Review of a condition of the Dead Sea

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Abstract

This article examines several proposals of "saving the Dead Sea". The analysis is based on combination of multiple types of data such as latent heat of evaporation; history of the sea levels over the past 1000 years; satellite measurements of the temperature of the surface of the sea; data published by Israeli and Jordanian factories and others. We show that if none of the proposals is realized, the area of the northern basin will shrink to 350 km^2. If one of the proposals is realized, it will take dozens of years for the sea level to reach equilibrium. Lacking direct experimental data, analysis in this article used some assumptions and extrapolations. Experimental verification of these results would lead to better understanding of the optimal level of the Dead Sean and better prognosis its future. It would also help to make precise estimates of the parameters such as size of tunnels and power of the pumps for any of the proposals to transfer water into the Dead Sea.

Projects to save the Dead Sea are not being realized

The water level of the northern basin is dropping by 1m per annum. This happens because evaporation of the water from the surface of the sea exceeds inflow from rain, from the river Jordan and from smaller rivers, creeks and subterranean currents. Jordanian and Israeli factories on the Dead Sea are pumping water from the northern basin into the south-eastern and south-western basins. As a result, the water level in the southern basins is 20 m higher, than in the northern basin.

Over the past 20 years, there were different ideas how to "save" the Dead Sea. Two conferences dedicated to this topic took place at conferences in Rehovot on November 15, 2012 and in Jerusalem on December 10, 2012. Proposals to increase the sea level included projects such pumping water from the Red Sea of from the Mediterranean Sea; pumping desalinated water; adding "native" water from Jordan River; reducing water evaporation from the surface of the sea by covering it with a "floating roof" [1,2,3,4,5,6,7]. Unfortunately the program and the proceedings of these conferences are not published.

1. Currently none of the proposals is being realized

1.1. Let us analyze what may happen to the Dead Sea if no action is taken. Satellite images (www.googleearth.com) reveal that in April 2011 the area of the northern basin was 624 km^2; the area of the south-western, Israeli, basin was 145 km^2 and the area of the south-eastern, Jordanian, basin was 113 km^2. In October 2011 the areas of these basins were 603 km^2; 141 km^2 and 105 km^2 respectively. The area of the northern basin at the end of 2009 was 637 km^2 (Fig 2 in [8]).

Factories of the Jordanian south-eastern basin belonging to Arab Potash Corporation [9] are utilizing the following technology for extracting salts. They pump 250-300 million m^3 of water from the northern basin annually. Water with initial density of 1235 kg/m^3 is transferred into a network of evaporating small basins. As water evaporates, different salts are deposited in different basins and the density of the brine gradually increases. The brine leaving the factory basins has density of 1345 kg/m^3 and flows into the southern basin. There evaporation continues and the remaining salts are dropped to the bottom. The salt from the bottom is removed by five dredgers.

In 2011, Israeli factories pumped 448 million m^3 [10] from northern basin into south-western basin, and returned 161 million m^3. Most likely, they are using technology similar to Jordanian ones and return water with all commercially useful salts already extracted. So every year, about 20 cm of salts is deposited on the bottom of the southern basins.

Israeli hotels are situated on the shores of southern basis to the north of the factories. As the factories are pumping millions of cubic meters of water, the sea level is rising and hotels are forced to take measures against flooding.

1.2. In 2011, the Sun evaporated 448 million m^3 from the surface of the south-western basin, which has the area of 141-145 km^2. As brine moves along the network of factory basins, its density changes from 1235 to 1345 kg/m^3. Specific latent heat of vaporization of the brine depends on the concentration of salts: the more saline is the brine, the lower is specific heat and the less energy is required for evaporation. Sharqawy et al investigated properties of sea water and more saline brines [11, 12]. In particular, they show the relationship between salinity and specific latent heat, and between salinity and density of the brine. The dependency graphs from [11, 12] are reproduced in Figs 1 and 2.

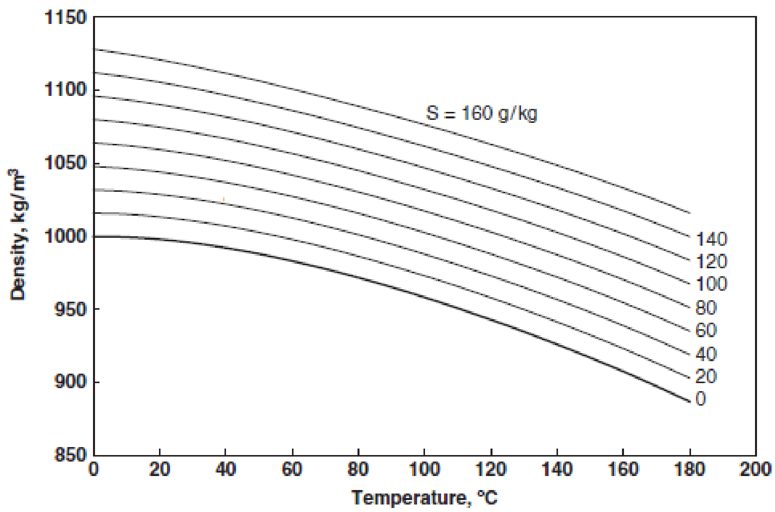

Fig. 3. Seawater density variations with temperature and salinity calculated using Eq. (8).

Fig. 1: salinity S v.s. density ρ_{sw}

The graph on the figure above corresponds to formula (8) from [11]:

$$\rho_{sw} = \left(a_1 + a_2 t + a_3 t^2 + a_4 t^3 + a_5 t^4\right) + \left(b_1 S + b_2 S\,t + b_3 S\,t^2 + b_4 S\,t^3 + b_5 S^2 t^2\right)$$

where

$a_1 = 9.999 \times 10^2$, $a_2 = 2.034 \times 10^{-2}$, $a_3 = -6.162 \times 10^{-3}$, $a_4 = 2.261 \times 10^{-5}$, $a_5 = -4.657 \times 10^{-8}$,
$b_1 = 8.020 \times 10^2$, $b_2 = -2.001$, $b_3 = 1.677 \times 10^{-2}$, $b_4 = -3.060 \times 10^{-5}$, $b_5 = -1.613 \times 10^{-5}$

Validity: ρ_{sw} in (kg/m³); $0 < t < 180$ °C; $0 < S < 0.16$ kg/kg
Accuracy: ±0.1 %

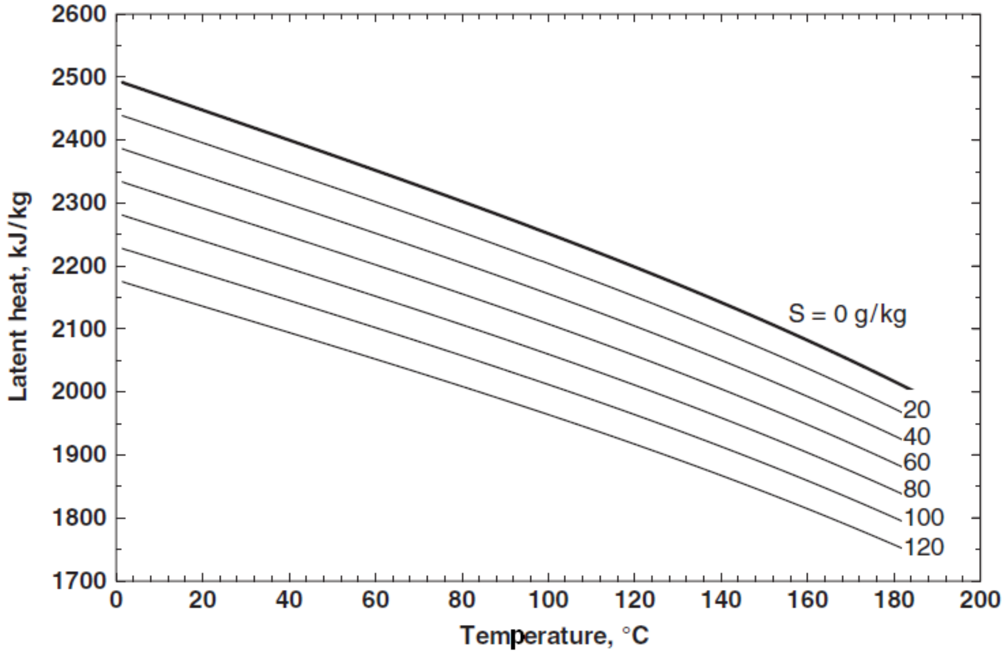

Fig. 12. Seawater latent heat variations with temperature and salinity calculated using Eq. (37)

Fig. 2: Salinity S v.s. specific latent heat of vaporization h

The graphs on Fig 2 correspond to formula (39) from [11]:

$$h_{fg,sw} = (1 - S/1000)\left(h_{fg,w} - \frac{RT^2}{1000}\frac{\partial\phi}{\partial T}M\right)$$

Reference [11] investigates properties of the brines with saliniities up to 160 g/kg, as it is mostly concerned with desalination via reverse osmosis. If follows from the above formula, that at constant temperature, latent heat of vaporization linearly depends on the salinity S. Therefore, let us assume that we can extrapolate this dependency to higher values of salinity. Similarly, we will extrapolate formula for the density, as due to the small coefficient $b_5 = -1.613*10^{-5}$, the quadratic term is small compared to the linear term for relevant values of salinity and temperature. Therefore, we will assume that density linearly depends on salinity at constant temperature. Extrapolated graphs are shown on Figs 3 and 4.

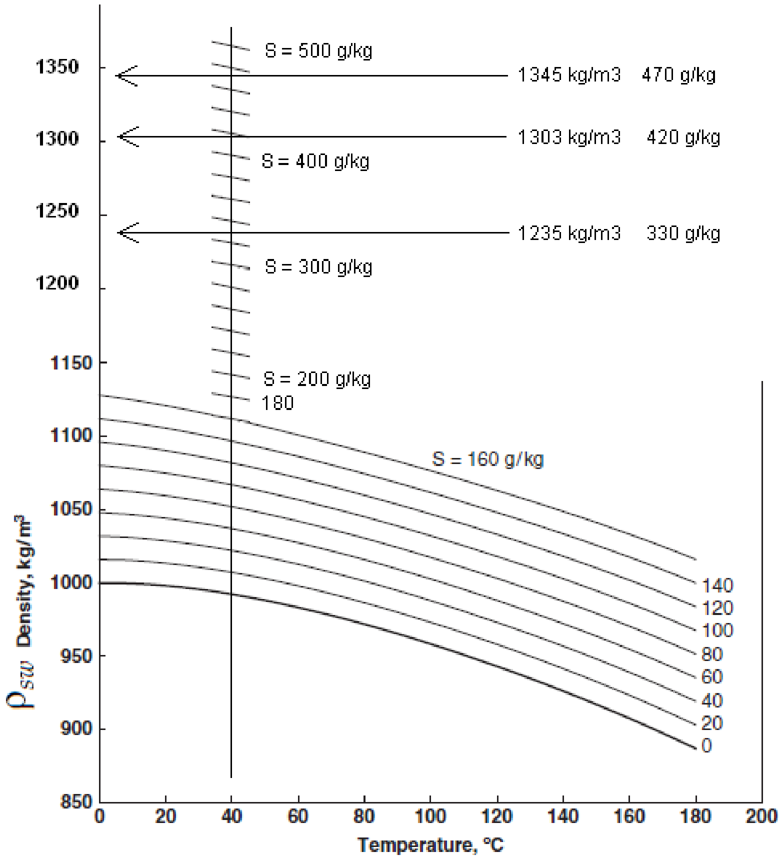

Fig. 3. Salinity S v.s. density ρ_{sw} extrapolated to 1345kg/m^3

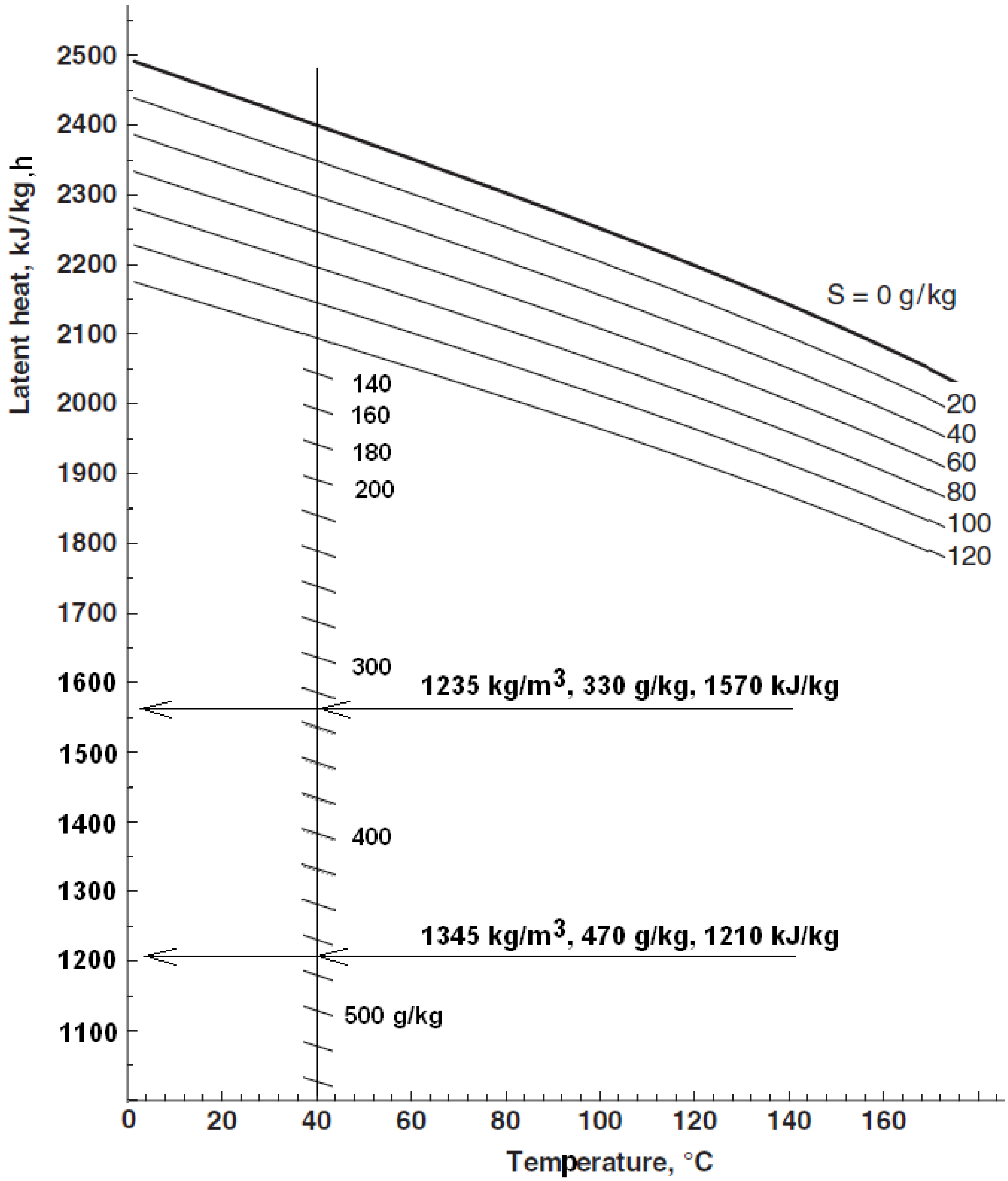

Fig. 4. Salinity v.s. specific latent heat of vaporization extrapolated to 1345 kg/m^3

1.3. According to figure 3, densities 1235, 1303 and 1345 kg/m^3 correspond to salinities 330, 420 and 470 g/kg at 40^{O}C. Fig 4 gives us the latent heat of 1570 and 1210 J/kg for densities of 1235 and 1345 kg/m^3.

Therefore, as brine is progressing along the factory basins and evaporates, it salinity increases and latent heat decreases. Exact amount of energy absorbed by south-western basin could be determined if we knew the area of every factory basin, its temperature, amount of evaporated water, and its density and salinity. Unfortunately, we don't have access to this information.

We do know, however, that 448 million m^3 of water was pumped into the south-western basin. The Sun evaporated all this water, partially in production facilities, partially in non-production areas. Salinity of water has changed from 330 g/kg to 470 g/kg and higher.

Ilyin established in [13]: "Equilibrium temperature [of the sea water at the surface] of 44-45 ^{O}C was observed in natural setting in the tropical zone of the Indian Ocean in large shallow (up to 1.5 m deep) coastal areas, where exchange of water with the Ocean is restricted due to the natural conditions. This temperature is achieved in the middle of the day. … Evaporation is the dominant factor of the heat loss. .."

As measured by satellites, water temperature in the northern basin of the Dead Sea is 20-35 ^{O}C depending on the season, time of the day and particular location. The author could not find information in the internet about surface temperature in the southern basins.

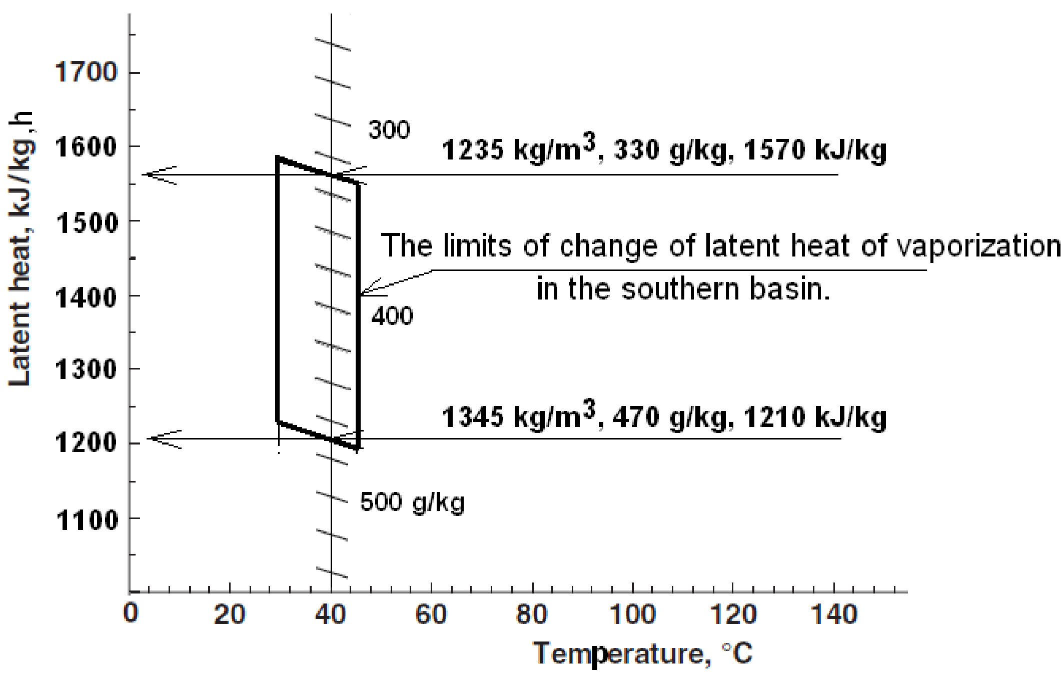

Fig. 5. Salinity S v.s. latent heat h. The countour on the graphs shows the limits of the latent heat within southern basin

Let us assume that water temperature at the surface of the south-western basin is between 30-45 ^{O}C. Fig 5 shows the area of interest for this article of the latent heat v.s. temperature diagram. Specifically, we are considering temperatures 30-45 ^{O}C and salinity of 330-470 g/kg. The specific latent heat of vaporization within this area is between 1200-1600 kJ/kg. Since we do not know temperature, salinity and so on for every point on the surface of the sea, we will assume latent heat to be the average value of 1400 kJ/kg for the entire southern basin.

In 2011, the southern basin received 448 million m^3 of sea water, which had density of 1235 kg/m^3, weight 553 million ton (=1.235*448) and salinity of 330 g/kg. This amount of sea water contained 183 million ton of salt (=553*0.33) and 370 million ton of water (=553 – 183). All water was evaporated, which required 5.18 * 10^{14} kJ (=1400 * 370 * 10^9). According to meteorological measurements [14], average annual solar energy in the vicinity of the Dead Sea is between 5 - 5.5 kWh/m^2 depending on the year. Assuming the average size of the southern basin to be 143 km^2, it receives the total solar energy of 2.74* 10^{11} kWh (=5.25 * 365*143 *10^6), or 9.86 * 10^{14} kJ (=3600*274*10^9). Therefore, efficiency of solar evaporation of water from the southern basin is 0.53 (=5.18/9.86). This is consistent with estimates given in Ilyin [13], who found the efficiency to be in the range 0.4-0.6.

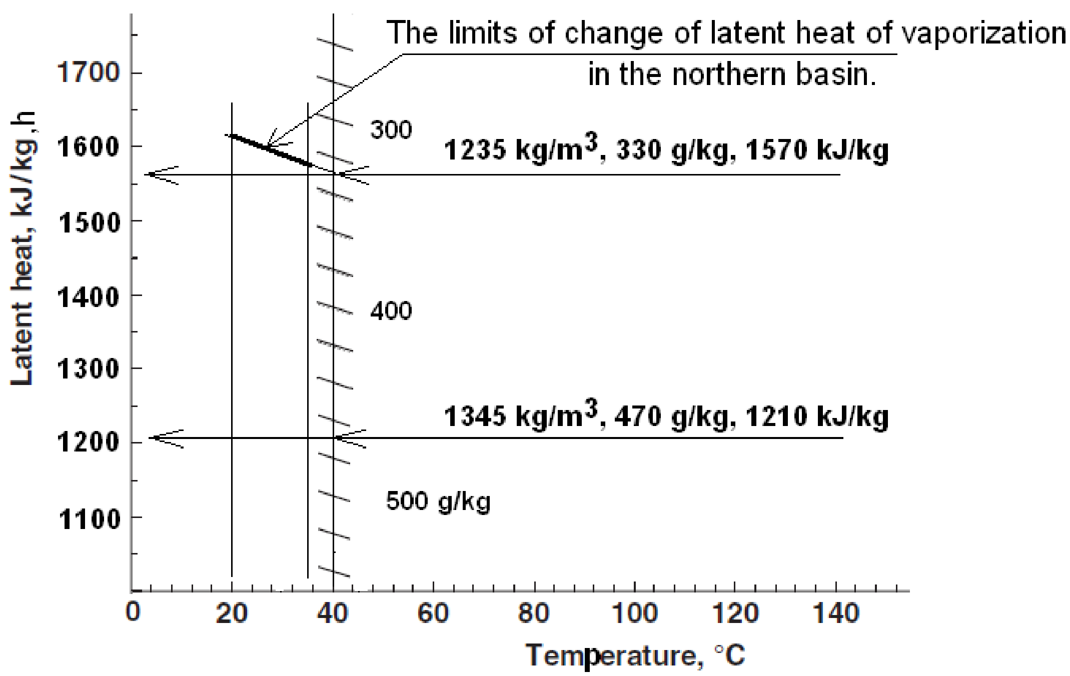

Fig.6. Salinity S v.s. latent heat h. The line on the graphs shows the dependency of the latent heat on temperature within northern basin

Figure 6 shows the line of the latent heat/temperature dependency for the conditions prevalent in the northern basin: temperatures 20-35 ^{O}C and salinity of 330 g/kg. The latent heat changes 1580-1620 kJ/kg and so we will assume average value of 1600 kJ/kg for the entire northern basin. Average annual solar energy in the vicinity of the northern basin is also between 5 - 5.5 kWh/m^2. The efficiency of solar evaporation of water from the northern basin we take also 0.53. Each square meter of the surface receives 1016 kWh (=5.25*365*0.53) or 3660 kJ/year

(=5.25*365*0.53*3600). Assuming the same efficiency of evaporation as previously obtained, this energy evaporates 2290 kg (=3660*10^3/1600) of water from 1 m^2 of surface area. The volume of the sea is reduced by 2.29 m^3/1 m^2.

1.4. The area of the northern basin in 2011 was between 603-624 km^2, and we can assume the average of 613.5 km^2. Using the results above, we can estimate that about 1405 million ton of (=2.29*613.5) water or 1405 million m^3 of the total sea volume was lost due to evaporation. Additionally, Israeli and Jordanian factories are consuming together about 723 million m^3 (=448+(250+300)/2). Thus, the northern basin of the Dead Sea is losing 2128 million m^3 (=1405+723) of water per year. At the same time, the volume of water reduced by only 613 million m^3, as the sea level dropped by 1 m. Therefore, the Dead Sea received 1515 million m^3 (=2128 – 613) of water from other sources. Rain contributed 26 million m^3 (42mm/year [15]), and the Jordan River about 100 million m^3. Creeks and subterranean currents contributed the rest 1400 million m^3.

The drainage basin of the Dead Sea extends to 40650 km^2 [16]. Different areas in this region receive different amount of rainfall in different years. For example, the Dead Sea itself receives 25-100 mm of rainfall per annum, in Jordan Munif annual rainfall of 250 mm to 1000 mm in different years [16]. Therefore, in order to supply the Dead Sea with 1515 million m^3 of water, the average rainfall over the drainage basin and eventually reaching the Dead Sea should be no less than 37 mm/year (=1515/40650).

1.5. Let us assume that during the next few years, the inflow and loss of water are approximately the same as in 2011: 1515 million m^3 is added by the Jordan River and other sources; 723 million m^3 is pumped out; solar evaporation rate is 2.29 m^3 from 1 m^2 of surface. Then the northern basin will continue to shrink and at some point the annual amount of evaporated water will be equal to the amount of added water. When the area of the northern basin is reduced to 350 km^2 (=(1515 – 723)/2.29), the sea level will stabilize, as the amount of evaporating water would be equal to the amount of added water. It may still change year to year depending on the particular conditions and commercial use, similarly to the Sea of Galilee.

Figure 7 shows how the surface area of the Dead Sea depends on the sea level. It is based on the work of Gertmann et all [8][1]. It shows, for example, that the northern basin will have the area of 350 km^2 when the sea level drops to -640 m, i.e. by 216 m compared to its current level. Since today the sea level is dropping by 1m/year, the average drop to -640 m mark will be 0.5 m/year and will take 430 years. Assumptions made in this paper will not hold over such long time period.

[1] In this paper, we estimated the area of the northern basin at the -370, -380 and -390m via site www.googleearth.com.

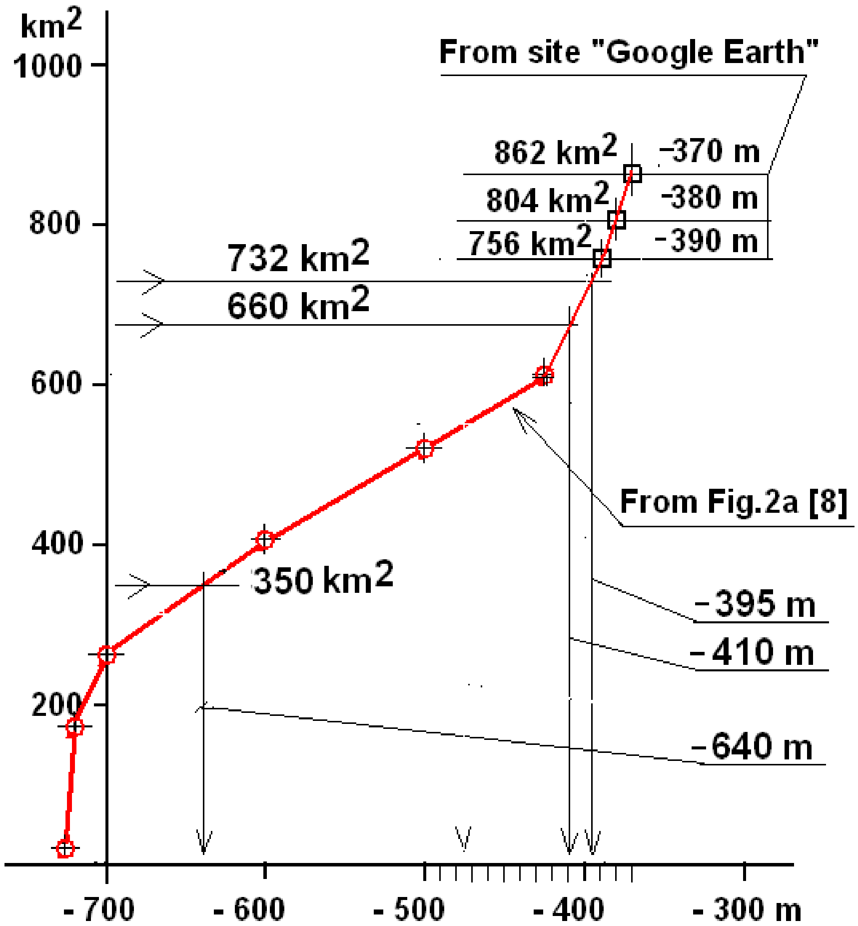

Fig. 7. Area of the northern basin of the Dead Sea

2. *Consider several proposals*

2.1. Let us assume for the sake of argument that Dead Sea factories are prohibited to pump water out of the northern basin. In October 2011, the area of this basin was 603 km^2. Given the rate of evaporation of 2.29 m^3 /m^2, 1381 (=2.29*603) million m^3 of water will evaporate annually from the northern basin**.** Therefore, the inflow of 1515 million m^3 will exceed evaporation and the water level will start increasing by 0.22 m/year (=(1515 – 1381)/603). The equilibrium will be achieved when the area of the northern basin reaches 660 km^2 (=1515/2.29), which corresponds to the Sea level of -410 m. The average rate of rising sea level will be 0.11 m/year, and therefore the sea level will stabilize after 130 years. Notice that this level of equilibrium is lower than the level of the southern basins (-395 m), and therefore water will not flow into southern basins.

If Dead Sea factories stop pumping water into the southern basins, the southern basins will completely evaporate in a couple of years, and Dead Sea hotels will be facing a salt desert. Resorts and tourism will disappear. In 1977 the sea level in the southern basins was about -400 m

[17, fig 1] and they separated from the northern basin. Southern basins did not dry out only because factories are pumping water from the north. These basins, essentially artificial, are preserving the composition of ambient air in the coastal area near the resorts.

2.2. Imagine that water is not pumped out from the Dead Sea and from the Jordan River, just like it was before 1926. In this case, the Dead Sea would continue receiving 1430 million m^3 of water from the Jordan River. The annual water balance will be determined by the inflow from the Jordan River, the subterranean currents and evaporation and will lead to adding 1564 million m^3 (1430+1515 – 1381) of water. Therefore, the sea level would start rising by 2.6 m/year (=1564/603).

The sea level would reach the level of -395 m. At this level the southern basins and northern basins would merge, restoring the situation of hundreds years ago. It would take about 15 years to reach this mark, upon which the sea level would stabilize. For example, the level of the Dead Sea was -390 m from 1900 until 1930 [17, fig 2] and above -380 m from 1180 till 1240, from 1280 till 1310, from 1570 till 1590. See fig.8.

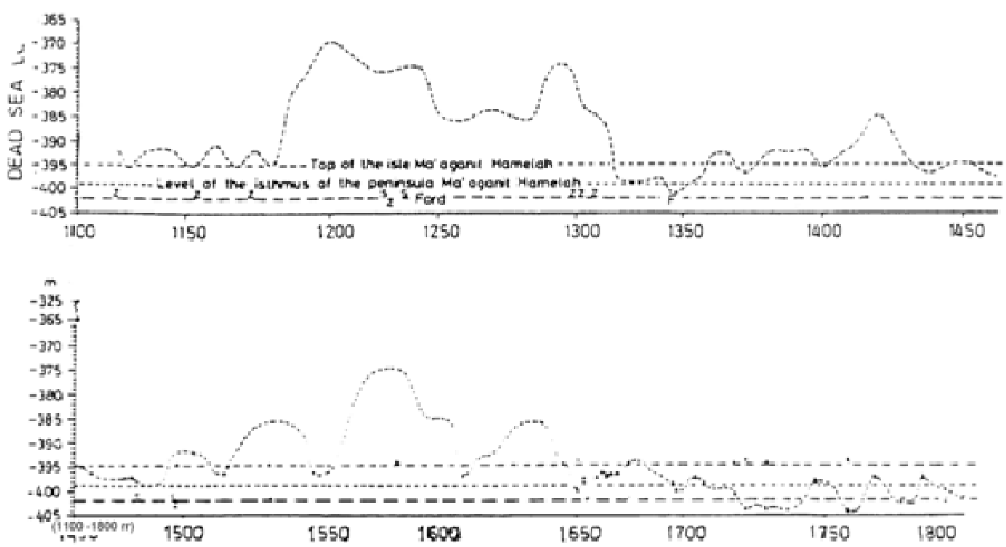

Fig. 3 [17]

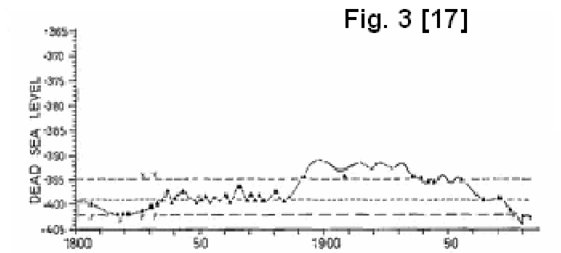

Fig. 2 [17]

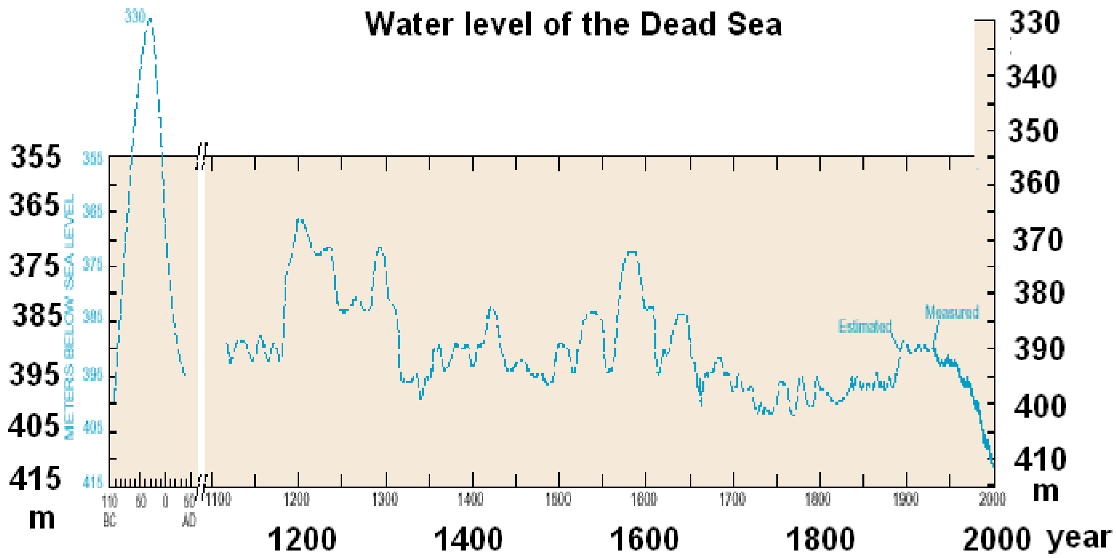

Fig. 8. Dead Sea level 1100 – 1982 [17, Fig. 2; 3]

3. Consider several projects

3.1. Let us consider consequences of realization of one of the projects to fill the Dead Sea with water from either Red Sea, or Mediterranean Sea, or with desalinated water. Different proposals suggest moving 600-1200 million m^3 of water per year (one proposal went as far as to suggest 4900 million m^3 /year). Let us assume that factories of the Dead Sea keep the current rate of pumping of 723 million m^3, and that natural inflow of water is on the current level of 1280 million m^3. Construction phase of these projects will take at least 10 years, during which the sea level will drop further 10 m and the area of the northern basin will become 600 km^2, which would mean 1381 million m^3 (=2.29*600) annual rate of evaporation.

With annual addition of 600 million m^3 fresh water, the number of evaporated water is equal to the amount of added water: 1515+600 -1381- 723=11. Sea level will stabilize at the current level.

With annual addition of 1200 million m^3 fresh water, the amount of added water would exceed the amount of evaporated water by 611 million m^3 (=1515+1200-723-1381). The rate of rising sea level would be 1 m/year (=611/600).

The sea level would reach -395 m. At this level, the basins would merge and the total area of the basins will be 732 km^2. The evaporation rate would be 1676 million m^3 /year (=2.29*732), which would generate a surplus of 316 million m^3 /year (=1515+1200 -723 - 1676) and would result in the rising level of 0.43 m/year (=316/732). Thus, the average rate of rising sea level would be 0.71 m/year (=(1+0.43)/2), and thus it would take 55 years (= (434-395)/0.71) to reach -395 m. At this point it would be better to reduce the amount of added water as rising sea would benefit neither the hotels nor the factories.

All publicly discussed projects are trying to advocate various ideas of “saving the Dead Sea”. However, what is the optimal sea level when we can say that the Dead Sea is “saved”? Clearly, the optimal sea level requires further investigation, considering ecological, commercial, touristic and other needs. One must have clear understanding of what is the optimal level in order to decide how much water to pump into the sea and therefore the size of the tunnels, the power of the pumps, etc.

3.2. Let us consider the proposal to build a “floating roof” made of plastic rafts over the Dead Sea. The roof will cost $250-300 millions and will take 6 months to a year to build. The suggested area covered by the rafts is 300 km^2. About 687 million m^3 of water (=2.29*300) will be evaporating from the uncovered 300 km^2 of the sea surface.

The annual balance would be a surplus of 105 million m^3 (=1515 – 723 – 687), which would lead to the rise of sea level by 0.17 m/year (=105/600).

Decision about the optimal level of the Dead Sea can be reached during the next 10-20 years. This is enough time to figure out the amount of water to be pumped into the sea, the size of the tunnels, the power of the pumps and the sources of financing $10 Billion for the construction. In the meanwhile the rafts can be added or removed from the floating roof to maintain the optimal level. The rafts will be floating over the northern basis, dozens of kilometers away from the hotels, which are situated along the cost of the southern basin. Therefore, they cannot affect the ambient air around the hotels.

4. *Resume*

4.1. If none of the proposals is being realized, and the inflow and loss of water are approximately the same as in 2011, the area of the northern basin is reduced to 350 km^2, the sea level drops to -640 m.

4.2. If Dead Sea factories stop pumping water into the southern basins , the area of the northern basin reach 675 km^2, the water level reaches - 410 m . This level is lower than the level of the southern basins (-395 m), and therefore water will not flow into southern basins. The southern basins will completely evaporate in a couple of years, and Dead Sea hotels will be facing a salt desert. Resorts and tourism will disappear.

4.3. If the water is not pumped out from the Dead Sea and from the Jordan River. The sea level would reach the level of -395 m. At this level the southern basins and northern basins would merge, restoring the situation of hundreds years ago.

4.4. With annual addition of 600 million m^3 fresh water, the sea level will stabilize at the current level.

4.5. With annual addition of 1200 million m^3 fresh water, the sea level would reach -395 m. At this level, the basins would merge. At this point it would be better to reduce the amount of added water as rising sea would benefit neither the hotels nor the factories.

4.6. The proposal to build a “floating roof” made from plastic rafts over the Dead Sea. The roof will cost $250-300 millions and will take 6 months to a year to build. The suggested area covered by the rafts is 300 km^2. The annual water balance would lead to the rise of sea level by 0.17 m/year.

5. Conclusion

The analysis presented in this article is based on the data obtained from the internet and on simple back of the envelope calculations. Better estimates can be obtained by verifying extrapolations and assumptions made in the article with direct experimental data. In particular, we need to measure the amount of water evaporating from 1 m^2 of the surface of the sea.

The author hopes that this analysis will help to raise awareness about the future of the Dead Sea and will energize involvement of the State of Israel in additional research and design of possible solutions. Lacking this involvement, the Dead Sea may shrink in half.

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