The salt-water body in the Northern part of Yarkon-Taninim aquifer: Field data analysis, conceptual model and prediction

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Abstract

The salinization processes of the Yarkon-Taninim aquifer (Israel) were investigated for many years, and so far little was known about the saline water body prevailing in the North-Western margin of the aquifer. The salinity of the water in this water body is close to that of seawater. Recently, in drilled wells in the Northern part of the aquifer, it was found that the freshwater and the saltwater are in direct contact, with no geological separation. A relatively thin transition zone, separates the freshwater from the saltwater beneath them.

A conceptual model is proposed, based on the field findings: the freshwater flows above the saltwater due to the different density and some mixing takes place around the thin transition zone, which can be approximately modeled as a sharp interface. The saltwater body is connected weakly with the sea, so that the freshwater body mainly determines the pressure and the resulting water head in the saltwater body. The flow in the saltwater body is very slow compared to the flow in the freshwater body.

Using water level measurements by monitoring wells, we were able to estimate the position of the interface as a function of time. In the last 50 years the interface elevation was continuously rising at an average rate of 2.8 m per year.

This study is a first attempt to derive a model of the saltwater body in the Yarkon-Taninim aquifer that is based on quantitative considerations.

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1. Introduction

The Yarkon-Taninim aquifer is one of the three major sources of freshwater of Israel, the other two being the Sea of Galilee and the coastal aquifer. It extends throughout the western part of Israel, from the Judea and Samaria ridge in the East, to the Mediterranean Sea in the West, beneath the coastal plain (Figs. 1 and 2; for detailed maps of the aquifer see Weinberger et al., 1994). The aquifer extends over an area of about 6000 sq km and it constitutes the western drainage of the Judea Group aquifer.

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The deep salt-water body at the bottom of the Yarkon-Taninim aquifer was identified by oil and monitoring wells drilled through the aquifer. This salt-water body contains water with Cl content of 16,000–21,000 mg/L, close to that of seawater, and was found near the western boundary of the aquifer, at depths of 700–1000 m and more. New monitoring wells drilled recently by the Israel Water Commission (Gev et al., 2001) revealed important findings concerning the transition zone between freshwater and saltwater. This article aims to analyze the existing data in light of the recent findings in order to propose a conceptual model of the two water bodies in the aquifer, to determine the time-behavior of the transition zone, and to arrive at an estimation of future changes.

Fig. 1. Location map of springs and wells in the Northern Yarkon-Taninim basin. Springs are denoted by triangles and wells referred to in the text by full circles. Pumping wells are denoted by hollow circles and the aquifer boundary follows Guttman and Zukerman, 1995.
2. Field data

2.1. Hydrogeology

The aquifer was described by Weinberger et al. (1994). For the sake of completeness we recall briefly a few features.

The thickness of the Judea Group is between 1000 m in the northern part of the aquifer and 600 m in the southern part. The Judea Group aquifer is composed mainly of karstic and permeable limestones and dolomites interbedded with argillaceous rock units, characterized by much lower permeabilities. In some areas, the argillaceous beds...
separate the upper and lower parts of the Judea Group sequence, creating two subaquifers (Mercado, 1980b; Guttman et al., 1988b; Weinberger et al., 1994; Fig. 2).

The replenishment area of the aquifer is the Judea and Samaria Mountain Range. A recharge of about 360 MCM/yr (Million cubic meters per year) on the average originates from rainfall on the outcrops of the aquifer, which extend over an area of about 1800 sq km.

The aquifer is phreatic in the recharge area, and is confined by the Senonian Mt. Scopus Group, west of the recharge area (Fig. 2). The flow is primarily directed westward, from the recharge area through the aquiferous units of the Judea Group, and then northward towards the Rosh Ha-Ayin (Yarkon) and the Taninim springs. The annual discharge of these springs in the undisturbed period (until the 1950s) was estimated as 220 MCM/yr and 100 MCM/yr, respectively (Hydrological Service of Israel, 2004).

The western boundary of the aquifer was defined by the gradual lateral transition from the permeable Judea Group sequence, to the mainly argillaceous and non-permeable Talme-Yafe Group, which is its synchronous equivalent (Fig. 2). In the south it lies beneath the Coastal Plain, whereas west and northward of Tel Aviv, this boundary extends west of the Mediterranean coastline. Weinberger et al. (1994) review many previous works that arrived at the conclusion that this facies transition acts as a hydrological barrier, preventing groundwater flow from the Judea Group aquifer to the Mediterranean Sea.

In the region of the Taninim springs, it was assumed in previous works (Mandel, 1961; Bar-Yosef, 1978; Mercado, 1980a; Guttman, 1980, 1988b, 1998; Guttman and Zukerman, 1995), that the Judea Group aquifer may be connected with the Mediterranean Sea, either directly or along the buried Or-Akiva fault system. In the area near the Taninim springs, the Pleistocene aquifer is laid with unconformity over the dolomite rock of the Turonian aquifer. The Pleistocene aquifer itself is connected to the sea, but a hydrological barrier is assumed to separate the aquifer from the sea, thus preventing seawater intrusion (Guttman, 1998).

### 2.2. Pumping regime

Aquifer exploitation started in the 1930s, but became significant only in the 1950s. In 1951, 24 MCM/yr were pumped by 46 (mostly shallow) wells. Since that year, the drilling and the exploitation developed at a steady rate to sustain the development of the economy. Thus, in the hydrological year 1965/66, 327 MCM were pumped by 219 wells. The pumping remained around this level since, with an average annual pumping rate of 295 MCM (with a standard deviation of 80 MCM) in the 1960–2000 period (Hydrological Service of Israel, 2004).

The intensive exploitation since the 1950s caused a drop of the water levels of the aquifer by 5–10 m in the confined zone; as a result the springs outflow diminished considerably. Thus, starting from 1963 the Rosh Ha-Ayin (Yarkon) springs practically dried up whereas the Taninim springs discharge has decreased to a level of 20–40 MCM/yr. The water levels in the aquifer were low at the 1970s and the 1980s, and rose sharply following the extremely rainy winters of 1991/2–1992/3 (Figs. 3 and 4); in those years they reached levels close to those observed at the historical, undisturbed period, before 1950.

### 2.3. The existence of saline water in the aquifer

Freshwater of low salinities (50–250 mg/L Cl) prevails in most of the Yarkon-Taninim aquifer, in the recharge zones and in the foothills area. It emerged in the Yarkon Springs at an average Cl content of 165 mg/L (Mandel, 1961; Kronfeld, 1997). Water of much higher salinity was detected in the North-Western part of the aquifer. The field findings about these waters are described in the following.

#### 2.3.1. The Taninim springs

The Taninim springs behave differently from those of the Yarkon: their salinity is much higher, as was recognized long before the intensive pumping started (Blake and Goldschmidt, 1947). In the early 1950s, when the discharge was around 95–100 MCM/yr, the average Cl content \( C_T \) in the springs was around 900–950 mg/L and had changed little with time (Mercado, 1980a). The chemical and isotopic composition of the water of the springs was inspected in a few studies, and the results show that the water is a mixture of the
aquifer’s freshwater on one hand, and seawater on the other (Bar, 1983; Guttman et al., 1988b; Schilman and Almogi-Labin, 2003). The discharge of seawater in the mixture $Q_{ST}$ can be determined approximately by the Chloride mass balance

$$Q_{ST}C_S + (Q - Q_{ST})C_f = QC_T$$ (1)

where $Q$ is the total discharge of the springs, $C_S = 22,000$ mg/L is the seawater content, and $C_f$ is the freshwater Cl content, estimated as 100 mg/L. For $Q = 95–100$ MCM/yr, we find $Q_{ST} = 3.5–3.9$ MCM/yr. Thus, the discharge of the Taninim springs in the undisturbed period was a mixture of about 3.5–3.9 MCM/yr of seawater and 91–97 MCM/yr of aquifer freshwater.

The salinity of the Taninim springs changed since the 1950s in an intricate manner: the average chloride content in the springs decreased from 900–950 mg/L in the 1950s to a minimum of about 600–700 mg/L in the 1960s and then increased again to 1000–1400 mg/L in the 1980s and to 1300–2000 mg/L in the 1990s (Hydrological Service of Israel, 2004).

Inspection of the salinity and discharge variations of the Taninim Springs reveals two types of trends: (i) a persistent trend of rise in salinity since the late 1950s, and (ii) a variable component correlated to the discharge rate, expressed by the fact that high discharge periods are also characterized by high salinity values. This process was especially noticed following the extremely rainy winter of 1991/2, when...
Table 1
Information about wells that reached the saline water body in the northern part of the Yarkon-Taninim aquifer

<table>
<thead>
<tr>
<th>#</th>
<th>Well name</th>
<th>Year drilled</th>
<th>Ground level [m above MSL]</th>
<th>Total depth drilled [m]</th>
<th>Interface depth [m below MSL] and (year of measurement)</th>
<th>Transition zone width [m]</th>
<th>Cl content of saline water [mg/L]</th>
<th>Measured salt water density [gr/cm³]</th>
<th>Salt water head [m above MSL] and (date)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ga’ash 1</td>
<td>1958</td>
<td>26</td>
<td>1115</td>
<td>–</td>
<td>–</td>
<td>15,800–16,870 in pumped water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Tanimim deep</td>
<td>1977–1978</td>
<td>7</td>
<td>650</td>
<td>–</td>
<td>–</td>
<td>17,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Netanya Oil 1</td>
<td>1986</td>
<td>40</td>
<td>1362</td>
<td>Saline water only</td>
<td>–</td>
<td>18,500; 20,250</td>
<td>1.02–1.026</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Menashe T/3</td>
<td>1986–1987</td>
<td>20</td>
<td>1140</td>
<td>Saline water only</td>
<td>–</td>
<td>19,500–22,200</td>
<td>1.025</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Pardes Hana monitoring</td>
<td>2002</td>
<td>43</td>
<td>1008</td>
<td>882 (2002)</td>
<td>5</td>
<td>17,600</td>
<td>~8.44 (1.9.2002)</td>
<td></td>
</tr>
</tbody>
</table>

Data based on Bar-Yosef and Michaeli (1999); Guttman (1986); Guttman and Rosenthal (2001); Shachnai (1989); Guttman et al. (1988a, 1999, 2002a,b,c, 2003, 2004a,b); Baida et al. (1987).
the salinity rise is closely correlated with the discharge rise.

Further important information regarding the Taninim springs stems from the fact that the springs appear as dozens of outlets over an area of about a hectare, with varying salinity and temperature. As indicated by Blake and Goldschmidt (1947), the salinity of the water in the Taninim springs increases as one proceeds towards West–North–West (which is also the local underground flow direction). As for temperature distribution, a correlation between salinity and water temperature was observed: in the less saline springs, lower temperatures were recorded, whereas the more saline springs displayed higher temperatures (Bar-Yosef, 1974).

These findings suggest a mechanism of cold fresh water flowing above warmer saltwater, with mixing along the contact zone between the two.

2.3.2. Old monitoring wells

The first direct evidence of existence of water of salinity close to seawater came up in the 1950s from deep wells drilled in the aquifer for the purpose of oil exploration. Much later, starting in the 1970s, until 1999, wells were drilled in order to investigate the saline water body. These deep wells reached a water body with salinity close to that of seawater (16,000–21,000 mg/L Cl) as shown in Table 1. Saltwater age was estimated in a few wells as following: 7,500–20,000 years in Menashe T/3 well (Baida et al., 1987, Guttman et al., 1988a); at least 15,000 years in Netanya Oil well (Guttman, 1986).

Also, the water levels in these two wells were measured on a monthly basis (Fig. 5). Since the pipes of these wells contain saltwater solely, the water level represents the saltwater head. It is seen that it is lower than the sea level and it follows closely the fresh water head measured in two neighboring wells that tapped fresh water only (Guttman et al., 1988a). Thus, Netanya Oil saltwater head and Hadasim Oil freshwater head display a difference of about 23–24 m (Fig. 3); these wells are located 3 km apart. Similarly, the difference between the Menashe T/3 saltwater head and Menashe T/1 freshwater head is about 21–21.5 m (Fig. 4); these wells are located 5 km apart.

In contrast, the much smaller difference between the saltwater head in Menashe T/3 and Netanya Oil (Fig. 5) is around 1–2 m at most during the period 1987–1995. The difference rose slightly between 1987 and 1991, tended to zero (or even to a negative value) following the 1991/2 rainy winter and stayed near zero in the years 1992–1994.

![Fig. 5. Water levels in the Menashe T/3 and Netanya Oil saltwater wells, relative to MSL. The difference between the water levels in Menashe T/3 and Netanya Oil wells is also shown.](image)
2.3.3. Recent monitoring wells

In order to capture and follow the evolution of the saline water body, the Israel Water Commission has initiated drilling a few monitoring wells that cross the transition zone between fresh and salt water, starting 2001 (Table 1). Besides measuring the heads in the two bodies, the salinity profile was determined by EC (electrical conductivity) logs (Fig. 6). The most interesting feature is that no sign of geological separation between the two water bodies was detected; furthermore, in five of these wells, a transition zone between the water bodies was detected. As shown in Table 1, the thickness of the transition zone varied between 5 and 40 m in those wells. These estimates are based on visual inspection of the EC logs. The higher value of 40 can be attributed to a measurement artifact (as a result of the pumping prior to the measurement). Thus, it seems reasonable that the range of 5–20 m should be used as a guideline for approximating the thickness of the transition zone throughout the aquifer.

All these data are integrated in a conceptual model and analyzed in a quantitative manner for the first time in the present study.

3. Analysis of field data

3.1. General

The field findings described in the previous section lead to the conclusion that a saline water body with salinity close to seawater is lying in the deeper part of the aquifer, while freshwater is above it, without a geological separation in between (Figs. 2 and 7). The fact that the saltwater head is lower than the sea level indicates that this body is well separated from the sea, as it was inferred in the past on geological ground.
(Section 2.1). Another important finding is that the transition zone between fresh and saline water is relatively thin. Such a thin transition zone can be modeled as a sharp interface, defined by the median concentration of the two bodies of water. The salient question is whether one can infer the location of the interface in the past, before its detection in the recent years by the new monitoring wells. Such an analysis is undertaken here by examining the difference between the fresh and salt water heads in neighboring wells.

Thus, when examining the difference between the water levels in Hadasim Oil freshwater well and Netanya Oil well (Fig. 3), it can be clearly seen that the difference slightly decreases through the years of measurement. This small but steady change in the difference is used in the following to determine the interface upward motion.

A calculation of the depth of the interface is possible when two monitoring wells are located nearby, and when one of these wells reaches the freshwater body while the other taps the saline water body, and when the composition of the water in the well pipes is known (Fig. 7). The calculation is based on the known Ghyben–Herzberg formula.

The present derivation follows the one that leads to the Ghyben–Herzberg formula.

In the more general case of a varying density along the transition zone, it can be shown that a symmetric change of the density is equivalent to an abrupt change in density. The continuity of pressure gives for that case:

\[
\rho_i g(h_i + \zeta) + \int_{-\zeta}^{\zeta_u} \rho(\xi)g d\xi = \rho_s g(h_s + \zeta),
\]

where \(\zeta_i\) and \(\zeta_u\) are the lower and upper boundaries of the transition zone. The integral term in Eq. (3c) is which can be neglected (however, if a hydraulic gradient exists, and can be estimated, the fresh water head in the aquifer should be projected at the saline well location),

- A sharp interface that models the middle of the transition zone separating water of constant densities (however, the variable density can be taken into account if the profile is known, as shown below).

On the basis of the above assumptions, the pressure at the interface can be expressed as the hydrostatic pressure of the freshwater \((p_i)\) on one hand, or that of the saline water \((p_s)\) on the other hand. At the interface

\[
p_i = p_s \quad \text{for} \quad z = -\zeta
\]

where \(z\) is the vertical coordinate pointing upwards, and \(\zeta\) is the depth of the interface below MSL (mean sea level) (Fig. 7).

Eq. (2a) leads to

\[
\rho_i g(h_i + \zeta) = \rho_s g(h_s + \zeta)
\]

where \(h_i = p_i/\rho_i + z\) is freshwater head, \(h_s = p_s/\rho_s + z\) is saltwater head (negative in our case), \(\rho_i\)-specific mass of freshwater, \(\rho_s\)-specific mass of saltwater, \(g\)-acceleration of gravity.

Solving Eq. (2b) for \(\zeta\), we get

\[
\zeta = \frac{1}{\delta} [h_i - (1 + \delta)h_s]
\]

where

\[
\delta = \frac{\rho_s - \rho_i}{\rho_i}
\]
actually an average of $\rho$ multiplied by the depth of the transition zone. If $\rho$ changes symmetrically from $\zeta_u$ to $\zeta_l$ then the middle of the transition zone $(\zeta_u + \zeta_l)/2$ can be defined as $\zeta$ and is given simply by Eq. (3a).

Thus, the interface depth can be computed by (3a) for any point in time for which the water levels in both wells, representing $h_l$ and $h_s$, were measured simultaneously.

### 3.2. Calculation of the interface elevation in Menashe T/3 and Netanya

The depth of the interface was computed in two locations: near the Netanya Oil well and near the Menashe T/3 well. In both cases the estimated value\(^1\) of $\delta$ (Eq. 3b) was $(1.021 - 0.998)/0.998 \approx 0.023 \pm 0.002$.

The depth near the Netanya Oil well was computed by using the measurements from Netanya Oil (saline well) and from the Hadasim Oil well (freshwater monitoring well). The distance between these two wells is 3 km (Fig. 1) and the freshwater flow in that region of the aquifer is very slow. Indeed, freshwater head difference between the wells is a few centimeters (following Guttman and Zukerman, 1995) and can be neglected for our purposes. Furthermore, since the wells are far away from the recharge zone and from pumping wells, Dupuit’s assumption is applicable.

The depth of the interface $\zeta$ in Netanya was computed by Eq. (3a) at different times in the measurement period of the Netanya Oil well (1987–2004).

As for the calculation of the interface depth near the Menashe T/3 well, here the closest freshwater monitoring well—Menashe T/1—is located at a distance of 5 km away, and a significant head difference exists between the two wells. Hence, extrapolation was carried out by using the following relationship

$$h_{T/3} = h_{T/1} - \Delta h$$

Where $h_{T/3}$ is the projected freshwater head in Menashe T/3, computed from the measured $h_{T/1}$ level in the Menashe T/1 well. The small difference $\Delta h$ is given by the assumed linear relation

$$\Delta h = 0.25 + (1.3 - 0.25) \frac{h_{T/1} - 10}{20 - 10}$$

This formula is based on the results of the numerical models of the freshwater flow by Guttman and Zukerman (1995), and Zukerman and Shachnai (1999). Further details may be found in Paster, 2004 (p. 44). Again, the wells are separated from pumping wells.

The depth of the interface $\zeta$ in Menashe T/3 was computed by Eq. (3a), using the extrapolation (4a,b) for the measurement period of Menashe T/3 (1987–1995).

The measurements in nearby wells are usually done in the same day. If this is not the case, then the measurement was neglected or the water level was estimated for the date of the measurement in the second well, by linear interpolation in time.

### 3.3. Error estimation

The error in estimating $\zeta$ depends strongly on the accuracy of the head measurements and the accuracy of estimation of $\delta$. Assuming reasonable possible errors of 10 cm in the head measurements, and a possible error of 0.002 in $\delta$, a combined relative error of 10% in $\zeta$ is expected (an absolute error of 100 m). However, this error is mostly a consistent one and, therefore, cannot have a significant effect on the conclusions regarding the rate of change in time.

Further error is introduced by the projection of the freshwater head (in the case of Menashe T/3); the error in $\Delta h$ as given by (4b) was estimated as 15%, so that an additional error of 7 m in $\zeta$ is expected (Paster, 2004, p. 44).

### 3.4. Results

The computed depths of the interface ($\zeta$) in Netanya Oil and in Menashe T/3 are shown in Fig. 8. Examination of this figure reveals a few findings:

- There is a clear trend of rise of the interface with time, in both locations. However, the rates are different: in the Netanya area, the interface rose
slowly from around 1045 m below MSL in 1988 to 1000 m below MSL in 2004. In the Menashe T/3 area, the interface moved at a faster rate from around 930 m below MSL in 1987 to 870 m below MSL in 1995.

- In 1987, the first year after completion of the drilling of both wells-Menashe T/3 and Netanya Oil, head measurements suggest a rise of 40–60 m in one year. This large rise is regarded as an artifact, and was not taken into consideration when computing the rise of the interface in the entire aquifer.

- Subsequently the interface rose continuously at rates shown in Fig. 8.

- The results are consistent with the recent direct measurements of interface elevation by EC logs in a few monitoring wells (Netanya South, Ra’anana deep, Pardes-Hana, Gan-Shmu’el; Table 1).

4. The proposed conceptual model and discussion of results

4.1. The conceptual model

The field findings and the data analysis of the preceding sections have led us to propose a conceptual model of the saline water body and of its dynamics as follows.

1. Unlike coastal aquifers, the salt water body is confined at the bottom of the aquifer and it is separated from the sea, being in direct contact with the overlying fresh water body. This is supported by geological evidence (Weinberger, 1991), by the consistent lower head below sea level $h_s < 0$ (Fig. 7), by the high correlation between the heads $h_s$ and $h_f$ in the two bodies and by the direct findings of the new monitoring wells (Figs. 3–6).

2. The saline water body is practically stagnant, with slow changes of $h_s$ in space and time. This conclusion stems from the small difference in head of the two wells of Meanshe T/3 and Netanya Oil (Fig. 5) as well as from the slow rate of rise of the interface (Fig. 8).

3. A weak connection with the Mediterranean Sea exists. Indeed, in the historical, undisturbed period, equilibrium must have been reached, characterized by a steady interface and a permanent salt flushing by the fresh water flowing to the Taninim Springs outlet. Hence, the estimated salt water discharge $Q_T = 3.5–3.9$ MCM/yr had to be balanced by an equal inflow.
from the sea. There are a few indications that the connection exists in the Or-Akiva fault area, besides geological evidence. First, a weak Southward $h_s$ gradient was observed (Fig. 5). Secondly, the relatively fast rise of the interface in Menashe T/3 (compared to the slow rate in Netanya) can be attributed to the proximity of this well to the region of connection with the sea. The connecting rock may be viewed as a low permeability zone that operates under the difference of head between the sea and $h_s$, conveying sea water to the bottom of the aquifer. This, together with the Taninim outlet may be viewed as a doublet that is causing the upconing of the interface. When the intensive pumping started, the head difference between the sea and the salt water body increased considerably causing a parallel increase of the sea water inflow $Q_S$. As a result, an upconing of the interface took place, with a higher rate at the Menashe T/3 well that is close to the inlet than the one at the remote Netanya well, similar to the situation prevailing beneath a pumping well (Dagan and Bear, 1968).

This picture is consistent with the different reaction of the interface in the two wells to the quick rise of $h_s$ (and subsequent drop of $Q_S$) after the rainy year 1991–1992, when the interface rose relatively fast in Netanya while dropping at Menashe (Figs. 5 and 8).

This picture does not exclude the presence of additional possible connections with the Mediterranean Sea.

4. The mechanism of salinization of the Taninim Springs is flushing of salt water in the mixing zone by the flowing fresh water. The effect of dispersion is indeed supported by the presence of the transition zone in the density profiles of the new monitoring wells (Fig. 6). The positive correlation between the Taninim discharge and its salinity (Section 2.4) is also consistent with this picture: dispersion increases with fresh water velocity.

4.2. Average interface rate of rise

The average rate of interface rise in Netanya during the period 1988–2004, of about 2.8 m/yr, can be used as a guide for the average everywhere. This can be justified by a few reasons:

1. In Netanya, the period of measurements is quite long (18 years so far), during which there were periods of very high levels as well as very low. The variations of the interface rise are assumed to be smoothed out over this period. It is reasonable to assume that the same rate prevailed in the period of intensive pumping 1952–1991. Indeed, the average representative freshwater levels in the northern part of the aquifer in the 1952–1991 and in the 1988–2004 periods were 13.69 and 13.35 m, respectively (Hydrological Service of Israel, 2004).

2. In Netanya, unlike Menashe T/3, there is no need to make an interpolation of the freshwater head between neighboring wells, thus avoiding a possible additional error.

3. The large distance of Netanya from the assumed area of seawater inlet to the aquifer, is attenuating the fluctuations of the interface elevation that occur near the inlet.

4.3. Computing the saltwater body head $h_s$ in the historical (undisturbed) period

The average rate of the interface rise, of 2.8 m/yr, can be used for determining the head of the saltwater body in the historical period (i.e. before 1950), which is an important parameter in the modeling of the saltwater body in the aquifer.

The head in the saltwater body in the rainy year of 1992/3 reached 2 m below MSL, when the fresh water levels in the aquifer were similar to those of the historical period. Assuming this saltwater head to be the same as in the historical period will be inaccurate, because the situation in 1992 is different. Indeed, the interface rose significantly in the 40 years period of pumping until 1992. That rise can be approximated as 112 m (40 years $\times$ 2.8 m/yr). The freshwater level in the historical period near Netanya can be approximated as $h_{f,\text{hist,Netanya}} \approx 20.7$ m (following Guttman and Zukerman, 1995 and Hydrological Service of Israel, 2004). Hence, Eq. (3a) yields for the saltwater head in the
historical period

\[ h_{s, \text{hist}} = \frac{1}{1 + \delta} \left( h_{I, \text{hist}} - h_{I, 1992} - (1 + \delta) h_{s, 1992} \right) \]

\[ -\delta (\zeta_{\text{hist}} - \zeta_{1992}) \approx \frac{1}{1.023} (20.7 - 23.9) \]

\[ -0.023 \times 112 \]

\[ = -5.6 \text{ m} \] (5)

i.e. 5.6 m below MSL in the average.

The error of the estimate (5) is about \( \pm 1.5 \text{ m} \), and it mainly originates from the approximative values of \( h_{I, \text{hist}} \) and \( \zeta_{\text{hist}} \).

4.4. Conjecture about future steady state

In the future, if the low freshwater levels of the pumping period will be maintained, the interface may keep rising and it is possible that a new steady state will be achieved. The depth of the interface in this new equilibrium state may be roughly estimated by assuming that the Taninim salt water component will be equal to the rate of flushing, both having the historical values of \( Q_s = 3.5–3.9 \text{ MCM/yr} \) of seawater. To ensure this seawater discharge through the inlet from the sea, the saltwater head has to reach the historical value (5.6 m below MSL). In order to attain this state, the saltwater head must rise by around 2 m above the present value of about \( -7.5 \text{ m} \) (Fig. 5). According to Eq. (3a), this will result in a further rising of the interface by appr. 90 m. Such a rise will be accompanied by the saltwater body invasion of areas of the aquifer where currently only freshwater exists.

If we assume that the rate of rise is constant and equal to the average one of 2.8 m/yr, the total time needed is around 30 years.

These are rough estimates based on far reaching assumptions: maintaining the current freshwater levels in the aquifer; dependence of the sea water inflow on the head differences only; same amount of flushing in the mixing zone for two different configurations of the interface and constant rate of rise.

A more accurate analysis of the interface change in space and time should be based on modeling flow and transport in the entire aquifer. Such a model is under development.

5. Summary and conclusions

This study is the first attempt to develop a quantitative model of the saltwater body in the northern Yarkon-Taninim aquifer. The proposed conceptual model of the flow regime in the Yarkon-Taninim aquifer is summarized as follows.

Freshwater flow, originating in the high recharge area, flows above a stagnant saline water body at the bottom of the aquifer. A narrow transition zone, which can be approximated by a sharp interface, separates them. Salt water that mixes by dispersion with fresh water is flushed to the Taninim Springs. A low permeability zone of connection with the Mediterranean Sea is needed in order to maintain the steady state, which is supposed to have prevailed in the historical period (until 1950). This historical flow regime had presumably existed for a few thousands of years before intensive pumping started in the 1950s. The latter caused a drop of the fresh water levels in the aquifer, which in turn led to a drop of the saltwater head and an increase of the inflow of sea water. As a result, the interface rose in the pumping period, e.g. in Netanya–Hadasim region, where the interface rose by about 48 m between 1988 and 2004.

The average rate of rise of the interface in the pumping period was estimated as 2.8 m/yr.

A few hydrological findings support the assumption made in the past, on geological grounds, that the connection with the sea is in the Or-Akiva fault area.

Understanding the dynamics of the salt water body is of great importance for the management of the aquifer. For this reason the Israel Water Commission has initiated drilling a few monitoring wells. At present we are in the process of developing a comprehensive model of the aquifer that will provide a more accurate tool for predicting the saline water motion under different pumping scenarios.

It is hoped that the present study is of relevance to similar cases of freshwater–saltwater flow elsewhere in the world.

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