaza Strip by the Israeli, and by the abstraction of Palestinians inside the Gaza area within this period due to the high increase of the population after the occupation in 1948 and 1967. Furthermore, the intrusion rate within the period 1969 to 1996 was about 14 m/year. The changes in the salinity at the eastern border are very small, due to continuous lateral low-salinity flow (200 mg/l).

Table 1 summarises the final input parameters after calibration for the SUTRA model.

Table 1: Calibrated flow and transport parameters for SUTRA.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unconsolidated Sandstone</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity$^1$</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>Specific storage$^2$ (m$^{-1}$)</td>
<td>2.2*10$^{-6}$</td>
<td>3.1*10$^{-6}$</td>
</tr>
<tr>
<td>Hydraulic conductivity (m/day)</td>
<td>30</td>
<td>0.001</td>
</tr>
</tbody>
</table>


| Longitudinal dispersivity (m) | 25 | 50 |
| Transversal dispersivity(m)  | 2.5 | 0.2 |

1: The porosity value for upper cells of the aquifer (sand) can be considered the specific yield value.

2: The specific storage is differing very slightly according to the fluid density.

Table 2 showing the predicted value of the distance (m) extent, of inland salt migration represented by the end line of the transition zone which is close to the fresh water of the aquifer.

Table 2: The predicted value of the distance extent for inland salt migration (m).

<table>
<thead>
<tr>
<th>Sub-aquifer</th>
<th>year 1996</th>
<th>year 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1600</td>
<td>2300</td>
</tr>
<tr>
<td>B</td>
<td>2200</td>
<td>2800</td>
</tr>
</tbody>
</table>

**DESIGN OF MONITORING ALTERNATIVES**

It is not possible to enumerate all feasible alternatives, which are subjected to the constraints and provide a contribution to the network objectives. Even so, a selection of networks, based on geohydrological insight, can provide enough alternatives for designing a sub-optimal network (Zhou, 1992).

According to the results of the previous chapter about the width of the saltwater/freshwater transition zone, it was clear that the width of the transition zone is considerable. It ranges between 600 m to 1000 m, so it may be useful in the Gaza Strip to monitor the transition zone. This is due to the water scarcity problem in the Gaza area. On the other hand this monitoring scheme will give a high number of monitoring wells, so another option for monitoring was to concentrate on the chloride line of concentration about 10000 mg/l. This chloride contour line represents the mid-line of the transition zone, which defines the position of the interface without mixing.

The approach for locating the monitoring sites was carried out according to the analysis of the chloride contour line patterns. For identifying the boundaries of the transition zone, two chloride contour lines was considered: the 20000 mg/l chloride line (saltwater), which separate the saltwater from the mixing zone, and the 100 mg/l chloride line (fresh water), which separate the mixing zone from the fresh water. **Figure 10** showing the best-fit lines for the transition zone boundary and also for the midline of the transition zone (10000 mg/l Cl). This analysis based upon the value of the coefficient of determination ($R^2$). The coefficient of determination varies from zero to unity. If the coefficient of determination is large, the figure is good and fit.

In order to satisfy the objectives, three monitoring alternatives were developed for the Gaza strip:
• The combined monitoring system of the transition zone for both the sub-aquifers.
• The separate monitoring system of the transition zone for each sub-aquifer.
• The separate monitoring system of the chloride line of 10000 mg/l for each sub-aquifer.

It can be concluded from the above analysis that most of the chloride concentration contour lines have a linear trend, which can be identified if two points on it are known. This can be justified by comparing these results with the current seawater intrusion monitoring model which is used in Israel. This model assumes that the saltwater/fresh water interface is linear, which can be located if two points on it are known, but for more accurate line determination, the monitoring locations were identified according to three sampling points.

ANALYSIS OF THE ALTERNATIVES

According to the previous discussion about the methods of seawater monitoring in chapter 3, the monitoring of the electrical resistivity at specific depth (monitoring clusters) was selected to be the suitable monitoring method for the transition zone movement. This method is used successfully by Amsterdam Water Company, and it can determine the saltwater/fresh water interface with acceptable accuracy.

In the following monitoring alternatives, the number of monitoring clusters and the sampling points were determined according to the locations of the predicted chloride contour lines every 5 years of the period 2000-2015.

**Combined monitoring system of the transition zone (Alternative 1)**

This alternative was suggested to monitor the transition zone (saltwater/freshwater) as a combined system for both the sub-aquifers. This means that the same monitoring clusters can be used for both sub-aquifers.

It can be realised from the schematisation in figure 11, that the total number of monitoring clusters was 16, and the total number of sampling points 48. These numbers were determined according to the assumption that the trend line of the chloride concentration contour lines is linear. Accordingly three sampling points with approximately the same electrical resistivity on each contour line is enough to locate the line.

**Separate monitoring system of the transition zone (Alternative 2)**

The second alternative was suggested to monitor the transition zone as a separate system for each sub-aquifer (figure 12).

The number of monitoring clusters for the upper sub-aquifer was 6, and the number of sampling points was 24. In addition to that, the number of monitoring clusters for the lower sub-aquifer was 11 and the number of sampling points was 24.

**Separate monitoring system for the chloride line (10000 mg/l) (Alternative 3)**
In alternative 3, a separate monitoring system for the chloride 10000 mg/l contour line was suggested (figure 13).

THE SELECTION OF SUB-OPTIMAL NETWORK

The final network is designed taking into account the continuity of the existing observation wells, the accessibility of locations, the cost of the installation of observation wells and the cost of administration of the network. The following selection of the network will consider only some of the above mentioned factors, so the selected network can only be a sub-optimal network.

According to the existing situation of groundwater abstraction in the Gaza strip, most of the groundwater is abstracted from the upper sub-aquifer. This means the priority for seawater intrusion monitoring is for the upper sub-aquifer. Moreover, the economic situation in the Gaza strip is not good which will not allow the construction of a typical seawater intrusion monitoring network. According to the previous mentioned reasons, it seems that the most suitable alternative for seawater monitoring in the Gaza strip is the third alternative. This alternative was the separate monitoring system for the chloride contour line with 10000 mg/l content for each sub-aquifer.

CHOICE OF SAMPLING FREQUENCY

Sample location and frequency are among the most critical aspects of sampling because sample collection at the wrong location and time can give erroneous results even when executed carefully. Initial selection locations for sampling was selected previously.

In order to select an appropriate sampling frequency, very good monthly historical data, mainly for the chloride concentrations, is needed. Unfortunately, monthly data is not available for the Gaza aquifer. So, the output from the SUTRA model for one year have been used to evaluate the chloride concentration fluctuations with time in the Gaza aquifer strip 99 (figure 14).

CONCLUSIONS

- The deterioration of groundwater quality in the Gaza Strip coastal aquifer mainly the result of the seawater intrusion in to the aquifer and the local upconing. This is due to the lowering of fresh water level in the relation to excessive groundwater abstraction.

- According to the available geological cross-sectional data, the aquifer in the northern part of the Gaza Strip can be sub-divided into two sub-aquifers. This aquifer can be considered mainly as unconfined aquifer.

- A vertical cross-section of the aquifer along strip 99 in the northern part was simulated by SUTRA-ANE computer 2-D code. The total number of rectangular elements (100 m X 10 m) was 1402 with nodes 1527. The time step for the transport model was 15 days and the total time of simulations was for 1935-2015. Better discritisation can give a more accurate
solution but this depends very much on the available computer capacity.

- The widths of the transition zone, for the upper sub-aquifer, simulated by SUTRA-ANE in years 1996 and 2015 were 1600 m and 2300 m respectively. The widths for the lower sub-aquifer in years 1996 and 2015 were 2200 m and 2800 m respectively.

- Most of the seawater intrusion along strip 99 was happened within the period 1948 to 1969 with intrusion rate of 17 m/year. This was due to the large amount of groundwater abstraction at the eastern border of Gaza within that period.

- SUTRA-ANE computer code was a useful tool for predicting the transition zone of the Gaza Strip aquifer. The result of the model was used for identifying locations and number of monitoring sites for seawater intrusion.

- Monitoring of the coastal aquifer should start early before intrusion occurs. This can be accomplished by establishing the early warning monitoring network based mainly on the geophysical method, which is not considered an expensive method.

- The coastal aquifer should be continuously monitored in order to determine the progress of the saline intrusion and check the model predictions carefully. This can be accomplished by establishing a detection monitoring network using conventional observation wells for groundwater sampling.

- Monitoring of seawater intrusion should include water level, water abstraction, temperature and electrical conductivity as well as chloride, sulphate, sodium and calcium ion concentration.

- Three monitoring alternatives were proposed for seawater intrusion monitoring the combined system for monitoring the transition zone (alternative 1), and the systems for monitoring the transition zone. The third alternative was considered to be a good alternative for the Gaza Strip. In this alternative, three monitoring cluster areas proposed to monitor the upper sub-aquifer and five monitoring clusters for the lower sub-aquifer, which is a low number if it is compared with alternatives 1 and 2 with 16 and 17 monitoring clusters respectively.

- Concerning the sampling frequency, the fresh water level should be measured monthly and the major chemical ions in the groundwater should be measured twice a year due to the seasonal fluctuations in summer and winter.

**RECOMMENDATIONS**

- The Palestinian Water Authority should establish a monitoring division to be responsible for collecting, screening and interpreting the data.

- An extensive geological, hydrogeological investigation programme should be carried out before establishing the long term monitoring programme in the Gaza Strip.
• The modelling and monitoring approach for designing the monitoring network can be used for the other cross-sections of the Gaza Strip. The suggested total number of cross-sections for the entire Gaza Strip is four sections. This is based on the geological cross-section data.

• The overlapping monitoring wells should be determined and the deep wells for monitoring should be constructed. The upconning can be monitored using the existing shallow wells after investigating their adequacy.

• The time domain electromagnetic method (TDEM) is recommended for investigating seawater intrusion. This method can be used in an area where is no chance to establish observation wells.
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