STATE OF ISRAEL

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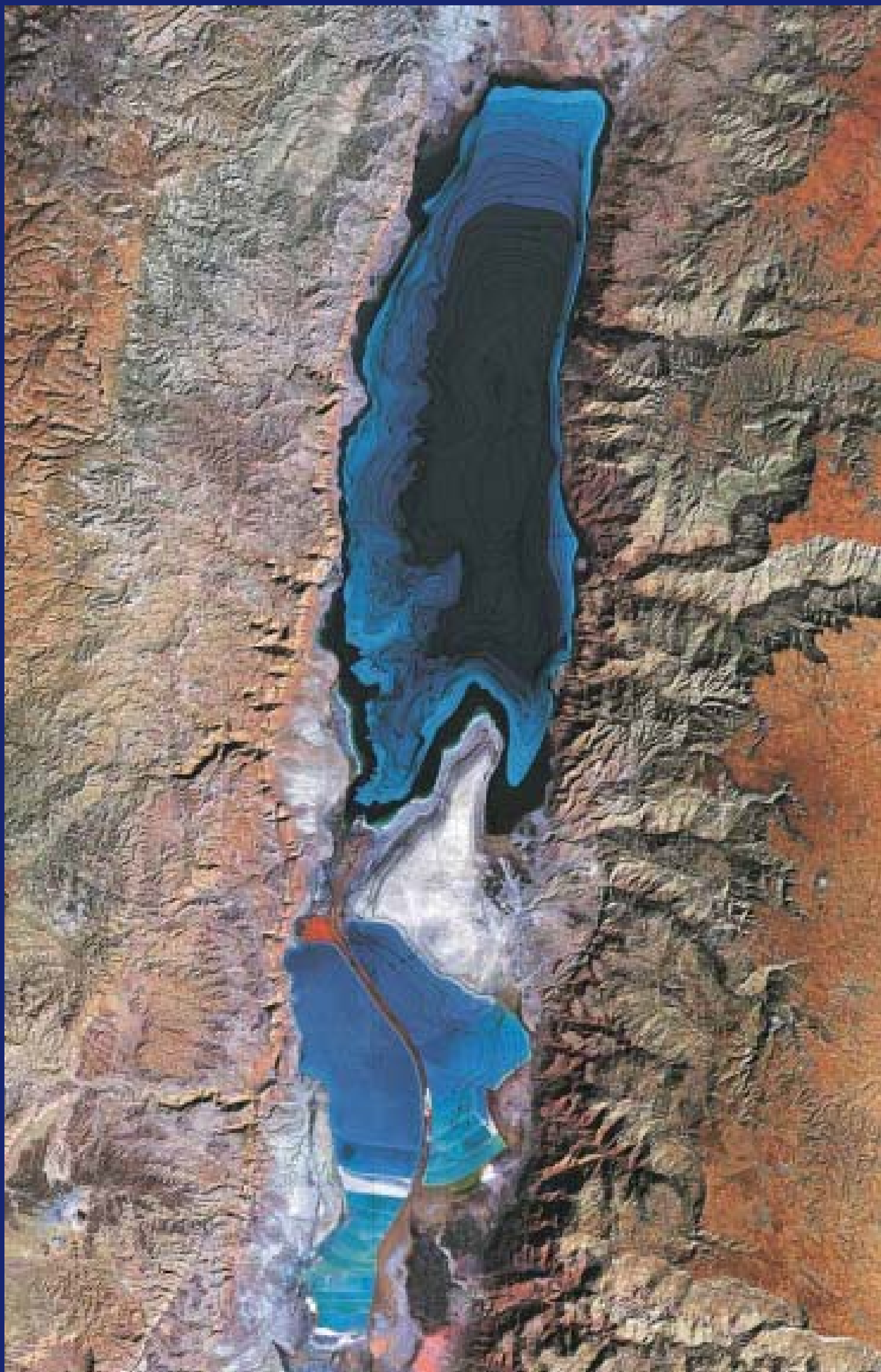

Report GSI/23/2002
Jerusalem, September 2002

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THE IMPACT OF THE PROPOSED "PEACE CONDUIT" ON THE DEAD SEA

Evaluation of Current Knowledge on Dead Sea – Seawater Mixing

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Jerusalem, September 2002 **GSI/23/2002**

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Introduction

The renewed interest in the construction of a conduit from the Red Sea to the Dead Sea has focused attention on the future and fate of the Dead Sea. The new project, the "Peace Conduit" is aimed at discharging seawater or reject brine (concentrated seawater after desalinization), into the Dead Sea, thereby raising and later stabilizing its level and allowing a sustainable development along its shores. Yet, the inflow of seawater or reject brine to the Dead Sea will have a major impact on its limnology, geochemistry and biology. Therefore, before a decision is made on the planning and construction of the Conduit, it is essential that the characteristics of the "renewed" Dead Sea be known and anticipated changes examined. In particular, environmental elements that may hinder the project all together must be identified. Once decided upon, the planning and construction of the Conduit should be conducted so as to minimize possible negative impacts of seawater introduction on the Dead Sea. This can only be achieved through a thorough understanding of the limnological physical/chemical characteristics of the Dead Sea and its unique brine.

Our current understanding of the processes expected to occur upon the introduction of seawater or reject brine to the Dead Sea is largely based on studies performed within the framework of the Mediterranean-Dead Sea Co. Ltd (Med-Dead Co.) in the late 1970s early 1980s. These were also the basis for the pre-feasibility study for the Red Sea- Dead Sea Canal (RSDSC) carried out by the Harza JRV group in the mid 1990s. It should be emphasized that the approach taken at the time by the Med-Dead Co. was to study the various aspects mentioned above independently of one another. **The data available from these studies and conclusions derived from them are indispensable**. Yet, the information is not integrated into a single dynamic-limnological model that can reliably forecast the future evolution of the Dead Sea over a prolonged period (decades) of seawater inflow. Such a model is currently under construction as a joint endeavor of the Geological Survey of Israel and the Ministry of Regional Cooperation.

We present here an overview and evaluation of the Dead Sea limnology and the expected changes that will take place following mixing of seawater with Dead Sea brine. This overview is a synthesis of current understanding of the dynamics of the Dead Sea and studies performed by the Med-Dead Co. and those that followed. It evaluates the expected outcome of each of the parameters under consideration, and identifies questions that decision makers will need to address during the early stages of discussion and planning of the Conduit. In the review, the term “seawater” includes also concentrated seawater after desalinization. The latter will have similar ionic ratios but be about twice more concentrated than seawater.

Background

The vision of a canal or pipeline connecting the Mediterranean or the Red Sea with the Dead Sea has captured the imagination of people for nearly 150 years. The first to propose it was William Allen, who in 1855, not realizing the difference in elevations, suggested the use of such canals as a waterway connecting the Mediterranean with the Red Sea (Vardi, 1960). Some 50 years later Herzl envisioned a canal between the Mediterranean and the Dead Sea that would serve as a hydroelectric power source. This vision was also the foundation for the Mediterranean Sea – Dead Sea Company which funded the feasibility study of such a canal following the 1973 energy crisis (Mediterranean Sea-Dead Sea Company, 1984). More recently, following the peace treaty between Israel and the Hashemite Kingdom of Jordan, a pre-feasibility study was conducted to study a proposed Red Sea - Dead Sea Canal (RSDSC). The principal objective of this project was to utilize the 400 meter elevation to desalinize seawater on the shores of the Dead Sea by reverse osmosis, thereby producing 800 to 850 million cubic meters (MCM) of desalinated drinking water annually while discharging the reject brine to the Dead Sea. (Harza JRV Group, 1996). An additional goal was to raise the Dead Sea level and stabilize it. The recommendation presented by the Harza group was to proceed with a full feasibility study. However, to date, the two countries have not implemented this recommendation.

The renewed interest in Israel and the Hashemite Kingdom of Jordan in the construction of a canal/pipeline, termed lately as the “Peace Conduit”, is due to a number of related issues: (1) a growing concern that the Dead Sea must be “saved” in order to maintain the scenic beauty of the area and preserve its historical and environmental uniqueness for future generations. (2) The development of infrastructure and tourism facilities around the lake has been brought to a standstill due to the receding shoreline and the danger presented by the regional collapse of infrastructure (sinkholes, sinking and collapsed structures, swampy mud, etc.). (3) The possibility of utilizing the proposed Conduit for desalinization of the inflowing seawater, thereby providing freshwater to the surrounding entities. This aspect of the project is particularly attractive to Jordan which suffers from a major water shortage.

Recent and Future Changes in the Dead Sea

During the 20th century, the Dead Sea level has dropped by more than 20 meters, and presently stands at approximately 416 meters below mean sea level (-416m). In 1976, when lake level reached an elevation of –400 the southern basin dried up (Fig. 1), requiring the potash industries to pump water to the evaporation ponds, located within the Southern Basin, from the deep Northern Basin of the Dead Sea. The decline in the Dead Sea level is a manifestation of the negative water balance of the lake, whereby evaporation greatly exceeds inflow. The rate of water level drop over the last few years is more than 1 m/yr (Fig. 2). This negative water balance is attributed primarily to diversion of water from Lake Kinneret to the National Water Carrier, and from the Yarmuk River to the King Abdullah Canal in Jordan. Additional water is captured upstream by the Syrians. The average annual water deficit of the Dead Sea, assuming an annual water level drop of 1 m/yr, is 625 million cubic meters (taking

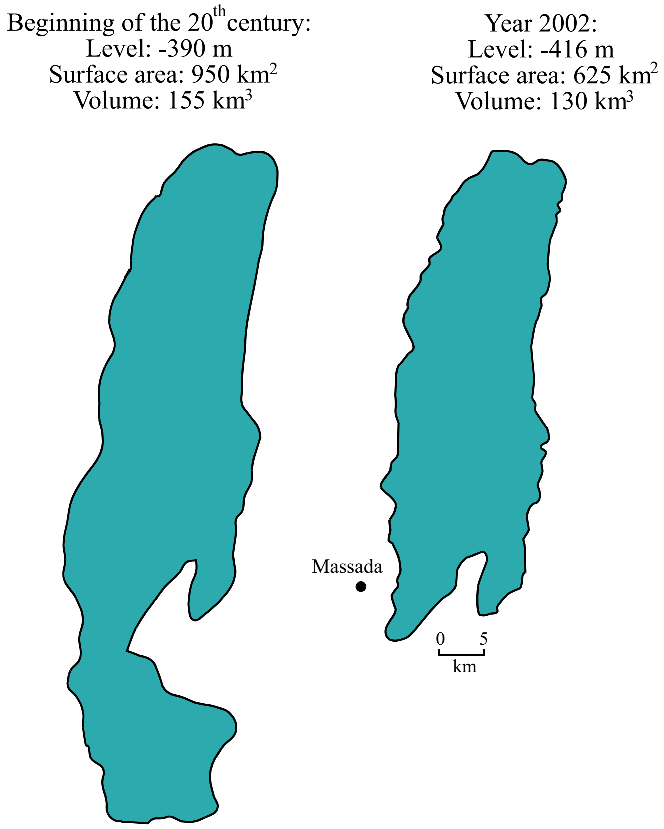

Fig. 1. Comparison between the Dead Sea in the beginning of the 20th century and today.

the surface area of the Dead Sea at elevation of –416 as 625 km^2, Hall, pers. com). Over the last few years the rate of decline has been even greater, 1.3m between October 1999 and 2000, and 1.07m between October 2000 and 2001, indicating even greater annual water deficits.

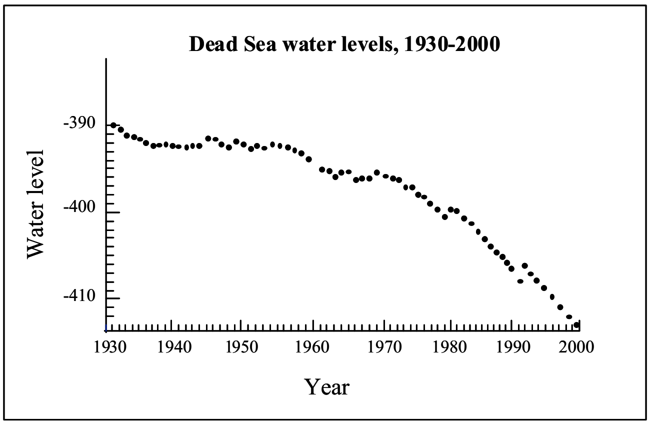

Fig. 2. Dead Sea levels, 1930-2000.

If the current situation prevails, the Dead Sea level is expected to continue to decline. In fact, future inflow to the Dead Sea is only expected to decrease further, as more of the water currently flowing to the lake will be captured and diverted to meet growing needs for freshwater. More of the Wadi's on the eastern escarpment of the Dead Sea Rift, such as Nahal Arnon (Wadi Mujib) with its perennial flow, are planned to be dammed, while the discharge of the major spring system around the lake, En Feshcha, will probably decline as water is pumped upstream. On the other hand, the rate of groundwater discharge to the lake increases due to the receding base level and the consequent increase in the hydraulic gradient and seaward migration of the brine/freshwater interface (Salameh and El-Naser, 1999, 2000a,b). Salameh and El-Naser (1999, 200a,b) estimate this additional groundwater discharge to readjust the interface at over 400 MCM per meter drop in DS level in recent years. However, other researchers do not support these figures, as they require very high evaporation rates from the Dead Sea surface.

A model proposed by Yechieli et al. (1998) for the future evolution of the lake suggests that under current conditions the lake level will continue to decline but will approach a steady state level some 400 years from now, at an elevation of about –510m, i.e. ~100m below the present level (Fig. 3). This steady state will be achieved when the volume of inflowing water will compensate for water evaporated from the Dead Sea surface. Such conditions will be achieved due to the decreasing surface area of the lake and the decrease in evaporation rate, the latter resulting from the increasing brine salinity.

Similar steady state lake level forecasts were obtained by Krumgalz et al. (2000), who based their calculations on a thermodynamic approach. However, Asmar and Ergenzinger (2002) predict a continuous decline in the level over 500 years that does not approach a steady state.

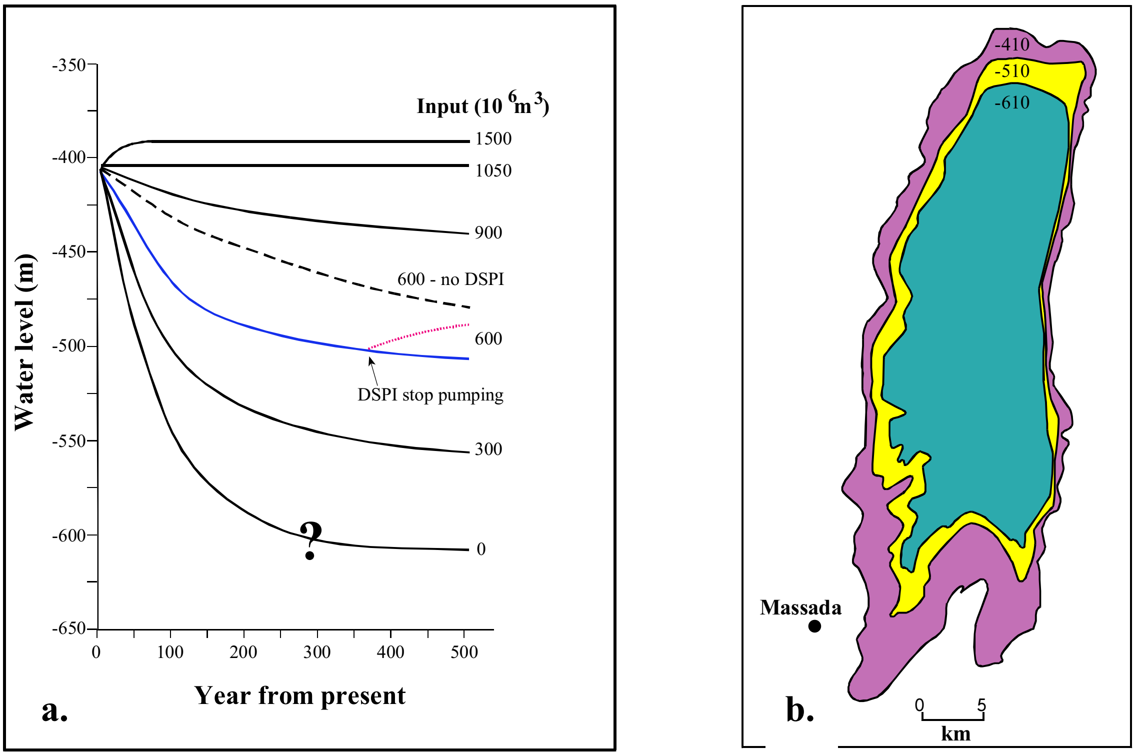

Fig. 3. The future evolution of the Dead Sea (after Yechieli et al., 1998) **a**) Forecasts for future Dead Sea water levels as a function of different annual inflow rates. At assumed input rate of 600 MCM the model was run with and without the potash industries (DSPI). **b**) Dead Sea coastlines at -410, -510 and -610 meter elevations. At annual water inflow rate of 600 MCM the Dead Sea level is expected to continue to drop until a steady state water level of -510m will be reached, 200-400 hundred years from now. The present inflow (rain, surface and groundwater) to the Dead Sea is not known and estimates vary over a large range. Yechieli et al. (1998) estimated the inflow at 600 MCM/yr, while recent rate of Dead Sea level decline suggests even lower inflow volumes. Accordingly, the Dead Sea level is expected to continue to decline unless measures, such as the "Peace Conduit" are taken to increase the annual inflow volume.

Until 1979, the Dead Sea was stratified with a relatively diluted upper water body and an isolated and anoxic lower water body. The drop in the water level was accompanied by an increase in salinity and density of the upper water body. By 1979, the density of the

upper water body equaled that of the lower water body, resulting in an overturn and homogenization of the water column (Steinhorn et al., 1979; Beyth, 1980).
Since the major 1978/9 overturn, the Dead Sea experiences annual hydrographic cycles in which density stratification develops during winter or spring due to freshwater input and/or warming of the upper water layer (Anati et al., 1987). The continuous evaporation from this layer eventually results in a destabilizing salinity profile, but stratification is maintained by the strong thermal gradient which develops through the summer. In autumn, as the upper layer cools, its density increases until it attains the density of the lower water body. When this situation is reached, usually in November-December, the water column overturns. These annual cycles were disrupted by two prolonged stratification periods, which followed the particularly rainy winters of 1979/80 and 1991/92. The former ended in 1982 (Steinhorn et al., 1985) while the latter ended in 1995 (Anati et al., 1995). At the onset of these stratified periods, freshwater mixed with the surface water of the Dead Sea to form a diluted surface water layer as lake level rose. For example, by the end of winter 1991/2 the lake level rose by 2 meters and surface water were diluted by 30% with decreasing dilution factor down to a depth of 20m. During the subsequent three years, lake level dropped while the upper water became more saline and the thermocline and halocline deepened, before overturn took place in 1995.

Impact of Seawater Mixing in the Dead Sea

The operation of the proposed “Peace Conduit” would include two stages: (1) a filling stage, during which the Dead Sea level will be raised and (2) a steady state phase in which lake level will be kept at the desired elevation: evaporation from the lake will be compensated by the inflow of seawater or reject brine, or a mixture of both. It should be noted that reject brine has a nearly similar composition to seawater but is about twice as concentrated. In the discussion that follows, the term seawater stands for both kind of water.

The target level to which the Dead Sea will be raised and later maintained is a matter to be decided between Israel and Jordan. In the early 1980’s the target of the Med-Dead Canal was 390.5m below mean sea level, (–390.5m), while in the RSDSC prefeasibility study the maximum level considered was -395m. It is recommended here that the levels to be considered in the framework of the "Peace Conduit" will not exceed -402m. The elevation of the sill dividing between the Northern and Southern Basin of the Dead Sea is –400m. Thus, raising the lake level above this elevation will result in the flooding of the Southern basin, thereby endangering the dams of the evaporation ponds of the potash industries of both Israel and Jordan. Major investments would be required to protect these dams under this scenario. An additional buffer of at least 2 meters below the –400m sill is required in order to accommodate a possible sharp lake level rise following particularly rainy winters such as that occurred in winter 1991/92. At that time some 1.5 billion cubic meters of water reached the Dead Sea raising it level by about 2 meters (Beyth et al., 1993).

Lake Stratification

Neglecting the impact of ocean-salts, inflow of seawater (density = 1.03 g/ml) to the saline Dead Sea (density = 1.24 g/ml) can be approximated to the inflow of freshwater. At large volumes, such inflow results in the dilution of the surface water and the formation of a stratified water body. This effect can be appreciated from the impact of the freshwater inflow during the rainy winter of 1991/2, when the lake level rose by 2 meters and the surface brines were diluted by up to 30% (Beyth et al., 1993). However, a distinction must be made between the two stages of operation of the "Peace Conduit". During the filling stage, as lake level rises, stratification is expected to prevail. In fact during this stage, the salinity of the surface water will continuously decrease because the inflowing water will mix with brines that are already a mixture of Dead Sea-seawater. It follows that the slower the rate of level rise, the longer the filling stage will last and the higher the density of the surface brine will be once the target level is attained. The salinity of the upper water and the structure of the water column (multi layering vs. two layers) at the target level will therefore be determined by the rate at which the Dead Sea level will be raised, i.e., by the length of the filling stage.

Once the desired lake level is achieved, the volume of inflowing seawater will have to be controlled to maintain a constant level. Incoming seawater will evaporate and the seawater-derived salts will accumulate in the upper water column. Thus, while on an annual basis the net water balance of the lake will be zero, the salinity and density of the surface water will continuously increase. Under such conditions, the stability of the stratification will decrease until the density of the upper water body will reach that of the lower water body, and overturn (mixing) will occur. From this point in time, prolonged periods of stratification are not expected, and the net result of seawater inflow would be increasing salinity of the Dead Sea. If stratification were to develop, it would be short-termed, probably with annual overturns. The mode of stratification will be a function of the volume that can be pumped into the lake and its distribution over the year.

Only few attempts have been made to quantitatively model the evolution of the stratification of the Dead Sea during seawater inflow (Blasberger and Elata, 1983; Harza JRV group, 1996; Asmar, 1998). Additional models were formulated to reconstruct past changes in the Dead Sea limnology, but these are not easily applied to seawater inflow (Vadasz et al., 1983; Gertman et al., 2002, Asmar and Ergenzinger, 2002). The most detailed Dead - seawater mixing model is the one-dimensional (1D) model developed by Blasberger and Elata (1983). The model accounts for seawater inflow, currents and waves caused by wind, evaporation and thermal effects. The variations of the water density and the level of the Dead Sea between the years 1819-1983 were used to calibrate the model. Once calibrated, the model calculated the density at the surface layer, the vertical density profiles, evaporation rate and the flux needed to keep Dead Sea at a certain level. Blasberger and Elata simulated three future inflow scenarios (Table 1).

Based on the model, Blasberger and Elata (1983) concluded that during the filling period, the depth of interface (the depth of transition from the upper to the lower water body) will exceed 35 m, and that it will be shallower than 60 m after 35 years of steady-state level. During the filling period, several layers of different densities will develop, and these will coalesce to two layers during the steady-state period. As expected, during the filling period, seawater inflow will decrease with time because of increasing salinity and the resulting decrease in evaporation rate. Finally, the model shows that the duration of the balance period before overturn occurs depends on the rate of influx during the filling period; faster influx will yield a longer period of a steady-state water level before overturn occurs. The calculated surface density of the Dead Sea as a function of time under the three operational scenarios examined (Table 1) is depicted in Fig. 4.

Table 1: Scenarios from Blasberger and Elata (1983) for the evolution of the Dead Sea during the filling and steady-state periods until overturn. Calculation assumes beginning of operation at Dead Sea level of –408m.

Duration (years)	Target elev. (m)	Influx ($10^6 m^3$ per year)		Density of surface water		Depth of layering[2] (m) during		Evaporation (m/year)	
		filling period	steady-state period	end of filling (g/cc)	steady-state period	filling period	steady-state period	beginning of balance	stable balance
12 years of elevation of the DS surface at a constant rate	-392 (input)	2213 at the beginning – 2800 at the end	1985 at the beginning – 1510 at the end	1.102	1.216 (after 40 years)	30	100 (40 years)	2.08	1.91
12 years of inflow of seawater into the DS at a constant rate	-396	2300 (input)	1553 at the beginning – 1300 at the end	1.128	1.228 (after 40 years)	30	100 (30 years)	1.97	1.64
20 years of inflow of seawater into the DS at a constant rate	-391	2300 (input)	1676 at the beginning – 1550 at the end	1.122	1.216 (after 32 years)	30	80 (32 years)	1.99	1.84

(1) Before reaching the target elevation
(2) Depth of the interface between the DS brine and the upper buoyant layer

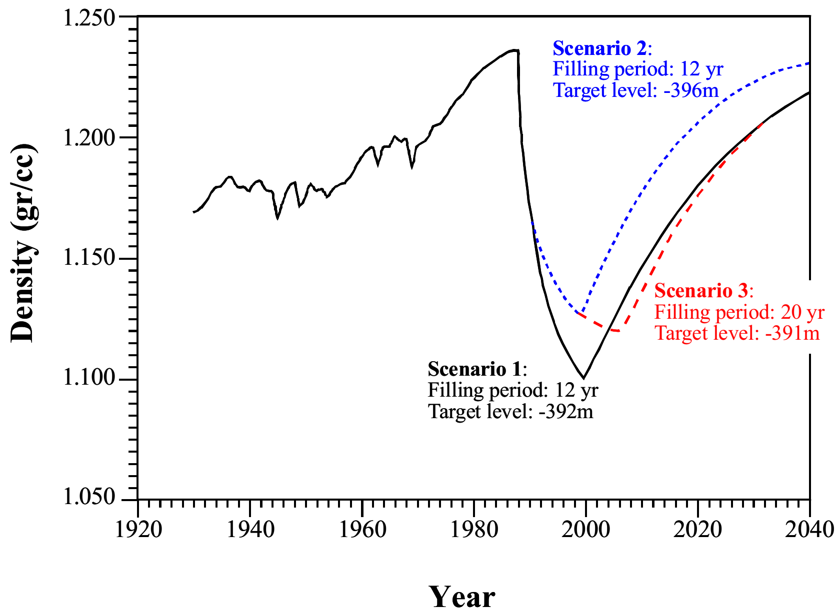

Fig. 4. Dead Sea Surface density vs. time as a function of conduit operational scenarios based on Blasberger and Elata (1983) model. While the calculated densities are incorrect due to drawbacks in basic assumptions in the model, the graph clearly depicts the expected trends during the filling stage and the following steady-state water level period.

While the model reconstructs the expected trends in the Dead Sea, it has several drawbacks, which lead to faulty figures. Therefore the values obtained are far from actual figures and cannot serve as basis for planning:

1. The calculated density of the brines following evaporation is incorrect. In the mass balance equation (3.3.2), the mass added to the remaining brine following evaporation of a water column (Hv) is calculated as: Hv·(ψi-1000), where ψi is the density of the brine before evaporation. This is an underestimation of about 50% relative to the true total dissolved solids (TDS) (ψi-1000~235 kg/m^3 vs. TDS~350 kg/m^3). Since density is the governing parameter on the Dead Sea dynamics, this may alter the model results significantly.

2. The density of the mixture of different water bodies is assumed to be the weighted average of the densities and volumes. This approximation cannot be taken for granted because crystallization and the volume reduction due to electrolytic solution mixture may change the density of the mixture significantly, thereby changing the output of the model.

3. The transition layer in the model is assumed to be a transition surface, having no thickness. The depth and thickness of the thermocline and halocline are important parameters in any limnological modeling, and mixing process at this depth has to be included to properly model the water column and the mixing process.

4. The calculated evaporation rate (see appropriate section hereafter) is based on the energy balance with a correction factor that is not accounted for. The dilution of the surface water has relatively little impact on the rate of evaporation, increasing it from a suggested very high initial value of 1.90 m/yr in 1990, just before the onset of seawater inflow, to a maximum of 2.08 m/yr for the least diluted surface waters in the second scenario. Both the initial value and the change appear to be inaccurate and far from true figures.

The Harza JRV group (1996) constructed a model that is largely based on a water balance, and predicted the response of the Dead Sea to the proposed RSDSC. This model was calibrated using historic data (inflows, evaporation and lake level), and then applied to simulate several inflow scenarios. The Dead Sea water balance includes data on:

surface inflow, surface rainfall, surface density estimates, evaporation estimates, abstraction from potash industries, and estimated groundwater inflows. However, the various parameters are estimated or assumed without calculating the dynamic response of the Dead Sea to changes in these parameters. The surface density, for example, was estimated in the Harza model using results of simulations conducted by Blasberger and Elata (1983). The evaporation rate was adjusted to fit water mass balance calculations, and was latter used to derive the volume of groundwater inflow to the Dead Sea.

Based on Harza model, without the RSDSC project the Dead Sea level was expected to reach an elevation of -417m by the year 2010 and–431m by year 2050. It was also assumed that evaporation rate would be reduced by 2050 and the rate of lake level decline will only be 0.2 m/year (about sixth of present rate). In reality, the lake level forecast turned out to be inaccurate: The current level of the Dead Sea is nearly –416m and is expected to decline below –417m by summer 2003, i.e. 7 years earlier than anticipated. The slower lake level decline predicted by the model is attributed to exaggerated groundwater inflow in the model and less to withdrawal of freshwater from the drainage basin. Accordingly, based on the more detailed model of Yechieli et al. (1998) the rate of sea level drop at elevation of –431m will be greater than 0.2 m/yr, unless inflows to the Dead Sea will increase drastically.

The Harza model was operated for five scenarios representing a range of volumes, 40–80 m^3/s (1260-2520 MCM/yr), pumped from the Red Sea. The model assumed 45% efficiency in desalinization, thus, diversion of 55% of the volume as reject brine into the Dead Sea. During the initial phases of the project, when production capacity of freshwater exceeds the demand, it was suggested to generate electricity with the seawater surplus. The model predicted that during such operation, lake level will rise from –417 at the onset of the project in year 2010, to –408, -405 and –397m in year 2050 for the 40, 50, 60 m^3/s pumping scenarios, respectively (Fig. 5). The target level of –395m would be achieved in the years 2045 and 2028 for 70 and 80 m^3/s, respectively.

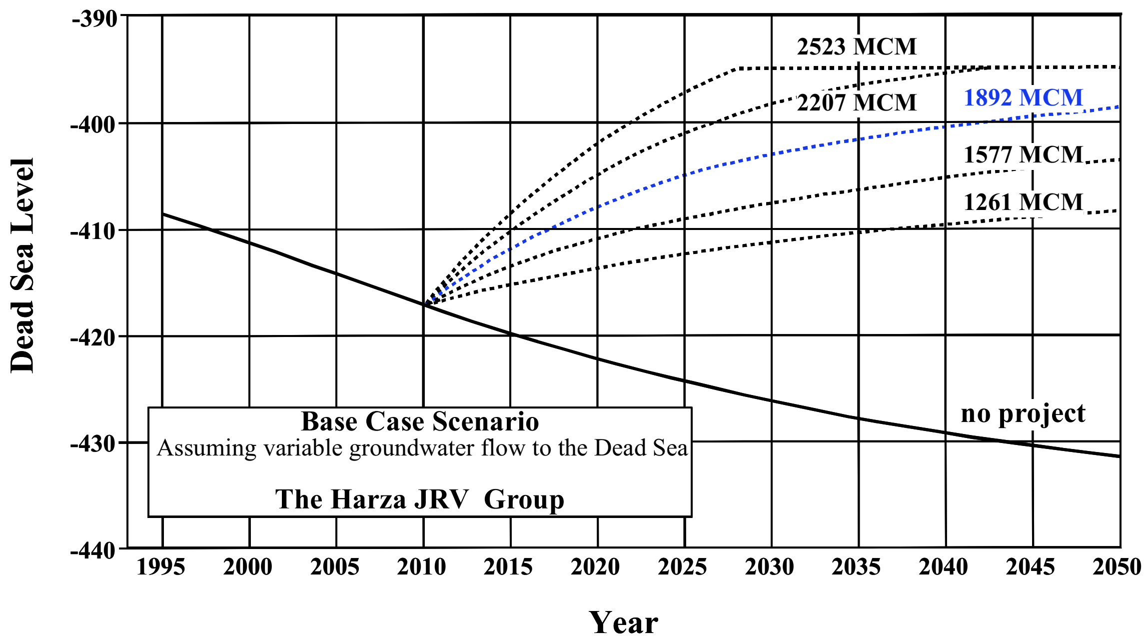

Fig. 5. Predicted Dead Sea water level for different intake volumes from the Red Sea (after Harza, 1996). The model assumes 45% desalinization efficiency and production of electricity with excess water that is not needed for desalinization. Note the intake volume of 1892 MCM/yr (calculated from 60 m^3/s) which was recommended by Harza and which is often quoted in the context of the "Peace Conduit". The model is biased for high inflow of groundwater to the Dead Sea and therefore assumes high evaporation rate. Depth of stratification and the volume of Dead Sea brine that mixes with the inflowing seawater were not discussed in the model while surface density was adopted from Blasberger and Elata (1983) model, which has some incorrect assumptions.

While the model accounts for inflow of water and outflow by evaporation, it does not account for hydro-dynamical effects such as wind stirring as does the Blasberger and Elata model. In fact, the Harza report states that “*significant assumptions concerning the response of the Dead Sea to hydrologic or other events*” were made. Variations of these parameters will, however, result in changing flow patterns in the Dead Sea and thus will result in coupling effects between them, thereby changing the parameters assumed in the model. Such coupling effects can only be estimated by a dynamic model. For example, the depth of stratification, and the volume of Dead Sea brine that mixes with the inflowing seawater were not discussed. These need to be determined in order to calculate surface density, a factors that, as pointed out, was adopted in the Harza model from Blasberger and Elata model. Similarly, estimation of the evaporation rate, which is a prime factor of the entire system, should not be derived from water balance estimates, but estimated independently as part of the model, based on salinity and the climatic input (see evaporation rate section).

Asmar (1998) constructed a one-dimensional dynamical model for the Dead Sea and studied three operative scenarios: 1) No canal; 2) The "Peace Conduit" operating as of year 2010, with a fixed inflow rate of 900 MCM/yr and with no desalinization plant. 3) The "Peace Conduit" operating with the desalination plant proposed by Harza (1996). The variables incorporated in the model included evaporation rate, salinity, number of layers and mineral crystallization. As expected, the model predicts that upon the operation of the "Peace Conduit", stratification will develop with a diluted upper water layer, but with no change in its salinity once stratification is established. Consequently, the evaporation rate will increase from about 1.23 m/y to a constant rate of 1.54-1.55 m/y. After 25 years of operation, the desired level is reached and evaporation slightly decreases, along with an increase in salinity. The model predicts that seasonal variation in salinity will decline significantly due to the operation of the Conduit, since the stratification will be stable and overturn will not occur before 2050. According to Asmar (1998) the current temporal surface water salinity variation ranges between 100 kg/m^3 during the rainy season, and 340 kg/m^3 during the dry season. Due to the operation of the "Peace Conduit", the surface water will remain fairly constant at a low salinity of 100 kg/m^3 while the lower brine will maintain a salinity of 340 kg/m^3. Asmar (1998) also claims that gypsum and aragonite are the main crystallizing phases in the current DS and that their seasonal precipitation will cease as soon as the canal starts to operate. Gypsum precipitation is expected to reoccur as soon as the filling period ends and precipitation will then occur seasonally.

Some of the basic assumptions in the model proposed by Asmar (1998) are problematic. The assumed low salinity of the Dead Sea during the rainy season (100 kg/m^3) is incorrect: During regular winters and springs, stratification develops primarily due to thermal effects with no or only slight dilution. Even during the rainiest winter of 1991/2, the minimum salinity of the surface layer was 231 kg/m^3, much higher than Asmar's (1998) assumed salinity. In addition, unlike the assumption in the model, nearly no gypsum and aragonite currently precipitate from the lake. Rather, massive halite precipitation occurs. On the other hand, all experiments show that upon mixing of seawater in the Dead Sea, gypsum will begin to precipitate, while halite will cease to precipitate (see relevant section on Dead Sea chemistry and gypsum precipitation).

While all the models outlined above include assumptions that are difficult to reconcile with, they clearly demonstrate the interdependencies between the influx rate, the density of the surface water, evaporation rate and the length of the steady state period prior to the onset of overturn. These interdependencies are important in outlining the trends of the physical behavior of the Dead Sea during the two periods, emphasizing the need for a reliable forecast for the evolution of the lake under various operating scenarios, and high-lightening the difficulties in constructing such a model. However, the models do not provide reliable estimates of surface densities and depth of stratification for various inflow scenarios. As outlined above, these parameters are of utmost importance for understanding the evolutionary trend of the Dead Sea under seawater inflow and for proper planning and management of the "Peace Conduit", should a positive decision regarding its construction be made.

With the above in mind, the GSI has begun formulating a dynamic-limnological model that will integrate all available physical and chemical data, in order to provide the most reliable forecast for the evolution of the Dead Sea. Once developed, the model will facilitate simulation of mixing seawater (and/or reject brine) in the Dead Sea under various operating scenarios, including different volume inflows, location of inflow along the shores, introduction of seawater at depth, etc. For each scenario the model will provide a forecast for the change as a function of time in water level, chemical composition, density, temperature and rate of evaporation at any given point on the lake. Additional output will include: depth of stratification, thickness of thermocline and timing and frequency of overturn. This dynamic- limnological model should thus provide decision makers with the tools necessary to assess the feasibility of constructing the "Peace Conduit" from environmental, economic and operational standpoints.

Dead Sea Chemistry and Gypsum and Halite Precipitation

The Dead Sea is presently saturated to oversaturated with respect to aragonite ($CaCO_3$), anhydrite ($CaSO_4$) and halite (NaCl) (Gavrieli et al., 1989). Kinetic factors dictate that gypsum ($CaSO_4 \cdot 2H_2O$), the hydrated form of anhydrite, is the actual Ca-sulfate mineral that precipitates from the Dead Sea brine. Prior to the 1979 overturn, the lower water body was saturated with respect to these minerals, whereas the upper water body was undersaturated with respect to halite and saturated to oversaturated with respect to aragonite and anhydrite (Neev and Emery, 1967). Aragonite crystallized from the upper water body and settled to the bottom, forming the white laminae of the Dead Sea sediments, whereas gypsum crystallized on exposed and submerged surfaces along the shores. The "whitening" of the Dead Sea surface, which has been described by several observers (Bloch et al., 1943; Neev and Emery, 1967), is attributed to spontaneous crystallization of aragonite, possibly with some gypsum, from the surface water. At present, despite the saturation to oversaturation of the Dead Sea with respect to aragonite and the Ca-sulfate phases, their precipitation is rather limited. This is due to the decreasing freshwater input to the Dead Sea, which supplied bicarbonate and sulfate to the lake. These have relatively low concentration in the Dead Sea brine (alkalinity as HCO_3 – 280 mg/l; SO_4 – 500 mg/l) as compared to the calcium concentration (Ca – 17,500 mg/l).

In 1982 halite began to precipitate from the Dead Sea (Steinhorn, 1983), and its precipitation has continued nearly uninterrupted since then (Gavrieli, 1997). A decrease in halite precipitation rate was observed in 1992-3 to 1995. This was due to the 1991-1995 stratification which diluted the upper water body and isolated the lower water body (Beyth et al., 1993; Anati et al., 1995). Massive halite precipitation was restored following the November 1995 overturn. Under the current condition of negative water balance and increasing salinity, halite will continue to precipitate from the brine. It should be noted that since 1982, any object suspended within the deeper Dead Sea brines was immediately covered by massive halite crystals. A somewhat similar situation existed in the 1960's when gypsum, rather than halite, quickly covered exposed surfaces, although this was limited only to the upper waters.

Gypsum precipitation

One of the major concerns raised in the context of the planned “Peace Conduit” and all previous plans to discharge seawater to the Dead Sea was the expected gypsum precipitation from the mixture. The mixing of seawater with the Dead Sea will introduce relatively high concentrations of sulfate (3000 mg/l) that will mix with the high concentration of calcium (17,500 mg/l) found in the Dead Sea, resulting in spontaneous gypsum precipitation. That such crystallization will occur was shown in laboratory and field experiments in several studies (Katz et al., 1977; Levy, 1984 and therein). Evaporation of such mixtures was shown to accelerate this process. The major concern raised regarding gypsum crystallization is the possibility that it will remain suspended in the upper water column for a long time, thereby "whitening" the Dead Sea surface (Katz et al., 1977). Such whitening that lasted for two weeks was in fact observed in laboratory experiments of Dead Sea–seawater mixing (Katz et al., 1977) and may have physical, ecological, operational and industrial consequences. For example if the gypsum will form a film of crystals on the surface of the water it may increase the reflectivity of the Dead Sea surface thereby decreasing the rate of evaporation. Alternatively, tiny gypsum crystals may not float on the surface but remain suspended in the upper-most part of the water column. In this case, they may lead to the opposite effect; increased scattering of light within the Dead Sea water body resulting in increased water temperature and evaporation rate. Both scenarios are likely to affect the climate in the Dead Sea area while changing the appearance of the lake. The most desired scenario is therefore that gypsum will precipitate to the bottom upon its crystallization or shortly thereafter, as is the case with halite that currently crystallizes in the Dead Sea.

The kinetics and thermodynamics of gypsum precipitation is fundamental to understanding the fate of gypsum precipitation in the mixing process. Due to kinetics, the Dead Sea can maintain oversaturation with respect to gypsum (Katz et al., 1982), and it may also control the timing of the precipitation from the Dead Sea - seawater mixture. In fact, laboratory and field experiments have shown that gypsum nucleation (induction time) could take hours to days after mixing and consequently high oversaturation would be attained (Katz et al., 1977, Levy and Koshnir, 1982). However, slight evaporation greatly increased the amount of gypsum that precipitated. This could be due to the increased oversaturation following the evaporation, which enabled overcoming the kinetic barrier.

Levy (1984a) conducted experiments that attempted to simulate mixing rates of seawater with Dead Sea brine, by slowly introducing concentrated seawater to Dead Sea water over a period of 9-12 months. At the end of the experiments a Dead Sea: seawater mixing ratio of 5:1 was attained. His results suggest that most of the gypsum crystals that form are coarse, and settle to the bottom with no whitening of the mixture. The finer grain gypsum that remains suspended in the water column generated only a slight increase in the turbidity of the water column.

An extensive field study of gypsum precipitation was conducted by Ben Yaakov and Katz (1982) in experimental ponds in Beth Ha'Arava. The study included various operating scenarios such as freshwater used to compensate for evaporation, seawater used to compensate for evaporation, and mixing vs. no mixing of the ponds. The "whitening effect" was not observed in the experiments while massive gypsum crystallization took place on the frame of the pond, particularly at the depth of the interface between seawater and Dead Sea water, in the non-mixed ponds. Massive gypsum precipitation also occurred when the mixtures were allowed to evaporate. Despite these findings, Ben Yaacov and Katz (1982) warn that whitening may develop during seawater inflow because of a higher volume/surface ratio in the Dead Sea than that prevailing in their experimental ponds.

The size of gypsum crystals/agglomerate and their morphology will determine the mode of gypsum settling to the bottom. The finer the crystals, the slower their settling rate will be. Generally, crystal size is a function of the rate of crystallization; large crystals tend to develop under conditions of slow and prolonged growth, while rapid crystallization from a large number of nuclei is characteristic of high oversaturation and results in fine-grained crystals (Levy and Koshnir, 1981; Levy, 1984). Levy (1983) found that the settling velocity of gypsum bearing the dimensions of 60X3X60 σm is about 1 cm/min. These findings were confirmed in laboratory experiments conducted in containers of various sizes, as well as in field experiments, including in the Dead Sea proper. The crystal size used in the experiments represents the common size found in mixing experiments, 5 hours after the mixing. Levy (1983) therefore concluded that gypsum having the above dimension would sink to a depth of 2 meters within 8 hours of mixing (5 hours for nucleation + 3 hours for sinking). His calculations suggests that prolonged whitening would not occur independent if the crystallization occurs continuously (once a day) or periodically (once every month or once every year). Consequently, enhanced light scattering would be limited to few hours/day or days/months. It should be noted that the grain size used in the above experiments does not deviate significantly from that observed by Levy and Kushnir (1981), who studied the nucleation and growth of gypsum in Dead Sea-seawater mixtures. They found that gypsum crystallizes mostly as prisms/needle-like crystals, though flatter morphology patterns appear at the lower end of supersaturation. While induction time was found to decrease with the increase in supersaturation, it was also found to be strongly dependent on the presence of nucleation sites; when solutions were filtered, the induction time increased by a factor of 15, suggesting that nucleation is heterogeneous. This is of major importance because the presence of suspended particular matter, such as wind blown dust, in the Dead Sea can serve as nucleation sites for gypsum.

In view of the above, it appears that most researchers agree that prolonged events of whitening of the Dead Sea surface are unlikely. However, this subject merits much attention because of the potential physical, environmental and operational consequences that such whitening may have. In this respect it is worth noting that Katz (pers. com.), who conducted the laboratory experiments where prolonged whitening was observed (Katz et al., 1977) and later the field experiment where this phenomenon was not observed (Ben Yaacov and Katz, 1982), states that he still does not possess the insight as to the fate of the gypsum that will crystallize in the mixing process.

Halite precipitation

The re-establishment of stratification of the Dead Sea during the filling period will halt halite precipitation from the Dead Sea water. The upper water body will stop precipitating halite immediately upon its formation, due to the dilution of Dead Sea brine and the attainment of undersaturation with respect to halite; the lower layer will continue to precipitate halite for a short period until its saturation degree with respect to halite will drop from slight oversaturation to saturation. However, halite precipitation is expected to commence during the steady-state period, once the salinity of the upper water has increased enough to re-attain saturation with respect to this mineral. It is yet to be determined if halite will first precipitate from the upper water body or if its precipitation will occur only after the overturn. However, once it starts, halite precipitation will continue alongside with gypsum precipitation.

Salinity increase

The overall impact of seawater inflow on the major chemical composition of the Dead Sea over a time span of decades can be calculated. The following simplified calculations neglect precipitation of gypsum and halite from the mixture. The latter must be conducted in conjunction with the dilution factors and saturation indices that are based on mixing rates and ratios.

Annual inflow of 1000MCM of seawater (40 g/l, Red Sea water) over a 20 year period would contribute some $0.8 \cdot 10^9$ tons of salt, which amounts to about 2% of the present salt load of the Dead Sea (340 g/l; $4.4 \cdot 10^6$ ton). The additional salts would increase the salinity of the brine, thereby enhancing, over the long run, the rate of mineral precipitation from the Dead Sea. Since the proposed "Peace Conduit" is planned to last longer than 20 years, the percent of seawater-derived salts in the Dead Sea will increase accordingly. Furthermore, if for the same volume, some of the inflowing water is reject brine from desalinization, the portion of seawater-derived salts will increase accordingly. While the above calculation assumes mixing in the entire water column of the Dead Sea (a process that will certainly happen on the long run), the fraction of seawater-derived salts in the upper water column during the stratified period would be substantially greater. This fraction will be determined by the original thickness of Dead Sea layer that mixed into this upper water column. This parameter is currently difficult to estimate without a dynamic-limnological model. However, for the sake of the calculation, if the original Dead Sea brine in the diluted upper water column had a thickness of 10 meters, the percentage of seawater derived-salts in this water body, after 20 years of stratification and accumulation, would be 26%. For original thickness of 30m, 11% of the salts in the mixed layer would be derived from seawater. The salinity of the latter will be greater than the former, though the exact salinities cannot be estimated without the appropriate evaporation rates.

Evaporation Rate Estimates and their Implications

Evaporation is the only process that eliminates water from the Dead Sea system. Therefore, in order to foresee the evolution of the Dead Sea during the operation of the "Peace Conduit", it is essential that a reliable estimate of the evaporation rate from the Dead Sea surface as a function of salinity be established. The rate of evaporation is strongly dependent on the salinity of the surface water: As the salinity of a water body increases, the free energy of the water molecules, or their activity, decreases, thereby lowering the rate of evaporation. The evaporation rate, along with the net water loss in the evaporation ponds of the potash industries, will determine the exact volume of seawater required to raise the Dead Sea level at the desired rate and later maintain it at the target level. During the first period, as the salinity of the surface water decreases, the required volume increases. In contrast, during the steady-state period that follows, salinity will increase and the volume of seawater required to maintain the desired level will decrease.

The evaporation rate as a function of salinity is either derived from mass balance considerations or based on meteorological and limnological parameters. There are two possible approaches to calculate the latter:

1) The aerodynamic approach takes into consideration the factors responsible for removing vapor from the water surface. This method relates average monthly evaporation (E) from large water bodies to mean wind speed (u) and the mean vapor pressure difference between the water surface and the air (e_w-e_d):

$$E = Ku(e_w - e_d)$$

2) The heat balance approach, or the energy budget, uses the net balance of solar and terrestrial radiation at the surface (R_n) to calculate evaporation (E) and the transfer of

heat to the atmosphere (H). A small proportion also heats the soil by day, but since nearly all of this is lost at night it can be disregarded in estimating average rates:

$$R_n = LE + H$$

where R_n is measured, L is the latent heat of evaporation ($2.5 \cdot 10^6$ J·Kg^{-1}) and $\frac{H}{LE} = \eta$ is Bowen`s ratio. Bowen`s ratio can be estimated from measurements of temperature and vapor content at two levels near the surface. Its values range from <0.1 for water to >10 for desert surfaces. The use of this ratio assumes that the vertical transfers of heat and water vapor by turbulence occurs with equal efficiency. Evaporation estimates than take the form:

$$E = \frac{R_n}{L(1 + \eta)}$$

The change in the evaporation rate as a function of salinity in the Dead Sea is presented by Levy (1984b), who summarizes the estimation of the rate calculated by several researchers during the period between the 1950s and the 1980s. During this period the salinity of the surface brine increased from 225 g/kg to 279 g/kg. Appendix 2 presents this summary with additional work published since that time. However, while a general trend of decreasing evaporation rate is clearly identified, major uncertainties regarding actual rates exist. This is well demonstrated by the work of Stanhill (1994), who calculated new evaporation rates based on reevaluation of old data, including his own. Stanhill's (1994) latest estimation of 1.05 m/yr is for the period of 1983-1987, at a surface density of 1.235 (~340 g/l). His earlier estimate for the same salinity was 1.13 m/yr (Stanhill, 1985) while an earlier report suggests a value of 1.38 m/yr (Stanhill, 1983). All studies were based on energy balances, and the difference in the estimates stems from changes in the calculated distribution of the energy input between evaporation and potential energy of the water. Harza (1996) and Al-Weshah (2000) suggest that both of Stanhill's values are conservative, and added a factor of 35% in order to balance their historic and current water balance calculations. Blasberger and Elata (1983) modified Stanhill's values, yielding a calculated value of 1.8-1.9 m/yr for the years 1980-1988, during the assumed operation of the Med-Dead canal. The assumptions made and rational behind these modifications were not specified. An even higher evaporation rate, 2.0 m/yr, was suggested for the period of 1980-1997 by Salameh and El-Naser (1999, 2000a). This value was based on water balance calculations, including assumed unmonitored groundwater inflow, and comparison with evaporation experiments in the Arab Potash Co. A more detailed approach was taken by Gertman et al. (2002), who introduced hourly averages of hydrometeorological parameters in a simulation model for the Dead Sea. The data were collected by a meteorological buoy, located 4 km east of En-Gedi, that has been functioning since 1992. Computed model results agree quite well with measurements of sea level, temperature, salinity and integral stability. According to this model, evaporation varies within 3-4.8 mm/day, which yields annual values greater than Stanhill`s but less than 1.5 m/year.

The estimation of the evaporation rate from the Dead Sea becomes even more difficult when the calculation has to account for changes in salinity. Stanhill (1994) provided an empirical equation of evaporation rate as a function of salinity (Evaporation (m/yr) = 4.701-2.926Xdensity). This relationship is based on calculated evaporation rates during a number of discrete periods that cover different salinities. Harza (1996) adopted the above equation but added a factor of 35% in order to balance water mass calculations. Asmar and Ergenzinger (1999) examined the two approaches to modeling evaporation and modified them to incorporate changes in salinity, from 0 to 470 g/l (Fig. 6). They suggest adopting the Penmann formulation, which yield estimates similar to those of Stanhill. Higher estimates deduced from the Dalton formulation yield higher rates of evaporation, though not as high as those suggested by Salameh and El-Naser (1999, 2000a).

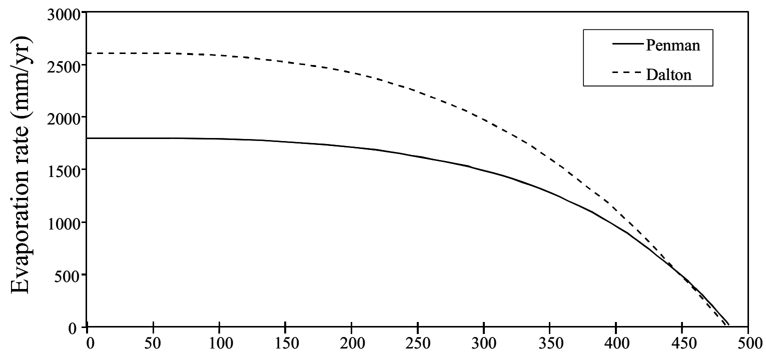

Fig. 6. Evaporation rates from the Dead Sea as a function of salinity calculated after the Penman and Dalton formulations (after Asmar and Ergenzinger, 1999).

As is evident from the above, there is little agreement between the researchers regarding the present rate of evaporation from the Dead Sea (salinity of about 340 g/l). A difference of nearly 100% exists between the estimates, i.e. 1.05 m/yr (Stanhill, 1994) and 2.00 m/yr (Salameh and El-Naser, 1999). Generally, the energy balance approach yields lower evaporation rates than those based on water balance calculations. It should be emphasized that the heat balance calculations are based largely on old meteorological records, whose reliability are questionable. In addition, the extent to which they represent current conditions should be evaluated and results properly verified by empirical methods and/or by more modern measuring techniques. The water balance calculations, on the other hand, assume groundwater discharge into the Dead Sea of over 400 MCM/yr due to the decline in lake level and receding base level. No evidence for such major inflow is found, and it is based solely on hydrological and hydrographic assumptions and calculations (Salameh and El-Naser, 2000b).

It should be pointed out that the calculated net water deficit of the lake during lake level drop is independent of evaporation rate assumptions. It is directly determined through a simple water level-volume relationship. However, raising the Dead Sea level would result in increased surface area from which evaporation takes place. To maintain the new level, the higher evaporation rate estimates require higher inflow rates. The required inflow will be even higher if the extra groundwater discharge to the lake will cease as implied by the water balance model (Salameh and El-Naser, 1999). In fact, the latter models implies that just stabilizing the Dead Sea level at its present elevation would require not only compensation for the present net deficit of about 625 MCM/yr (assuming water level drop of 1 m/yr), but an additional 460 MCM/yr to compensate for the groundwater that on the long run would cease to flow to the lake. It follows therefore that in order to properly plan the "Peace Conduit" so that it will be capable of conveying the required volumes to raise and maintain the new lake elevation, it is essential that the present and expected evaporation rate be better constrained. This should be done independent of assumptions on the hydrology of the surrounding areas, and without relying on water balance calculations.

Algal and Bacterial Growth

In spite of the hostility of the environment, the Dead Sea is inhabited by a variety of microorganisms: autotrophic unicellular green algae (*Dunaliella* sp.), aerobic heterotrophic prokaryotes (mainly red halophilic Archaea belonging to the family *Halobacteriaceae*: *Halorubrum sodomense*, *Halobaculum gomorrense*, *Haloferax volcanii* and others, and also a few halophilic or halotolerant members of the domain Bacteria), anaerobic bacteria in the sediments, and possibly even fungi (for reviews see Nissenbaum, 1975; Oren, 1988, 1997, 1998, 2000).

Our understanding of the Dead Sea as an ecosystem is based both on observations of microbial blooms in the lake in the course of a comprehensive sampling and monitoring program that has been carried out from 1980 onwards, and on laboratory simulations. Quantitative information on the biological properties of the lake prior to 1980 is virtually absent, but microbial densities were high at least at certain times: up to 40,000 *Dunaliella* cells/ml were counted in surface water in 1964 (Kaplan and Friedmann, 1970).

Mass development of *Dunaliella* was observed in the lake during the period 1980-1981 and again in 1992-1994, in both cases following the formation of a meromictic state with the establishment of a diluted epilimnion after massive rain floods entered the lake. *Dunaliella* densities up to 8.8×10^3 cells/ml were counted in the epilimnion in 1980 (Oren and Shilo, 1982), and 1.5×10^4 cells/ml and maybe even higher in 1992 (Oren 1993; Oren et al., 1995). Between periods of blooms the algae probably survive as cysts in the bottom sediments (Oren et al., 1995). Evidence that new blooms originate from an inoculum present in the lake bottom was obtained from remote sensing images of the distribution of chlorophyll in the Dead Sea at the onset of the 1992 algal bloom: The bloom started in the shallow areas along the shore, where cysts in the bottom sediments germinated, triggered by the local reduction in salinity (Oren and Ben-Yosef, 1997).

Whenever *Dunaliella* is present in large numbers, blooms of halophilic Archaea develop at the expense of organic material produced by the alga (Oren, 1983, 1993; Oren and Gurevich, 1995). Up to 1.9×10^7 cells/ml were found in the lake's surface layers in the summer of 1980 (Oren, 1983, 1985), and in the spring of 1992 a maximum community density of $3.5x10^7$ cells/ml was reached (Oren, 1993; Oren and Gurevich, 1995). Halophilic Archaea of the family *Halobacteriaceae* are colored red due to a high content of C-50 carotenoid pigments (ζ-bacterioruberin derivatives). The dense communities of the Archaea imparted a reddish color to the Dead Sea water both in 1980 (Oren, 1983) and in 1992 (Oren, 1993; Oren and Gurevich, 1995). Lysis of halophilic Archaea by bacteriophages has been implicated as one of the causes for the subsequent decline of the population (Oren et al., 1997). During the prolonged periods between the bloom events, a small community of Archaea remains present in a state of little activity, but ready to resume growth as soon as a suitable source of organic material becomes available (Oren, 1992).

The variability in the extent of the development of microorganisms in the Dead Sea relates to the factors that limit the growth of the Dead Sea biota. The Dead Sea brine is far from being the ideal environment for the development of even the best salt-adapted microorganisms. All Dead Sea microorganisms prefer to thrive at far lower salinities and in particular at much lower divalent cation concentrations. Development of algae and bacteria in the lake thus depends primarily on the extent of the input of fresh water into the lake and the resulting dilution of the surface water layers. Dead Sea water with a ω_{25} above 220 (i.e. density of 1.220 at 25ºC) does not support growth of *Dunaliella*. Growth is possible only when the salinity of the brine drops to ω_{25} values below 210-220. Thus, dilution of the upper water body with more than 10% fresh water is required to initiate a mass development of the alga, provided that all essential nutrients are available. The inorganic nutrient that limits the extent of development of both *Dunaliella* and halophilic Archaea is phosphate (Oren, 1983; Oren and Shilo, 1985). Laboratory simulations have demonstrated that addition of phosphate to Dead Sea water is required to trigger development of *Dunaliella* (Oren and Shilo, 1985). Inorganic nitrogen is present in excess in the form of ammonium ions.

Life in the Dead Sea in its present state depends primarily on those rare events of abundant rainfall in the catchment area that lead to the formation of a sufficiently diluted epilimnion. The drop in water level of the lake in recent years has resulted in an increase in overall salinity, accompanied by an increase in the relative abundance of divalent cations due to the mass precipitation of halite. Thus, the Dead Sea becomes an ever increasingly hostile environment for halophilic microorganisms. In view of the increasing salinity of the Dead Sea water and the concomitantly increasing relative concentrations of inhibitory divalent cations, and also in view of the increasing extent in which excess rainwater in the catchment area is diverted for human consumption, such microbial bloom events may be expected to become rarer and rarer.

Implementation of the "Peace Conduit" between the Red Sea and the Dead Sea is expected to drastically change the properties of the Dead Sea as an ecosystem. The massive inflow of sea water and/or reject brine will result in the establishment of a meromictic state (stratification) and the renewed formation of a diluted epilimnion in the Dead Sea. This may possibly lead to mass development of unicellular algae and bacteria. The extent of these blooms will depend on factors such as the mode of mixing of the less saline waters with the Dead Sea brines, the changing salinity of the upper water layer, and the availability of phosphate and other nutrients that otherwise limit the development of the biota. The common use of antiscalants to protect membranes used in the reverse osmosis desalinization process has also to be taken into account, as most of these antiscalants are based on polyphosphates, which upon degradation yield inorganic phosphate.

In the past, a number of outdoor simulation experiments were conducted at the Beit Ha'arava experimental station to simulate the possible effect of dilution (with Mediterranean water) and phosphate addition on the biological processes in Dead Sea water. These studies have clearly shown that dilution of Dead Sea water combined with the addition of phosphate may cause the formation of exceedingly turbid, reddish-green brines (for example: densities of 10^5 *Dunaliella* cells/ml and 10^8 bacteria/ml were obtained in 65% Dead Sea water supplemented with phosphate) (Oren and Shilo, 1985). No such studies have yet been performed with mixtures of Dead Sea water and Red Sea water or concentrates of Red Sea water after desalinization (reject brine). Another question not addressed in previous studies is whether microbial blooms will be of short duration, followed by a decline, or whether dense communities of algae and bacteria will prevail for prolonged periods of time. The latter is clearly not a desired outcome of the "Peace Conduit" as it implies major changes in the ecology of the Dead Sea, in the scenery around the lake and in its attractiveness. In addition, prolonged blooming can lead to increased surface water turbidity, which may increase the rate of evaporation due to light scattering. This implies that larger volumes of seawater will be needed to raise, and later maintain, the Dead Sea at the desired water level. These issues are major factors in the decision on the future of the "Peace Conduit".

Within the frame of the present study led by the GSI, a new series of simulation experiments have been initiated on the grounds of the Dead Sea Works Ltd. at Sdom. The experimental setup consists of ten ponds (volume 900 liter each), which are filled with different concentrations of Dead Sea water and Red Sea water concentrate, amended with various phosphate concentrations, to test the effect of different mixing scenarios and nutrient availability. Parameters monitored include algal (*Dunaliella*) and bacterial numbers, total microbial biomass as particulate protein, turbidity, quantization of bacterial and algal pigments, and others. These experiments are expected to yield a better understanding of the possible biological impact of different scenarios of short-term and long-term influx of seawater in the Dead Sea. The question whether microbial blooms will be of short or long duration will also be addressed in these experiments. The outcome of these simulations is expected to enhance our understanding of the biology of the lake and the consequence of seawater mixing and provide essential data required for the decision regarding the feasibility of the "Peace Conduit" and its planning.

Development of Anoxic Lower Water Mass

The development of density stratification in the Dead Sea will isolate its main water mass from the atmosphere. This water mass may well develop anoxic conditions, similar to the situation that prevailed in the lake prior to the 1979 overturn, when the lower water body contained no dissolved oxygen, and had up to 15 ppm H_2S and 250 ppb Fe^{2+} (Nissenbaum and Kaplan, 1976; Nishri, 1984). The new anoxic conditions will probably evolve within a few years after the inauguration of the "Peace Conduit", after the dissolved oxygen has been consumed through the oxidation of the organic matter that will sink from the upper layer. In the absence of oxygen and nitrate, bacterial sulfate reduction will develop and H_2S produced.

Under the reducing condition iron will becomes more mobile through its reduction to Fe^{2+}. However, its concentration, and the concentration of other trace metals more soluble in anoxic conditions will be limited by precipitation as sulfide. By its nature, the anoxic brine will not have a direct environmental impact on the surrounding of the Dead Sea. However, it may have a major impact on the potash industries and their surroundings because these would probably prefer to pump brine from the more concentrated lower water body. During the brine's flow in the feeding canal and in the evaporation ponds, most of the H_2S will be emitted (the rest chemically or bacterially oxidized) and the permanent disagreeable smell of H_2S may decrease the attractiveness of the area in the vicinity of the canal and the evaporation ponds. From an industrial standpoint, it is anticipated that by the time the brine reaches the carnallite ponds it would contain no sulfide. If this assumption is incorrect, the industries will need to deal with brine that is even more corrosive than the brine pumped today from these ponds. The iron in the anoxic brine will precipitate when exposed to oxygen as Fe-oxyhydroxides. Depending on the rate of oxidation, some of the iron and other trace metals precipitation may occur in the carnallite ponds, in which case the industries will have to learn how to separate these elements from their products.

The environmental and industrial aspects outlined above, which originate from withdrawal of anoxic brine from the lower water body, were never examined previously. Thus, there is no estimate for the rate at which the anoxic conditions will develop and what H_2S and Fe concentrations should be expected in the lower water. It should be clear that the respective 15 ppm and 250 ppb concentrations that coexisted in the water column in the late 1970s do not represent a maximum concentration limit. However, simultaneous increase in concentration of both H_2S and Fe above these concentrations is probably not possible because of Fe-sulfide precipitation. Rather, either H_2S or Fe supply may turn to be the limiting factor, thereby enabling increased concentrations of the other.

If the potash industries did not exist, the interest in the development of anoxic lower water column would have been limited mainly to the scientific community. No environmental issues would have been raised in conjunction with the proposed “Peace Conduit”. However, since the anoxic brines would be pumped to the surface by the industries, it is recommended that they will urgently undertake the study of this subject and provide economic and environmental assessment of the expected outcome of pumping and diversion of the anoxic brine to the evaporation ponds.

Development of Sinkholes along the Shores of the Dead Sea

The development of sinkholes along the shores of the Dead Sea (Fig. 7) is linked to the drop in the level of the Dead Sea (Wachs et al., 2000). The disturbed balance between Dead Sea brines and groundwater in the subsurface along the shores of the Dead Sea results in the movement of the freshwater - brine interface towards the sea. Areas that were previously saturated with saline Dead Sea brines are thus flushed by freshwater. This results in the dissolution of halite, present in the subsurface, and the development of subsurface cavities, which in time collapse. In addition, de-watering and sediment shrinkage lead to local ground sinking.

Fig. 7. A sinkhole near the fan of Wadi Hever.

The rise in the Dead Sea level by inflowing seawater will result in re-flooding of large areas where the sinkholes developed, thereby diminishing to a great extent the exposed areas in which the infrastructure is prone to collapse. However, other areas will remain at risk. Brines that are undersaturated with respect to halite will push back the freshwater - saline interface in the subsurface. These brines which will be derived from the upper water body will remain undersaturated until either they dissolve enough halite in the subsurface or until they are replaced by more concentrated brines. The latter will be present in the upper water column only after many years of operation of the “Peace Conduit” when the filling stage has been completed and the salinity of the upper water column begins to increase again. Thus, while the “Peace Conduit” will provide some answer to the collapse of the infrastructure in the vicinity of the Dead Sea, it will not totally do away with the problem.

It should be emphasized that the present understanding of the evolution of the sinkholes along the Dead Sea is based on the work currently undertaken by the Geological Survey of Israel. As work progresses and better understanding will be gained on the mechanism behind the infrastructure collapse, it will be possible to map the areas under immediate risk of infrastructure collapse. Such mapping will enable better management of the surroundings in order to avoid hazardous areas.

Summary and Conclusions

The "Peace Conduit" project is a large scale and unique project aimed at raising and stabilizing the Dead Sea level through pumping of seawater from the Red Sea. In addition, the elevation difference between the two Seas can be exploited to desalinize seawater. Implementation of the project will bring about major changes to the Dead Sea and its surroundings. It should be emphasized that the implementation of the "Peace Conduit" differs from intervention with an undisturbed natural ecosystem: the Dead Sea has been undergoing a process of degradation that has accelerated over the past thirty years. The project, therefore, has the potential to stop undesired environmental processes that currently occur in the basin such as the decline in lake level, retreat of the shoreline, and the collapse of the surrounding infrastructure. However, there is a possibility that the mixing of seawater in the Dead Sea brine may also bring about undesirable changes to the Dead Sea which may impact negatively on the feasibility of project.

The present report summarizes the expected impact of the "Peace Conduit" on the Dead Sea on the basis of available data and studies conducted in the past on the impact of discharge and mixing of seawater in the Dead Sea brine. It is submitted to the Ministry of Regional Cooperation as part of the assessment of the feasibility and impact of the "Peace Conduit" on the Dead Sea and is the opening phase in the formulation of a dynamic-limnological model for the Dead Sea. This model will integrate the various parameters that will control the evolution of the lake once the "Peace Conduit" is operative. The report does not present new data; rather, the available information and studies are summarized and critically evaluated based on current understanding of the dynamics of the Dead Sea. We also identify and outline areas in which data and information are missing.

The implementation of the “Peace Conduit” and the inflow of seawater (and/or reject brine from proposed desalinization plant) into the Dead Sea involves two stages:

1. The “filling period” during which the level of the lake is raised to the desired level at a designated rate. It is recommended that the target level not exceed -402m in order to allow for floodwater discharge while

avoiding flooding of the Southern Basin that may endanger the dams of the potash industries in both Israel and Jordan.

2. The “steady state period” during which lake level will be maintained at a constant level.

Following is a summary of the identified changes in the limnology of the Dead Sea that will accompany the inflow of seawater into the Dead Sea. It should be kept in mind that other changes that were not yet identified might also take place.

Stratification of the water column: During the filling period, mixing of seawater and Dead Sea brine will lead to formation of a stratified water column with a diluted surface layer, composed of a mixture of Dead Sea brine and seawater, and a lower water body with salinity similar to that of current Dead Sea. The dilution and continuous decrease in surface water density will continue throughout the filling period. The rate at which the density will decrease will be determined by the rate of inflow and depth of stratification. Once the desired lake level has been attained, inflow will be controlled so that it will only compensate for evaporation. The density of the upper water at this stage will begin to increase due to accumulation of seawater-derived salts. Its density will increase until it attains the density of the lower water column and overturn will occur. From this stage onward, the density of the entire water column will increase and the development of periodic stratification will depend primarily on the mode of operation.

Stratification of the Dead Sea water column is not a new phenomenon in the Dead Sea and in itself will not have a negative environmental impact, provided that the composition and density of the upper water body would not alter to the degree that the Dead Sea would loose its uniqueness. Current knowledge, however, does not allow us to determine either the depth of stratification and mixing ratio, or the composition and change in density of the upper water body. These depend on numerous physical and operational parameters which will have to be modeled in the dynamic-limnological model and considered when planning the Conduit.

Precipitation of gypsum: Mixing between the calcium (Ca) - rich Dead Sea brine and the sulfate (SO_4) - rich seawater will result in precipitation of gypsum ($CaSO_4 \cdot 2H_2O$). Kinetic effects will determine if the gypsum will precipitate continuously or if the incoming sulfate will accumulate in the mixture and precipitate periodically once over-saturation attains a critical value. The rate at which the gypsum crystals or agglomerates will settle from the upper water column will determine if, how, and to what extent the turbidity of the water column will increase. The most extreme case is that of "whitening" of the surface water for prolonged periods of time. An increase in surface water turbidity is not a desired outcome of the project because it may be accompanied by local climatic changes due to changes in the reflectivity of the water's surface and may also impact negatively on the visual attractiveness of the Dead Sea. It is still to be determined at what point, if at all, turbidity becomes unbearable to the extent that it could hamper the project. It should be noted however, that small-scale field studies conducted in the past do not support a scenario of prolonged whitening. Some laboratory experiments, however, do suggest that this phenomenon is nonetheless possible.

Microbial blooming: Field studies indicate that dilution of the Dead Sea brine by 10% and the addition of phosphate, which is a limiting nutrient in the Dead Sea, initiate bacterial blooming. In desalinization plants, anti-scaling agents, usually based on phosphate, are common additives. Thus, it is essential that the anti-scaling additives in the desalinization plant envisioned for the Dead Sea will not be phosphate-based. However, this does not ensure that bacterial blooming will not occur just as a result of the dilution of the upper water column. Bacterial blooming was observed in the Dead Sea in the past, following particularly rainy winters, when the upper water column was diluted. Blooming lasted for several weeks during which the Dead Sea had a reddish hue. There is no evidence of prolonged blooming from earlier periods, when large volumes of freshwater reached the Dead Sea on a regular basis. Yet, the duration of blooming events that may take place in the Dead Sea following the continuous introduction of seawater and the consequent dilution of the surface water and change in its composition has never been studied and is uncertain. Should this phenomenon occur, it will have both limnological and industrial consequences that must be examined carefully. The basic assumption is that bacterial blooming is not desired in the Dead Sea just as it is not desired in any other open water system. Such prolonged blooming will impact on the ecology of the Dead Sea and its surrounding, decrease the attractiveness of the lake, which will cease to be "Dead" and will have negative impact on the potash industries. Here too it is not possible yet to define if or at what point the increased turbidity of the water due to blooming becomes unbearable to the extend that could hamper the project.

Increased rate of evaporation: Water balance calculations constitute an integral and crucial part in the proper planning and management of the "Peace Conduit". Yet even the present-day water balance of the Dead Sea is not agreed upon. One of the most critical factors in the calculation of the water balance is the rate of evaporation, which has yet to be definitively established. Disagreement as to the current evaporation rates reign and estimates range between 1.05 and 2 m/yr. Dilution of the surface water due to the inflow of seawater will invariably increase the rate of evaporation and will have a major impact on the required capacity of the "Peace Conduit". Increased turbidity of the upper water column due to possible suspended gypsum crystals and/or microbial blooming may increase evaporation rates even more than what would be expected from dilution alone. If, on the other hand, the gypsum concentrates at the surface, evaporation rate may in fact decrease due to changes in the Dead Sea's reflectivity.

Development of anoxic conditions in the lower water column: The development of long-term stratification of the Dead Sea water column will lead to the removal of oxygen and development of anoxic conditions in the lower water column. Under these conditions the anoxic lower water column will have dissolved H_2S, elevated levels of iron (Fe^{2+}) and other trace metals at lower concentrations. Similar conditions existed in the Dead Sea prior to the 1979 overturn of the water column that ended the stratification that lasted for hundreds of years. However, at that time, the anoxic brine was not brought to the surface. The potash industry (only the Dead Sea Works existed at the time) pumped its brine from the less saline surface layer. In the context of the "Peace Conduit" and expected dilution and compositional changes in the surface water, the potash industries would most likely prefer to pump brine from the concentrated lower water body. Exposure of large volumes of anoxic brine (hundreds of million cubic meters per year) to the atmosphere in the feeding canals and the evaporation ponds will be accompanied by release of sulfur gasses (H_2S). This, as well as the presence of iron in the brine, may have an environmental impact and can impair the industrial processes. It is therefore important to determine if it will be possible to overcome the above impacts through development of appropriate industrial methods.

Infrastructure collapse and sinkholes: The rise in Dead Sea level will lead to re-flooding of large areas where sinkholes have developed. Thus, much of the areas that currently experience collapse and destruction will again be covered by water. Water from the upper water column, which will be unsaturated with respect to halite, will replace freshwater in the subsurface. Thus, some exposed parts of the shorelines will still be susceptible to development of sinkholes because of halite dissolution and development of cavities in the subsurface. However, over the long run, with the gradual rise in salinity in the entire Dead Sea system, these processes will slowly come to a standstill.

To conclude, the "Peace Conduit" will have both positive and negative impacts on the future evolution of the Dead Sea. Based on ***current knowledge***, the various aspects of Dead Sea - seawater mixing discussed above do not provide grounds for overall negation of the proposed project. Yet, the ***final decision*** regarding the implementation of the "Peace Conduit" needs to take into consideration the expected changes in the Dead Sea following the discharge and mixing of seawater. The "Peace Conduit" can potentially reverse processes of environmental degradation that have resulted from the diversion of water from the Jordan River and other fresh water tributaries. Accordingly, the importance of the project and its positive outcome in raising and stabilizing the Dead Sea level, halting the collapse of the infrastructure, reducing groundwater looses, providing freshwater through desalinization of seawater and facilitating planning and development in the region is well-established. Also, the contribution to regional cooperation and the consolidation of peace cannot be ignored. Yet, based on current knowledge it is not possible at this stage to quantify expected changes in the Dead Sea and therefore their environmental, industrial and economical outcome cannot be assessed. Such examination requires quantification of the processes described in the report and their interdependencies in the long run. A long-term complex forecast and integration of these processes is possible only through a dynamic limnological model. The construction of such a model is the next stage of this study which is conducted by the Geological Survey of Israel (Ministry of National Infrastructure) and is jointly sponsored by the Ministry of National Infrastructures and the Ministry of Regional Cooperation. The environmental and economic assessments that will be based on the outcome of the model will provide decision makers with the information required to determine and shape the future of the proposed "Peace Conduit" project.

References

Al-Weshah R.A. 2000. The water balance of the Dead Sea: An integral approach. Hydrol. Proc., 14: 145-154.

Anati D.A. 1992. How much salt precipitates from the brines of a hypersaline lake? The Dead Sea as a case study. Geochim. Cosmochim. Acta, 57: 2191-2196.

Anati D.A., Gavrieli I. and Oren A. 1995. The residual effect of the 1991-1993 rainy winters on the Dead Sea stratification. Isr. J. Earth Sci., 44: 63-70.

Anati D.A., Stiller M., Shasha S. and Gat J.R. 1987. Changes in the thermo-haline structure of the Dead Sea. Earth Planet. Sci. Lett., 84: 109-121.

Anati D.A. 1999. The salinity of hypersaline brines: concepts and misconceptions. Int. J. Salt Lake Res., 8: 55-70.

Asmar B.N. 1998. Dynamic simulation of the Dead Sea water body and the effects of the Dead Sea- Red Sea Canal. PhD Dissertation, Freie Universitat, Berlin.

Asmar B.N. and Ergenzinger P. 1999. Dynamic simulation of the Dead Sea. Hydrol. Process., 13: 2743-2750.

Asmar B.N. and Ergenzinger P. 2002. Dynamic simulation of the Dead Sea. Adv. Water Res., 25: 263-277.

Ben Yaakov S. and Katz A. 1982. Field experiments in mixing Mediterranean water with Dead Sea water. Preliminary report for the period July – Oct. 1982. In Hebrew. Rep. submitted to the Mediterranean – Dead Sea Co. 87 p.

Beyth M. 1980. Recent evolution and present stage of the Dead Sea brines. In: A. Nissenbaum (ed.), Hypersaline Brines and Evaporitic Environments. Amsterdam, Elsevier Scientific Publishers., pp. 155-166.

Beyth M., Gavrieli I., Anati D. and Katz O. 1993. Effects of the December 1991 - May 1992 floods on the Dead Sea vertical structure. Isr. J. Earth Sci., 42: 45-47.

Blasberger A. and Elata C. 1983. Hydrodynamic model for the Dead Sea: Summary report for the 3rd year. Ben Gurion Univ., Mechanical Eng. Dept., 61 p. (in Hebrew).

Bloch R. Littman H.Z. and Elazari-Volcani B. 1943. Occasional whiteness of the Dead Sea. Nature, 154: 402.

Elata C. 1984. Hydrodynamic model of the Dead Sea. Mediterranean - Dead Sea project. Vol. 5, Summary of Research and Surveys, pp. 38-47.

Elazari-Volcani B. 1936. Life in the Dead Sea. Nature, 138: 467.

Gavrieli I. 1997. Halite deposition in the Dead Sea: 1960-1993. In: The Dead Sea - The Lake and its Setting (eds. Niemi T.M., Ben-Avraham Z. and Ginzburg A.). Oxford monographs on Geol. and Geophysics no. 36, ch.14 , pp. 161-170. Oxford Univ. Press.

Gavrieli I., Starinsky A. and Bein A. 1989. The solubility of halite as a function of temperature in the highly saline Dead Sea brine system. Limnol. Oceanogr., 34: 1224-1234.

Gertman I., Ivanov V.A., Liubartseva S.P., Mikhailova E.N. and Shapiro N.B. 2002. Dead Sea model simulation of variability of thermohaline water structure 1992-2000 (in Russian). Mar. Geoph. J., *in press.*

Harza JRV Group. 1996. Red Sea-Dead Sea Canal Project, Draft Prefeasibility Report, Main Report. Jordan Rift Valley Steering Committee of the Trilateral Economic Committee.

Israel Hydrological Service 1999. Hydrological Data (Israel), July 1999, Jerusalem (in Hebrew): 25 p.

Kaplan I.R. and Friedmann A. 1970. Biological productivity in the Dead Sea. Part 1. Microorganisms in the water column. Israel J. Chem., 8: 513-528.

Katz A., Taitel-Goldman N., Starinsky A. and Beyth M. 1977. Chemical reaction of the Dead Sea brines to the Mediterranean - Dead Sea project. Hebrew Univ., 71 p. (in Hebrew).

Katz A., Starinsky A., Taitel-Goldman N. and Beyth M. 1981. Solubilities of gypsum and halite in the Dead Sea in its mixtures with seawater: Limnol. Oceanogr., 26: 709-716.

Krumgaltz B., Hecht A., Starinsky A. and Katz A. 2000. Thermodynamic constraints on Dead Sea evaporation: how much can the Dead Sea evaporate?. Chem. Geol., 165: 1-11.

Levy Y. 1982**.** Calculations of chemical composition of mixed layers of Mediterranean Sea and Dead Sea water. Geol. Surv. Isr., Rep. MGG/1/82.

Levy Y. 1983. Gypsum behavior in the Dead Sea water- summary of experimental study. In Hebrew, Geol. Surv. Rep/3/83 9p.

Levy Y. 1984a. The influence of the admixture rate of partly evaporated Mediterranean water to the Dead Sea on the properties of gypsum that is formed in the brine. in Hebrew. Mediterranean - Dead Sea projects; summary of research and surveys. Medit.- Dead Sea Co., Vol. 5, pp. 279-282 (in Hebrew).

Levy Y. 1984b. Evaporation from the Dead Sea. Mediterranean - Dead Sea projects. Earth Science Research Administration, Vol. 5, summary of research and surveys. pp. 201-210.

Levy Y. and Kushnir Y. 1981. Laboratory measurements of nucleation processes and the growth of gypsum in the Mediterranean - Dead Sea mixed brine. Geol. Surv. Isr., Rep. and Weizmann Inst. Sci. 18 p.

Mediterranean - Dead Sea Co. 1984. Mediterranean - Dead Sea projects. Vol. 5, summary of research and surveys. 467 p. (reports in Hebrew and English).

Mero F., Simon E. and Last Y. 1982. Estimation of evaporation rates from the Dead Sea at various conditions. Interim report (04/82/06) TAHAL, 29 p. (in Hebrew).

Neev D. and Emery K.O. 1967. The Dead Sea: depositional processes and environments of evaporites. Geol. Surv. Isr., Bull. 41, 147 p.

Nishri A. 1984. The geochemistry of manganese in the Dead Sea. Earth. Planet. Sci. Lett., 71: 415-426.

Nissenbaum A. 1975. The microbiology and biogeochemistry of the Dead Sea. Microb. Ecol., 2: 139-161.

Nissenbaum A. and Kaplan I. 1976. Sulfur and carbon isotopic evidence for biogeochemical processes in the Dead Sea ecosystem. In: J. Nriagu (ed.): Environmental biogeochemistry, Ann Arbor Sci., Publ., Ann Arbor, Michigan, 1, pp. 309-325.

Oren A. 1983. Population dynamics of halobacteria in the Dead Sea water column. Limnol. Oceanogr., 28: 1094-1103.

Oren A. 1985. The rise and decline of a bloom of halobacteria in the Dead Sea. Limnol. Oceanogr., 30: 911-915.

Oren A. 1988. The microbial ecology of the Dead Sea. In: Marshall, K.C. (ed.): Advances in microbial ecology, Vol. 10. Plenum Publishing Company, New York. pp. 193-229.

Oren A. 1992. Bacterial activities in the Dead Sea, 1980-1991: survival at the upper limit of salinity. Int. J. Salt Lake Res., 1: 7-20.

Oren A. 1993. The Dead Sea - alive again. Experientia, 49: 518-522.

Oren A. 1997. Microbiological studies in the Dead Sea: 1892-1992. In: T.M. Niemi, Z. Ben-Avraham and A. Ginzburg (eds.), The Dead Sea - The Lake and its Setting). Oxford Monographs Geol. and Geophysics, Oxford Univ. Press, no. 36, ch.19, pp. 205-213.

Oren A. 1998. The rise and decline of a bloom of halophilic algae and Archaea in the Dead Sea: 1992-1995. In: Oren, A. (ed.), Microbiology and biogeochemistry of hypersaline environments. CRC Press, Boca Raton, pp. 129-138.

Oren A. 2000. Biological processes in the Dead Sea as influenced by short-term and long-term salinity changes. Arch. Hydrobiol. Spec. Issues Advanc. Limnol., 55: 531-542.

Oren A. and Ben-Yosef N. 1997. Development and spatial distribution of an algal blooms in the Dead Sea: A remote sensing study. Aquat. Microb. Ecol., 13: 219-223.

Oren A. and Gurevich P. 1995. Dynamics of a bloom of halophilic Archaea in the Dead Sea. Hydrobiologia, 315: 149-158.

Oren A. and Shilo M. 1982. Population dynamics of *Dunaliella parva* in the Dead Sea. Limnol. Oceanogr., 27: 201-211.

Oren A. and Shilo M. 1985. Factors determining the development of algal and bacterial blooms in the Dead Sea: a study of simulation experiments in outdoor ponds. FEMS Microbiol. Ecol., 31: 229-237.

Oren A. Bratbak G. and Heldal M. 1997. Occurrence of virus-like particles in the Dead Sea. Extremophiles, 1: 143-149.

Oren A., Gurrevich P., Anati D.A., Barkan E. and Luz B. 1995. A bloom of *Dunaliella parva* in the Dead Sea in 1992: Biological and biogeochemical aspects. Hydrobiologia, 297: 173-185.

Salameh E. and El-Naser H.1999. Does the actual drop in the Dead Sea level reflect the development of water sources within its drainage basin?. Acta Hydrochim. Hydrobiol., 27: 5-11.

Salameh E. and El-Naser H. 2000a. Changes in the Dead Sea level and their impacts on the surrounding groundwater bodies. Acta Hydrochim. Hydrobiol., 28: 24-33.

Salameh E. and El-Naser H. 2000b. The interface configuration of the fresh-/Dead Sea water- theory and measurements. Acta Hydrochim. Hydrobiol., 28: 323-328.

Stanhill G. 1984. Evaporation from the Dead Sea. A summery of research till September 1984. Dead Sea projects. Earth Science Research Administration, Vol. 5, summary of research and surveys. pp. 251-277.

Stanhill G. 1985. An updated energy balance estimate of evaporation from the Dead Israel Meteorol. Res. Pap., 4: 98-116.

Stanhill G. 1994. Changes in the rate of evaporation from the Dead Sea. Internat. J. Climat., 14: 465-471.

Steinhorn I. 1983. In situ salt precipitation at the Dead Sea: Limnol. Oceanog., 28: 580-583.

Steinhorn I. 1985. The disappearance of the long-term meromictic stratification of the Dead Sea. Limnol. Oceanog., 30: 451-472.

Steinhorn I., Assaf G., Gat J.R., Nishri A. Nissenbaum A., Stiller M., Beyth M., Neev D., Grader R., Friedman G.M. and Weiss W. 1979. The Dead Sea: Deepening of the mixolimnion signifies the overturn of the water column. Science, 206: 55-57.

Vadasz P., Weiner D. and Zvirin Y. 1983. A halo-thermal simulation of the Dead Sea for application to solar energy projects. Trans. of the ASME, Vol. 105, pp. 348-355.

Vardi J. 1990. Mediterranean-Dead Sea Project, Historical Review. Geol. Surv. Isr., Rep. GSI/9/90, pp. 31-50.

Wachs D., Yechieli Y., Shtivelman V., Itamar A., Baer G., Goldman M., Raz E., Rybekov M. and Schattner U. 2000. Formation of sinkholes along the Dead Sea shore – summary of findings from the first stage of research. Geol. Surv. Isr., Rep. GSI/41/2000.

Yechieli Y., Gavrieli I., Berkowitz B. and Ronen D. 1998. Will the Dead Sea die?. Geology, 26: 755-758.

Appendix 1: Summary of published evaporation rates for the Dead Sea (expansion of a table presented by Levy, 1983)

#	Source	Model type and remarks	Time period of comparison	Dead Sea level	Evaporation estimate [cm/yr]	Salinity /density
1	Neumann, 1958	Energy balance	1942-1946	-395	147 (north basin) 180 (south basin) 155 (avg. for lake)	225 gr/kg
2	Steinhorn, 1997	Revised Neumann, 1958			172 (north basin) 213 (south basin)	225 gr/kg
		Energy balance	1940-1950		166.5	1.17 gr/cm^3
		Energy balance			147	1.20 gr/cm^3
					116-130	1.23 gr/cm^3
3	Miro and Shechter, 1974	Energy balance	(T varies 0.5°)		162-70	1.193-1.335 gr/cm^3
4	Calder and Neal, 1984	Penman formula	Lake Kinneret data		104.3	318 gr/l
5	Simon and Miro, 1985	From Lake Kinneret evaporation estimates- model vs. measured	1969-1977		Model-168-173 Measured- 162-170	Lake Kinneret
6	Stanhill, 1982		1982		1.127	256 gr/kg*
	Stanhill, 1984		1983-1984	-403	1.38	260 gr/kg*
	Stanhill, 1994		1942-1950		104.9 127 (north basin)	340.5 gr/l
7	Oroud, 1995	Energy balance			163.3	258.5 gr/kg
8	Asmar and Ergenzinger, 1999	Penman formula	Published data of Stanhill (1987,1994) i.e. monthly averages 1983-1987		177 to 0	0-470 gr/l
		Dalton formula			260 to 0	0-470 g/l
	Asmar and Ergenzinger, 2000	Mass balance			0.5 to 2.16	100-350 Kg/m^3
9	Salameh and Al-Naser, 2000	Water balance of a terminal lake	1994-1998		242.4	235 Kg/m^3 *
10	Carmi, Gat and Stiller	Tritium balance			146 (y.l. 147)	240

Appendix 1: (Continued).

	Source	**Model type and remarks**	**Time period of comparison**	**Dead Sea level**	**Evaporation estimate [cm/yr]**	**Salinity /density**
11	Salhotra *et al.*, 1985	Based on pan evaporation experiments and Dalton formula (aerodynamic approach)			1.53	1.225-1.240 gr/cm^3
12	Marinov, 2002	Using transformation on pan data	1970		129	1.233 gr/cm^3
			1990-2000		164	1.233 gr/cm^3
13	Mero, 1975				170	225 gr/kg
					158	240
14	Assaf (1980)	Heat balance			175	225 gr/kg
15	Harleman *et al.*,				135	256-279
16	Harza JRV Group, 1996	Adjusted Stanhill estimates based on heat balance and 35%			127	1.235 Kg/m^3
17	Blasberger and Elata, (1983)				208	260 gr/kg*
18	Arab Potash Company	based on Salameh and El-Naser (2000)	1980-1997		242	Not reported

* assumed value (not reported)