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# EFFECTS OF RAISING THE DEAD SEA WATER LEVEL ON JORDAN'S GROUNDWATER RESOURCES

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## ملخـــــص

ان ربط البحر الأبيض المتوسط بالبحر الميت بقناة تنقل الماء من الأول إلى الثاني وللإستفادة من فرق الارتفاع بين البحرين لانتاج الطاقة له نتائجه السلبية على المنطقة ومنها الغمر التدريجي لبعض المنشآت مثل البوتاس والطرق والجسور وبعض الأراضي الزراعية. يضاف إلى هذه التأثيرات السلبية عملية دفع جبهة المياه المالحة باتجاه الشرق في الجهة الشرقية من البحر الميت وباتجاه الغرب في الجهة الغربية منه وذلك على امتداد البحر الميت البالغ ٨٠كم.

ان مثل هذا العمل له تأثيراته السيئة على مصادر المياه الجوفية في الاردن حيث سيتم احلال ٦،١ × ١٠٩ متر مكعب من مخزون المياه الجوفية العذب بمياه البحر الميت المالحة اثناء عملية رفع مستوى البحر الميت بعشرة أمتار، كما هو مخطط يضاف اليها احلال ٤،٥ × ١٠٩ متر مكعب اخرى وذلك الى حين حصول التوازن الديناميكي على طول جبهة المياه العذبة المالحة.

## ABSTRACT

Connecting the Mediterranean and the Dead Sea with a canal, utilizing the difference in sea levels to produce energy, is fraught with side effects, such as the gradual flooding of existing structures and the raising of the salt water front which has started to regress at the northern and southern ends of the Dead Sea. In addition, the canal would displace the fresh-salt water interface at the eastern edge of the Dead Sea landward along about 80 km. Such an alteration would have grave consequences for Jordan's groundwater resources. This displacement would amount to replacing $6.1 \times 10^9 m^3$ of fresh groundwater with water from the Dead Sea during the initial stage, and an additional $4.5 \times 10^9 m^3$ during the later stage until a dynamic equilibrium is achieved.

## INTRODUCTION

Generally, any change in sea water level is followed by a transition period, during which the flow in the coastal aquifer is unsteady, and where the interface seeks a relevant equilibrium condition. The Mediterranean Dead Sea Canal, as currently planned, will transport water from the Mediterranean to the Dead Sea and raise the level of the Dead Sea by 10 m., from −400.5 m. to −390.5 m. within 12 to 15 years of its completion, which is expected in 1990 (M.D. Project). The transition period will prevail not only until the planned water level of −390.5 m. is reached, but rather it will last until a new equilibrium in the hydrodynamic process is achieved.

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### The interface configuration

The interface configuration of salt and fresh water starts at the shores or beneath the Dead Sea (Fig. 1), with a relatively high gradient of inclination. The interface then flattens out landward where it tends to become horizontal or to end at an aquiclude (Salameh & Khudier, 1983), Fig. 2. The nearly horizontal interface is the depth to which precipitated water percolates, mixes within the dispersion zone with intruding Dead Sea water, and then rises along faults to the surface at the western slope of the Dead Sea (Salameh & Khudier, 1983). The interface configuration is a function of the densities of the two fluid phases (Dead Sea and fresh groundwater), the inland distance from the shorelines and the hydraulic gradient, as well as the amount of discharged groundwater (Ghyben-Herzberg, 1888; Glover 1959; Bear, 1972).

The densities of Dead Sea water and fresh water, and the fresh water level at certain distances from the Dead Sea shores are already known(Neev & Emery, 1967; Salameh & Khudier, 1983). The hydraulic gradient within the Zarqa-Ma'in area and along its longitude is 4% (Salameh & Udluft 1984). To the west it in creases gradually to give the pattern shown in Figure 2. The amount of fresh groundwater in hydraulic equilibrium with Dead Sea water which flows to the Dead Sea is calculated to 6 $m^3/s$ (Salameh Udluft 1984).

### Configuration of the interface

From the known methods for calculating the interface configuration of salt and fresh water, with the available data, the approximation of Ghyben-Herzberg (1888) and the method from Glover (1959) proved appropriate for this paper.

As a result of raising the Dead Sea's water level by 10 m., from −400.5 m. to −390.5 m. (M.D. Project), the interface will adjust itself to the new potential by moving landward to achieve a relevant state of equilibrium with a stationary interface and a fresh water flow to the Dead Sea.

The Gyben-Herzberg approximation was developed for the calculation of the interface configuration in coastal phreatic aquifers. It assumes a static equilibrium, hydrostatic pressure distribution of the fresh water, and stationary sea water. The Ghyben-Herzberg equation for the above conditions is:

$$\frac{hs}{hf} = \gamma_f(\gamma_s - \gamma_f)$$

*where:* $hs$ = depth of the salt water column to the interface.

$hf$ = depth of the fresh water column to the interface.

$\gamma_s$ = density of the salt water.

$\gamma_f$ = density of the fresh water.

For oceanic water with a density of 1.025, $\frac{hs}{hf} = 40$.

For the Dead Sea water with a density of 1.255, $\frac{hs}{hf} = 4.44$.

This shows that the depth of the interface of Dead Sea fresh water is only about

$\frac{1}{10}$ of the interface depth of oceanic fresh water.

Using the Ghyben-Herzberg approximation for the special case of the Dead Sea gives the following equation (Fig. 2):

$$Yiid\gamma_s = Yiid\ \gamma_f + (400.5 + Yfi)\ \gamma_f$$

where: Yiid = depth of point Xi at the interface below Dead Sea level.
Yii = depth of point Xi at the interface below sea level.
Yiid = Yii − 400.5 m.
Yfi = elevation of point Xi at the fresh groundwater table with respect to sea level.
$\gamma_s$ = density of Dead Sea water, 1.225 g/cm³.
$\gamma_f$ = density of fresh water, 1 g/cm³.
400.5 m = Dead Sea level below sea level.

By rearranging and substituting the densities

$$Yii = \frac{488.6 + Y_{fi}}{-0.225}$$ is obtained

The interface on figure 2 is plotted using the above calculated depths, Yii.

The plot of these values shows that the interface configuration flattens rapidly landward.

Another method for the calculation of the interface configuration was approximated by Glover (1959) and Kremer (1977). This approximation is given in the following equation:

$$Z = \sqrt{\frac{2q\ X}{(\gamma_s - \gamma_f)k} + \frac{q^2}{(\gamma_s - \gamma_f)^2 k^2}}$$ (Langguth 1980)

where: Z = the depth of the interface in a landward lying point (X) in respect to sea water level.

q = the quantity of fresh groundwater flowing to the sea per unit length (m²/s).

k = the permeability of the aquifer for fresh water (m /s).

The intersection of the interface with the sea bottom occurs at point $X_0$

$$X_0 = \frac{q}{2\ (\gamma_s - \gamma_f)\ k}$$

At the shore line, X = 0, the depth of the interface equals

$$Z_0 = \frac{q}{(\gamma_s - \gamma_f)\ k}$$

Since the main interest in this study is concerned with the landward movement of the interface and not the interface configuration itself and because of the complexity of the boundary conditions accompanying the solution of the partial differential equations of continuity, the Ghyben-Herzberg approximation and the Glover

equations are applied to the present state of Dead Sea level of −400.5 m. and for the raised level of −390.5 m.
The area between the two interfaces gives the amount of fresh water which will be substituted by Dead Sea water.

Because the calculations involve the densities of the water, some considerations concerning the density of the added Mediterranean water should be made. After connecting the Mediteranean Sea and the Dead Sea by a conduit and transferring the water to the Dead Sea the level of the latter, according to published data (M.D.Project), will be raised to an elevation of −390.5 m. within 12-15 years.

The evaporation from the water brought to the Dead Sea equals 1600mm. (Bentor 1961, Neuman in United Nations 1982). If 15 years is assumed to be the filling period, then the accumulative evaporation equals 1.600m. × 15 = 24m. of Mediterranean Sea water with a salinity of 3.8% and a density of 1.025 g./cm$^3$. The salt content of the 24m. water column will be effectively concentrated in the remaining 10m., which represent the rise in the Dead Sea level. This makes the density of these 10m. equal:

$$1 + \frac{24 + 10}{10} (1-1.025) = 1.085 \text{ g./cm}^3$$

An additional pressure of 1085 g/cm$^2$ at the present level of the Dead Sea will result after 15 years when this level is raised by 10m. This leads to a landward movement of the salt-fresh water interface which, in turn leads to a rise in the fresh groundwater level.

### The interface movement

The volume of the portion of the aquifer which will be occupied by Dead Sea water after raising, considering the eastern shore of the Dead Sea with a length of 80 km. as the site of intrusion and taking 10 km. as the width at which the interface is bounded by an impervious bottom (this assumption is justified when one considers the different geological cross sections of Quennell (1959) and Bender (1968), can be approximated according to the Ghyben-Herzberg equation. This increase in pressure is 1085 g/cm$^2$ corresponding to a fresh water column of 10.85 m. The volume of the portion of aquifer = $80 \times 10^3 \times 10^4 \times 10.85 = 8.68 \times 10^9$ m$^3$.

The interface goes down to about 2000m and the shore is enlarged by an average of 333m giving an aquifer volume intruded by Dead Sea water due to horizontal shift of $80 \times 10^3 \times 2 \times 10^3 \times 333 = 53.28 \times 10$m$^3$ added together give a volume of $61.96 \times 10^9$ m$^3$.

The porosity of the aquifer averages 17% (Salameh and Udulft 1984). According to Schneider *et. al.*, (1983), it ranges from 25 to 30%, and, due to pore space reduction, from 15-24%. To be on the safe side a porosity of 10% is used in this paper. The volume of water filling the above calculated volume of the aquifer portion equals $61.96 \times 10^9 \times 10\% = 6.196 \times 10^8$ m$^3$. The same boundary conditions as above are used to calcultate the interface depth according to the equation developed by Glover (1959):

$$Z = \sqrt{\frac{2q\,X}{(\gamma_s - \gamma_f)k} + \left(\frac{q}{(\gamma_s - \gamma_f)k}\right)^2}$$

where: Z is the depth of the interface at point X, measured landward from the shore line.

In the case of the Dead Sea the coordinate origin is taken along the raised level for the X-coordinate and along the present shore line for the Z-coordinate (Fig. 3).

For calculating the aquifer area which will be occupied by intruding Dead Sea water due to the shift in the interface, the above equation from Glover (1959) should be accommodated to the geometry of the shorelines and integrated accordingly. The present depth of the interface (Fig. 3) equals:

$$Z_p = \sqrt{\frac{2qX}{(\gamma_s - \gamma_f)k} + \frac{q^2}{(\gamma_s - \gamma_f)^2k^2}} + R$$

And for the raised level (Fig. 3):

$$Z_r = \sqrt{\frac{2q\ (X-Xr)}{(\gamma_s - \gamma_f} + \frac{q^2}{(\gamma_s - \gamma_f)^2k^2}}$$

where: Xr equals the average width of the coast which will be covered due to the rising sea level. R is the amount by which the sea level will be raised.

After integration:

$$\int Zp\ dx = \frac{2(\gamma_s - \gamma_f)k}{3 \times 2q} \sqrt{\left(\frac{2qX}{(\gamma_s - \gamma_f)k} + \frac{q^2}{(\gamma_s - \gamma_f)^2k^2}\right)^3} + RX$$

and

$$\int Zr\ dx = \frac{2(\gamma_s - \gamma_f)k}{3 \times 2q} \sqrt{\left(\frac{2qX}{(\gamma_s - \gamma_f)k} - \frac{2qXr}{(\gamma_s - \gamma_f)k} + \frac{q^2}{(\gamma_s - \gamma_f)^2k^2}\right)^3} + XrX$$

To calculate *Xr* the average slope along the eastern shore of the Dead Sea is measured from available topographic maps and found to be 3%.

$$Xr = \frac{10m.}{3\%} = 333m.$$

The limits of integration of X are chosen as 333m., new shoreline, and 10,000m., the boundary at which the interface is bounded by an impervious bottom.

The area between the X-coordinate, Y = 0, and the present interface from x = 333 to x = 10000m is

$$A1 = \frac{2(\gamma_s - \gamma_f)k}{6q} \sqrt{\left(\frac{2q \times 10^4}{(\gamma_s - \gamma_f)k} + \frac{q^2}{(\gamma_s - \gamma_f)^2k^2}\right)^3} + 10^4 \times 10 -$$

$$- \frac{2(\gamma_s - \gamma_f)k}{6q} \sqrt{\left(\frac{2q \times 333}{(\gamma_s - \gamma_f)k} + \frac{q^2}{(\gamma_s - \gamma_f)^2 k^2}\right)^3} + 333 \times 10$$

$= 2.53987 \times 10^6\ m^2$.

The area between the x-coordinate, y = 0, and the shifted interface from x = 333 to x = $10^4$m is:

$$A2 = \frac{2(\gamma s - \gamma f)k}{3 \times 2q} \sqrt{\left[\frac{2q \times 10^4}{(\gamma s - \gamma f)k} - \frac{2q \times 333}{(\gamma s - \gamma f)k} + \left(\frac{q}{(\gamma s - \gamma f)k}\right)^2\right]^3} + 10^5$$

$$- \frac{2(\gamma s - \gamma f)k}{3 \times 2q} \sqrt{\left[\frac{2q \times 43}{(\gamma s - \gamma f)k} - \frac{2q \times 333}{(\gamma s - \gamma f)k} + \left(\frac{q}{(\gamma s - \gamma f)k}\right)^2\right]^3} + 333Xr$$

$= 1,77219 \times 10^6$

$A1 - A2 = 766 \times 10^5\ m^2$

The volume of the aquifer at a length of 80km. equals: $61.28 \times 10^9\ m^3$

Using the above given porosity of 10%, the volume of fresh waterwhich will be substituted by sea water is 6.128. $10^8\ m^3$. The Ghyben-Herzberg approximation gave $6.198 \times 10^8 m^3$, this is a very good correspondence with a difference of only 1.1%.

### Effects on groundwater resources

The raising of the Dead Sea level, leading to the landward movement of the interface, must be balanced in the fresh water area by a higher water level. Since the additional pressure at the surface of the Dead Sea as calculated above equals 1085 g/cm², the equivalent rise in the fresh water level must equal

$$\frac{1085}{100} = 10.85\ m.$$

The aquifer at the present sites of discharge is highly leached. The smaller particles of the semi-indurated sandstone are loosened and removed by the action of hot water discharges. Large, widened water paths developed along fissures and joints. All this resulted in high permeability of the aquifer at the water table level and above it. This elevated premeability will not allow the water level in the aquifer to rise. The additional amount of groundwater will leave the aquifer at its saturated top. Therefore, no equilibrium corresponding to the above calculated interface will be achieved, and the interface will move further landward until a new equilibrium corresponding to the initial fresh water level in the aquifer and to the raised Dead Sea level is reached. If this situation is illustrated by a communicating vessel scheme and using the Ghyben-Herzberg approximation, then the following equation describes the two equilibrium states (Fig. 4):

1. $h_1 \gamma f + h_3 \gamma s = h_2\ \gamma s$ before raising.

2. $h_{1r}\ \gamma f + h_{3r}\gamma s = h_2\gamma s + 10 \times 1.085$ after raising.
3. $h_1 - h_{1r} = h_{3r} - hr$ (for nomenclature refer to Figure 4).

After rearranging, subtracting eq. 1 from eq. 2 and substituting eq. 3 in the result, we obtain

$h_{3r} - h3\ (\gamma s - \gamma f) = 10.85$

and hence $h_{3r} - h3 = 49.32$ m.

Therefore, the interface landward movement should account for a water head of 49.32m., and not only 10.85m. as calculated above. This head of water multiplied by the extensions of the interface and the porosity of the aquifer should give us the amount of water which will be forced to leave the aquifer due to raising of Dead Sea level, and it equals:

head × length × width × porosity
49.32m. × 80km. × 10km. × 10% = $3.95 \times 10^9 m^3$

If the Glover equation (developed above) is used for the same conditions, then the amount of water is calculated according to the following equations:

$$\int (Zr + 49.32)dx = \frac{2(\gamma x - \gamma f)k}{3 \times 2q} \sqrt{\left(\frac{2qX}{(\gamma s - \gamma f)k} - \frac{2qXr}{(\gamma s - \gamma f)k} + \frac{q^2}{(\gamma s - \gamma f)^2 k^2}\right)}$$

In correspondence with $A_2$ calculated above:

$A_2 eq = \int_{x=333}^{x=10^4} (Zr + 49)dx = 2.85108 \times 10^6 - 0.4932 \times 10^6 = 2.35788 \times 10^6 m^2$

$A_1 - A_2 eq = 2.96268 \times 10^6 - 2.35788 \times 10^6 = 6.048 \times 10^5 m^2$

The volume of water = cross sectional area × length × porosity = $6.048 \times 10^5 \times 8 \times 10^4 \times 10\% = 4.838 \times 10^9 m^3$

The difference between the amount calculated using the Ghyben-Herzberg approximation of $3.95 \times 10^9\ m^3$ and that calculated by integrating the Glover equation of $4.838 \times 10^9 m^3$ is attributed to the more accurate non-linear approach of Glover. The above calculated quantity of fresh groundwater is going to flow out of the aquifer during and beyond the rising phase due to the idleness of the system. According to Schneider *et. al.*, (1983), the porosity of the sequence decreases with increasing depth, and reaches 10% in the Cambrian sandstones. Therefore, it is not expected that an equivalent amount of Dead Sea water will flow into the aquifer.

## Density increase due to evaporation:

The quantities of water added to the Dead Sea, with a density of $1.025\ g./cm^3$, will be calculated after the raising period to a density of $1.085\ g./cm^3$ as calculated above. The concentration process will continue after this period due to the evaporation of the Mediterranean water employed to sustain the raised Dead Sea level. The added 10m. of Mediterranean Sea water will reach the present concentration of the upper portion of Dead Sea water of $1.22\ g./m^3$ after 54 years:

(1.025 − 1) x = (1.22 − 1.085) 10 x = 54 years.

Further, this increase will cause another landward movement of the interface and, hence, additional discharge of fresh groundwater.

Using the same conditions as above with an end density of 1.22 g./$cm^3$ for the raised 10m. after (54 + 10) = 64 years results in a total amount of discharged water of:

$$(\gamma s - \gamma f) h_s r - h_s = 1.22 \times 10$$

$$h_s r - h_s = 55.5 \text{ m pressure head}$$

$$A_2 \text{ after 64 years} = \int (Z_r + 55.5) dz =$$

$$\frac{2(\gamma s - \gamma f)k}{6q} \sqrt{\left( \frac{2qX}{(\gamma s - \gamma f)k} - \frac{2qXr}{(\gamma s - \gamma f)k} + \frac{q^2}{(\gamma s - \gamma f)^2 k^2} \right)^3} = 2.29608 \times 10^6$$

$$A_1 - A_2(64) = 6.666 \times 10^5 m^2$$

$$Q = 6.666 \times 10^5 \times 8 \times 10^4 \times 10\% = 5.33 \times 10^9 m^3.$$

## CONCLUSIONS

1. The raising of the water level of the Dead Sea will not only flood existing structures, such as the potash works, 8oads, and tourist facilities of the Dead Sea area, but it will also have bad consequences on Jordan's groundwater resources.
2. Increasingly, saline water will intrude landward along the Dead Sea fresh groundwater interface, and as a result, more fresh water will be discharged from the upper portions of the aquifer.
3. In general, the whole operation will involve the substitution of fresh groundwater for hypersaline Dead Sea water.
4. The actual groundwater resources of Jordan will decrease by approximately 6.1 × $10^9$ $m^3$ until an hydrostatic equilibrium is achieved, and an additional 4.5 × $10^9$ $m^3$ until a density equilibrium is reached.
5. Contemporaneous to raising the Dead Sea level, consideration should be given to utilizing the additional discharges from the groundwater resources, and not letting these discharges flow unutilized out of the aquifer and evaporate or flow into the Dead Sea.

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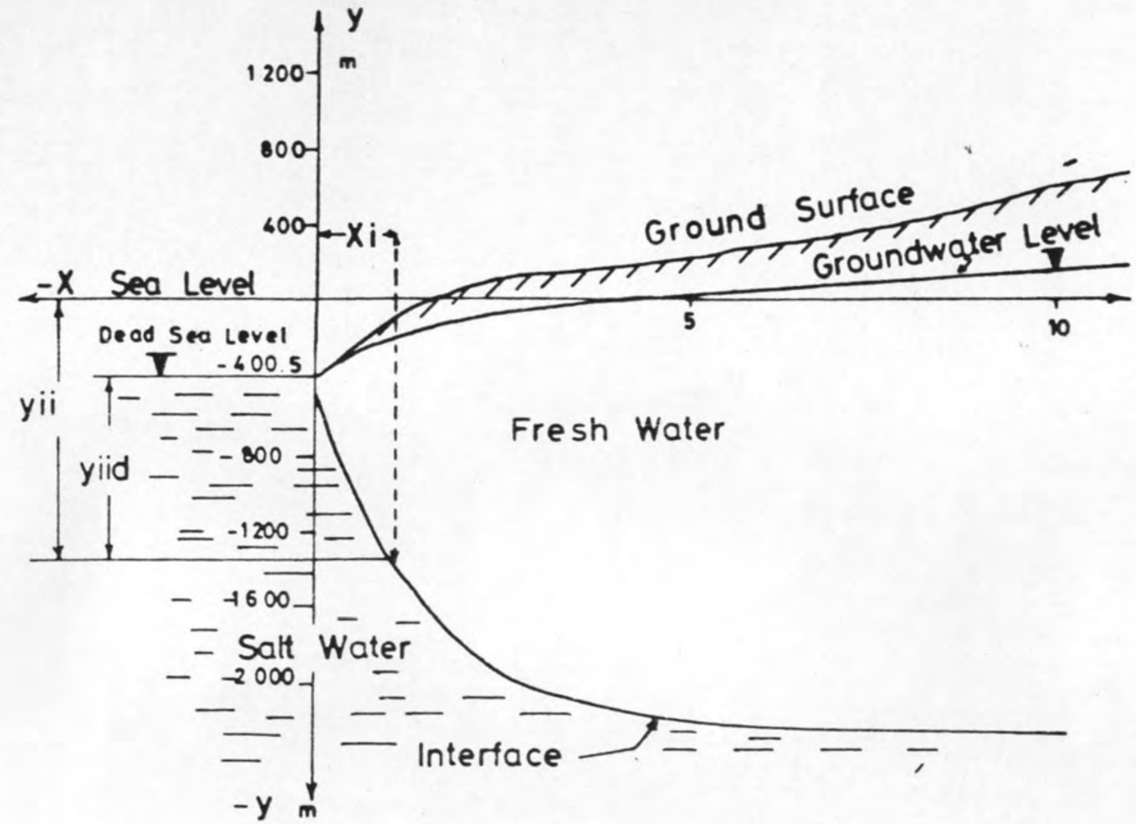


Fig. 2: Present configuration of the interface between Dead Sea water and fresh water at Wadi Zerka Main latitude.

(Calculated using the equation of Ghyben - Herzberg)

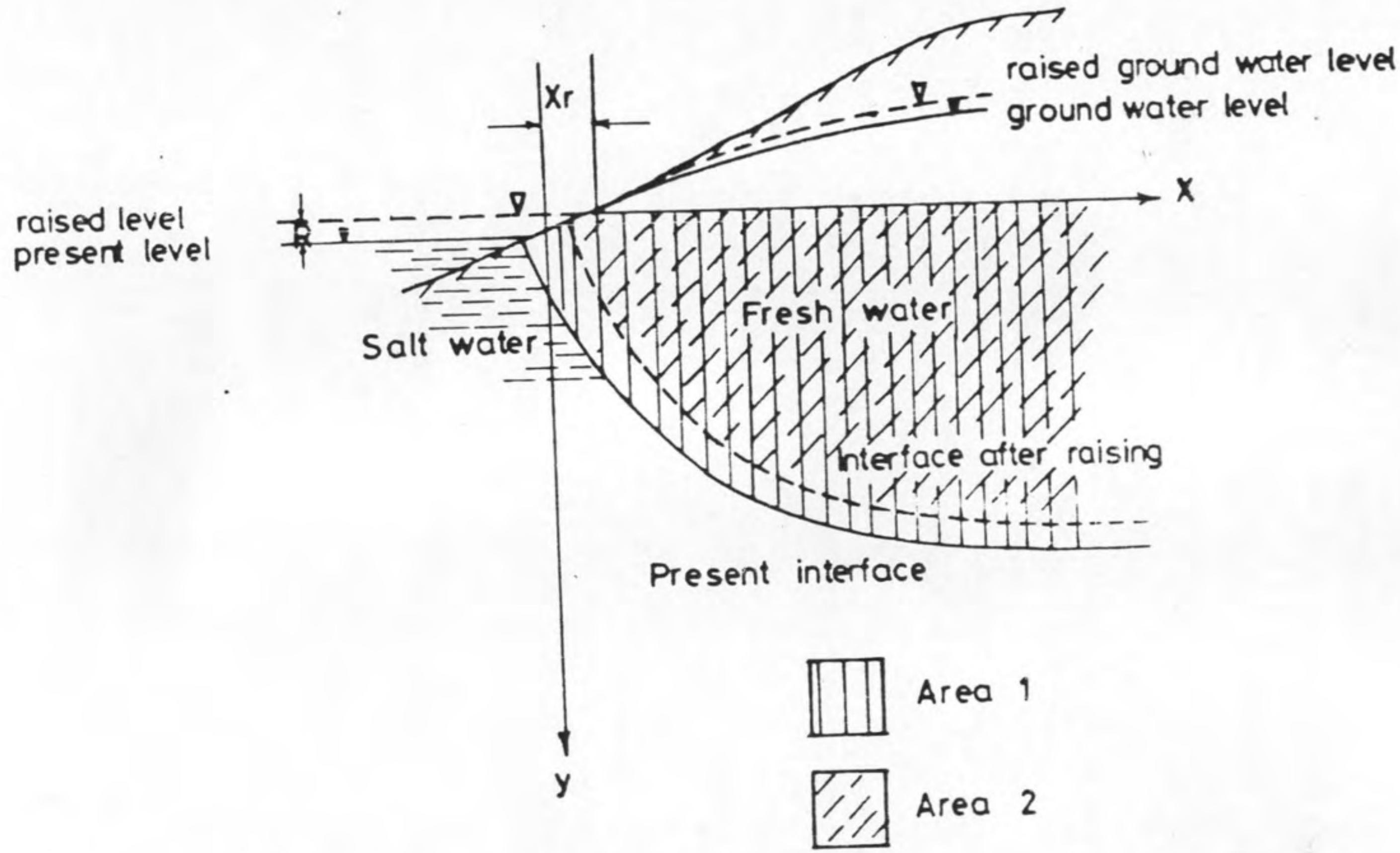


Fig. 3 : Movement of interface after raising the Dead Sea level showing the new area occupied by salt water intrusions.

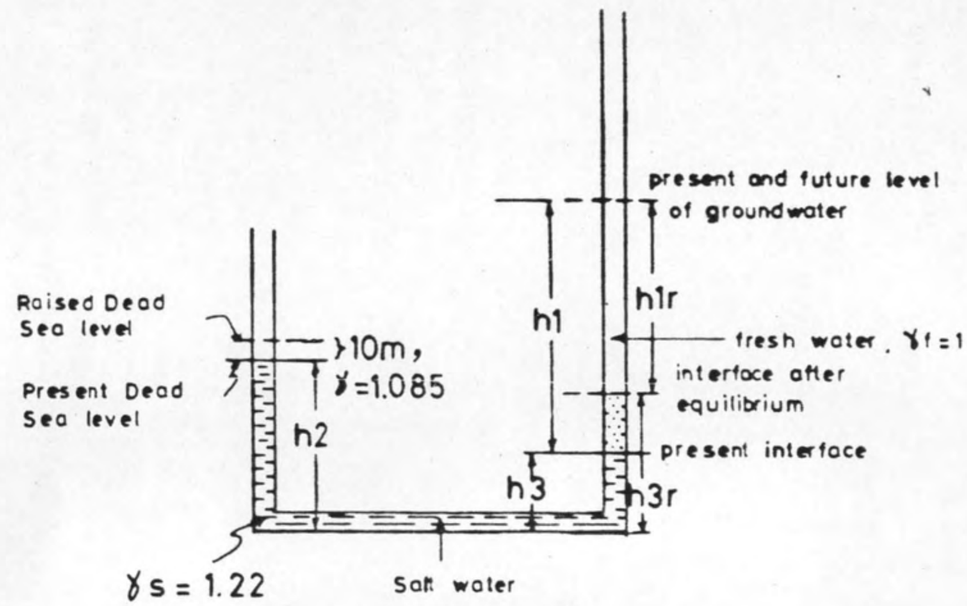


Fig. 4 : A model representing raising of Dead Sea level and interface movement by constant fresh water level.

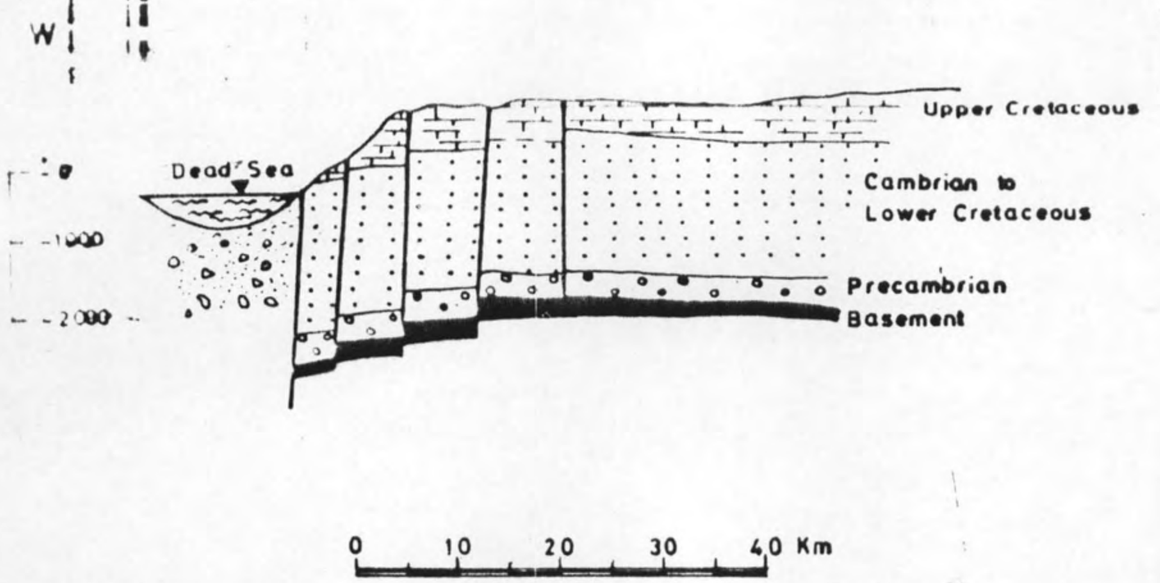


Fig. 4: Schematic geological cross section in the Dead Sea eastern graben flank area

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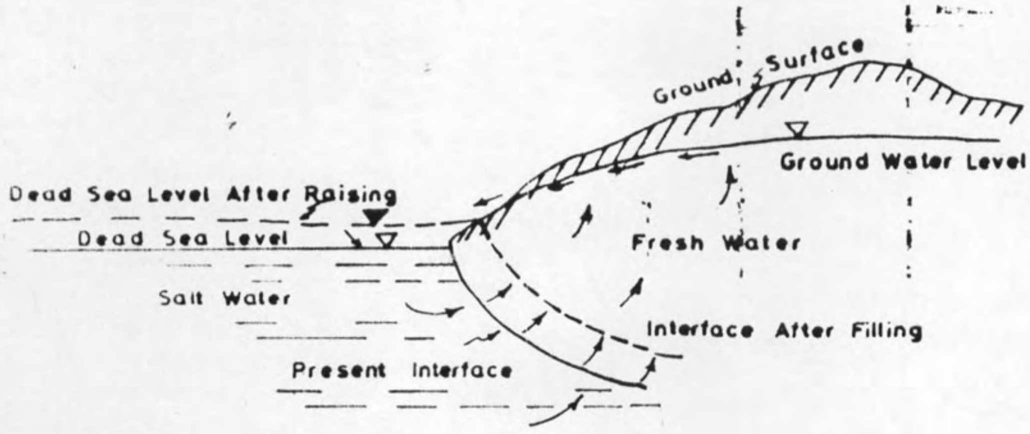


Fig 3: Schematic Pattern showing the displacement (arrows) of the interface after the addition of the mediterrnean sea water and the resulting replacement and discharge of groundwater.

Salameh, E. 1983

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# Effects of the Mediterranean-Dead Sea Canal Project on Jordan's Groundwater Resources

by Elias Salameh

The conduit between the Mediterranean and the Dead Sea has been a topic of interest to many people in the last few years, and there have been several attempts to set up a water balance for the Dead Sea. These attempts were made by non-specialists who reproduced numbers and ideas published by others without any interest explaining the real conditions. This is apparent from Israel's failure to cooperate with the UN delegations and indicates that these balances are built on misleading figures and assumptions resulting in incorrect conclusions. Their aim was only to attract the attention of the local mass media and public concern.

The fact that about 17 billion cubic metres of fresh water were diverted and prevented from reaching the Dead Sea in the last two decades means that they are lost to the Dead Sea through evaporation. But the Dead Sea lost only about 6 billion $m^3$. From what source have the remaining losses been recovered?

This fact, which has not been considered in any of the attempts to set up a water balance, shows the findings to be misleading. It also demonstrates that a water balance is not as easy to achieve as many naive people imagine.

Generally, any change in sea water level is followed by a transitional period, during which the flow in the coastal aquifer is unsteady and the interface seeks a relevant equilibrium condition. The Mediterranean-Dead Sea Canal is planned to transport water from the Mediterranean to the Dead Sea, the Dead Sea level being raised by 10m, from 400.5 to 390.5 within 12 to 15 years of completion, which is expected in 1990.

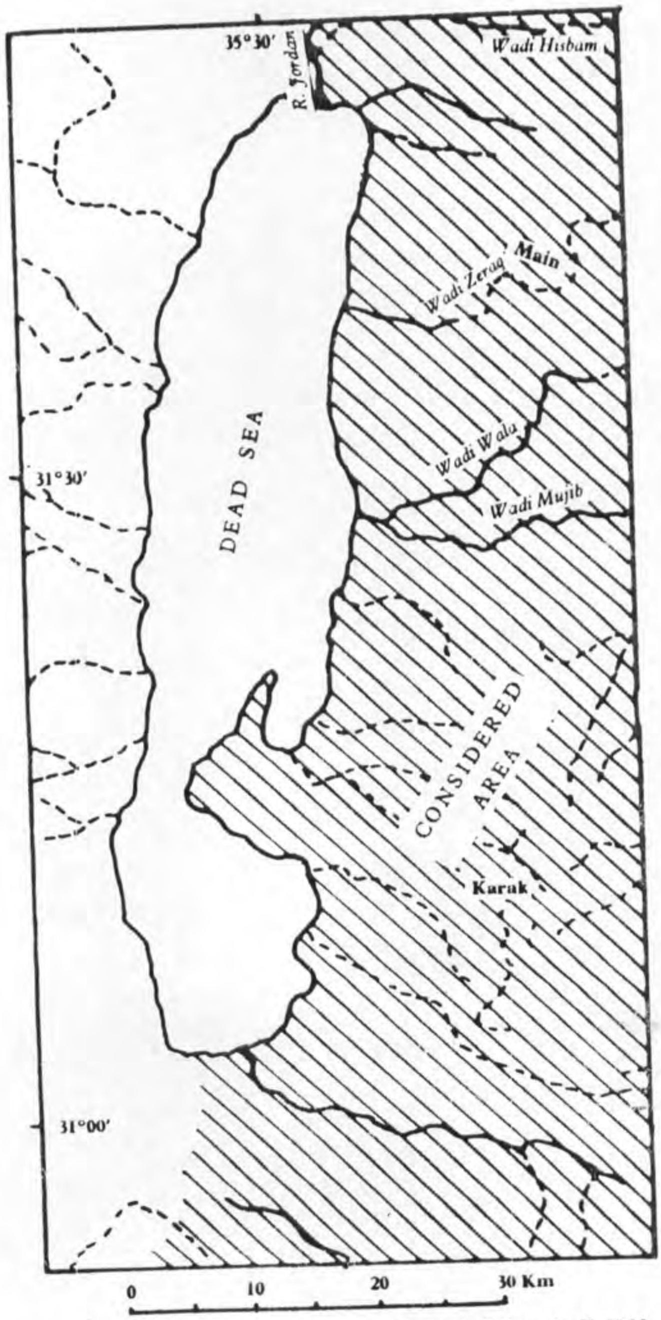
The transitional period will prevail not only until the planned water level of 390.5 is reached, but will continue until a new equilibrium in the hydrodynamic process is achieved.

*The Interface Configuration*

The interface configuration of salt and fresh water starts on the shores or beneath the Dead Sea (Fig. 1) with a relatively high gradient of inclination. It then evens out landward where it tends to become horizontal, or to end at an aquiclude (Fig. 2). The nearly horizontal interface is the depth to which precipitated water perculates, mixes within the dispersion zone with intruding Dead Sea water and then rises along faults to the surface on the western slopes of the Dead Sea.

The interface configuration is a function of the densities of the two fluid phases (Dead Sea and fresh groundwater), the inland distance from the shorelines and the hydraulic gradient, as well as the amount of discharged

**Fig. 1: Location Map**




Source: Salameh, E.1983

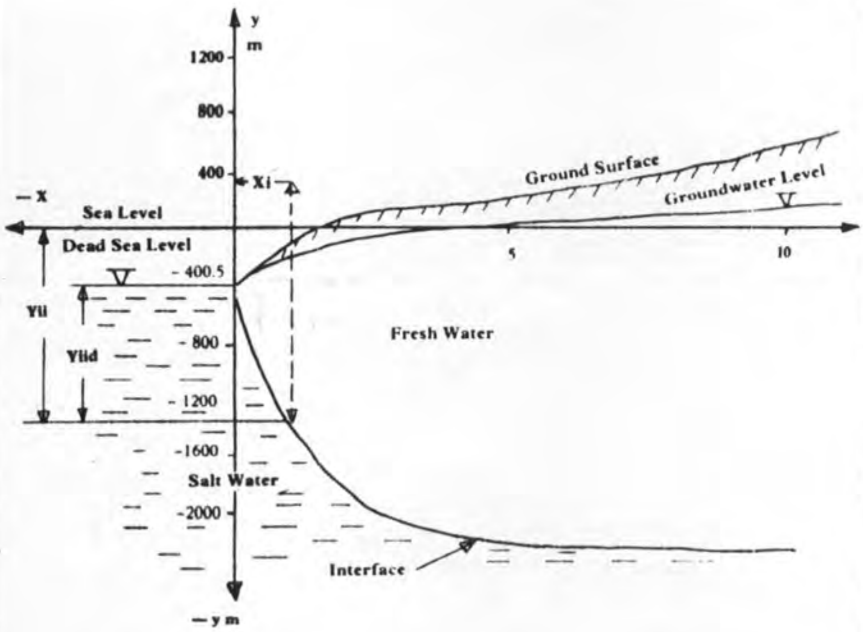



**Fig. 2: Present configuration of the interface between Dead Sea water and fresh water at Wadi Zerka Main latitude. (Calculated using the equation of Ghyben-Herzberg)**

groundwater.

The densities of the Dead Sea water and fresh water and the fresh water level at certain distances from the Dead Sea shores are already known.

The hydraulic gradient within the Zerka Ma'in area and along its longitude is 4%. To the west it increases gradually to give the pattern shown in Figure 2.

The amount of fresh groundwater in hydraulic equilibrium with Dead Sea water which flows to the Dead Sea is calculated as $6m^3/s$.

*Configuration of the Interface*:

From the known methods for the calculation of the interface configuration of salt and fresh water with the available data the approximation of Ghyben - Herzberg (1888) and the method after Glover (1959) proved to be approximate and are used in this paper.

As a result of raising the Dead Sea level by 10m, from 400.5 to 390.5 below seal level, the interface adjusting itself to the new potential will move landward to achieve a relevant state of equilibrium with a stationary interface and a fresh water flow to the Dead Sea.

The Ghyben - Herzberg approximation was developed for the calculation of the interface configuration in coastal phreatic aquifers. It assumes static equilibrium, hydrostatic pressure distribution of the fresh water and stationary sea water. The Ghyben - Herzberg equation for the above conditions is:

$$\frac{hs}{hf} = \gamma f/\gamma s - \gamma f)$$

where, hs = depth of salt water column to the interface.
hf = depth of fresh water column to the interface.
$\gamma s$ = density of salt water.
$\gamma f$ = density of fresh water.

For oceanic water with a density of 1.025, $\frac{hs}{hf} = 40$

For the Dead Sea water with a density of 1.255, $\frac{hs}{hf} = 4.44$

This show the depth of the interface of Dead Sea fresh water is only around one tenth of the interface depth of oceanic fresh water.

Using the Ghyben – Herzberg approximation for the special case of the Dead Sea gives the following equation (Fig. 2).

$$Yiid\ \gamma s = Yiid\ \gamma f + (400.5 + Yfi)\ \gamma f$$

where, Yiid = depth of point Xi at the interface below Dead Sea level.
Yii = depth of point Xi at the interface below sea level.
Yiid = Yii – 400.5m.
Yfi = elevation of point Xi at the fresh ground water table with respect to sea level.
$\gamma s$ = density of Dead Sea water 1.225g/cm$^3$.
$\gamma f$ = density of fresh water 1g/cm$^3$.
400.5m = Dead Sea level below sea level.

By rearranging and substituting the densities

$$Yii = \frac{488.6 + Yfi}{-\ 0.225}$$ is obtained.

The interface on Figure 2 is plotted using the above calculated depths, Yii.
The plot of these values shows that the interface configuration flattens rapidly landward.
Another method for the calculation of the interface configuration was approximated by Glover (1959) and Kremer (1977). This approximation is given in the following equations:

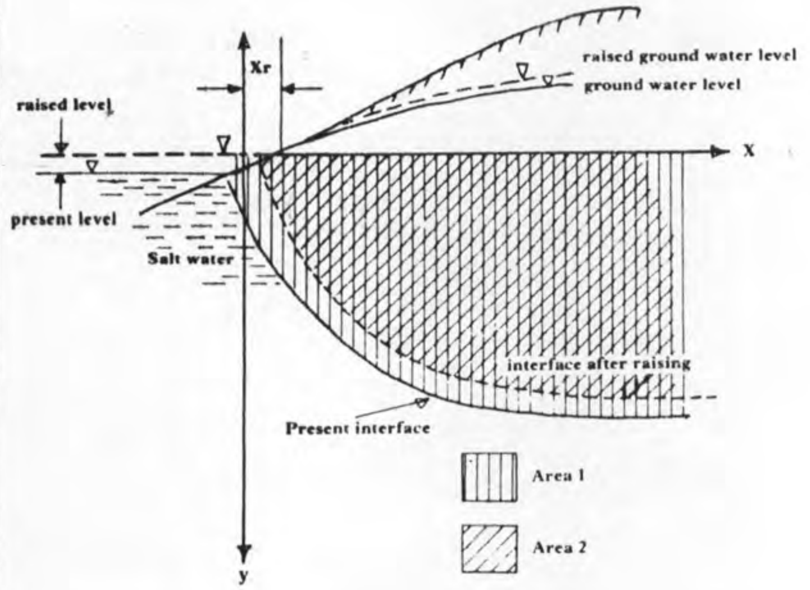



**Fig. 3: Movement of interface after raising the Dead Sea level showing the new area occupied by salt water intrusions.**

$$Z = \sqrt{\frac{2q\,X}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2 K^2}}$$

where, Z = the depth of the interface in a landward lying point (X) in respect to sea water level.

q = the quantity of fresh groundwater flowing to the sea per unit length ($m^2/s$).
K = the permeability of the aquifer for fresh water ($m^2/s$).

The intersection of the interface with the sea bottom occurs at point $X_0$.

$$X_0 = \frac{q}{2(\gamma s - \gamma f)K}$$

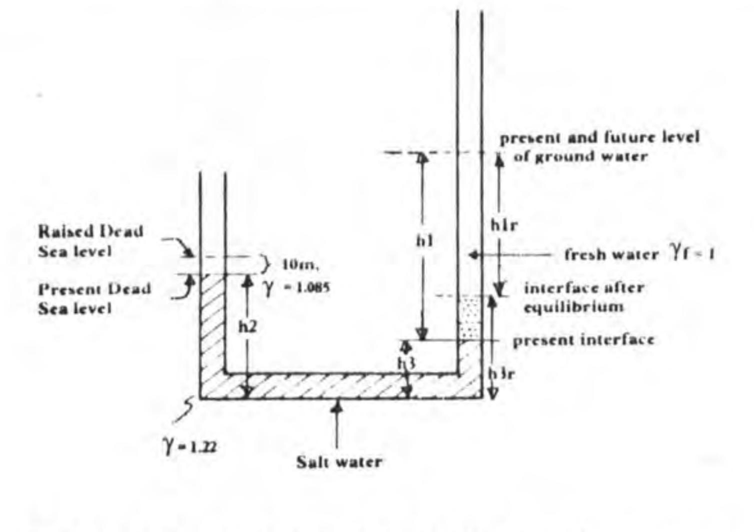



**Fig. 4: A model representing raising of Dead Sea level and interface movement by constant fresh water level.**

At the shoreline, X = 0 the depth of the interface equals

$$Z_0 = \frac{q}{(\gamma s - \gamma f)\,K}$$

Since the main interest in this study is in the landward movement of the interface and not the interface configuration itself and because of the complexity of the boundary conditions accompanying the solution of the partial differential equations of continuity, the Ghyben – Herzberg approximation and the Glover equations are applied to the present state of Dead Sea level of -400.5m and for the raised level of -390.5.

The area between both interfaces gives the amount of fresh water which will be substituted by Dead Sea water.

Because the calculations involve the densities of the water, some considerations concerning the density of the added Mediterranean water should be made. After connecting the Mediterranean and the Dead Sea by a conduit and transferring the water to the Dead Sea, the level of the Dead Sea, according to published data, will be raised to an elevation of -390.5m within 12-15 years. The evaporation from the water brought to it equals 1600mm.

Taking 15 years as the filling period, then the accumulative evaporation equals 1.600m × 15 = 24m of Mediterranean Sea water with a salinity of 3.8% and a density of 1.025g/cm³.

The salt content of the 24m water column will be effectively concentrated in the remaining 10m which represent the rise in Dead Sea level. This makes the density of these 10m equal:

$$1 + \frac{24 + 10}{10}(1 - 1.025) = 1.085 \text{ g/cm}^3$$

An additional pressure of 10.85g/cm² at the present level of the Dead Sea will result after 15 years when this level is raised by 10m. This leads to a landward movement of the salt fresh water interface, which, in turn, leads to a rise in fresh groundwater level.

*The Interface Movement*

The volume of the portion of the aquifer which will be occupied by Dead Sea water after raising, considering the eastern shore of the Dead Sea with a length the vertical component = $80 \times 10^3 \times 10^4 \times 8.68 \times 10^9 m^3$. The interface is bounded by an impervious bottom (this assumption is justified when one considers the different geological cross sections of Quennell (1959) and Bender (1968) can be approximated according to Ghyben – Herzberg equation. The increase in pressure is 10.85g/cm² corresponding to a fresh water column of 10.85m.

The volume of the portion of aquifer into which salt water intrudes due to the vertical component = $80 \times 10^3 \times 10.85 = 8.68 \times 10^9 m^3$. The interface goes down to about 2000m and the shore is enlarged by an average of 333m. This gives an aquifer volume with an intrusion of Dead Sea water due to horizontal shift of $80 \times 10^3 \times 2 \times 10^3 \times 333 = 53.28 \times 10 m^3$ added together, giving a volume of $61.96 \times 10^9 m^3$.

The porosity of the aquifer has an average of 17% according to Schneider et al (1983), it ranges from 25 to 30% and due to pore space reduction from 15-24%. If kaoline commentation takes place it is reduced to less than 5%.

To be on the safe side, a porosity of 10% is used in this paper. The volume of water filling the above calculated volume of aquifer portion equals $61.95 \times 10^9 \times 10\% = 6.2 \times 10^9 m^3$.

The same boundary conditions as above are used to calculate the interface depth according to the equation developed by Glover (1959)

$$Z = \sqrt{\frac{2qX}{(\gamma s - \gamma f)K} + \left(\frac{q}{(\gamma s - \gamma f)K}\right)^2}$$

where Z is the depth of the interface at point X, measured landward from the shore line.

In the case of the Dead Sea the coordinate origin is taken along the raised level for the X-Coordinate and along the present shore line for the Z-Coordinate (Fig. 3).

For calculating the aquifer area which will be occupied by intruding Dead Sea water due to the shift in the interface, the above equation after Glover (1959) should be accomodated to the geometry of the shorelines and integrated accordingly. The present depth of the interface (Fig. 3) equals:

$$Zp = \sqrt{\frac{2qX}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2 K^2}} + R$$

and for the raised level (Fig. 3).

$$Zr = \sqrt{\frac{2q\,(X - Xr)}{(\gamma s - \gamma f)} + \frac{q^2}{(\gamma s - \gamma f)^2 K^2}}$$

where, Xr equals the average width of the coast which will be covered due to sea level raising, R is the amount by which the sea level will be raised.

After integration:

$$\int Zp\,dX = \frac{2\,(\gamma s - \gamma g)\,K}{6q}\sqrt{\left(\frac{2qX}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2 K^2}\right)^3} + RX$$

and

$$\int Zr\,dx = \frac{2(\gamma s - \gamma f)K}{3 \times 2q} - \sqrt{\left(\frac{2qX}{(\gamma s - \gamma f)K} - \frac{2qXr}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2 K^2}\right)^3} + XrX$$

To calculate Xr the average slope along the eastern shore of the Dead Sea is measured from available topographical maps and it is found to be 3%.

$$Xr = \frac{10m}{3\%} = 333m$$

The limits of integration of X are chosen as 333m, the new shoreline, and 10,000m, the limit at which the interface is bounded by an impervious bottom.

The area between the X-Coordinate, Y = O and the present interface from x = 333 to x = 10000m is

$$A1 = \frac{2(\gamma s - \gamma f)K}{6q}\sqrt{\left(\frac{2q \times 10^4}{(\gamma s - \gamma f)K} + \frac{{}^2q}{(\gamma s - \gamma f)^2 K^2}\right)^3} + 10^4 \times 10$$

$$- \frac{2(\gamma s - \gamma f)K}{6q}\sqrt{\left(\frac{2q \times 333}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2 K^2}\right)^3} + 333 \times 10$$

$= 2.539870 \times 10^6 m^2$

The area between the x - coordinate, y = O and the shifted interface from x = 333 to x = $10^4$m is:

$$A2 = \frac{2(\gamma s - \gamma f)K}{3 \times 2q} \sqrt{\left[\frac{2q \times 10^4}{(\gamma s - \gamma f)K} - \frac{2q \times 333}{(\gamma s - \gamma f)K} + \left(\frac{q}{(\gamma s - \gamma f)K}\right)^2\right]^3} + 10^5$$

$$- \frac{2(\gamma s - \gamma f)K}{3 \times 2q} \sqrt{\left[\frac{2q \times 333}{(\gamma s - \gamma f)K} - \frac{2q \times 333}{(\gamma s - \gamma f)K} + \left(\frac{q}{(\gamma s - \gamma f)K}\right)^2\right]^3} + 333Xr$$

$= 1.77219 \times 10^6\ m^2$

$A1 - A2 = 766 \times 10^5 m^2$.

The volume of the aquifer by a length of 80km = $61.28 \times 10^9 m^3$

Using the above given porosity of 10%, the volume of fresh water which will be substituted by sea water is $6.128.10^9 m^3$. The Ghyben - Herzberg approximation gave $61.98 \times 10^9 m^2$, which represents a very good correspondence with almost no difference.

*Effects on the Groundwater Resources*

The new potential created by raising the Dead Seal level, which leads to the landward movement of the interface, must be balanced in the fresh water area by a higher water level. Since the additional pressure at the surface of the Dead Sea, as calculated above, equals 10.85g/cm², the equivalent rise in fresh water level must equal

$$\frac{10.85}{100} = 10.85m.$$

The aquifer at the present sites of discharge is highly leached. The smaller particles of the semi-indurated sandstone are loosened and removed by the action of hot water discharges. Large widened water paths developed along fissures and joints. All this resulted in high permeabilities of the aquifer at water table level and above. These elevated permeabilities will not allow the water level in the aquifer to rise. The additional amount of groundwater will leave the aquifer at its saturated top.

Therefore, no equilibrium corresponding to the above calculated interface will be achieved and the interface will move further landward, until a new equilibrium corresponding to the initial fresh water level in the aquifer and to the raised Dead Sea level is reached.

If this situation is illustrated by a communicating vessel scheme and using the Ghyben - Herzberg approximation, then the following equation describes the two equilibrium states (Fig. 4).

1. $h_1\gamma f + h_3\gamma s = h_2\gamma s$ before raising

2. $h_{1r}\gamma f + h_{3r}\gamma s = h_2\gamma s + 10 \times 1.085$ after raising

3. $h_1 - h_1 r = h_3 r - h_3$ (for nomenclature refer to Figure 4)

After rearranging, subtracting eq. 1 from eq. 2 and substituting eq. 3 in the result, we obtain

$$h3r - h3\,(\gamma f - \gamma s) = 10.85$$

and hence $h3r - h3 = 49.32$m.

Therefore, the interface landward movement should account for a water head of 49.32m, and not only 10.85m as calculated above.

This head of water multiplied by the extensions of the interface and the porosity of the aquifer should give us the amount of water which will be forced to leave the aquifer due to the vertical component of raising the Dead Sea level, and it equals:

$$\text{head} \times \text{length} \times \text{width} \times \text{porosity} = 49.32 \times 80\text{km} \times 10\% = 3.95 \times 10^9\text{m}^3$$

If the Glover equation (developed above) is used for the same conditions, then the amount of water is calculated according to the following equations:

$$\int (Zr + 49.32)dx = \frac{2(\gamma x - \gamma f)K}{3 \times 2q}\sqrt{\left(\frac{2qX}{(\gamma s - \gamma f)K} - \frac{2qXr}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2K^2}\right)^3}$$

In correspondence with $A_2$ calculated above:

$$A_2eq = \int_{x=333}^{x=10^4} (Zr + 49)dx = 2.85108 \times 10^6 - 0.4932 \times 10^6 = 2.35788 \times 10^6\text{m}^2$$

$$A_1 - A_2\,eq = 2.96268 \times 10^6 - 2.35788 \times 10^6 = 6.048 \times 10^5\text{m}^2$$

The volume of water = cross sectional area × length × porosity =
$6.048 \times 10^5 \times 8 \times 10^4 \times 10\% = 4.838 \times 10^9\text{m}^3$

The difference between the amount calculated using the Ghyben – Herzberg approximation of $3.95 \times 10^9\text{m}^3$ and that calculated by integrating Glover equation of $4.838 \times 10^9\text{m}^3$ is attributed to the more accurate non-linear approach of Glover.

The above calculated quantity of fresh groundwater is going to flow out of the aquifer during and beyond the raising phase due to the vertical shift and idleness of the system.

According to Schneider et al (1983), the porosity of the sequence decreases with increasing depth and reaches 10% in the Cambrian sandstones. Therefore, it is not expected than an equivalent amount of Dead Sea water will flow into the aquifer.

*Density Increase due to Evaporation*

The quantities of water added to the Dead Sea with a density of $1.025g/cm^3$ will be calculated after the raising period to a density of $1.085g/cm^3$, as calculated above. The concentration process will continue after this period due to the evaporation of the Mediterranean water which will be brought to sustain the raised Dead Sea level.

The added 10m of Mediterranean Sea water will reach the present concentration of the upper portion of Dead Sea water of $1.22g/cm^3$ after 54 years:

$$(1.025 - 1)\ x = (1.22 - 1.085)\ 10x = 54 \text{ years.}$$

This density increase will also cause a further landward movement of the interface and hence additional discharges of fresh groundwater.

Using the same conditions as above with an end density of $1.22g/cm^3$ for the raised 10m after (54 + 10) = 64 years results in a total amount of discharged water due to vertical shift of:

$$(\gamma s - \gamma f)h_3r - h_3 = 1.22 \times 10$$

$$h_3r - h_3 = 55.5\text{m pressure head}$$

$A_2$ after 64 years =

$$\int (Zr + 55.5)\ dz = \frac{2(\gamma s - \gamma f)K}{6q} \sqrt{\left(\frac{2qX}{(\gamma s - \gamma g)K} - \frac{2qXr}{(\gamma s - \gamma f)K} + \frac{q^2}{(\gamma s - \gamma f)^2K^2}\right)^3}$$

$$= 2.29608 \times 10^6$$

$$A_1 - A_2(64) = 6.666 \times 10^5 m^2$$

$$Q = 6.666 \times 10^5 \times 8 \times 10^4 \times 10\%$$

$$= 5.33 \times 10^9 m$$

*Conclusions*

1. The raising of the Dead Sea level not only involves flooding the potash works, roads, touristic facilities, and some agricultural lands, but above all it affects the groundwater resources of Jordan.
2. Saline water will intrude more and more landward along the Dead Sea fresh groundwater interface and this will result in more fresh water being discharged from the upper portions of the aquifer.
3. In general, the whole operation involves the substitution of fresh groundwater by hypersaline dead Sea water.
4. The actual groundwater resources of Jordan will decrease by some $6.1 \times 10^9 m^3$ until hydrostatic equilibrium is achieved and additional $4.5 \times 10^9 m^3$ until density equilibrium is reached.
5. While considering the raising of the Dead Sea level, attention should also be given to utilizing the additional discharges from the groundwater resources, and not letting these discharges flow unutilized out of the aquifer and evaporate or flow into the Dead Sea.

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