

## Dead Sea Rate of Evaporation

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**Abstract:** The Dead Sea is exceptional by many standards. It is the saltiest and lowest lake in the world. Moreover it is a closed lake with very large variations in its water level caused by both man-made and natural oscillations of the components that make up the water balance. Most of the fundamental studies on the Dead Sea focused on the sea water contents, Dead Sea geology, salt origin, ground-water sea intrusion, and qualitative analysis of the material balance. The objective of the present paper is to develop the needed mathematical model that can describe the Dead-Sea rate of evaporation. The model demonstrated a significant influence of relative humidity, air and water temperatures on the rate of evaporation.

**Key words:** Dead Sea, mass, energy, flux, evaporation, sea level

### INTRODUCTION

Dead Sea is a terminal lake of the Jordan Rift Valley bounded on the east by Jordan and on the west by the West Bank and Israel Fig. 1. The Dead Sea is the lowest point on the surface of the earth, and its waters have the highest density and salinity of any sea in the world. Dead Sea, for centuries, has been receiving the waters of the Jordan River, wadies, and the springs but due to evaporation very slowly concentrating the salts into what has become one of the greatest mineral reservoirs known to man<sup>[1]</sup>. The level of the Dead Sea has been declining since the beginning of the century<sup>[2]</sup>.

The origin of the salts is believed to be a leaching of soluble salts from the surrounding areas through the ages<sup>[3]</sup>. The local climate of the Dead Sea is extremely arid and hot. The rate of water evaporation is relatively slow because the water's dissolved salts lower the vapor pressure over the surface. According to Frumkin and Elitzer<sup>[2]</sup> the Dead Sea can serve as an excellent recorder of variations in precipitation/evaporation ratio. Over 43 billion tons of salts are thought to be available in the Dead Sea, of which almost 2 billion tons are Potassium Chloride<sup>[4]</sup>. The volume of the Dead Sea is about 132 km<sup>3</sup>, with surface area of about 625 km<sup>2</sup>, maximum depth of about 300 m and surface level at about 418 m below minimum sea level<sup>[5]</sup>. More general information about the Dead Sea water composition and reserves are shown in Table 1<sup>[6]</sup>.

Table 1: Dead sea composition (by weight) and reserves

Composition	Weight %	Amount (tons)
Magnesium chloride	14.5	22 billion
Sodium chloride	7.5	12 billion
Calcium chloride	3.8	6 billion
Potassium chloride	1.2	2 billion
Magnesium bromide	0.5	1 billion
Water	72.5	-
Total reserves	-	43 billion



Fig. 1: Dead Sea Location Map

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There are no rivers that drain out of the Dead Sea and the only way water gets out of the sea is by evaporation. This part of the world gets very hot, when water evaporates it leaves behind all the dissolved minerals, just making it saltier. Very few models were found in literature that looked into modeling and simulating the behavior of the Dead Sea as a whole. Asmar and Ergenzinger<sup>[7]</sup> presented a detailed model of the Dead Sea dynamic behavior, they took into account the existence of two-layer systems. On the other hand the model developed by Salameh and El-Naser<sup>[8]</sup> dealt with the quantification of groundwater inflows into the Dead Sea as a result of the Dead Sea level decline. The present rate of evaporation from the Dead Sea is not well defined yet. Estimates range from 1.05 m/year<sup>[9]</sup> to 2 m/year<sup>[8]</sup> for the current salinity. The first value was determined using heat balance approach while the latter value was found based on water balance calculations. Lensky *et al.*<sup>[5]</sup> determined that the evaporation rate ranges from 1.1 to 1.2 m year<sup>-1</sup>. The above studies and others showed that detailed evaporation model of the Dead Sea is needed in order to have more understanding about its dynamics.

In this work, two different approaches were used to address the Dead Sea rate of evaporation. The first one is the mass balance approach, which uses the components of the hydrologic cycle. The second is the energy balance approach, which investigates the effects of different modes of heat transfer on evaporation.

### MASS AND ENERGY BALANCES

During the last decade the Dead-Sea level decreased by about one meter a year<sup>[3;5]</sup>. Several factors contribute to the decline of the Dead Sea level, most of which are anthropogenic and caused by non-sustainable modes of developmental activities mainly from industry, agriculture and tourism. The main cause is the increased rate of evaporation of the Dead Sea water compared to the decrease in feeding water influx from adjacent natural tributaries.

There is a limited amount of information regarding the Dead Sea evaporation, particularly with regard to simultaneous solution of mass and energy balances. The studies that do exist have, by and large, focused on the sea water contents, Dead Sea geology, salt origin, ground-water sea intrusion, and qualitative analysis of the material balance. The rate of evaporation as a function of salinity in the Dead Sea was investigated by different researchers<sup>[10;11;12]</sup>. During the period of their studies (1950-1980s) the salinity of the surface brine increased from 225 g kg<sup>-1</sup> to 277 g kg<sup>-1</sup>. Very few papers focused on evaporation from pans containing

fresh water that was recognized to exceed evaporation from shallow lakes<sup>[13;14;15]</sup>. Neev and Emery<sup>[11]</sup> and Stanhill<sup>[16]</sup> were the first to talk about evaporation from the Dead Sea and Lake Tiberias. Their models were based on the mass balance concept. Since that time other investigators used Neev and Emery<sup>[11]</sup> model where their results have been added to the volume of literature on Dead Sea evaporation. Alpert *et al.*<sup>[17]</sup> showed that evaporation rates in the evaporation ponds of the Dead Sea southern basin have increased during the last decades due to the shrinkage of the northern basin. Recently, Lensky *et al.*<sup>[5]</sup> had developed a model to estimate the water balance of the lake that reflects the unknown subsurface water inflow, the rate of evaporation, and the lake of salt accumulation at the lake bottom. The evaporation process on free water surface of the Dead Sea is modeled based on the following two approaches: 1) Mass balance approach and 2) Energy balance approach.

**Mass balance approach:** The general mass balance equation is:

$$\left\{ \begin{array}{l} \text{Rate of mass} \\ \text{Accumulation} \end{array} \right\} = \left\{ \begin{array}{l} \text{Rate of mass} \\ \text{In} \end{array} \right\} - \left\{ \begin{array}{l} \text{Rate of mass} \\ \text{Out} \end{array} \right\} \quad (1)$$

In the above balance we assume that the Dead Sea water is neither generated nor consumed by chemical reaction, Eq. 1 can be written, based on volume, in terms of flow rates as<sup>[14]</sup>:

$$\frac{dV}{dt} = I - Q \quad (2)$$

Where V is the Dead Sea water volume, I is the water flow rate into the Dead Sea and Q is the water flow rate out of the Dead Sea. The above mass balance is influenced by Dead Sea surface and bed systems. The Dead Sea surface water mass equation is<sup>[18]</sup>:

$$\Delta V_s = P + Q_{in} - Q_{out} + Q_g - E_s - T_s - I_{inf} \quad (3)$$

Where;  $\Delta V$  is the change in the Dead Sea water volume over time, m<sup>3</sup> year<sup>-1</sup>, P is rate of precipitation over the Dead Sea, m<sup>3</sup> year<sup>-1</sup>  $Q_{in}$  and  $Q_{out}$  are the rates of surface water flows into and out of the Dead Sea, respectively, m<sup>3</sup> year<sup>-1</sup>,  $Q_g$  is the ground water rate of flow into surface streams, m<sup>3</sup> year<sup>-1</sup>,  $E_s$  is the Dead Sea surface evaporation rate, m<sup>3</sup> year<sup>-1</sup>,  $T_s$  is the plant transpiration rate of surface moisture, m<sup>3</sup> year<sup>-1</sup>,  $I_{inf}$  is water infiltration rate into the soil, m<sup>3</sup> year<sup>-1</sup>.

Because the outflow from the Dead Sea is caused mainly by evaporation where the flow into ground water is almost negligible because saline waters migrate very slowly within the low permeability basin, and there is no outflow then  $Q_{out} \approx 0$  and Eq. 3 reduces to:

$$\Delta V_s = P + Q_{in} + Q_g - E_s - T_s - I_{inf} \quad (4)$$

Similarly, the groundwater budget equation is determined as:

$$\Delta V_g = I_{inf} + G_{in} - G_{out} - Q_g - E_g - T_g \quad (5)$$

Where;  $G_{in}$  and  $G_{out}$  are the groundwater flow rates into and out of the Dead Sea. All other variables have definitions equivalent to the surface counterparts but refer to water in and out of the groundwater.

The net rate of water volume change is obtained by adding both Eq. 3 and 5:

$$\Delta(V_s + V_g) = P - (Q_{out} - Q_{in}) - (E_s + E_g) - (T_s + T_g) - (G_{out} - G_{in}) \quad (6)$$

Because of the fact that the Dead Sea has no outflow  $Q_{out} = 0$  and a groundwater flows mainly into the Dead Sea ( $G_{out} = 0$ ),  $T_s = 0$ ,  $T_g = 0$ , moreover  $E_g = 0$ , then Eq. 6, using the concept of net volume exchanges, can be written as:

$$\Delta V = P + Q_{in} + G_{in} - E_s \quad (7)$$

From Eq. 7 one can understand that the changes of lake water storage are governed by the incoming fluxes ( $P$ ,  $Q_{in}$ ,  $G_{in}$ ) and outgoing flux ( $E_s$ ). The average precipitation over the Dead Sea surface ( $P$ ) based on average rain fall of  $70 \text{ m year}^{-1}$  is  $45 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ .

The inflow of surface water into the Dead Sea ( $Q_{in}$ ) comes mainly from the Jordan River and can be determined as:

$$Q_{in} = q_r + q_{ew} + q_{ww} \quad (8)$$

Where;  $q_r$  is the surface water from Jordan River (main contributor) that is estimated to be  $(60-150) \times 10^6 \text{ m}^3 \text{ year}^{-1}$ ,  $q_{ew}$  and  $q_{ww}$  are the surface water from the eastern and western wadis of the Dead Sea, respectively  $(150-370) \times 10^6 \text{ m}^3 \text{ year}^{-1}$  [1;19].

The groundwater flow ( $G_{in}$ ) into the Dead Sea is determined as;

$$G_{in} = g_{ES} + g_{WS} + g_{NSB} \quad (9)$$

Where;  $g_{ES}$  is the eastern side groundwater flow,  $g_{WS}$  is the western side groundwater flow and  $g_{NSB}$  is the northern and southern basin groundwater flow.

The uncontrolled groundwater flow to the Dead Sea along its eastern side was calculated by Salameh and El-Naser<sup>[20]</sup> to be  $90 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ . Groundwater flow from western side is given by Wolf<sup>[21]</sup> to be  $100 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ . Northern and Southern basins flow into the Dead Sea is relatively small and can be estimated as  $30 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  [8].

As long as there is a decline in the Dead Sea level by about one meter per year, the change in the Dead Sea volume can be determined as:

$$\Delta V = \Delta h \times (\text{DS surface area}) \quad (10)$$

And the yearly rate of evaporation, based on the mass balance approach Eq. (7), is determined as:

$$E_s = P + Q_{in} + G_{in} - \Delta V \quad (11)$$

If one assumes that there is no change in the Dead Sea water volume then the maximum rate of evaporation is estimated, based on Eq. 11, to be about  $160 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ .

**Energy balance approach:** Heat transfer in Dead Sea water body can be described by the equation of thermal energy<sup>[22]</sup>. We consider a fixed volume of Dead Sea water  $V$  containing an air-water interface of area  $A_{aw}$  and a water-sediment interface of area  $A_{ws}$ , the equation of energy can be written as<sup>[22]</sup>;

$$\rho \hat{C}_p \frac{dT}{dt} = \frac{1}{V} (q_{aw} A_{aw} + q_{ws} A_{ws}) \quad (12)$$

Where gradient of temperatures right above the Dead Sea level, convective flow, and heat generations within the volume are neglected. Equation 12 states that the change in enthalpy of a fixed water body is the result of heat flow through the interfaces (sea-surface and water-sediment). The sign convention adopted is that: energy additions to a surface are positive and energy losses are negative. All energy or heat flux relations are in  $J/m^2 \text{ s}$ .

Assuming steady state and neglecting heat losses through the bottom and sides of Dead Sea, the heat flux through the air-water interface consists of four major sources;

$$q_{aw} = q_{lw} + q_c + q_e + q_s \quad (13)$$

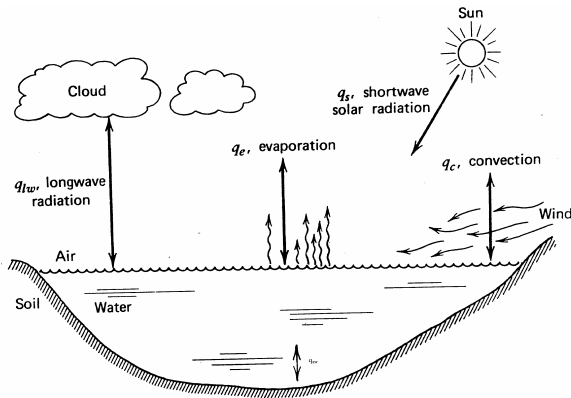


Fig. 2: Heat transfer mechanisms

Where;  $q_{lw}$  is the long wave radiant energy flux (incident, direct and diffusive solar energy),  $J/m^2 \cdot s$ ,  $q_e$  is the evaporative heat flux,  $J/m^2 \cdot s$ ,  $q_c$  is the sensible heat flux,  $J/m^2 \cdot s$ ,  $q_s$  is the short-wave radiant energy flux, (incident, direct and diffusive solar energy),  $J/m^2 \cdot s$ .

Figure 2 shows the above transfer mechanisms. The magnitude of the fluxes depends on the water body, its geographic location and time. All fluxes except  $q_s$  can be positive or negative.

**Short-wave radiation ( $q_s$ ):** originates directly from the sun. The amount of solar radiation incident on horizontal surface varies, depending on geographic location, elevation, season, and meteorological conditions, date during the year and time during the day. The total daily solar radiation at the top of the atmosphere, at  $31^\circ N$  and  $34^\circ E$ , for this radiation flux can be found in List<sup>[23]</sup>. Annual average percentage of possible sunshine in Mediterranean or dry summer subtropical regions is 9.75 according to JMD<sup>[24]</sup>. Short-wave radiation can be estimated by the following equation<sup>[25,26]</sup>:

$$q_s = q_{s_0}(0.80 - 0.34n - 0.46n^2) \quad (14)$$

Where:  $q_{s_0}$  value is obtained from List<sup>[23]</sup> and  $n$  is the fractional cloud cover which is always less than or equals to one and determined as:

$$n = 1 - \text{fraction sunshine} \quad (15)$$

Where the fraction sunshine is provide by the sunshine information<sup>[24]</sup>.

**Long wave radiation ( $q_{lw}$ ):** By virtue of a temperature difference, the water and its surrounding air exchange radiant energy. The rate equation for net exchange is<sup>[22]</sup>:

$$q_{lw} = \beta \sigma T_a^4 - e_w \sigma T_w^4 \quad (16)$$

Where;  $\beta$  is the cloud cover factor,  $\sigma$  is the Stefan-Boltzman constant ( $5.67 \times 10^{-12} J/s \cdot cm^2 \cdot K^4$ ),  $T_a$  is the air temperature in Kelvin,  $e_w$  is the emissivity of the water surface,  $T_w$  is the water surface temperature in Kelvin.

The first term on the right-hand side of Eq. (16) is the Long wave atmospheric radiation.  $\beta$  is a function of the type of cloud cover, given by;

$$\beta = a + b p_v \quad (17)$$

Where  $p_u$  is the partial pressure of water vapor in inches of mercury and  $a$  and  $b$  are constants. For each value of cloud cover, these constants were approximated by Sax<sup>[27]</sup>. Over the range from 0 to  $50^\circ C$  the vapor pressure of water in Pascal can be calculated within  $\pm 4\%$  error by;

$$P_v = 99.62 \left[ \exp\left(21.66 - \frac{5431.3}{T}\right) \right] H_R \quad (18)$$

Where:  $T$  is in Kelvin and  $H_R$  is the fraction relative humidity  $0 < H_R < 1$ . The second term on the right-hand side of Eq. (16) is the long wave radiation originating at the water surface, a reasonable value for the emissivity of water is  $0.97$ <sup>[22]</sup>.

**Evaporation energy exchange ( $q_e$ ):** If the air above a body of sea water is less than 100% saturated with water vapor (i.e.,  $H_R < 1$ ), there is a potential for evaporation from the sea surface. The evaporated water requires energy, latent heat of evaporation, as it changes from a liquid to a vapor phase. Latent heat is defined as the amount of heat absorbed or evolved by 1 mole, or a unit mass, of a substance during a change of state (such as fusion, sublimation, or vaporization) at constant temperature and pressure. At the sea surface, water is present and changes phase, either from a liquid to a gas (vaporization) or from a gas to a liquid (condensation). As one may expect, the relationship of energy movement rate is related to the water movement rate<sup>[28]</sup>.

$$q_l = n_w \lambda_w \quad (19)$$

Where:  $q_l$  is the rate of latent heat transfer at the interface in units of  $J/m^2 \cdot s$ ,  $n_w$  is the mass flux rate of water moving across the interface in units of  $g/m^2 \cdot s$ ,

and  $\lambda_w$  is the latent heat of vaporization of water in units of J/g. The latent heat of vaporization of water at 24°C is  $2.44 \times 10^6$  J/kg<sup>[28]</sup>.

Even though chemicals may be moving across the interface with accompanying heat of vaporization or condensation effects; their contribution to the latent heat transfer is negligible because of their dilute nature. It is therefore necessary to account for the water only when quantifying latent heat effects across the air-water or the air-soil interface<sup>[28]</sup>.

The American National Weather Service has developed a monograph<sup>[29]</sup> for calculating lake evaporation. This calculation requires the following input data: mean daily temperature, solar radiation in langleys (cal/cm<sup>2</sup>) per day, mean daily dew point temperature, and wind movement in miles per day. Experimental field measurements on the evaporation of water from the lake Hefner and a resulting correlation developed by Harbeck<sup>[30]</sup> results in:

$$q_e = -30.5 \times v_x \times (P_v^\circ - P_v) \quad (20)$$

Where  $q_e$  is evaporative heat loss in J/m<sup>2</sup>.s,  $v_x$  the wind speed in km/h,  $P_v^\circ$  the vapor pressure of water in in.Hg at  $T_w$  (the water surface temperature) and  $P_v$  is the partial pressure of water vapor in the air far above the sea removed from the sea (lake) surface. Note that  $P_v^\circ$  can be obtained from Eq. 18 with  $H_R = 1$  and  $T = T_w$ . Atmospheric temperature ( $T_a$ ), relative humidity ( $H_R$ ), and wind velocity ( $v_x$ ) are usually measured at 8 to 10 m above the sea surface, their values, for the Dead Sea, are shown in Table 2 according to Oroud<sup>[13]</sup>.

**Sensible heat exchange ( $q_c$ ):** Heat enters or leaves water by conduction if the air temperature is greater or less than the water temperature. The rate of sensible heat transfer can be written in terms of Newton's law of cooling<sup>[31]</sup>:

$$q_c = 0.27 \times v_x \times (T_a - T_w) \quad (21)$$

Where:  $q_c$  is the sensible heat transfer rate in J/m<sup>2</sup>.s and  $T_a$  and  $T_w$  are the air and water temperatures, respectively, in Kelvin.

**Heat flux across the sediment-water interface ( $q_{ws}$ ):** The heat exchange across the water-sediment interface is occurring by conductive mechanism and can be determined as<sup>[32]</sup>:

$$q_{ws} = h_{ws} \Delta T \quad (22)$$

Table 2: Average Monthly Meteorological Conditions of the Dead Sea

Month	$T_a$ (°C)	$T_w$ (°C)	$v_x$ (m/s)
Jan.	15.0	17.3	1.5
Feb.	16.2	18.4	1.7
Mar.	20.2	22.3	2.2
Apr.	24.9	26.7	2.0
May	28.3	29.4	2.2
June	31.2	32.5	2.1
July	33.4	34.4	2.0
Aug.	33.4	34.6	1.9
Sept.	31.3	33.3	1.9
Oct.	27.9	29.9	1.4
Nov.	22.9	24.9	1.4
Dec.	18.3	19.7	1.4
Average	25.3	26.95	1.8

Where:  $q_{ws}$  is heat flux across the sediment-water interface rate per unit area of interface,  $h_{ws}$  the local value of the heat transfer coefficient,  $\Delta T$  is the temperature difference between the water at the sea bottom and mud surface which usually can be on the order of a tenth of a degree Celsius ( $\Delta T = \pm 0.1^\circ\text{C}$ )<sup>[33]</sup>.

Assuming steady state condition, then Equation (12) becomes:

$$-q_{aw} A_{aw} = q_{ws} A_{ws} \quad (23)$$

Substitute both Equations 13 and 22 into Equation 23, we obtain:

$$-(q_{lw} + q_c + q_e + q_s) = \frac{A_{ws}}{A_{aw}} (h_{ws} \Delta T) \quad (24)$$

From Eq. 24 one can calculate the evaporative heat flux as:

$$q_e = -\frac{A_{ws}}{A_{aw}} (h_{ws} \Delta T) - (q_{lw} + q_c + q_s) \quad (25)$$

## RESULTS AND DISCUSSION

**Mass balance:** The decline in the Dead Sea level is a sign of the negative water balance, whereby evaporation greatly exceeds inflow. This is due to the diversion of fresh water from the catchment area of the Dead Sea and results in the collapse of the infrastructure around the Dead Sea.

The Dead Sea unique ecosystem was threatened after diversions from feeding streams and increasing rate of evaporation caused by lowering of the water level and an increase in salinity. Figure 3 shows the decreasing Sea level<sup>[20;34]</sup>. The water level of the Dead Sea has been monitored continuously and has declined

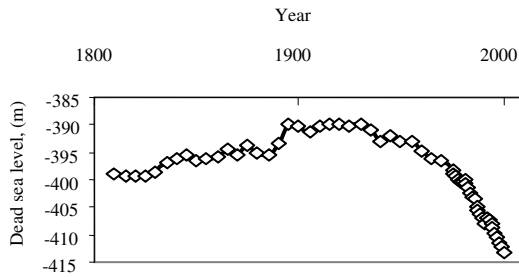


Fig. 3: Historical dead sea water level<sup>[20,34]</sup>

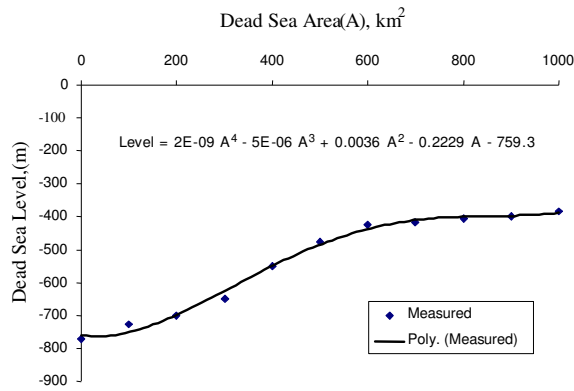


Fig. 4: Dead sea level versus surface area<sup>[4]</sup>

over 25 m from 1930 to 2004. Such a large decline raises questions of whether there are precedents for this water level change and whether they can be explained by normal variances in climate. Fortunately, evidence of historical Dead Sea water level changes may be found from several independent sources. Omari and Sharayea<sup>[4]</sup> had showed that a stable Dead Sea shoreline has not been maintained due to the above-mentioned reasons (Figure 4). Since the measured data showed a nonlinear relation between Dead Sea level and Dead Sea surface area as shown in Fig. 4. and because of the fact that with a variable surface area, the Dead Sea water surface elevation cannot be calculated simply from the water volume and the surface area.

A nonlinear regression was used to fit a trend line to the data to obtain a best-fit line that relates Dead Sea water level elevation to surface area.

As seen in Fig. 4, the best-fit model was found to be a fourth-order polynomial equation as follows:

$$DSL = 2 \times 10^{-9} A^4 - 5 \times 10^{-6} A^3 + 0.0036 A^2 - 0.2229 A - 759.3 \quad (26)$$

where DSL stands for Dead Sea level in meters and A for surface area in km<sup>2</sup>. Using combined mass and energy balance approaches (Equations 11 and 20)

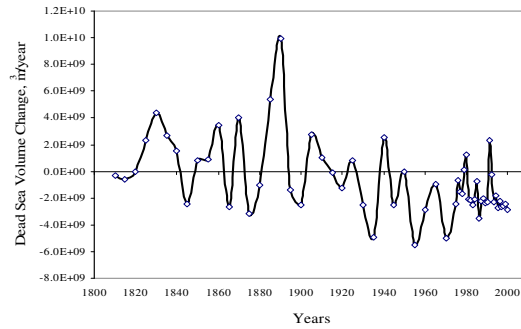


Fig. 5: Yearly change in the dead sea volume based on the mass balance

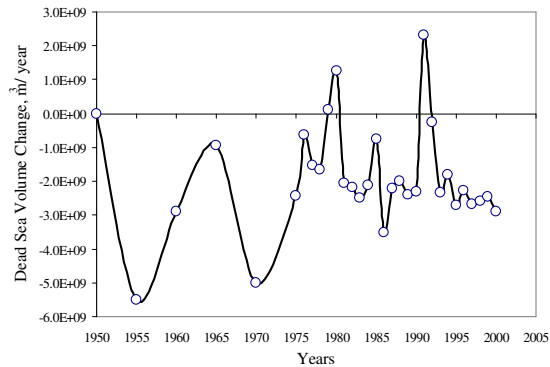


Fig. 6: Yearly change in the dead sea volume based on the mass balance for the last 50 years

and Fig. 3, we can determine the yearly change in the Dead Sea volume. From Fig. 5 and 6 negative values of the volume change represent the Dead Sea water losses caused by evaporation and industrial pumping of water from the Dead Sea into evaporation ponds constructed in the shallow southern basin while the positive values were caused by excess inflow rates of precipitation, surface and groundwater flows. It is clear, from Fig. 6, that the mean annual volume change is about  $2 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ . These results vary within less than 1-3% of the results obtained previously<sup>[20;13;35]</sup>. As the Dead Sea water volume increases, the surface area will increase. The function relating the surface area to the Dead Sea water volume is Dead Sea-specific and depends on its bathymetry.

**Energy balance:** Equation 12 is a transient first order differential equation where the temperature (dependent variable) is changing with time (independent variable) and called initial valued problem. The fourth order Runge-Kutta method was used to solve this equation because it provides high order approximations for the explicit integration of initial valued ODE's.

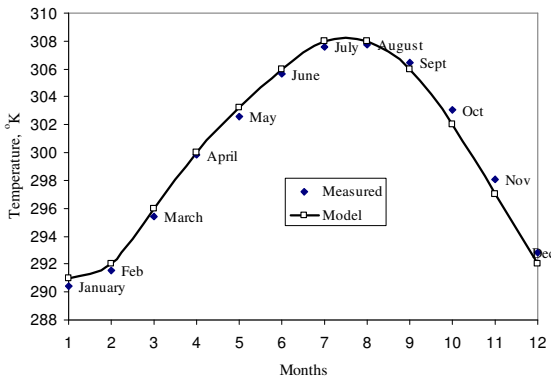


Fig. 7: Comparison between measured<sup>[4]</sup> and modeled dead sea temperatures for the Year 2004

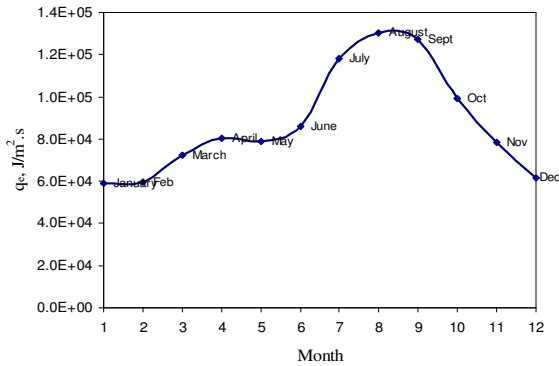


Fig. 8: Evaporative Heat Flux for the Dead Sea during the Year 2004

Figure 7 shows a comparison between measured Dead Sea temperature<sup>[4]</sup> and the approximated temperature values by the model. It is clear from this figure that there is very good match between both values of temperature throughout the year.

The calculated evaporative heat flux that was absorbed by the Dead Sea profile is shown in Fig. 8, this profile was calculated using Eq. 25 and based on the information given in Fig. 7 (measured Dead Sea temperature). As long as the evaporative heat flux is a strong function of sea temperature and the temperature of the air above the sea, it behaves almost in the same fashion as temperature does. The minimum values of the evaporative heat flux were observed during the months of December and January, and the maximum value takes place during the summer time, in August, when the temperature has its maximum value. At the beginning of the year the evaporative heat flux was minimum and has a value of 58977 J/m<sup>2</sup>.s, it then increased to reach the first maximum value of 80642 J/m<sup>2</sup>.s in April, the heat flux value decreased a little bit and became almost steady during the month of May,

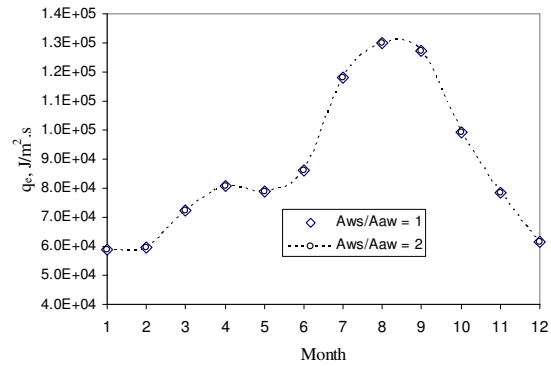


Fig. 9: Effect of the Ratio between Water-Sediment Interface Area ( $A_{ws}$ ) and Air-Water Interface Area ( $A_{aw}$ ) on Evaporative Heat Flux

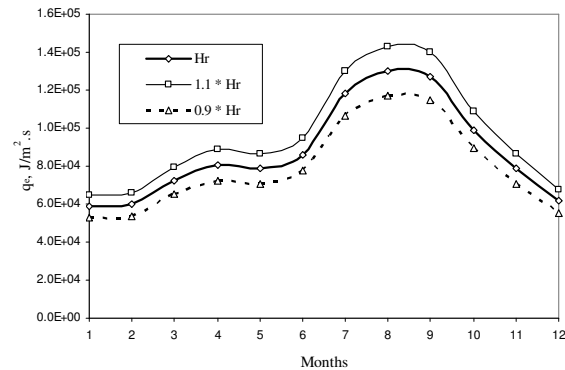


Fig. 10: Effect of Relative Humidity on the Evaporative Heat Flux

this trend might be caused by the khamasini (sand storms from the east). In June the evaporative heat flux gradually increased to reach another maximum value of 130133 J/m<sup>2</sup>.s in August, then it decreased exponentially to reach a value of 61670 J/m<sup>2</sup>.s in December.

The effects of changing some parameters on the value of evaporative heat flux were investigated and the results were as follows:

**Effect of  $A_{ws}/A_{aw}$  on evaporative heat flux:** If the ratio between water-sediment interface area and air-water interface area is doubled which means that the sea bottom area is twice of the sea surface area, the value of the evaporative heat flux is not affected significantly as shown in Fig. 9.

**Effect of relative humidity (Hr):** When the relative humidity was increased throughout the year by 10% a positive shift in the evaporative heat flux curve occurred as shown in Fig. 10. The same direct proportionality between evaporative heat flux and a

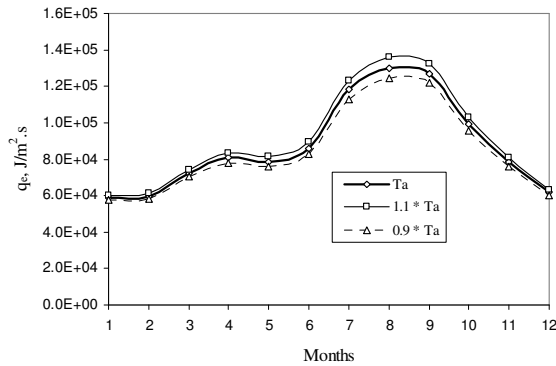


Fig. 11: Effect of air temperature on the evaporative heat flux

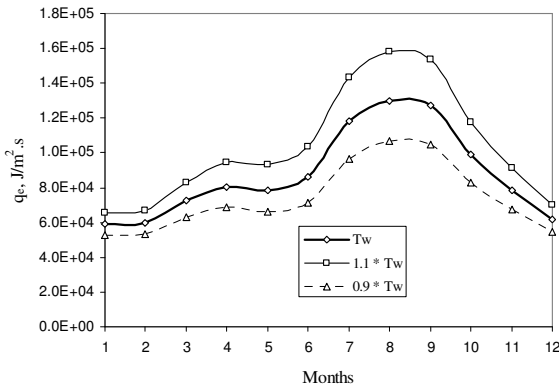


Fig. 12: Effect of water temperature on the evaporative heat flux

decrease in relative humidity was observed. This proportionality occurs because of the fact that long wave radiation equation contains the cloud cover factor that is a function of vapor pressure where the latest depends on relative humidity along with temperature.

**Effect of air temperature ( $T_a$ ):** Figure 11 shows the evaporative heat flux curves for different values of air temperature. One can see that an increase in the air temperature by 10% results in a positive shift in the evaporative heat flux curve while a 10% decrease in air temperature throughout the year results in a negative shift. These shifts occurred because both long wave radiation and sensible heat exchange are strong functions of air temperature.

**Effect of water temperature ( $T_w$ ):** The profiles of evaporative heat flux for different water temperature throughout the year are shown in Fig. 12. Similar trends were observed for similar changes that were taking place in the case of air temperature effect (Figure 11).

The only difference is that at higher temperature, in August, the increase in the evaporative heat flux is larger for an increase in water temperature by 10% (Figure 12) compared to the change in the flux during the same month for the same change in air temperature. Similar phenomenon occurs with a decrease in temperature with the same proportion. Dead Sea surface temperature present special concerns in heat flux applications because of the variety of measurement methods. Because latent, sensible, and longwave radiative fluxes occur in the upper fractions of a millimeter of the Dead Sea surface, they lead to a "cool sink" that has been recognized long time ago<sup>[29]</sup>. Therefore the air-water interface is up to 0.5 K cooler than the water that is one millimeter below the sea surface. About half the solar radiation is absorbed in the upper meter of the ocean<sup>[28]</sup>, so there are substantial diurnal variations in the water temperature profiles in the upper few meters, where the evaporative heat flux is believed to be absorbed.

## CONCLUSIONS

A mathematical model, based on the basic principles of conservation of mass and conservation of energy, was developed to describe the dynamic behavior of the Dead Sea. The Dead Sea balances decreased inflows not only by a decline in water level but also by decreased evaporation losses. As the water level of the Dead Sea declines, the Dead Sea surface area decreases causing a corresponding decrease in the volume of evaporated water. Greater than 300 km<sup>2</sup> decrease in surface area between elevations -385 and -414 would decrease the annual volume of evaporated water from about 4x10<sup>9</sup> m<sup>3</sup>/year to about 2x10<sup>9</sup> m<sup>3</sup>/year. Evaporation during periods of low water level is further decreased by an increase in water salinity near the surface.

Energy balance calculations were performed by separate calculations of the several heat budget terms that include short-wave radiation, long-wave radiation, evaporation energy exchange, sensible heat exchange and conductive heat flux. The effects of some parameters on the evaporative heat flux value were investigated.

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