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SHORT COMMUNICATION

Water input requirements of the rapidly shrinking Dead Sea

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Abstract The deepest point on Earth, the Dead Sea level, has been dropping alarmingly since 1978 by 0.7 m/a on average due to the accelerating water consumption in the Jordan catchment and stood in 2008 at 420 m below sea level. In this study, a terrain model of the surface area and water volume of the Dead Sea was developed from the Shuttle Radar Topography Mission data using ArcGIS. The model shows that the lake shrinks on average by 4 km^2/a in area and by 0.47 km^3/a in volume, amounting to a cumulative loss of 14 km^3 in the last 30 years. The receding level leaves almost annually erosional terraces, recorded here for the first time by Differential Global Positioning System field surveys. The terrace altitudes were correlated among the different profiles and dated to specific years of the lake level regression, illustrating the tight correlation between the morphology of the terrace sequence and the receding lake level. Our volume-level model described here and previous work on groundwater inflow suggest that the projected Dead Sea–Red Sea channel or the Mediterranean–Dead Sea channel must have a carrying capacity of >0.9 km^3/a in order to slowly re-fill the lake to its former level and to create a sustainable system of electricity generation and freshwater production by desalinization. Moreover, such a channel will maintain tourism and potash industry on both sides of the Dead Sea and reduce the natural hazard caused by the recession.

Keywords Dead Sea · Lake-level drop · Lacustrine terraces · SRTM-based model · Water volume and surface area loss

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Introduction

The Dead Sea surface is the lowest terrestrial point on Earth at 420.86 m below sea level as of 20 January 2008 (Arab Potash Company records) and it is shrinking rapidly. The salt concentration of 34% is already close to halite saturation. The Dead Sea occupies the central part of the Jordan Rift Valley and serves as a terminal lake for a catchment area of 40,650 km^2, with the Jordan River as the main tributary. It used to deliver 1.21 km^3/a (Salameh and El-Naser 1999) to the Dead Sea, to which water of several wadis draining to the lake from the western and eastern peripheral mountains is added (Fig. 1a).

The interest in the Dead Sea and its fate has been constant throughout history due to its prominent role in religious mythology. The first serious expedition was conducted by Lt. W.F. Lynch of the US Navy in 1848. With a blunderbuss-armed crew of 14 and two patent metal boats, he managed not only to establish the lake's altitude below sea level correctly but also to produce the first accurate map of the Jordan and of the lake and to measure its depth by plumbing (Lynch 1854). The channel between the eastern Lisan Peninsula and the western Dead Sea bank, named Lynch Strait, was about 5 m deep in 1848 but is now more than 20 m above the current level. Since that time, the

Fig. 1 **a** Location of the Dead Sea and the measured terrace profiles. The image was taken from w.NASA World Wind. **b** Recent Dead Sea terraces north of Wadi Al-Shaqiq fan delta. **c** The coordinates of the highest and lowest points of the surveyed profiles

c

Profile name	Highest point/m	Lowest point/m	Northing	Easting
Al-Shaqiq	-389.8		31° 24' 22.59951"	35° 33' 28.09234"
		-419.1	31° 24' 23.03547"	35° 33' 27.88186"
Al-Mujib	-392.9		31° 28' 12.67609"	35° 34' 19.48848"
		-418.7	31° 28' 14.85862"	35° 34' 18.66505"
Ma'een	-398.5		31° 37' 24.54979"	35° 34' 10.86602"
		-418.3	31° 37' 25.74080"	35° 34' 08.45923"

lake shrank from >90 km in length to 52 km today. At the same time, a series of terraces was left along the shores evidencing the drop in water level (Fig. 1b).

This study aims at: (a) developing a terrain model based on the Shuttle Radar Topography Mission (SRTM) data of the Dead Sea Rift that allows calculating the area and volume losses of the lake for the various stages of its recession; and (b) investigating the most recent changes in the Dead Sea level and the shore morphology by surveying the modern lacustrine terraces and dating them according to the Dead Sea hydrograph.

Materials and methods

Accurate level records are kept since 1976 by the Israel Hydrological Survey when the lake stood at –398 m. To calculate the volume and area loss functions of the Dead Sea, a model of the rift valley volume and surface area in meter intervals was developed from SRTM data (3 arc second; CIAT 2004). ArcGIS (3D)-Analyst (ESRI)-"Surface Volume" tool-functionality was used to calculate surface area and water volume of the Dead Sea below a certain altitude. The tool was applied for each meter change of the level from −389 to −415 m. Since the bathymetric contours of the Dead Sea below −415 m are not available in the SRTM data, the water volume of the current Dead Sea below −415 m (Dead Sea Data Summary. *International Lake Environment Committee Foundation*) was added to our calculated volume in order to determine the total volume of the Dead Sea. The calculated water volume and surface area were plotted against the altitude. A polynomial function was derived that best fits the calculated graph using a least-square method.

In order to investigate the terraces formed by the lake level drop, we used aerial photos of 1:25,000 (Royal Jordanian Geographical Centre) to pinpoint the locations of the most continuous and best preserved sequences of terraces. Then, a field survey of the eastern coast of the Dead Sea was conducted to examine the suitability of the chosen sites for cross-section measurements and to determine the location of the Global Positioning System (GPS) benchmarks available in the area. We chose the benchmark at Ghour Hadithah (31°17′21″.7455 N, 35º32′09″.13807 E and −346.428 m) for our Differential Global Positioning System (DGPS) base station. Three profiles of the Dead Sea terraces were surveyed with the DGPS rover (Leica SR-20). These are the profiles at (1) Al-Shaqiq in the northern part of the Wadi Al-Shaqiq fan delta, (2) Al-Mujib in the northern part of the Wadi Al-Mujib fan delta, and (3) Ma'een, north of the Wadi Ma'een fan delta (Fig. 1a).

Two GPS altimetry points were measured on each terrace; each was occupied for 15 min for high accuracy. The measured data were then processed using Leica Geo Office (LGO) software in order to obtain accurate altitude, latitude, and longitude. The coordinates of the measured profiles are presented in Fig. 1c.

In addition, the width and slope of the terraces were measured using tape and inclinometer. The terrace altitudes were correlated among the different profiles and dated to specific years of the lake level regression according to the hydrograph of the Dead Sea as made available by the Hydrological Survey of Israel (personal communication, Eliyahu Wakshal) and previous publications.

The data of the shore terrace levels and their morphology were derived from the three terrace profiles that represent the sample population. The target population consists of all lake terraces. The sites of the profiles were selected to represent the best continuous and best preserved terrace series, as well as the different parts of the lake (north, center, and south). However, it was difficult to select the sites using probability sampling because the terraces vary in their degree of preservation and lateral continuation. The profiles represent a large enough sample of the terraces, i.e., n=68. Since the sample population is large enough and the current lake represents one water body experiencing similar regression rates in its different parts, the obtained conclusions from the measured profiles can be extended to the whole lake basin.

Results

Surface area and water volume of the Dead Sea

The level of closed lakes—such as the Dead Sea—is a result of the hydrological balance between runoff into the lake plus direct precipitation on the lake surface minus evaporation; therefore, it serves as an indicator of climatic conditions. However, the recent Dead Sea level change (and its associated changes in surface area and volume) is mainly due to (a) transferring 500 Mio m³/a of water from the upper Jordan River by the Israel National Water Carrier project to the Mediterranean coastal plain; (b) diverting an additional water amount of 75 Mio m³/a from the Yarmouk River to the same carrier; (c) diverting 110 Mio m³/a of the Yarmouk River water to the King Abdullah Channel in Jordan and an additional 135 Mio m³/a from the same resource by Syria; (d) consuming (cumulative from 1976 to 1997) 2.4 km³ of the surface and ground water inflow to the Dead Sea from the eastern coast and Wadi Araba by Jordan and 3.3 km³ from the same resource in the western side by Israel; and (e) abstracting 5 km³ from the Dead Sea water for the potash industry by both Israel and Jordan (Salameh and El-Naser 1999; Al-Weshah 2000). The level change is therefore mainly due to human water consumption and not a result of climate change.

The terrain model shows that water volume and surface area correlate highly with lake level (volume R^2=0.9993, area R^2=0.9899; Fig. 2a, b) reflecting the bathymetry of the flanks of the former Dead Sea and the morphology of the rift valley, according to Eqs. 1 and 2 developed based on our model.

$$\text{water volume} = 0.0077x^2 + 6.8905x + 1,688.8 \tag{1}$$

$$\text{surface area} = -0.0008x^5 - 1.6141x^4 - 1,301.9x^3 - 524,930x^2 - 1^{*}10^8x - 9^{*}10^9 \tag{2}$$

According to our GIS data analysis, the Dead Sea has lost 9.7 km³ (0.2 km³/a) from its volume and 365 km² (7.9 km²/a) from its area during the period between 1932 and 1978. Since 1978, the volume decreased dramatically from ~157.7 to ~147 km³ with an average of 0.47 km³/a (Fig. 2a, b). Meanwhile, the surface area shrank from 729.4 to 636.7 km² with 4 km²/a on average. The recession of the

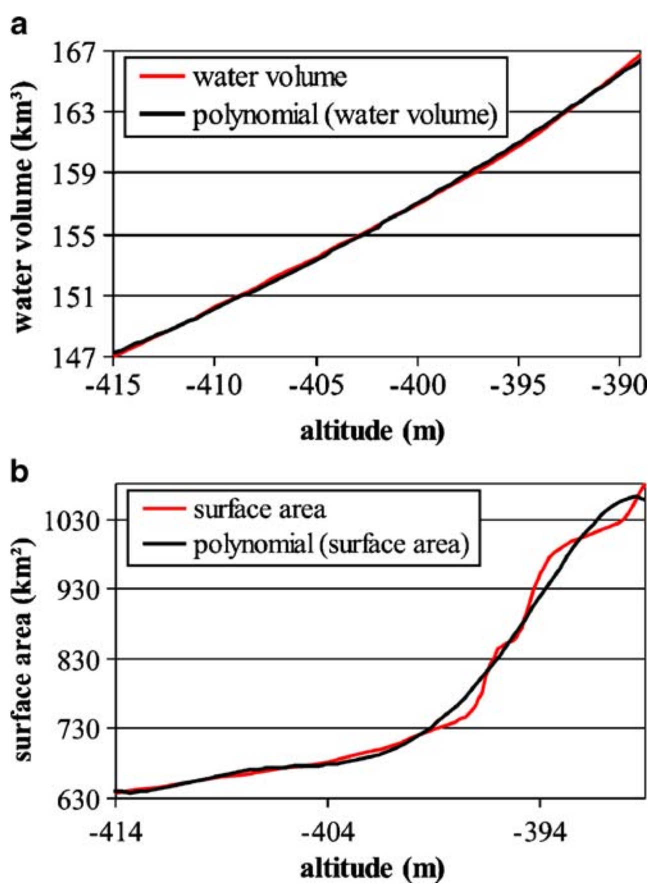

Fig. 2 **a** Volume–altitude model of the Dead Sea. **b** Surface area–altitude model of the Dead Sea

lake level caused additional groundwater inflows of about 0.5 km^3/a (Salameh and El-Naser 2000). This, plus our calculated volume loss, suggests that surface water inflow has to increase by more than 150% or by ~0.9 km^3/a, in order to stop the continuous drop of the Dead Sea. However, this is unlikely to happen due to the current intensive consumption of water resources in the Dead Sea basin that is still increasing, e.g., by recent migrations to Jordan from Iraq and Lebanon.

Shoreline terraces and level changes

The wadis draining to the Dead Sea experienced rapid erosion due to the lowering of the base level during the Holocene. Consequently, Gilbert-type fan deltas (consisting of horizontally bedded bottomsets that deposited radially in front of the river mouth, basinward-dipping foreset beds that prograde from the river mouth and horizontal topset beds which result from the river downcutting and advance of the channel deposits; Richard and Davis 1985) were formed in front of the mouths of the main wadis such as Al-Mujib, Al-Shaqiq, and Ma'een (Fig. 3a). These unconsolidated delta bodies are now emerging from the receding lake. Wave action has cut a unique set of shoreline terraces into these deltaic, lacustrine–alluvial foreset deposits composed of gravel and sand (Figs. 1b and 3a). Each terrace consists of a sub-flat foreshore (tread) and a steep backshore cliff (riser). Widths and slopes of the treads show normal distribution with averages of 1.68±0.8 m and 4.5°± 1.2°, means and standard deviations, respectively. Although the widths of the risers show also normal distribution with an average of 1.91±1.2 m, the slopes of the risers show non-normal distribution with an average of 24.4°±6.6°.

These terraces are not long-living since the wadis have already started to cut into the topsets of the delta bodies, creating new streambeds with migrating mouths (Fig. 3a).

As it turned out, the best preserved terrace profiles all are along the northern corners of the deltas. This is possibly because the wadis tend to discharge their water near the apex of the delta and because winter storms have a northwesterly direction so that the waves are more intensive on the northern shores of the deltas, compared to their southern banks. It is interesting to note that the delta bodies do not show any morphological traces of recent movements of the eastern boundary transform fault of the Dead Sea pull-apart structure that should run through the landward section of the deltas (Fig. 3a).

In Fig. 3b, the three terrace profiles are compared and their terraces correlated. These terraces were formed during the last 77 years as a result of a lake level drop of 30 m with an average of 0.4 m/a. Recorded levels (Klein 1986; Hassan and Klein 2002; Hydrological Survey of Israel) suggest that the highest terrace at −389 m formed in 1932 (and previous years). The recorded level curve allows correlating most of the terraces to specific years. The lowest here documented terrace at −419 m formed in winter 2006–2007 (Fig. 3b). Levels stagnate in winter when more water input occurs and recede most steeply in summer during times of high evaporation. Some years show a more pronounced recession than others but many of the terraces represent one winter season only. The comparison between the Dead Sea hydrograph and total annual precipitation (Fig. 4) shows that changes in rainfall do not contribute significantly to lake level changes. For instance, the Dead Sea continued its rapid lowering in 1997 in spite of the high precipitation amount of 849 mm compared to 571 in 1996. Only exceptional high rainfall such as in 1991 and 1992 (915 and 1,038 mm, respectively) was able to cause a noticeable rise in the lake level of 2 m. This wet event destroyed any pronounced terraces in this period by the lake level rise (Fig. 3b).

The average of lake level recession increased in rate throughout time: From 1932 to 1977, the Dead Sea level dropped relatively slowly from −389 to −399 m with an average of 0.2 m/a. In this relatively long period, only seven larger terraces can be recognized in the different profiles. This could be due to the prolonged times of stable water level that allowed the waves to abrade wide terraces. The intensive water consumption in the Dead Sea basin in the last 29 years caused an accelerated drop from −399 m in 1978 to −419 m in 2007 with an average of 0.7 m/a. In this short period, 25 terraces formed, but with smaller dimensions. This is interpreted as a result of the fast recession and of the short period of constant water level that has not allowed the waves to form wide terraces.

Moreover, the low-level terraces are less affected by rill erosion and gravitational mass movements due to the short time of their exposure and due to their wetness (caused by sea spray) compared to the high-level ones. This explains the good correlation between the low-level terraces and the poor correlation between the high-level ones. Furthermore, it implies a relation between the age of the terraces and their degree of preservation.

Discussion

The hydrological balance of the Dead Sea significantly changed since the beginning of the twentieth century mainly due to (a) the consumption of water from the Jordan River and other tributaries for irrigation, and (b) the use of the Dead Sea water for potash industry. Our terrain model of the Dead Sea shows that water volume and surface area correlate highly with lake level throughout the observation period, reflecting the basin morphology of the Dead Sea Rift Valley. These equations allow calculating

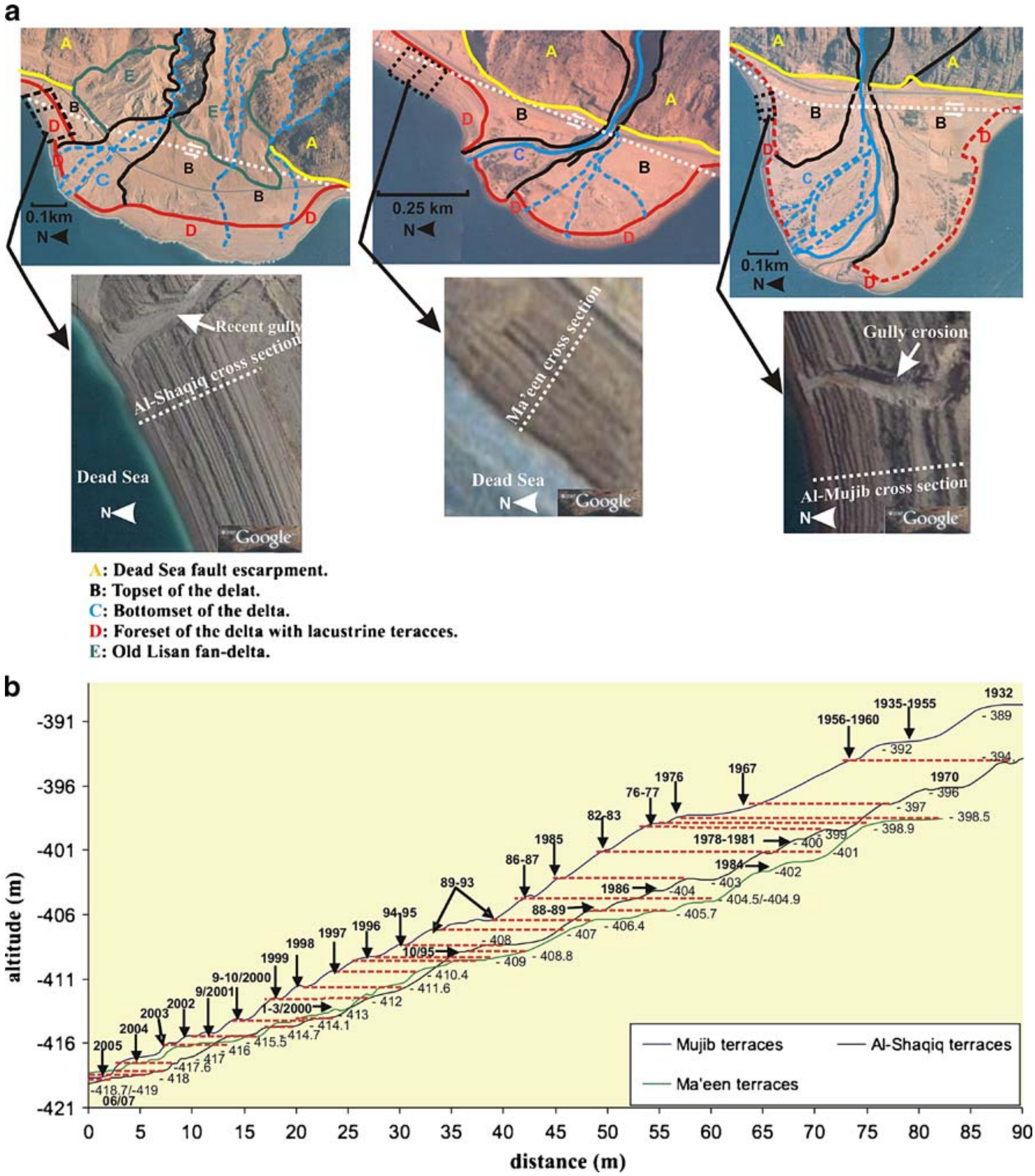

Fig. 3 **a** Gilbert fan deltas and sequences of lacustrine terraces north of Wadi Al-Shaqiq (*upper left*), north of Wadi Ma'een (*upper middle*), and north of Wadi Al-Mujib (*upper right*). Note roads crossing the deltas on the landward sections at positions near to the presumed trace of the Dead Sea eastern boundary transform fault. The *lower images* in this figure were taken from Google Earth.The date of these photos is 16 January 2007 http://earth.google.com. **b** Three profiles of Dead Sea terraces surveyed by DGPS, correlated among each other and dated according to the recorded Dead Sea levels

volume and area losses from lake level curves: During the last 30 years, water consumption caused an accelerated decrease in the water level, volume, and surface area amounting to 0.7 m, 0.47 km^3, and 4 km^2 per year, respectively. Based on the assumption that the basic morphology of the lake's basin will not drastically change within the next decades, the polynomials can also be used to predict near-future volume and area losses. Thus, in 2020, the lake will have dropped presumably to −427.8 m and will have lost 5.6 km^3 and 48 km^2 of its current volume and area, respectively.

The rapid drop of the Dead Sea level is accompanied by the formation of new shoreline terraces as well as it causes rapid erosion of the topsets of the emerging deltas. Wide

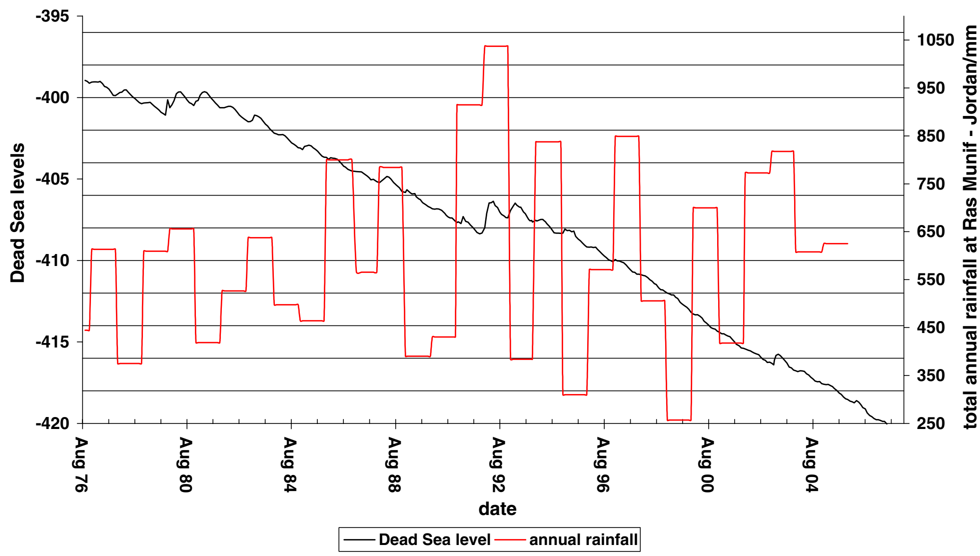

Fig. 4 Dead Sea hydrograph (Hydrological Survey of Israel) and total annual rainfall in Ras Munif/Jordan (Jordan Metrological Department)

terraces reflect a slow drop rate and a longer time of water level stability, while narrow terraces represent a fast drop rate and shorter times of water level stability.

The rapid lake level drop has caused and will continue to cause severe detrimental effects both to its function as a resource and to the natural state of its shores. These effects include:

- Higher pumping costs for the factories using the former southern sections of the Dead Sea to extract potash, salt, and magnesium.
- The declining water level causes an accelerated outflow of fresh water from surrounding aquifers, thus causing a loss of this important resource.
- The receding shoreline makes it difficult (and in some places even dangerous) for tourists and hotel guests to access the water of the Dead Sea for medical bathes.
- The freshwater outflow has enhanced the dissolution of buried salt deposits creating a treacherous landscape of sinkholes and mud along the entire shore of the Dead Sea (Closson et al. 2005; Yechieli et al. 2002, 2004) that caused severe damage to roads, salt pans, and other civil engineering structures.
- The rapid emergence of delta bodies and the thereby caused decrease in buoyancy could cause sudden (or earthquake-triggered) slips (mass waste movement and landslides, such as what happened in the north of the Dead Sea in 2000) of sections of the deltas with the prospect to trigger small tsunamis within the lake.
- The rapid downcutting of the west-draining wadis due to the lake level lowering threatens the bases of the bridges built at the mouths of these wadis.
- The lake could soon become halite-saturated, causing incrustation along its entire perimeter (today only spray water forms intermittent salt deposits).

Given the mounting stress on the water resources in the Dead Sea basin and the environmental hazard caused by its lowering, two projects were suggested to maintain the Dead Sea and stop its lowering: the Red Sea–Dead Sea Channel (RSDSC) and the Mediterranean–Dead Sea Channel (MDSC). Two alignments were suggested for the MDSC: in the north from the Mediterranean coast through Bet She'an to the Jordan River and in the south from the Gaza strip to Masada at the Dead Sea (The Harza JRV Group 1996). Although the northern route of the MDSC is the shortest and the cheapest one, the RSDSC would be under the control of all riparian countries, and its benefits could therefore be distributed fairly. Such projects cannot only stop the level decrease, but can also exploit the net altitude difference of 400 m to produce energy and hence freshwater by desalinization. It also introduces new salt to the lake, ensuring the long-term sustainability of the salt extraction. However, one of the long-term negative impacts of the channel might be the continuous infiltration of seawater into underground aquifers. Since this would diminish energy output, the channel should be planned with an impermeable bed to begin with. Possible ruptures of the RSDSC bed during earthquakes along the Dead Sea Fault would not be such a risk since the channel would be segmented by pumping and turbine stations, thus sections of it could temporarily be emptied and repaired. Based on the water volume loss calculated by our model and the ground water inflow to the Dead Sea, we suggest that the RSDS or MDSC should have a capacity of more than 0.9 km^3/a in order to slowly fill the lake back to levels as of 30 years ago and to ensure its long-term sustainability.

If the diversion of Jordan water to the Mediterranean coast would be stopped (replacing the water need by desalinization of seawater), then the recession of the Dead

Sea could be considerably slowed, buying time to consider the long-term alternatives.

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