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THE EXPECTED IMPACT OF THE PEACE CONDUIT PROJECT (THE RED SEA – DEAD SEA PIPELINE) ON THE DEAD SEA

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Abstract. The Dead Sea of Israel, Jordan and Syria is a severely disturbed ecosystem, greatly damaged by anthropogenic intervention in its water balance. During the 20th century, the Dead Sea level dropped by more than 25 meters, and presently (2003) it is at about 416 meters below mean sea level. This negative water balance is mainly due to the diversion of water from the catchment area of the lake by Israel, Jordan and Syria. During the 2002 World Summit on Sustainable Development Israel and Jordan jointly announced their interest in saving the Dead Sea by constructing the 'Peace Conduit' that will pipe water from the Red Sea to the Dead Sea. The inflow of seawater (or reject brine after desalinization) into the Dead Sea will have a major impact on its limnology, geochemistry and biology. During the filling stage, relatively diluted surface water will form and the rate of evaporation will therefore increase. Dilution of the surface water will most likely result in microbial blooming whose duration is not known, while the lower water layer is likely to develop reducing conditions, including bacterial sulfate reduction and presence of hydrogen sulfide (H_2S). Mixing between the calcium-rich Dead Sea brine and the sulfate-rich seawater will result in gypsum precipitation ($CaSO_4{\cdot}2H_2O$). Once the target level is reached, inflow will be outbalanced by evaporation and salinity of the surface water will increase due to accumulation of seawater-salts. The water column will re-mix when the density of the surface water will equal that of the lower water column. In spite of its large volume and high salinity relative to that of the inflowing water, over the long run the composition of this unique lake will change. Before a decision is made on the planning and construction of the Conduit, it is essential that the long term evolution and characteristics of the 'renewed' Dead Sea be known and anticipated changes examined. 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 expected changes in the limnological physical/chemical characteristics of the Dead Sea and its unique brine.

Keywords: brines, Dead Sea, desalinization, gypsum precipitation, Israel, Jordan, microbial blooming, peace conduit, sustainable development, water balance, water level

1. Introduction

The Dead Sea of Israel, Jordan and Syria is a hypersaline terminal lake located in the Dead Sea Rift valley which developed along the Dead Sea Transform (Figure 1). Its water level is the lowest surface on earth and is currently (year 2003)

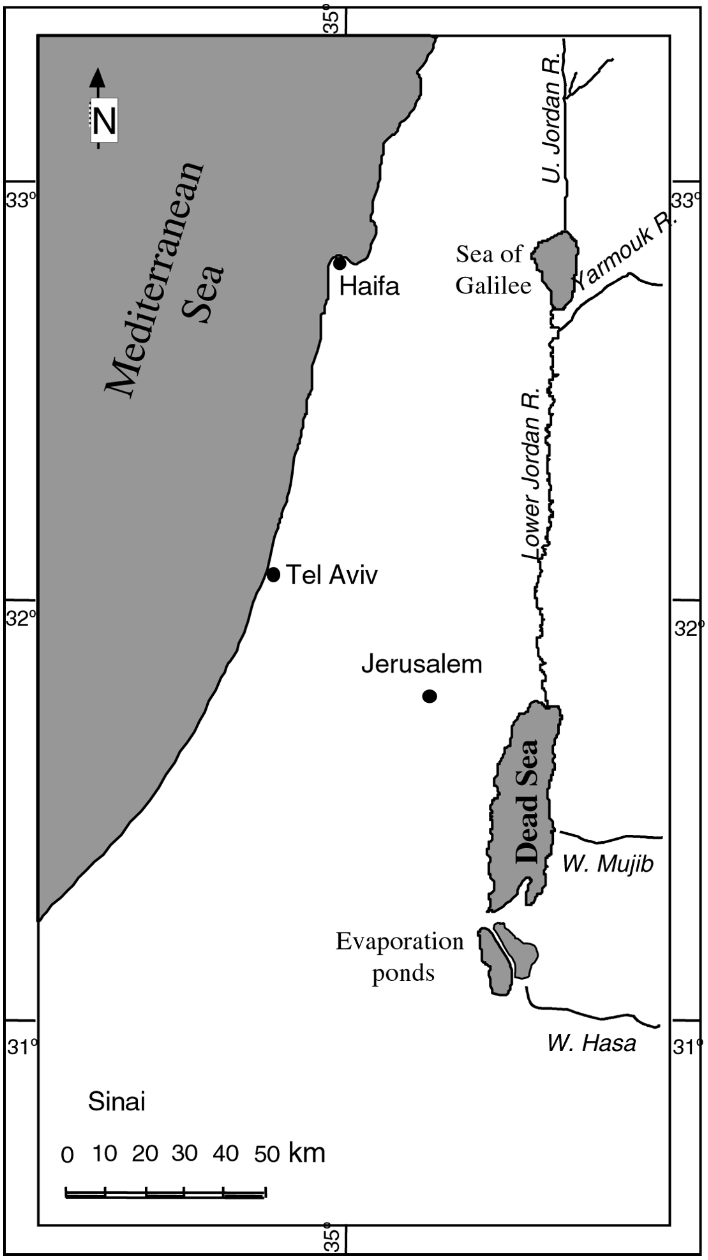

Figure 1. Location map of the Dead Sea.

TABLE I

Dead Sea composition during summer 2002 (in g l^{-1}). Density: 1.237 at 25 °C.

Na	K	Ca	Mg	Cl	Br	Alkalinity (as HCO_3)	SO_4	TDS
34.3	8.0	18.3	47.1	228.6	5.4	0.3	0.4	342.4

416 m below mean sea level while at its deepest place, the lake is over 300 meters deep, making it the lowest terrestrial place on Earth (–730 m). The Dead Sea brine is characterized by high salinity (TDS $>$340 g l^{-1}), high density ($>$1.236 kg/l) and a unique Ca-chloride composition ($Ca/(HCO_3+SO_4)>1$; $Na/Cl<1$; Table I).

The precursor of the Dead Sea is Lake Lisan, which existed in the late Pleistocene, between 70 and 15 Kyr before present. This lake occupied a larger area of the Rift Valley, attaining its maximum extension during the last glacial maximum (22–20 Kyr). At that time Lake Lisan level was –160 and it extended from Lake Kinneret (Sea of Galilee) in the north to few tens of km south of the present Dead Sea (Begin et al. 1974; Katz et al. 1977; Stein 2001; Bartov et al. 2002).

The modern Dead Sea evolved in the early Holocene after a major decline in the water level of Lake Lisan. Since then the water level of the Dead Sea fluctuated around –400 m (Stein 2002; Bookman 2004), which is the elevation of the sill dividing between the shallow southern basin of the lake and the much deeper northern basin. Higher water levels were attained during rainy periods when the lake extended into the southern basin and the surface water was diluted. Lower levels reflect dry periods, with negative water balance and large area shrinkage, including the drying out of the southern basin. The smaller surface area and higher salinity resulted in a drastic decrease in evaporation which served to buffer further lake level drop.

2. Recent and Future Changes in the Dead Sea

During the 20th century, the Dead Sea level has dropped by more than 25 meters (Figure 2), and presently is $\sim$416 meters below mean sea level (–416 m). In 1976, when the lake level reached an elevation of –400 m the southern basin dried up (Steinhorn et al. 1979; Figure 3). Few years later, in 1979, the Dead Sea water column overturned and mixed (Steinhorn 1985), ending a period of about 300 years of stratification (Stiller and Chung 1984), whereby the upper water column of the lake was relatively diluted while the lower brine was more concentrated (Neev and Emery 1967). Since then the Dead Sea experiences mostly annual stratification and overturns, while its salinity rises (Anati and Stiller 1991; Gertman and Hecht 2002).

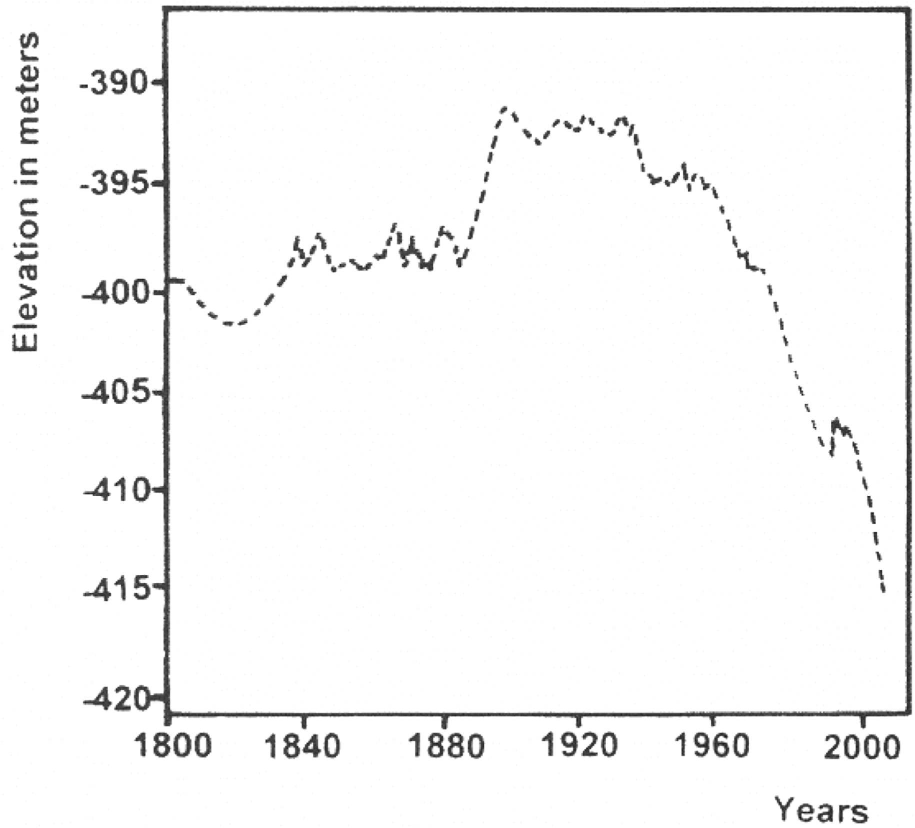

Figure 2. Dead Sea water levels: 1800–2000.

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 has been about 1 m yr^{-1} (Figure 2). This negative water balance is attributed primarily to water pumping from Lake Kinneret to the Israel National Water Carrier and diversion of water from the Yarmuk River by Syria and Jordan. The latter constructed the King Abdullah Canal which runs along the eastern side of the Jordan Rift Valley and supplies Yarmouk water for irrigation in the region. Additional water is captured from smaller tributaries either draining to the Jordan River or directly to the Dead Sea. The average annual water deficit of the Dead Sea, assuming an annual water level drop of 1 m yr^{-1}, is 625×10^6 m^{-3} (surface area of the Dead Sea at elevation of –416 being ~625 km^2, Hall, pers. com).

About 30% of the water level decline of the Dead Sea is attributed to evaporation of Dead Sea brine in the evaporation ponds of the Israeli and Jordanian mineral industries located in the southern basin of the Dead Sea. These industries pump together 400–450 $\times 10^6$ m^{-3} from the Dead Sea into the evaporation ponds where

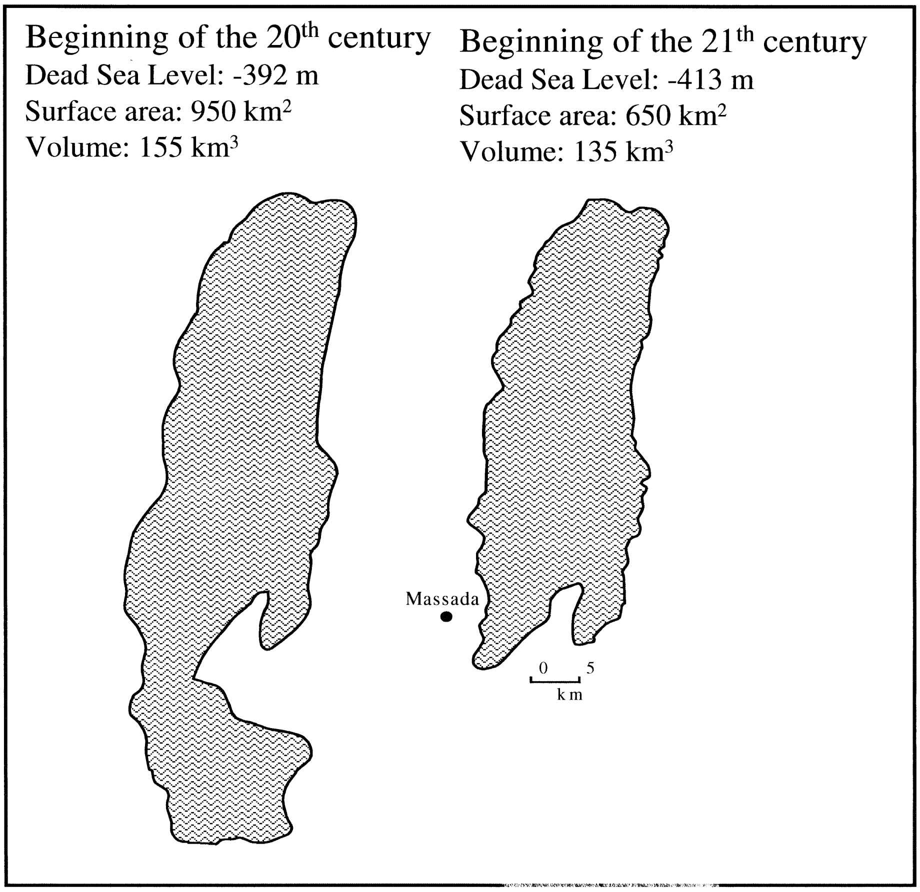

Figure 3. Comparison between the Dead Sea at the beginning of the 20th and 21st centuries.

halite (NaCl) and carnallite ($KMgCl_3 \cdot 6H_2O$) precipitate. At the end of the process about 200×10^6 m^{-3} of concentrated end brines (density = 1.35 kg/l; TDS = 500 g l^{-1}), composed mainly of Mg-Ca-Cl, are returned to the Dead Sea.

If the current situation will prevail, 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 diverted to meet growing demand for freshwater. 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, 2000a, b) estimate this additional groundwater discharge at over 400×10^6 m^{-3} per meter drop in DS level in recent years. Other researchers estimate a much smaller discharge volume and

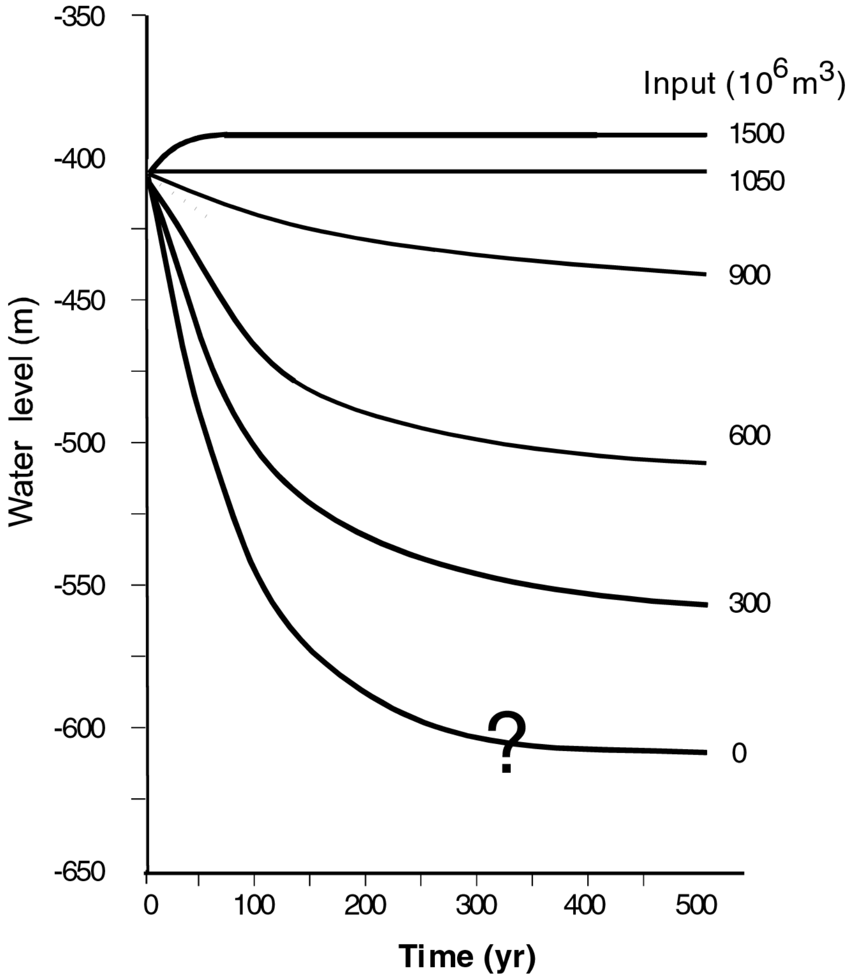

Figure 4. Predicted changes in the water level of the Dead Sea for different water inputs (in 10^6 m^3/yr). All cases assume continued evaporation from the evaporation ponds of the potash industries (after Yechieli et al. 1997).

argue that the higher volumes require unreasonably high evaporation rates from the Dead Sea surface (Gavrieli et al. 2002).

Models and thermodynamic calculations proposed by Yechieli et al. (1998) and Krumgalz et al. (2000), respectively, 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 at an elevation of about –510 m, i.e. ~100 m below the present level (Figure 4). The rapid water level decline will continue during the coming decades but will begin leveling off within a few hundred years. A steady state level will be approached when the evaporation will be compensated by inflowing water. Such conditions will be achieved due to the combined effect of diminishing surface area and decrease in evaporation rate due to the increasing salinity of the brine. An even lower water level of –565 m by year 2500 was predicted by Asmar and Ergenzinger (2002a), though according to their model no steady state level will be achieved.

Over the last decade hundreds of sinkholes developed along the shores of the Dead Sea and large areas are subsiding. This phenomenon, which has major economic and safety implications, is linked to the drop in the level of the Dead Sea and subsurface salt dissolution (Wachs et al. 2000; Yechieli et al. 2002; Abelson et al. 2003). In addition, de-watering and sediment shrinkage led to local ground sinking (Baer et al. 2002). The rapid drop in the water level results in rapid geomorphological changes, which lead to damages in the surrounding infrastructure, mainly to roads and bridges. Thus, the Dead Sea area, which has a major economic, touristic and environmental potential is in fact being abandoned, and future planning becomes impossible.

3. The History of the Med-Dead and Red-Dead Canals

The renewed interest in the construction of a canal/pipeline between the Red Sea and the Dead Sea, termed lately as the ‘Peace Conduit’, is due to a number of related issues: (1) a growing public 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 the Hashemite Kingdom of Jordan, which suffers from a major water shortage and its main consumption centers are far away from any coastline.

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, suggested the use of such canals as a waterway connecting the Mediterranean with the Red Sea (Allen 1855). Some 50 years later Herzl (1902) 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 following the 1973 energy crisis funded large scale feasibility studies to evaluate the economic, environmental and engineering prospect of such a canal (Mediterranean Sea-Dead Sea Company 1984). The project was abandoned by Israel when it became clear that it is not viable economically and due to international objection to the construction of such a project on a unilateral basis. 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 difference between the seas to desalinize seawater on the shores of the Dead Sea by reverse osmosis. An additional goal was to raise the Dead Sea level and stabilize it. The study concluded that the project is financially and environmentally feasible and can produce 800 to 850 $\times$ 10^6 m^{-3} of desalinated water annually. The reject brine coming out from this plant is to be discharged to the Dead Sea (Harza JRV Group 1996). The recommendation presented by the Harza group was to proceed with a full feasibility study. During the Johannesburg, South Africa, 2002 World Summit on Sustainable Development the two countries jointly announced their mutual commitment to the project. However, the primary aim of the project, as stated in the announcement, is to save the Dead Sea through stabilizing its level. Desalinization of seawater is a potential by-product of this proposed ‘Peace Conduit’ project.

It should be emphasized that the implementation of the ‘Peace Conduit’, or any other similar project, differ from intervention with an undisturbed natural ecosystem: the Dead Sea basin experiences major man-induced physical and infrastructure changes that have accelerated over the past thirty years. The project has the potential to stop and even reverse the 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 and its surrounding which may impact negatively on the feasibility of project. Below we outline the expected changes on the limnology of the Dead Sea. These changes will need to be quantified through an integrated lake-model, put into a time frame and weighed against the benefits of the project.

4. 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, although it will probably not exceed –400 m which is the elevation of the sill dividing between the northern and southern basin. 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 mineral 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 –400 m sill is required in order to accommodate possible sharp lake level rises following outstanding rainy winters such as that occurred in winters 1979/80, 1991/92 and 2002/03. At the second event some 1.5 billion cubic meters of water reached the Dead Sea raising it level by about 2 meters (Beyth et al. 1993).

It is worthwhile noting that the Israeli and Jordanian mineral industries (Dead Sea Works and Arab Potash Company) which are major economic elements in both countries, object to the 'Peace Conduit'. The current situation of increasing salinity, halite precipitation from the Dead Sea brine and decrease of local humidity increases their production capacity (Dead Sea Works, pers. com.). The more concentrated the brine they pump from the northern basin to the evaporation pond, the shorter its residence time and the less halite it precipitates in the evaporation ponds. Once the 'Peace Conduit' is constructed this trend will cease and new problems will arise, some of which are described below.

4.1. Re-development of water column stratification

Neglecting the impact of ocean-salts, inflow of seawater (density ≈ 1.03 g ml^{-1}) to the saline Dead Sea (density ≈ 1.24 g ml^{-1}) 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 (Blasberger and Elata 1983). 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 rate of sea water introduction and duration of the filling stage.

Once the desired lake level is attained, the volume of inflowing seawater will be adjusted to maintain a constant level. Incoming seawater will evaporate and the seawater-derived salts will accumulate in the upper water column. Thus, while the net annual 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 onward, prolonged periods of stratification are not expected, and if stratification will develop, it would be short-termed, probably with annual overturns. This will be accompanied by increasing salinity and mineral precipitation.

4.2. Mineral 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 SO_4^- 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 ions have relatively low concentration in the Dead Sea brine as compared to the calcium (Ca^+) concentration (Table I).

In 1982 halite (NaCl) began to precipitate from the Dead Sea (Steinhorn 1983), and its precipitation has continued nearly uninterrupted since then (Gavrieli 1997). A decrease in NaCl 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 NaCl precipitation was restored following the November 1995 overturn. Under the present condition of negative water balance and increasing salinity, NaCl 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 overgrown by massive NaCl crystals. A somewhat similar situation existed in the 1960s when gypsum, rather than halite, quickly covered exposed surfaces, although this was limited only to the upper waters.

4.2.1. *Gypsum precipitation from the mixed brine*

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^{-1}) that will mix with the high concentration of calcium ($>$18,000 mg l^{-1}) 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 1984a; Levy and Kushnir 1984), and evaporation of such mixtures will 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 might 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 from the surface. Alternatively, tiny gypsum crystals may not flow on the surface but rather remain suspended in the uppermost part of the water column. In this case, they may lead to the opposite effect: scattering of light within the Dead Sea resulting in an increased temperature and therefore increased evaporation. Both scenarios are likely to affect the climate in the Dead Sea area. 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 presently crystallizes in the Dead Sea. It is worth noting that while prolonged whitening was not observed in the laboratory experiments (Katz et al. 1981), a similar phenomenon was observed in a later field experiment (Ben Yaacov and Katz 1982). Most researchers agree that prolonged events of whitening of the Dead Sea surface are unlikely. However, this subject merits much attention because of the physical, environmental and operational consequences that such whitening may have.

4.2.2. *Halite precipitation*

As noted above, NaCl began precipitating in the Dead Sea in 1983, as a result of increasing salinity (Steinhorn 1983), and has continued precipitating nearly uninterrupted since then (Gavrieli et al. 1989; Gavrieli 1997). It is anticipated that following the introduction of seawater and development of stratification in the Dead Sea halite precipitation will cease. In fact, during the first few years of operation of the Conduit, NaCl dissolution is expected to occur. This will take place at the shallow parts of the lake, where the recently deposited halite will be exposed to the diluted upper water column. The NaCl present at the bottom of the deeper parts of the lake, in contact with the concentrated lower brine, will remain intact. A similar dissolution phenomena occurred following the 1991/2 rainy winter when massive freshwater inflow diluted the brine and formed an upper water column in the Dead Sea (Beyth et al. 1993, 1998). However, NaCl precipitation is expected to re-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. Because of the accumulation of sodium (Na) and chloride (Cl) in the upper waters, derived from both the dissolution of halite and from the seawater, halite precipitation will commence even prior to the overturn of the water column. Once halite precipitation starts, it will continue along with gypsum precipitation. Overturn of the water column at some later stage will probably lead to a decline in the rate of precipitation of both minerals due to the effect of the mixing of seawater with the entire volume of the Dead Sea. However, as long as seawater is piped to the lake, both minerals will continue to precipitate.

4.3. Salinity and compositional changes

Inflow of seawater or reject brine to the Dead Sea will not result in the Dead Sea becoming a lake with seawater salinity or composition. This will not occur because of the high salt content of the Dead Sea and the extensive precipitation from the lake on which the entire project is based. Nevertheless, during the filling period, when lake level is raised, the salinity of the upper water column will decrease continuously. The dilution factor of the upper water column will be smaller than the mixing ratio between the two waters because of the impact of evaporation. Its composition will change in accordance with the ratio between total original Dead Sea salts in the upper water mass and the continuous inflowing sea salts. Once the steady state period begins and evaporation is completely compensated by seawater discharge, dilution of the surface water will cease and its salinity will start increasing. However, the increase in salinity would be largely buffered through removal from the brine of salts in the form of halite and gypsum precipitation. This is analogous to present day NaCl precipitation from the Dead Sea which buffers some of the expected salinity increase due to the evaporation from the lake (Gavrieli 1997).

When seawater evaporates and becomes concentrated by a factor of 3, gypsum begins to precipitate. Halite starts to precipitate at an evaporation factor of 10 (Braitsch 1971; Harvie et al. 1980). Because of excess sulfate over calcium in seawater, gypsum precipitation leads to increased SO_4/Ca ratios and to the near total removal of Ca from the brine. This contrasts with the very low SO_4/Ca ratio in the Dead Sea brine and its unique Ca-Chloride composition. The inflow of marine derived salts into the Dead Sea and its excess sulfate will, thus, over the long run, have the effect of titrating out some Ca from the Dead Sea. However, to drastically change the unique Ca-Chloride composition of the Dead Sea requires inflow to the Dead Sea and evaporation of huge volumes of seawater. The salinity of the Dead Sea is about 10 times greater than that of seawater (i.e. $\times$ 5 when compared to reject brine). The present volume of the Dead Sea is about 135 km^3, i.e. about 100 greater than the 1000–1800 $\times$ 10^6 m^{-3} yr^{-1} of seawater that are mentioned in the context of the 'Peace Conduit'. Accordingly, when the 'Peace Conduit' has operated for an entire century, the ratio between Dead Sea salts present in the original lake and the total input of marine salts would only be about 10:1. Over the time span of several decades, which is the time span that projects similar to the 'Peace Conduit' are planned for, this ratio would be even smaller and the impact on the overall composition of the Dead Sea will be relatively small. Thus, the lake would not loose its Ca-Cl chracteristics although its ionic ratios would change towards those

TABLE II

Range of estimated evaporation rates as a function of surface salinity in the Dead Sea (from Levy 1984b).

Salinity (g/kg)	Water level (m)	Period	Data source for calculations	Evaporation rates (m/yr)
225	–393	1942/46	Neumann 1958	1.70–1.75
240	–395	1959/60	Neev and Emery 1967	1.47–1.65
256–279	–401	1979/80	Anati et al. 1987*	1.30–1.54

of evaporated seawater while its salinity will continuously increase. It should again be reiterated that during the steady state period, the increase in the salinity of the brine will be buffered by the precipitation of gypsum and NaCl. At what stage additional mineral phases will begin to precipitates is a subject that merits more work.

4.4. Evaporation rate estimates and their implications

Evaporation is the only process that removes water from the Dead Sea. The rate of evaporation is strongly dependent on the salinity of the surface water and the relative humidity of the air above it. 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. 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 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.

A summary of estimated rates of evaporation as a function of salinity in the Dead Sea is presented in Table II and is based on the compilation made by Levy (1984b) for the period between the late 1950s and 1980. During this period the salinity of the surface brine increased from 225 g kg^{-1} to 279 g kg^{-1}. Additional studies and figures are summarized in Gavrieli et al. (2002). However, while a general trend of decreasing evaporation rate is clearly identified, major uncertainties regarding actual rates exist.

There is little agreement between the researchers regarding the present rate of evaporation from the Dead Sea (salinity of about 280 g kg^{-1}). Estimates range between 1.05 and 2.0 m yr^{-1} for the current salinity (Stanhill 1994 and Salameh and El-Naser 1999, respectively). The former value is based on heat balance consideration whereas the latter is derived from 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. For example, Alpert et al. (1997) recently showed that evaporation rates in the evaporation ponds of the southern basin have increased during the last decades due to the shrinkage of the northern basin. The water balance calculations, on the other hand, assume groundwater discharge into the Dead Sea of over 400×10^6 yr^{-1} 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). The problem with the water balance approach is that most of its components are poorly defined and rely on only a few measured values and mostly on various assumptions. Therefore, deriving a single component such as evaporation or unmonitored groundwater inflow includes the accumulating error in defining each element in the system.

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 an 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 model implies that just stabilizing the Dead Sea level at its present elevation would require not only compensation for the present net deficit of about 625×10^6 yr^{-1} (assuming a water level drop of 1 m/yr), but an additional 400×10^6 yr^{-1} to compensate for the groundwater that on the long run would cease to flow to the lake.

Clearly, 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 crucial that the present and expected evaporation rates be better constrained. This should be done independent of assumptions on the hydrology of the surrounding areas, and without relying on water balance calculations.

4.5. MICROBIAL BLOOMING

Despite its name, the Dead Sea is not a lake devoid of life (Elazari-Volcani 1940), and is inhabited by a variety of microorganisms (Oren 2000). Microbial blooming occurs in the Dead Sea following the dilution of the surface water as was evident following the rainy winters of 1980 and 1992 (Oren 1983, 1988, 1993, 2000; Oren et al. 1995). During blooming events, the primary producers are unicellular green algae (*Dunaliella* sp.) followed by autotrophic aerobic heterotrophic prokaryotes (mainly red halophilic Archaea) which develop at the expense of organic material produced by the alga.

For a proper planning of the ‘Peace Conduit’, an assessment of the possible effects of the addition of Red Sea water to the biological processes in the Dead Sea is essential. Previous simulation experiment in outdoor ponds, combined with laboratory experiments have shown that blooming is possible when Dead Sea brine is diluted with seawater or freshwater by a factor of 10% or more, and phosphate, which is the limiting nutrient, is supplied (Oren and Shilo 1985). Thus, it is likely that during the filling stage of the ‘Peace Conduit’ the dilution of the surface water by inflowing seawater will lead to microbial blooming.

The availability of phosphate proved to be a critical factor. Some phosphate enters the Dead Sea from the Jordan River and with winter rain floods. No quantitative estimates are available of the amounts of phosphorus thus added to the lake. Another source of phosphorus to the Dead Sea is dust from the atmosphere. Dust deposition over a three-year period (1997–1999) varied between 25.5–60.5 g m^{-2} yr^{-1}. The average phosphorus (P) content of this dust was 1.2% (calculated as P_2O_5). Thus, between 4 and 10 mmol·m^{-2} of P may be estimated to enter the Dead Sea annually from atmospheric dust (Singer et al. 2003). It is not clear whether this phosphate is at all liable to immediate dissolution within the water column. It must also be taken into account that in most reverse osmosis desalination plants polyphosphate-based antiscalants are used to protect the reverse osmosis membranes. Such polyphosphates, when released into the Dead Sea with the desalination reject brines, will eventually break down to orthophosphate and become available to the biological communities.

An important question is whether microbial blooms will be of short duration and will be followed by a decline, or whether dense communities of algae and bacteria will maintain themselves for prolonged periods. In the last case biological blooms will lead to increased surface water turbidity, which will probably result in a higher rate of evaporation. This implies that larger volume of seawater will be needed to raise, and later maintain, the Dead Sea at the desired water level. Prolonged biological blooming is clearly not a desired outcome of the ‘Peace Conduit’ as it implies a major change in the ecology of the Dead Sea, the scenery around the lake and its attractiveness.

New simulation experiments are presently being conducted in experimental ponds on the grounds of the Dead Sea Works Ltd. in Sedom. This study is conducted within the framework of a joint project undertaken by the Geological Survey of Israel and the Israel Ministry of Regional Cooperation to formulate a dynamic limnological model for the Dead Sea that will attempt to model the mixing of seawater in Dead Sea brine. The first results of these simulation experiments show that when PO_4^- is provided, even a moderate dilution (85% Dead Sea water, 15% Red Sea water) can give rise to extensive microbial blooms of the same order of magnitude as those witnessed in 1980 and 1992. Dilution of Dead Sea water by 30% Red Sea water caused the development of a prolonged algal and archaeal bloom that imparted a strong greenish-brown color to the water when 10 μm PO_4^- was added. The algal and archaeal densities reached exceeded by far any biological blooms that had been witnessed thus far in the lake (Oren et al. 2004). The above-mentioned biological simulation experiments are being continued and extended to provide more detailed answers about the expected biological properties of the Dead Sea during the different stages of the operation of the 'Peace Conduit'.

4.6. Development of an 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 (O_2), and had up to 15 ppm H_2S and 250 ppb Iron (Fe^{2+}) (Nissenbaum and Kaplan 1976; Nishri and Stiller 1984). The new anoxic conditions will probably evolve within a few years after the inauguration of the 'Peace Conduit', after the consumption of the dissolved O_2 through the oxidation of the organic matter that will sink from the upper layer. In the absence of O_2 and nitrate (NO_3^{-1}), bacterial sulfate (SO_4^-) reduction will occur and H_2S be produced. Under the reducing condition iron will become 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 the solubility product of their sulfide minerals.

By its nature, the anoxic brine will not have a direct environmental impact on the surrounding of the Dead Sea and 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. However, the development of anoxic lower brine 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 to the atmosphere (the rest will be chemically or bacterially oxidized) and the permanent poisonous and disagreeable smell of H_2S may become an environmental nuisance. 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 O_2 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 compounds from their products.

5. Towards a Dynamic-Limnological Model of the Dead Sea

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). 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; Asmar and Ergenzinger 2002b; Ivanov et al. 2002). However, none of the models integrated all the additional aspects, outlined above, that will be involved in seawater-Dead Sea mixing which will impact on the dynamic of the physical structure of the water column. While some of these aspects were already recognized, they could not be integrated to the models due to the then limited computer-power. A more up to date model is currently under construction at the Geological Survey of Israel. This dynamic-limnological model should provide decision makers with the tools necessary to assess the feasibility of constructing the 'Peace Conduit' from environmental, economic and operational standpoints.

6. Summary and Conclusions

The 'Peace Conduit' 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 for energy to desalinize seawater. However, the implementation of the 'Peace Conduit' differs from intervention with an undisturbed natural ecosystem; the Dead Sea has been undergoing a process of change 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, the mixing of seawater in the Dead Sea brine has the potential to bring about undesirable changes to the Dead Sea with significant negative environmental and economic impacts. The changes outlined above include renewed stratification of the water column, precipitation of gypsum upon mixing, change in rate of evaporation, microbial blooming in the diluted surface waters, development of anoxic conditions in the lower water column and on the long run, change in the composition of the Dead Sea brine.

It is imperative that the changes discussed in this paper be quantified in an integrative dynamic limnological model and evaluated before a decision is taken regarding the implementation of the Peace Conduit.

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