Groundwater flow patterns adjacent to a long-term stratified (meromictic) lake

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This paper examines, for the first time, the unique situation of a groundwater system adjacent to a long-term stratified (meromictic) lake. Using conceptual and numerical models, the configuration of groundwater interfaces between the three different water bodies (regional groundwater and upper and lower lake waters) and the flow patterns were quantitatively evaluated assuming a homogenous aquifer. A complex flow system, controlled by density difference, is created near the lake, where three circulation cells are developed. These results are different from the classic circulation cell that is found adjacent to nonstratified water bodies (lakes or oceans). Sensitivity analyses reveal that the results are sensitive to changes in thickness and density of the upper water mass of the lake. The Dead Sea, under its possible future meromictic conditions, serves as an ideal example of such a system. Thus, the model’s results can be used as a preliminary assessment for groundwater behavior adjacent to the lake, if and when stratification will develop.


1. Introduction

The occurrence of a fresh-saline water interface in an aquifer is due to density differences between fresh groundwater and a saline water body. Many researchers have modeled the fresh-saline interface within coastal aquifers under steady state and transient conditions [e.g., Abarca et al., 2007; Frind, 1982; Galeati et al., 1992; Henry, 1964; Michael et al., 2005; Pinder and Cooper, 1970; Sanford and Konikow, 1985; Segol et al., 1975; Simpson and Clement, 2003, 2004; Voss, 1984]. Others have modeled the effect of sea or lake level changes on the interface [e.g., Essaid, 1990; Essink et al., 2010; Harrar et al., 2001; Kiro et al., 2008; Meisler et al., 1985; Yechieli et al., 2010].

A first-order approximation for these relationships was given by Ghyben [1888] and Herzberg [1901]. Essentially, the Ghyben-Herzberg approximation assumes quasi-static equilibrium, with both saline and fresh water being stagnant. In addition, it considers the hydrostatic pressure distribution within the aquifer and a sharp interface between the two waters. Under these assumptions, the steady state geometry and location of the fresh-saline interface can be calculated, using the respective densities. A more realistic description, which also accounts for groundwater flow and dispersion, shows the dynamic nature of the interface and the mixing zone between the fresh and saline waters [e.g., Frind, 1982; Galeati et al., 1992; Henry, 1964; Lee and Cheng, 1974; Paster and Dagan, 2008; Pinder and Cooper, 1970; Sanford and Konikow, 1985; Segol et al., 1975; Simpson and Clement, 2003, 2004; Voss, 1984]. The mixing of the saline water with the fresh groundwater in the aquifer causes continuous seaward outflow of saline water, which drives a saline water circulation cell beneath the fresh-saline water interface [Cooper, 1959].

All the above studies considered seas and lakes with a homogenous water column. However, the configuration of the fresh-saline interface and the groundwater flow patterns adjacent to a long-term stratified lake, which is the topic of this study, might be different.

Stratification of the water column in a lake results from the density difference between the water layers. Temperature and/or solute concentration are the main contributors to these density differences. Generally, lakes can be classified as holomictic (nonstratified) or meromictic (stratified) on the basis of the duration of stratification prior to complete mixing of the water column [Findenegg, 1935]. Most of the inland water bodies in the world undergo a complete mixing in their water mass at least once a year and, as such, are defined as holomictic lakes. In contrast, meromictic lakes rarely experience complete mixing throughout their water column, between once in a few years and once in a few centuries. These lakes are divided into two water masses, which do not interact with each other, and may differ in their physical, chemical, and biological conditions. The monimolimnion, which is the upper water mass, undergoes seasonal mixing, similar to the mixing that occurs in holomictic lakes. The monimolimnion is the lower water mass, which is not affected by the seasonal mixing and exists only in these lakes. The bottom water mass remains isolated from the atmosphere, commonly developing anoxic conditions. The two water masses are separated by a density gradient, called the chemocline or halocline. Usually, a thermocline is associated with the chemocline. Resistance of the entire water column to
mixing depends mainly on the density differences across this layer.

[6] Selected examples for meromictic lakes are estuarine basins, such as the Black Sea, the largest meromictic basin in the world [Ozsoy and Unluata, 1997], mine pit lakes (e.g., Island Copper mine lake [Fisher and Lawrence, 2006]), lakes along marine coastal regions, where storms and unusual tidal events create intrusions of salt water (e.g., Lower Mystic Lake [Ludlam and Duval, 2001]), lakes with submerged springs that supply dense, saline groundwater into the lake (e.g., Lac Pavin [Aeschbach-Herzig et al., 2002] and Camp Lake [Moncur et al., 2006]), and lakes where accumulation of salts occurs by the decomposition of organic material in the deep water and dissolution of its end products (e.g., natural lakes in southern Norway and Finland [Honeyn, 1997, 2002; Merilainen, 1970]). The Mono Lake [Jellison et al., 1998], the Great Salt Lake [Lin, 1976], and the Dead Sea [Steinhorn, 1985; Stiller and Chung, 1984] are selected examples of saline lakes, which are known for their prolonged periods of meromixis. The fact that in the latter kind of meromictic lakes the lower water mass is significantly denser than the upper one can better emphasize the effect of stratification on their adjacent groundwater system. In this study we will use the Dead Sea as a case study. The Dead Sea was meromictic for several centuries prior to its 1979 overturn [Steinhorn, 1985] and might become a long-term meromictic lake once again if Red Sea water were to be conveyed to it via the Red Sea–Dead Sea conduit [Gavrieli et al., 2005].

[7] The Dead Sea is a hypersaline and extremely dense (total dissolved solids > 340 kg m$^{-3}$, density > 1240 kg m$^{-3}$) terminal lake located within a pull-apart basin formed by the Dead Sea transform fault. Its water level is the lowest terrestrial location on Earth, and it currently (year 2011) is located at 424 m below mean sea level (−424 m). As such, the lake defines the regional base level for the surrounding surface and groundwater drainage systems. The depth of the Dead Sea is ~300 m (its deepest point is −723 m). The Dead Sea vicinity consists of two main aquifers, the Quaternary alluvial and the Upper Cretaceous carbonate aquifers. The Quaternary alluvial aquifer is adjacent to the Dead Sea, and it consists mainly of gravel with intercalations of clay sediments and salt layers, which divide the gravel into a few subaquifers. This aquifer is bounded by normal faults, which set Upper Cretaceous carbonate rocks of the Judea Group against the Quaternary alluvial sediments. The recharge of the aquifer is mostly through lateral flow from the Judea Group aquifer, which is replenished in the highlands, 10–30 km to the west, and by flash floods. Direct rain is negligible because of the arid climate and high evaporation in the Dead Sea region. The fresh groundwater hydraulic gradient is 0.002–0.007 m m$^{-1}$ and varies in different parts of the Dead Sea coast [Yechieli, 2000].

[8] Unlike lake-aquifer relationships in holomictic lakes, the relationships between a long-term meromictic lake and the groundwater system in the adjacent coastal aquifer is a subject that has not yet been studied. Therefore, the primary objective of this study is to evaluate the steady state configuration of groundwater within a homogenous aquifer adjacent to any stratified lake. The processes affecting the location of the fresh-saline interface(s) and the flow regime next to such a lake were studied, using conceptual and numerical models. The second objective of this study is to provide a preliminary assessment to the configuration of groundwater within the aquifer adjacent to the Dead Sea when the latter is stratified.

2. Conceptual Model

[9] The objective of the conceptual model is to provide a basic assessment for the steady state shape and position of the interfaces between the fresh groundwater and the two water bodies from the stratified lake (the upper saline water and the lower brine) in the adjacent coastal aquifer. In order to do so, we used the first-order Ghyben-Herzberg approximation. For the case of a nonstratified lake, the equation is

$$h_i = \frac{\rho_f}{\rho_g - \rho_f} h_f,$$

where $h_f$ (m) and $h_s$ (m) are the hydraulic heads of the fresh and saline groundwater, respectively, and $\rho_f$ (kg m$^{-3}$) and $\rho_s$ (kg m$^{-3}$) are the densities of fresh and saline groundwater, respectively. Figure 1a describes the resulting configuration.

[10] Using the same approach, we introduce three different equations for the case of a stratified lake to determine the location of the three interfaces between the three water bodies within the aquifer (Figure 1b), for any given hydraulic gradient and density or thickness of the mixolimnion.

[11] The thickness of the fresh groundwater lens ($f_2$), between the fresh groundwater table and the mixolimnion interface (line 1 in Figure 1b) can be calculated using

$$f_2(x) = h(x) - \frac{\rho_s}{\rho_f - \rho_s},$$

where $h(x)$ (m) is the elevation of the groundwater table above the lake level at any horizontal distance $x$ from the shore line, $\rho_s$ is the density of the mixolimnion, and $\rho_f$ is the density of the fresh groundwater.

[12] The thickness of the intruded mixolimnion water ($D$), between interface 1 and interface 2 (line 2 in Figure 1b) can be calculated using

$$D(x) = f_2(x) \frac{\rho_b - \rho_s}{\rho_u - \rho_b} - d \frac{\rho_b - \rho_s}{\rho_u - \rho_b} - h(x) \frac{\rho_b}{\rho_u - \rho_b},$$

where $\rho_b$ is the density of the monimolimnion and $d$ is the thickness of the lake mixolimnion. Farther away from the lake, these two interfaces merge into one, creating a wedge-like shape of mixolimnion water, which intrudes into the aquifer (Figure 1b). From this merging point, only one interface (line 3 in Figure 1b), between the fresh groundwater and the monimolimnion water, exists. The groundwater lens thickness at this location can be determined using

$$f_1(x) = d \frac{\rho_b}{\rho_u - \rho_f} + h(x) \frac{\rho_b}{\rho_u - \rho_f}.$$

[13] The model parameters (Figure 1b) were taken from the Dead Sea (under the expected meromictic conditions) and its adjacent gravel aquifer. The value of the monimolimnion density ($\rho_b = 1236$ kg m$^{-3}$) was assumed to be
similar to that of the Dead Sea brine. The densities of the two other water bodies were set at 1000 kg m\(^{-3}\) for the fresh groundwater (\(\rho_f\)) and 1100 kg m\(^{-3}\) at the mixolimnion (upper lake layer; \(\rho_u\)). The fresh groundwater hydraulic gradient was set at 0.007 m m\(^{-1}\) [Yechieli, 2000], and the thickness of the mixolimnion (\(d\)) was set for 50 m, which is in the order of magnitude of the expected thickness [Gavrieli et al., 2006].

The importance of this conceptual model is that it provides a first-order assessment for this unique hydrological case. However, it does not take into account all physical mechanisms involved in this system. As such, this conceptual model cannot fully predict the exact configuration of the groundwater system adjacent to a stratified lake. In order to attain a higher-order assessment, we used numerical models as follows.

3. Numerical Simulations

Numerical simulations were run in order to provide a better description of the spatial configurations of the interfaces and the variable-density groundwater flow patterns. Several simulations under different lake conditions were conducted. As in the conceptual model, the hydrological and limnological parameters were based on the expected conditions of the Dead Sea under stratification and its adjacent gravel aquifer (Table 1).

3.1. Formulating the Problem

The governing equations for variable-density flow in porous media are conservation of fluid and solute masses. The flow equation, derived from Darcy’s law for a phreatic aquifer under isothermal conditions and variable densities, is described by the Richards equation:

\[
\rho_f [S, S] \frac{\partial p}{\partial t} + \nabla \cdot \left[ \frac{\bar{k} \rho_f}{\eta} \nabla (p + \rho_f g Z) \right] = q_s, \tag{5}
\]

where \(\rho_f\) is the fluid density \([M L^{-3}]\), \(S\) is the storage coefficient \([L^2]\), \(p\) is the fluid pressure \([M L^{-1} t^{-2}]\), \(t\) is the time \([t]\), \(\bar{k}\) is the intrinsic permeability tensor \([L^2]\), \(\eta\) is the viscosity of water \([M L^{-1} t^{-1}]\), \(g\) is the gravitational acceleration \([L t^{-2}]\), \(Z\) is the vertical coordinate \([L]\), \(q_s\) is the source or sink parameter \([M L^{-1} t^{-1}]\), and \(S_e\) (dimensionless) is the effective saturation and \(k_r\) (dimensionless) is the relative permeability, both calculated using the van Genuchten model for the unsaturated zone and their characteristic.

Figure 1. Groundwater interface configuration adjacent to (a) a holomictic lake and (b) a meromictic lake. Numbers represent the interfaces between the three water types.
Table 1. Hydrological Parameters of Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage coefficient</td>
<td>$S$</td>
<td>EPS</td>
<td>(kg m$^{-2}$)$^{-1}$</td>
<td>Freeze and Cherry [1979]</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\theta_s$</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid fraction, residual</td>
<td>$\theta_r$</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper layer thickness</td>
<td>$h$</td>
<td>50</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Permeability $b$</td>
<td>$k_b$</td>
<td>$1 \times 10^{-13}$</td>
<td>m$^2$</td>
<td>Gavrieli et al. [2006]</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>$\gamma$</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater density</td>
<td>$\rho_w$</td>
<td>1000</td>
<td>kg m$^{-3}$</td>
<td>Freeze and Cherry [1979]</td>
</tr>
<tr>
<td>Dead Sea water density</td>
<td>$\rho_s$</td>
<td>1236</td>
<td>kg m$^{-3}$</td>
<td>Gavrieli et al. [2005]</td>
</tr>
<tr>
<td>Dead Sea water concentration</td>
<td>$c_s$</td>
<td>340</td>
<td>kg m$^{-3}$</td>
<td>Gavrieli et al. [2005]</td>
</tr>
<tr>
<td>Mixolimnion water concentration</td>
<td>$c_{mw}$</td>
<td>140</td>
<td>kg m$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Fluid density (25°C)</td>
<td>$\rho$</td>
<td>$\rho_0 + 0.694c$</td>
<td>kg m$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Fluid viscosity $b$</td>
<td>$\mu$</td>
<td>0.001</td>
<td>kg s$^{-1}$ m$^{-1}$</td>
<td>Freeze and Cherry [1979]</td>
</tr>
<tr>
<td>van Genuchten constant for media type</td>
<td>$\alpha$</td>
<td>0.5</td>
<td>m$^{-1}$</td>
<td>van Genuchten [1980]</td>
</tr>
<tr>
<td>van Genuchten constant for media type</td>
<td>$n$</td>
<td>1.5</td>
<td></td>
<td>van Genuchten [1980]</td>
</tr>
<tr>
<td>van Genuchten constant for media type</td>
<td>$l$</td>
<td>0.1</td>
<td></td>
<td>van Genuchten [1980]</td>
</tr>
<tr>
<td>Longitudinal dispersivity</td>
<td>$\alpha_1$</td>
<td>1</td>
<td>m</td>
<td>Based on element size</td>
</tr>
<tr>
<td>Transverse dispersivity</td>
<td>$\alpha_2$</td>
<td>0.5</td>
<td>m</td>
<td>Based on element size</td>
</tr>
<tr>
<td>Molecular diffusion (25°C)</td>
<td>$D_m$</td>
<td>$1 \times 10^{-9}$</td>
<td>m$^2$ s$^{-1}$</td>
<td>Freeze and Cherry [1979]</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>$g$</td>
<td>9.81</td>
<td>m s$^{-2}$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$EPS, a function that depends on the storativity of the water and the solid and porous media; it has an infinitesimal value on the order of $10^{-15}$.

$^b$In order to adequately represent a coastal homogenous aquifer adjacent to the Dead Sea, which is built of gravel mixed with clay layers, we took a lower permeability value ($1 \times 10^{-13}$ m$^2$) than just for gravel material ($1 \times 10^{-11}$ m$^2$), estimated by the pumping test [Wollman et al., 2003].

$^c$The viscosity of the Dead Sea is 3 times that of fresh water. This issue is not considered in this study.

The solute transport through porous media is controlled by advection and dispersion. The conservation of solute mass may be written as

$$\frac{\partial c}{\partial t} = \nabla \cdot (\mathbf{D} \nabla c) - \nu \cdot \nabla c,$$

where $c$ is the concentration ($M L^{-3}$), $\mathbf{D}$ is the dispersion diffusion tensor ($L^2 T^{-1}$), and $\nu$ is the average linear velocity of the fluid ($L T^{-1}$). The coupling between the solute transport equations and the Richards equation is through two linear equations of state, describing changes in the density and viscosity of the fluid under isothermal conditions (25°C). The coupling between the Richards equation and the solute transport equation was made through the linear velocity expression:

$$\nu = -\left(\frac{\nabla_s}{\eta_0} \right) \cdot \nabla (p + \rho \gamma Z).$$

where $\theta_s$ is the porosity of the medium.

Table 1 presents the hydrological parameters used in the simulations, which are based on the properties of the Dead Sea.

3.2. Model Description

Equations (5) and (6) were solved numerically using COMSOL Multiphysics. This program solves partial differential equations using the Galerkin finite element technique. The groundwater configuration under steady state conditions was studied using a two-dimensional grid, subdivided into a triangular element net, which represents a homogenous gravel aquifer (Figure 2). Also included in the numerical model are the limnological and hydrological parameters (Table 1) representing the Dead Sea and the adjacent coastal aquifer. The length of the cross section was set to be 2000 m. This length was chosen to prevent the brine, which intrudes the aquifer from the lake, from reaching the left boundary (boundary 1, Figure 2) and flowing out of the cross section. Grid height above the bottom of the aquifer was set at 120 m. The fresh groundwater enters the cross section from the left boundary (labeled 1) with a constant flux of $3.5 \times 10^{-6}$ m s$^{-1}$, a reasonable value for the Dead Sea area [Shalev et al., 2006]. Neglecting the rainfall recharge for the Dead Sea area (which was very low under the arid condition in this area), the upper boundary (labeled 2) is defined as a no-flow boundary. The lower boundary (labeled 4) is also defined as no flow and represents the bottom of the aquifer. The lower part of boundary 3 is the lake’s floor, or the lake’s bathymetry. Above the lake level this boundary represents the exposed topography. The values of the density and thickness of the mixolimnion and the density of the monimolimnion are similar to those used in the conceptual model (Table 1).

Initial conditions for the solute transport equation were obtained by assigning the salinity of the Dead Sea to the entire porous medium and then flushing the cross section with fresh water from boundary 1 and intrusion of the mixolimnion water, forming several interfaces, until no changes in salinity and hydraulic head were observed and steady state conditions were attained.

3.3. Results

3.3.1. The Inner Structure of the Aquifer

The final results of the numerical simulation represent the steady state configuration. The distribution of concentrations within the aquifer under the parameters presented in Table 1 is shown in Figure 3. The lake mixolimnion water intruded into the aquifer under the fresh groundwater. Accordingly, three different water bodies are...
found within the coastal aquifer: fresh water, saline (mixolimnion-derived) water, and brine. As described in the conceptual model (Figure 1b), the existence of three water bodies, different in their densities, creates three interfaces and a wedge-like shape of mixolimnion water within the coastal aquifer. However, the geometry of the interfaces and their locations are different from those calculated in the conceptual model. In addition, the distance that the mixolimnion water intrudes into the aquifer is approximately 200 m in the numerical simulation (Figure 3), whereas in the conceptual model it intrudes about 700 m (Figure 1b). These differences are reasonable considering that the conceptual model neglects robust physical processes in the aquifer, assuming hydrostatic conditions with no flow and dispersion.

3.3.2. Groundwater Flow

The fresh groundwater flows on top of the denser water, which intrudes into the aquifer from the adjacent lake. Eventually, it discharges into the lake through a narrow section, which is located below the point where the groundwater table and lake water meet. The velocity of the fresh groundwater increases as it approaches the lake because the flow section becomes narrower [Yezieli et al., 2001].

The detailed flow patterns of the water bodies in the subsurface adjacent to the lake are shown in Figure 4. Water from the lake intrudes into the aquifer from the right boundary (Figure 2) and creates three circulation cells: The lower and largest circulation cell consists of the brine from the monimolimnion flowing into the aquifer and is carried back to the lake by the flow of fresh groundwater, thereby creating a dispersion zone between these two water bodies (interface 3 in Figure 1b). Part of it flows below the lower boundary of the wedge (i.e., interface 2),

![Figure 2](image1.png)  
**Figure 2.** Finite element mesh and boundary conditions for the numerical simulation model.

![Figure 3](image2.png)  
**Figure 3.** A steady state configuration of the water bodies within the aquifer. White, purple, and black arrows demonstrate schematic flow velocities of fresh, saline, and brine groundwater, respectively. The black box marks the intruded wedge-like zone that is enlarged in Figures 4 and 5.
reaching the lake at the depth of the halocline. In doing so, this flow also carries with it part of the water from the wedge of the mixolimnion waters, thereby initiating the intermediate circulation cell. The other part flows above the upper boundary of the wedge (i.e., interface 1), reaching the lake close to its surface. This flow initiates the upper circulation cell of the wedge of the mixolimnion waters. This latter cell is also the smallest circulation cell in this system.

### 3.3.3. Limnological Parameters

[24] The simulations described above deal with only one set of parameters for both the lake and the aquifer. However, in order to obtain a more generalized insight into groundwater behavior adjacent to meromictic lakes, we ran sensitivity analyses with regard to two parameters of the mixolimnion: (1) its density and (2) its thickness. Table 2 summarizes the values used in six different configurations of these two parameters. Other lake parameters and hydraulic parameters of the aquifer remained similar to those presented in the model description (Table 1).

[25] The results of the sensitivity tests are shown in Figure 5. Model results were found to be sensitive to changes in both parameters. They determine whether or not water from the mixolimnion will intrude into the aquifer. This in turn determines the groundwater configuration and flow patterns within the aquifer close to the lake.

[26] Model runs show that when the mixolimnion flows into the aquifer and floats on top of the denser water below (i.e., cases 2, 3, and 6 in Table 2), it creates a wedge-like shape and three interfaces between the water bodies. The intrusion distance increases with increasing values of density and thickness of the mixolimnion. The flow patterns within the aquifer are characterized by the development of the three circulation cells described above (Figures 5b, 5c, and 5f).

[27] When water from the mixolimnion does not intrude into the aquifer (i.e., cases 1, 4, and 5 in Table 2), the mixolimnion wedge does not form, and the only one interface is between the fresh groundwater and the denser water from the monimolimnion. However, this single interface is different from the case of one interface adjacent to a nonstratified lake since it extends from the depth of the lake's halocline and not from the lake level. As a result, all the lake's floor above the halocline is flushed by fresh groundwater. In these cases, only one, relatively large, circulation cell is found. This cell is formed when water from the monimolimnion intrudes into the aquifer and circulates back into the lake through the halocline (Figures 5a, 5d, and 5e).

### 4. Discussion

[28] Our numerical model reveals that the steady state groundwater configuration and the variable density flow patterns in the vicinity of a stratified lake are more complicated than that adjacent to a holomictic water body. These processes were studied with regard to two different limnological parameters of the lake.

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**Table 2. Parameter Values Used for the Sensitivity Analysis**

<table>
<thead>
<tr>
<th>Case</th>
<th>Upper Layer Density (kg m⁻³)</th>
<th>Upper Layer Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1050</td>
<td>50</td>
</tr>
<tr>
<td>Case 2</td>
<td>1100</td>
<td>50</td>
</tr>
<tr>
<td>Case 3</td>
<td>1150</td>
<td>50</td>
</tr>
<tr>
<td>Case 4</td>
<td>1050</td>
<td>30</td>
</tr>
<tr>
<td>Case 5</td>
<td>1100</td>
<td>30</td>
</tr>
<tr>
<td>Case 6</td>
<td>1150</td>
<td>30</td>
</tr>
</tbody>
</table>

*See Figure 5.*
Figure 5. Distribution of concentrations and flow patterns for the six different cases (Table 2). Schematic white arrows demonstrate fresh, brine, and saline groundwater flow patterns.
4.1. Intrusion of Mixolimnion Water Into the Aquifer

As shown in section 3.3.3, the occurrence of intrusion depends on the thickness and density of the mixolimnion. The intrusion of water from the mixolimnion into the aquifer dictates the groundwater configuration and the variable-density flow patterns adjacent to the stratified lake. The decrease in the thickness of the mixolimnion can prevent the development of the wedge and the additional circulation cells in the aquifer. A decrease in the density of the mixolimnion works similarly. On the other hand, an increase in its density allows the development of the wedge even when the depth of the mixolimnion is reduced. In our specific simulations, the intrusion of water from a 50 m thick mixolimnion ispossible for density differences between the mixolimnion and the fresh groundwater that are higher than 100 kg m$^{-3}$ (Figure 6). For the cases of a 30 m thick mixolimnion, these differences have to be at least 150 kg m$^{-3}$.

The pressure gradient between saline water and fresh groundwater is the main factor that drives the lake water intrusion and dictates its distance. In such system, fresh groundwater flow to the lake above the interface and saline water intrude into the aquifer below it. The situation in the three-interface system is more complicated. When the mixolimnion is relatively dense and thick, its pressure overcomes the pressure of the fresh groundwater flowing toward the lake, which acts in the opposite direction. Therefore, water from the mixolimnion intrudes into the aquifer and to a greater distance. In these cases, there is still fresh water, which flows to the lake above the interface. On the other hand, at low densities (small density differences) or a thin mixolimnion, the pressure of the fresh groundwater does not allow this intrusion, and the fresh groundwater flows to the lake above the interface through the whole section of the lake’s floor.

![Figure 6](image_url)

**Figure 6.** Intrusion of mixolimnion water into the aquifer as a function of the layer thickness and density difference between the mixolimnion and the fresh groundwater ($\Delta \rho$). The dashed line is a schematic border between the two areas.

4.2. The Case of the Dead Sea: Change From a Stratified to a Nonstratified Lake

During the twentieth century, the Dead Sea water level dropped by more than 30 m as a result of anthropogenic diversion of the fresh water for domestic, industrial, and agricultural consumption. The resulting negative water balance affected the limnological structure of the lake. When Neev and Emery [1967] carried out the first in-depth study of the Dead Sea in 1959–1960, the water column was meromictic. Twenty years later, in 1979, the Dead Sea water column overturned and mixed [Steinhorn, 1985], ending a period of about 300 years of stratification [Stiller and Chung, 1984]. Since then, the Dead Sea has been a holomictic lake, with stratification developing in the spring and overturn occurring in early winter [Anati and Stiller, 1991; Gertman and Hecht, 2002], except for two short meromictic periods following exceptionally heavy winter rain floods.

In order to stop the decline and to stabilize the lake water level, a project to convey seawater from the Red Sea to the Dead Sea is being considered [Gavrieli et al., 2005]. Preliminary results of a limnological modeling assuming a dramatic increase in inflow volumes to the Dead Sea reveal that it will have a major impact on the lake structure in addition to stabilizing or even raising its water level [Gavrieli et al., 2006]. The mixing of the Dead Sea brine with the seawater (or reject water after desalinization) is expected to change the lake from holomictic back to meromictic, as it was prior to 1979.

The Dead Sea was chosen here as a case study since its predicted future and its past limnological conditions of stratification are unique in comparison with other meromictic lakes in the world. Its uniqueness relates to its extremely dense brine in comparison to other water bodies, along with past and possible future long-term stratification. Given the large density differences that may develop between the mixolimnion and monimolimnion, it is possible that the aquifer adjacent to the stratified Dead Sea did and possibly will again develop the wedge and three circulation cells described here. These conditions are ideal for understanding the relationships between meromictic lakes and the adjacent coastal aquifer.

4.3. Possible Implications on Lakes and Their Immediate Surroundings

The model results show an unusual configuration of groundwater and variable density flow patterns adjacent to a long-term stratified lake in comparison to those next to a nonstratified one. This special structure might have some implications, as a feedback, on limnological parameters of the lake. The recharge of groundwater into the lake from two different locations (i.e., cases 2, 3, and 6) or from a wide section on the lake floor (i.e., cases 1, 4 and 5), instead of the single narrow section as in the usual case, can affect the composition of water near shores and therefore can be very important for chemical, biological, and ecological processes in the lake. In addition, the understanding of behavior of the freshwater-seawater interaction in the aquifer is essential for the assessment of groundwater resources in coastal zones. Therefore, the results of this model can be used for the evaluation of the location and configuration of the freshwater-seawater interface in aquifers adjacent to such lakes.
The described configuration and flow patterns might also have implications on hydrogeological processes in the aquifer. One example is the possible effect on the creation of sinkholes near the Dead Sea. During the decline in the Dead Sea water level the fresh-saline water interface along the shore receded too, and a salt layer, located within the subsurface of the aquifer adjacent to the Dead Sea, was exposed to freshwater unsaturated with respect to halite. This led to the dissolution of the salt layer and to the development of subsurface cavities. With time, these cavities collapse and form numerous sinkholes along the shores of the Dead Sea [Shalev et al., 2006; Yechieli et al., 2006]. The simulation results presented here show that in all six cases of the stratified lake, water with lower concentrations in comparison to the Dead Sea brine is expected to be found within the aquifer at a distance of several hundred meters from the shoreline (Figure 5). Under such conditions, the present dissolution of the salt layer and the formation of sinkholes might accelerate.

5. Summary

This study presents conceptual and numerical analyses for the steady state configuration and the variable density flow pattern of groundwater in a homogeneous coastal aquifer adjacent to a long-term meromictic lake. The results indicate that the groundwater configuration and flow patterns can be significantly different from those near a holomictic lake. These differences are expressed by the creation of a wedge-like structure of water from the mixolimnion that intrudes into the aquifer. In addition, three circulation cells, controlled by the density differences between the bodies, and three interfaces between three different water bodies within the aquifer (including the fresh groundwater) are formed. Sensitivity analyses to variations in the density and thickness of the mixolimnion reveal that only a thick mixolimnion and relatively large density differences between the three water bodies in the aquifer enable the intrusion of mixolimnion water and the creation of this unique groundwater configuration and flow patterns.

While model results successfully reproduce the groundwater flow configurations adjacent to a long-term meromictic lake, the model does possess a number of limitations beyond those accounted for in any numerical model: The treatment in this model is restricted to a simple homogeneous aquifer and abrupt boundary between the layers in the stratified lake. In addition, dynamic processes that lead to such a unique groundwater configuration and the sensitivity of the model to changes in its hydrogeological parameters were not examined.

Despite these restrictions, this model demonstrates, for the first time, the potential impact of a long-term stratified lake on its surrounding aquifer. Its strength is that it can be used for or any aquifer next to a meromictic lake on the basis of its specific hydrological and limnological parameters. In addition, this model provides preliminary assessment for the future conditions in the aquifer adjacent to the stratified Dead Sea. Reinforcement for the results presented in this study is obtained from the fact that both conceptual and numerical models show the creation of the wedge-like shape. This unique groundwater configuration can have an effect on the hydrogeological cross section of the aquifer and might have implications for water management.

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References


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