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The Aral Sea and the Dead Sea: Disparate lakes with similar histories

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Abstract

In spite of significant differences in their sizes, depths, salinity and other properties, the Aral Sea and the Dead Sea share many features, as illustrated by a comparison of the histories of both water bodies. Fifteenth and early sixteenth century maps, based on the 'Geography' of Ptolemy, contain both lakes. The first successful limnological surveys of the lakes were made in the same year 1848, when Alexey Butakov explored the Aral Sea and William Lynch mapped the Dead Sea. Paintings and drawings by Taras Shevchenko (Aral Sea) and David Roberts (Dead Sea) document the landscapes around the lakes in the first half of the 19th century. The water balance of both lakes has been strongly negative in the past decades, leading to a decreased water surface area and volume for both lakes, their increased salinity and deterioration of their local infrastructures. Complex and expensive mitigation schemes have been proposed for both lakes, based on the import of large quantities of water from distant sources via canals or pipelines (i.e. Siberian rivers or Caspian Sea to supply water to the Aral Sea, Mediterranean Sea or Red Sea, to be connected with the Dead Sea). Less dramatic solutions to improve the local situations already have resulted in improved water quality in the Aral Sea, and partial restoration of its fisheries. In contrast, the Dead Sea remains much too saline to support higher forms of life. Nevertheless, a biblical prophecy predicts that even this most hypersaline of all lakes will eventually be teeming with fish of many kinds.

Key words

Aral Sea, Butakov, Dead Sea, exploration, Lynch, mitigation.

INTRODUCTION

The Aral Sea, located on the border between Kazakhstan and Uzbekistan, and the Dead Sea, located on the border between Israel and Jordan, are both saline/hypersaline terminal desert lakes (Micklin 1988; Aladin & Williams 1993; Kostianoy & Zavialov 2004). These two lakes differ greatly in their properties. The Aral Sea was the fourth largest lake on Earth in 1960, after the Caspian Sea, Lake Superior and Lake Victoria. It had a surface area of 66 500 km^2, a volume of 970 km^3, a maximum depth of 67 m, and a total dissolved salt concentration of 10–11 g L^{-1} (Létolle & Mainguet 2003). The Dead Sea, with its current elevation of −423 m and being the lowest point on Earth, is much smaller. It has a surface area of 940 km^2, volume of 152 km^3, depth of 332 m and is saltier (290 g of salts per litre in the surface layers and 332 g L^{-1} in the deep waters; 1960 values) (Neev & Emery 1967; Raz 1993; Kreiger 1997; Niemi *et al.* 1997).

In spite of these obvious differences, nevertheless, there are striking similarities when the histories of these two lakes, their current properties and the prognoses for their future development are compared. The parallel events that have changed the Aral Sea and the Dead Sea over the past decades are, to some extent, due to similarities in their geographical conditions. Both lakes are located in arid areas, with scarce fresh water. The deterioration of both lakes is largely due to the diversion of fresh water in the drainage basin of the lakes for irrigation purposes. A survey of their histories, however, highlights many additional points of correspondence. Both lakes were first surveyed during cruises in the year 1848. The larger boats used for their early exploration were assembled locally from parts built elsewhere. Complex

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and expensive mitigation solutions have been proposed for both lakes, based on the import of large quantities of water via canals, tunnels or pipelines.

This short historical essay presents some features illustrating the common fate of the Aral Sea and the Dead Sea over the centuries. These features highlight the fact that, in spite of their obvious differences, there also are many striking similarities that link the fate of these two lakes. Different aspects of the history of exploration and exploitation of the two lakes have been reviewed in the past (e.g. see Freeman-Grenville *et al.* 2003; Kreiger 1997; Létolle & Mainguet 2003). To our knowledge, however, no comparative studies were ever published. The survey presented below demonstrates that the two lakes, although very dissimilar in limnological properties, salinity, modes of exploitation etc., have very much in common when viewed within a historical perspective.

THE ARAL SEA AND THE DEAD SEA ON ANCIENT MAPS

'All these were joined together in the vale of Siddim, which is the salt sea.' As found in Genesis 14:3, this is the first record of the Dead Sea. The Dead Sea is located in an area that has been a centre of civilization for more than 3000 years. Detailed descriptions were given by Pliny, Strabo and other authors from antiquity, as well as in the 'Onomasticon,' the compendium of biblical geography, compiled by Eusebius, bishop of Caesarea at the beginning of the 4th century. Thus, it is not surprising that the lake can be found on the oldest maps of the area. These include the 6th century mosaic map in the church of St. George in Madaba, Jordan, and the Peutinger Map (Tabula Peutingeriana), a 13th century copy of an ancient Roman map.

The Aral Sea area has always been inaccessible and remote from the main civilization centres. It is understandable, therefore, that the first representation of the lake on geographical maps dates from much later periods. Both the Aral Sea and the Dead Sea, however, can be recognized on late 15th and early 16th century maps, based on the 'Geography' of Ptolemy (Claudius Ptolemaeus 1511; 90–168 C.E.), the geographer and astronomer from Alexandria. It is highly improbable that Ptolemy knew of the existence of the Aral Sea (Létolle & Mainguet 2003). Ptolemy's writings were rediscovered around 1300 C.E., and texts and geographical entries were added during the Middle Ages (Bagrow 1945). Thus, information about remote parts such as the Aral Sea area might have been a later addition. The map reproduced in Fig. 1 was derived from an Italian edition of the 'Geography,' printed in 1511. The title page of the book clearly states that it includes later additions ('… et cum additione locorum quae a recentoribus reperta sunt …; with addition of those places which have been discovered by more recent authors). It illustrates two major rivers, the Oxus (=Amu Darya) and the Iaxartes (=Syr Darya), flowing into the Caspian Sea, depicting the Aral Sea ('oxium lacus', on other similar maps from the period 'oxianus lacus') as a

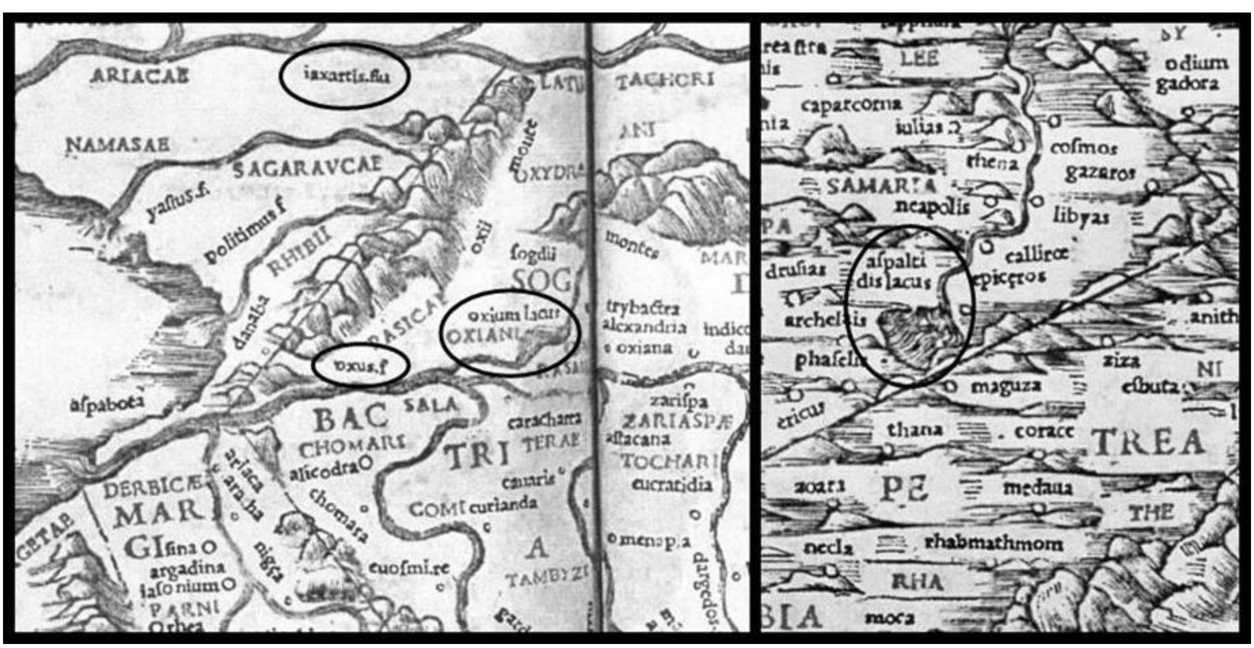

Fig. 1. An early 16th century map illustrating both Aral Sea and Dead Sea, derived from a 1511 edition of 'Geography' of Ptolemy.

rather small lake within the course of the Oxus River. The accompanying text (Book VI, Chapter XII – Sogdianorum situs; the area of the Sogdians) states: 'Protendunt aut montes qui Sogdii dicunt inter duos fluvios: quorum fines gra.hnt. 111.46½ & 121.46, ab his defluunt amnes pluros ignobiles secum admiscetes/unus eorum lacu Oxiam facit; cuius mediu 110½.45.' (Mountains also protrude, which the Sogdians say are between two rivers, and their borders are at 111.46½ and 121.46. Unknown streams flow from here and merge, one of which forms Lake Oxiam, which has its centre at 110½.45).

The representation of the Dead Sea ('Asfaltidis lacus') is based on Book V, Chapter XVI ('Palestinae Iudeae situs') (the area of Palestina – Judea): 'Dividit aut Iudeam Iordanis fluvii pars iuxta Aspaltide lacu/cui' mediu, 68½ 30½.' (Part of the River Jordan also divides Judea near the asphalt lake, the centre of which is at 68½ 30½).

THE EXPLORATION EXPEDITIONS OF 1848

The year 1848 was important for both the Aral Sea and the Dead Sea, in that both lakes were first successfully explored during research cruises undertaken that year. The first surveys were made with regard to the depth of the lakes and other limnological properties of their water column.

The 1848 Aral Sea expedition was led by Alexey Ivanovich Butakov (1816–1869) (Fig. 2, left panel). Captain Butakov and his crew of 26 men arrived at Orenburg on March 5, 1848, and started building a flat-bottomed schooner (*Konstantin*). It was completed on April 28 (Fig. 3, upper left panel). A caravan of 3000 camels, 800 horses and 1500 carriages left Orenburg on May 11, transporting the disassembled schooner and all necessary supplies.

After a long, difficult passage through the Karakum Desert, the convoy reached the newly founded fortification of Raim on the Syr Darya River. On July 20, the schooner was assembled, with expedition on the lake starting on July 25. Measurements were made in the summer and autumn of 1848, continuing in the summer of 1849 (Butakov 1853a,b). The first navigation map of the Aral Sea, based on the surveys of Butakov and K. Ye. Pospelov, was published by the Hydrographic Department of the Navy Ministry in 1850.

In the same year in which Butakov sailed the Aral Sea, Lieutenant William Lynch of the U.S. Navy (Fig. 2, right panel) made the first scientific exploration of the Dead Sea. The Lynch expedition was preceded by two unsuccessful attempts to explore the Dead Sea. The first was by a young Irishman (Christopher Costigan), who spent 8 days on the lake in a small rowboat in 1835. The second was by Thomas Molyneux of the British Royal Navy, who navigated the Dead Sea on September 3–5, 1847 in a dinghy of HMS *Spartan*. Molyneux's little wooden boat has been preserved (Fig. 3). Both Costigan and the Molyneux expeditions ended tragically, with both explorers dying from the heat, from lack of drinking water and from exhaustion. A short report of Molyneux's expedition, aimed 'to examine the course of the Jordan, as well as the valley through which it runs, and specially to measure the depth of the Dead Sea,' was published posthumously (Molyneux 1848).

In May 1847, Lt. Lynch submitted a request to the Secretary of the U.S. Navy (John Mason) to lead an

Fig. 2. Sketches of Aral Sea expedition leaders Alexey Ivanovich Butakov (left panel) and Lieutenant William Lynch (right panel).

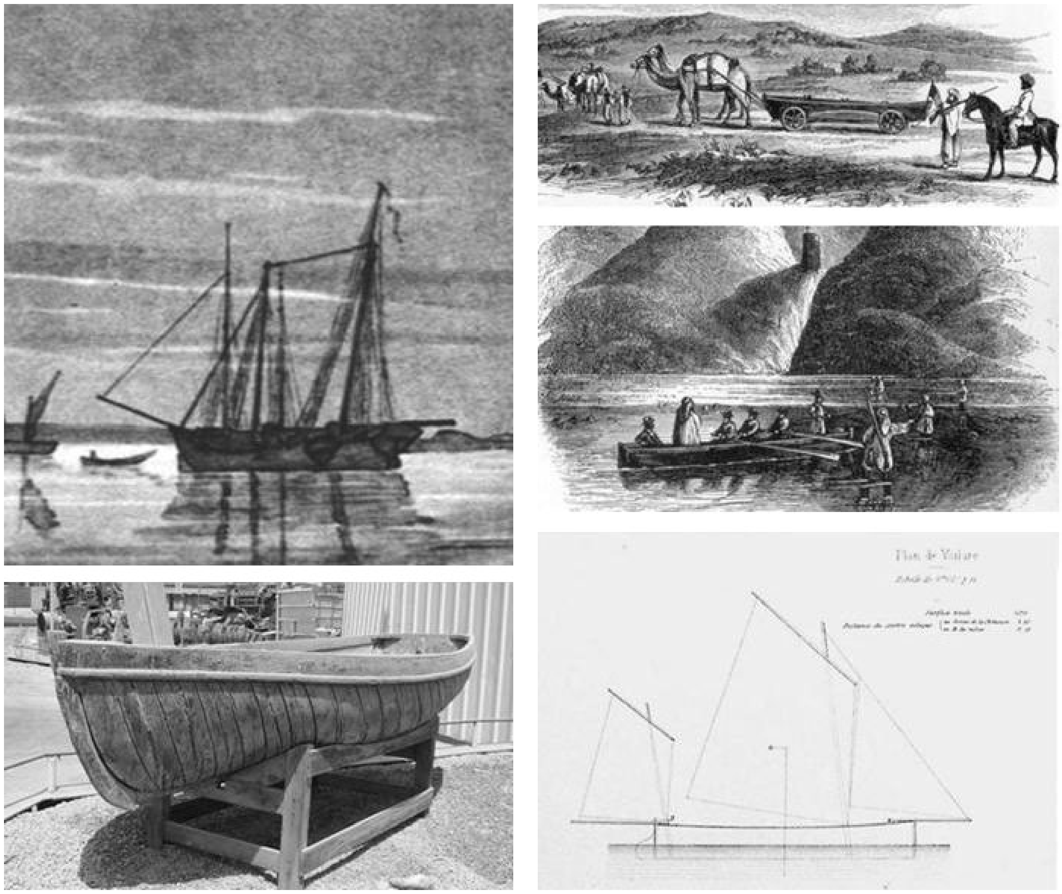

Fig. 3. Boats used for the exploration of the Aral Sea by Alexey Butakov in 1848 (the schooner *Konstantin*, upper left panel) and for the Dead Sea expeditions of Thomas Molyneux in 1847 (lower left panel), William Lynch in 1848 (upper right panels) and the Ségor used by the Duc de Luynes in 1864 (lower right panel).

expedition to the Holy Land to explore the Jordan River and the Dead Sea. His request was as follows: 'I respectfully submit a proposition to circumnavigate Lake Asphaltites or Dead Sea, and its entire coast. The expense will be trifling and the object easy of attainment.' With approval of this request, Lynch and his party carried two small rowing boats (the *Fanny Mason,* made of copper; the *Fanny Skinner*, made of galvanized iron; Fig. 3), over land by camels in the following spring from Acre to Tiberias on the shore of the Sea of Galilee. They entered the Jordan River on April 9, 1848, arriving at the mouth of the Dead Sea on April 18. With a crew of 11 sailors on two boats, and a shore party of four, Lynch made 162 bottom soundings in 14 straight lines, zigzagging across the sea over the course of 17 days. It is interesting to note that these portions of the bathymetric map of the eastern part of the Dead Sea remain even today that are based solely on the soundings of the 1848 Lynch expedition. The Narrative and the Official Report of the Lynch expedition have been published (Lynch 1849, 1852), and a monograph dedicated to Lt. Lynch and his travels in the Holy Land (Jampoler 2005).

The two tiny rowboats *Fanny Mason* and *Fanny Skinner* that served Lt. Lynch during his Dead Sea survey were surely much simpler vessels than Butakov's schooner. Nevertheless, the story of the *Konstantin* being carried in pieces by horses or camels and assembled locally has an interesting parallel in the history of the 1864 expedition to the Dead Sea by the French nobleman and archaeologist Honoré Théodore Paul Joseph D'Albert, duc de Luynes (1802–1867). In contrast to the expedition of Lt. Lynch, who had clear instructions from his superiors to economize to the maximum extent to save American taxpayer money, the duc de Luynes financed his trip from his large private fortune. Accordingly, to ensure conditions that would fit his financial status, he had a specially built large, comfortable sailing boat, hired the best crew of sailors and scientists available, and had the most modern, scientific equipment made to order. His 9.5 m sailing yacht (named *Ségor*, after the biblical city of

Zoar or Segor, mentioned in Genesis 14:2 and 19:30 was constructed near Toulon, France. It consisted of eight metal sections of a size that could be transported by camels (Fig. 3). The boat was transported from Marseille to Alexandria, and then to Jaffo, where it was loaded on camels and carried via Jerusalem and Jericho to the Dead Sea. It was then assembled and prepared for the survey. Between March 15 and April 7, 1864, the duc de Luynes surveyed the entire lake with three fellow scientists and a crew of four to operate the boat. Water samples were collected from different depths at a number of sampling sites, obtaining information for the first time on the density stratification of the lake's water column. The duc de Luynes report of his Dead Sea survey, and his further travels in the area, was published posthumously in three large volumes (Honoré Théodore Paul Joseph D'Albert, duc de Luynes, 1871–1877).

NINETEENTH CENTURY PAINTINGS AND DRAWINGS OF ARAL SEA AND DEAD SEA

One of the members of Butakov's 1848–1849 Aral Sea survey was Taras Hryhorovych Shevchenko (1814–1861), a Ukrainian poet, painter and humanist. Because of his political ideas, and his association with the Brotherhood of Saints Cyril and Methodius, a Pan-Slavist political society dedicated to the political liberalization of the Empire, with the aim of transforming it into a federation-like polity of Slavic nations, he was arrested in 1847. He was subsequently sent to prison in St. Petersburg, and then exiled to join the Russian military Orenburg garrison as a private. Having been sent as a soldier guard on the Butakov Expedition, Shevchenko served as the expedition's artist, producing many paintings of the lake and its different landscapes and peoples encountered. Figures 3 and 4 illustrate Shevchenko's artistic impressions of the expedition.

As Lieutenant Lynch did not have an accomplished artist in his expedition to the River Jordan and the Dead Sea, his official report to the U.S. Department of the Navy (Lynch 1852) was not illustrated with landscape drawings. Rather, the Narrative of the expedition (Lynch 1849) contained just three engravings showing the Dead Sea and its surroundings. In his preface to the Narrative, Lynch wrote: 'The drawings are by Lieutenant Dale and Passed-Midshipman Aulick, … To Messrs. Gilbert and Gihon, of this city, who undertook the illustrations, I am indebted for the beautiful wood-engravings which accompany the volume. They are all true to nature; each scene was taken upon the spot it was intended to delineate …'. Figure 3 illustrates two fragments from these engravings.

Beautiful, coloured illustrations of the Dead Sea were already available, however, by the time Lynch and his crew sailed the waters of the lake. The Scottish artist David Roberts (1796–1864) toured the Holy Land and surrounding countries in 1839, producing a number of paintings of the Dead Sea, one being reproduced in Fig. 4. (Roberts 1843). These artist impressions of the lake nicely complement the drawings made by the Lynch Expedition 9 years later.

FRESH WATER DIVERSIONS FROM CATCHMENT AREA

Both the Aral Sea and the Dead Sea receive a significant portion of their influent waters from rivers draining into them. The Amu Darya and the Syr Darya drain into the Aral Sea, while the Dead Sea is fed by the Jordan River. As a result of human interventions, the quantity of water flowing through these rivers to the lakes has decreased dramatically over the past decades.

The basins of the Amu Darya and Syr Darya Rivers have been irrigated areas from ancient times. Irrigation activities in these basins did not have a profound impact on the Aral Sea, however, until the 1960s. Large-scale irrigation for growing crops such as cotton and rice has utilized much of the water from the two rivers, severely decreasing their flows into the Aral Sea (Bortnik &


Fig. 4. Artists rendering of Aral Sea and Dead Sea expeditions.

Chistyaeva 1990; Micklin & Aladin 2008). Development of cotton-growing, and later of rice, was based on a progressive increase in the irrigated areas in the Amu Darya and Syr Darya basins (Ashirbekov & Zonn 2003). From the beginning of the 20th century, the area of irrigated land increased from 32 000–41 000 km^2 by 1960 to 74 000 km^2 by 1990 (Bortnik & Chistyaeva 1990; Ashirbekov & Zonn 2003).

The volume of irrecoverable run-off diversions before the 1960s was about 26–33 km^3 $year^{-1}$. This volume increased sharply from the 1950s, as a result of a significantly increased irrigated area, construction of water reservoirs on the Syr Darya and increased water delivery from the Amu Darya to the Karakum Canal beginning in 1956. Irrecoverable diversion of run-off increased to about 40 km^3 $year^{-1}$ during 1951–1960. Nevertheless, there was no decrease in the inflow of river waters into the Aral Sea before the 1960s because the rivers carried about 9% more water than in the previous 25 years. Increasing run-off diversions were also partially compensated for by reduced riverbed losses, construction of dikes and banks, and drainage of swamped areas, thereby reducing the extent of flooding. The compensatory potential of the rivers subsequently became exhausted, with increased losses and resulting long-term water shortages leading to a sharp reduction in the river inflows into the Aral Sea. Irrecoverable diversions of run-off were 55–57 km^3 $year^{-1}$ during 1961–1970. The run-off diversions increased to 64–66 km^3 $year^{-1}$ during 1971–1980 and the estimated diversions were 70–75 km^3 $year^{-1}$ during 1981–1985 (Bortnik & Chistyaeva 1990). During 1975–1988, 10–13.5 km^3 $year^{-1}$ of water was diverted from the Amu Darya to the 1400 km long Karakum Canal, with about 15 km^3 of water being delivered from the Amu Darya through the Amu-Bukhara and Karshi Canals (Ashirbekov & Zonn 2003). The estimated average annual irrecoverable diversion of run-off from both rivers was slightly more than 80 km^3 for 1989–2002. There also are many other smaller canals diverting water from these rivers.

The quantity of water flowing through the Jordan River, previously the most important water source to the Dead Sea, decreased from about 1500×10^6 m^3 $year^{-1}$ before 1950, to $<100 \times 10^6$ m^3 $year^{-1}$ (Salameh & El-Naser 1999; Al Weshah 2000). This dramatic decreased water flow was a result of water diversion from the Sea of Galilee (Lake Kinneret) and its catchment area. Beginning in the 1960s, Israel has been pumping water from Lake Kinneret to its National Water Carrier. At the same time, Syria and Jordan diverted the Yarmouk River, which discharges its water into the Jordan River south of Lake Kinneret. The Jordanian King Abdullah Canal runs along the eastern side of the Jordan Rift Valley, supplying parts of Jordan with water for domestic use and irrigation. Smaller tributaries to the Jordan River, and other streams flowing directly to the Dead Sea, also are captured.

The small quantities of water that currently flow through the Jordan River consists mainly of irrigation return flows, treated and untreated sewage, and saline groundwater that discharges to the river.

DECLINING WATER LEVELS

Mainly due to the above-described anthropogenic interventions in the water balances, the Aral Sea and Dead Sea water levels have decreased dramatically over the past decades (Table 1).

The water level of the Aral Sea state was relatively stable until the 1960s, at an elevation of 53 m, with small seasonal and long-term fluctuations of ±2 m arising from variable run-off from the Amu Darya and Syr Darya Rivers (56 km^3 $year^{-1}$ on average) (Bortnik & Chistyaeva 1990). The Aral Sea at the time consisted of the Small Aral Sea in the North and the Large Aral Sea in the South, separated by Kokaral Island, and connected by two straits (narrow and shallow Auzy-Kokaral; wide and deep Berg Strait). The Large Aral Sea consisted of a deep western part, an extensive shallow eastern basin, and Tschebas Bay.

As a result of massive water diversions from the Amu Darya and the Syr Darya, the lake water level decreased 3.3 m by 1974 (i.e. a decrease of 23 cm $year^{-1}$). No water inflows from the Amu Darya and Syr Darya reached the Aral Sea in 1982, 1983 and 1985. The lake water level decreased by another 10.2 m (i.e. a decrease of 68 cm $year^{-1}$) (Bortnik & Chistyaeva 1990). The Auzy-Kokaral Strait dried up in 1968–1969. Berg's Strait dried up as well in 1988–1989, when the water level decreased to 40 m a.s.l. The area and volume of the Aral Sea had decreased to 60% and 33% of the 1960 values, respectively, by 2009 (Table 1), with the former single Aral Sea water body now consisting of two terminal lakes – the Small and the Large Aral Sea (Aladin & Plotnikov 2008; Aladin *et al.* 2009).

The water run-off from the Syr Darya increased, in the beginning of the 1990s, with excess water flowing from the Small Aral Sea via Berg's Strait into the Large Aral Sea. A low dam was built in 1992 to control this run-off, causing the water level in the Small Aral Sea to increase (Aladin *et al.* 1995). This dam was not sufficiently strong, however, and when the elevation reached 43.5 m in 1999, it was destroyed in a storm. Kazakhstan authorities then decided to build a new dam, with a sluice for discharging

Table 1. Comparison of geographical, physical and chemical properties of the Aral Sea and Dead Sea (data derived from Beyth (1980); Létolle and Mainguet (2003); Micklin (2007); Neev and Emery (1967); Raz (1993); other sources)

	1960	1980	1989–1990	2000	2006	2009
Aral Sea						
Surface level (m above or below mean sea level)	+53.4	+45.7	+39.1	Small Aral: +40.8 Large Aral: +33.8	Small Aral: +42.3 Large Aral: +31.0	Small Aral: +42.0 Large Aral: +29.4
Surface (km^2)	67 500	51 700	39 100	22 900	17 400	8409
Small Aral			2800			3487
Large Aral			36 300			4922
Maximum depth (m)	67	59	53	54	56	56
Water volume (km^3)	1089	644	364	169	108	85
Small Aral			23			27
Large Aral			341			58
Salinity (g L^{-1})	10	17	30			
Small Aral				20	14	12
Large Aral				62	100–>100	East: >200 West: >100
Dead Sea						
Surface level (m above or below mean sea level)	−397	−401	−407	−413	−419	−423
Approximate surface area (km^2)	940	800	775	715	680	660
Maximum depth (m)	332	328	322	314*	307*	303*
Approximate water volume (km^3)	152	144	140	136	133	130
Salinity (g L^{-1})	290 (surface); 323 (deep waters)	340	342	343	345	347

*Estimates based on estimated annual accumulation of 10 cm of halite on lake bottom since mid-1980s.

surplus water. The initial intent was to increase the water level up to an elevation of 47 m. For financial and technical reasons, however, the dam, which was constructed in 2004–2005 by a Russian company (Zarubezhvodstroy), was designed to provide a lake level increase only up to an elevation of 42–43 m (Aladin & Plotnikov 2008; Aladin *et al.* 2009).

The water level in the Large Aral Sea continued to drop (Aladin *et al.* 1995). Water inflows from the Amu Darya decreased to very low levels in 2000–2001, stopping altogether in 2007. When the water level reached +34 m, the Large Aral Sea became divided into a Western and an Eastern part, joined north of the former Vozrozhdenie Island by a strait which transformed into long narrow channel in 2001–2002 (Zavialov *et al.* 2009). Tshebas Bay separated from the Eastern Large Aral in the autumn of 2004, and the connection between the Western and Eastern Large Aral was interrupted in the autumn of 2009. At a current water level of 29.4 m, the total area and volume of residual water bodies derived from the former Large Aral Sea have decreased to 12% and 6%, respectively, of the 1960 values (Table 1). It is anticipated by some that the Eastern Large Aral will dry up completely in the near future (Micklin P, pers. comm.; also see Micklin 2004).

The Dead Sea water level dropped by more than 25 m during the 20th century. Its water level in October 2009 was 423 m.b.s.l. The former southern basin ceased to exist in 1976, when the lake level reached an elevation of −400 m. This now-dry area is occupied by Israeli evaporation ponds and Jordanian mineral industries (see below). The rate of water level decrease over the past few years was about 1 m year^{-1} and the average annual water deficit is about 625×10^6 m^3.

About 30–40 cm year^{-1} of the water level decline of the Dead Sea is related to the activities of the Israeli and Jordanian mineral industries at the southern end of the lake, namely the Dead Sea Works and the Arab Potash Company. The main product of these industries is potash (KCl). Bromine and magnesium are also extracted. These industries together pump about $400–450 \times 10^6$ m^3 annually from the Dead Sea into shallow evaporation ponds, in which halite (NaCl) and carnallite ($KMgCl_3•6H_2O$) precipitate. At the end of these industrial processes, about 200×10^6 m^3 of concentrated end brines, composed mainly of Mg–Ca–Cl (approximately 500 g total dissolved salt per litre), is returned to the Dead Sea.

This decreased water level is accompanied by other undesirable changes. Hundreds of sinkholes have formed around the lakeshore (Abelson *et al.* 2003) as a result of dewatering and sediment shrinkage, which has led to local ground sinking (Baer *et al.* 2002). As a result of deterioration of the local infrastructure, planning for future development of the Dead Sea area as a major economic, tourism and environmental resource has become nearly impossible (Gavrieli & Oren 2004).

The Dead Sea is not expected to ever fully dry up because of the hygroscopic nature of its dissolved salts. Depending on the freshwater inflow volume in the future, it might be predicted that a steady state will be achieved about 200–400 years from now, when the water level will stabilize at an elevation of about −510 to 550 m (about 90–130 m below the current level) (Yechieli *et al.* 1998). As a result of the lake's diminished surface area, and the decreased evaporation rate due to highly increased brine salinity, the volume of inflowing water will then be equal to the quantity of water evaporating from the surface of the Dead Sea.

INCREASING WATER SALINITY

The negative water balance over the past decades has strongly influenced the salt content of the waters in both lakes.

The waters of the Aral Sea were brackish in the 1960s, with a salt content of 10 g L^{-1} (Bortnik & Chistyaeva 1990). A salinity gradient was found in the deltas of the rivers. In the Akpetkinsky (Karabaili) archipelago, the salinity increased to 50 g L^{-1} and higher as a result of intense evaporation and slow water exchange (Husainova 1960). With the continuing regression of the lake, the salinity steadily increased, resulting in a decreased biodiversity. Aquatic species of freshwater origin disappeared from the lake, followed late by the disappearance of brackish water species. When the Aral became divided into two basins during 1988–1989, the average salinity had reached 30 g L^{-1} (Table 1), with only widely euryhaline species able to survive. After construction of the dam in the former Berg's Strait, the water level of the Small Aral Sea increased, and the salinity gradually starting to decrease (Aladin *et al.* 1996, 1998). One result of this situation was the return of freshwater fish from the Syr Darya and the lakes in its lower reaches (Aladin & Plotnikov 2008; Aladin *et al.* 2009). The salinity in the Small Aral Sea is now about 11–14 g L^{-1}. However, the decreased water level in the Large Aral Sea has led to a dramatic increase in salinity. The salinity in the western portion of the Large Aral Sea reached 100 g L^{-1} in autumn 2009, with values of 200 g L^{-1} and higher being measured in the eastern portion (P. Micklin, pers. comm.). The Large Aral Sea had already been transformed into a hyperhaline water body by the end of the 1990s, exhibiting a very poor fauna (Aladin & Plotnikov 2008; Aladin *et al.* 2009). Due to inflowing groundwater from the Ustyurt Plateau, the deep western portion of the Large Aral Sea will not dry up completely, although its water level will continue to decrease, and its salinity will continue to increase, until a new equilibrium is reached. The brine shrimp *Artemia* and other aquatic invertebrates will disappear, and life in this part of the Aral Sea will then be represented only by the unicellular alga *Dunaliella* and by prokaryotes, similar to the situation in the Dead Sea.

The decreased water level in the Dead Sea since the beginning of the 20th century has resulted in an increased overall salt content in its upper water layers. During the 1959–1960 lake survey by the Israeli Geological Survey, the upper 35–40 m of the lake's water column contained about 290 g total dissolved salts per litre (Neev & Emery 1967). This concentration increased to about 340 g L^{-1} in 1979. The overall salinity of the lake has changed little since that time, in spite of a continuing decrease in its water level. This is because the Dead Sea is currently supersaturated with respect to NaCl and, with drying out of the lake, massive quantities of halite precipitate to the lake bottom. Halite precipitation began in 1982 and has continued nearly uninterrupted since that time (Gavrieli 1997). As a result, the actual Na^+ concentration in the water body decreased from 1.73 mol L^{-1} in 1977 to 1.54 mol L^{-1} in 2007. This decrease was offset by increase in concentrations of more soluble ions (e.g. Mg^{2+}; Ca^{2+}; K^+).

PLANNED WATER CONVEYANCE PROJECTS FOR MITIGATION OF THE LAKES

Complex and expensive mitigation schemes have been proposed for both the Aral Sea and the Dead Sea, involving the import of large quantities of water from distant sources by means of canals, tunnels or pipelines.

The first project, involving diversion of part of the flow of Siberian rivers to the Aral Sea basin, was proposed as early as 1868 by Ya. G. Demchenko (Demchenko 1871). A later proposal, known as the 'Davydov Plan,' proposed diverting between 27 and 30 km^3 $year^{-1}$ from Siberian rivers to irrigate agricultural lands in Uzbekistan and Turkmenistan (Davydov 1949). The plan was dismissed at that time as megalomaniac in scope, with predictions of dire climate change implications if it was implemented (Badescu & Schuiling 2010).

The plenum of the Central Committee of the CPSU charged the Ministry of Water Industry in 1968 to develop a plan to redistribute the drainage of the basin rivers. A final variant of this project was selected in 1976, with a decision to begin implementation of the plan. The project focused on diverting parts of the flows of the Irtysh and Ob' Rivers in Siberia to Kazakhstan and Central Asia, in order to irrigate existing cotton fields, and to further expand the cotton-growing areas. Part of this diverted water was also intended for restoration of the drying Aral Sea. A deep, navigable canal (2550 km length; 130–300 m width; 15 m depth) would be constructed in the first stage of this project, beginning at the Ob' River near Khanty-Mansiysk, and passing through western Siberia to the Syr Darya in Kazakhstan, and then further to the Amu Darya in Uzbekistan. It was planned that this canal would transport water at a rate of 1150 m^3 s^{-1}. Furthermore, a regulating water reservoir was to be built on the Ob' River, and 10 pumping stations on the canal. According to these plans, only a very small fraction of the water volume supplied by the channel would have reached the Aral Sea.

In the opinion of many experts, this proposed implementation would have resulted in many adverse consequences including: (i) flooding of agricultural lands and forests by water reservoirs; (ii) increased level of sub-soil waters along the channel, causing flooding of nearby settlements and roads; (iii) negative impacts on valuable fish species in the basin of the Ob' River; (iv) an unpredictable change in the permafrost regime; (v) climate change and change of ice cover in the Gulf of the Ob and the Kara Sea; (vi) formation of bogs and saline soils in Kazakhstan and Central Asia; and (vii) changes in the local flora and fauna.

During Perestroika, however, it became clear that the Soviet Union, then being in a period of deep economic crisis, could not finance the project. Thus, the Political Bureau of the Central Committee of the CPSU decided on August 14, 1986 to discontinue its implementation.

A new plan for diverting water from Siberian rivers was subsequently proposed (Pierce 2004). The intake point for this new plan was to be at the highest possible elevation in the Irtysh basin, thereby allowing water flow by gravity to the Aral Sea basin, thereby not requiring energy for pumping (Badescu & Schuiling 2009). The intake point would be Lake Zaisan (420 m elevation), permitting gravity flow-mediated water transport to Lake Balkash (341 m elevation) by means of an approximately 100 km long tunnel through the Tarbagataj Mountain chain. The construction cost of the somewhat smaller, but comparable, 75 km long tunnel project was estimated to be in the order of US$ 1.5–2 billion (Ezekiel Water Project 2008). Thus, the cost of the Tarbagataj tunnel would likely not exceed US$ 3–4 billion. Nearly 600 km of this course would pass through Lake Balkhash. The final discharge point would not be in the Aral Sea itself, but rather a point upstream of Kizil Orda along the Syr Darya, in order to facilitate restoration of the valuable ecology of the Syr Darya delta wetlands.

Inclusion of the Ural River also was included in this new proposed project. Its inclusion would possibly provide an elegant means of controlling the water level in the Caspian Sea. If the Caspian Sea water level increased, more water from the Ural River could be channelled into the Aral Sea Basin (Badescu & Schuiling 2009).

Other proposed projects recommended construction of a water conduit from the Caspian Sea to the Aral Sea. One recently proposed project involves refilling the Aral Sea by pumping seawater from the Black Sea (elevation approximately 0 m), via a approximately 500 km long pipeline to the Caspian Sea (elevation −26.5 m). The saltwater would then be pumped via a 650 km long pipeline into the Aral Sea (elevation +53 m). This pipeline could be constructed in the now-dry natural Uzboj Channel from Lake Sarykamysh to the Caspian Sea. With a planned water flow of 56 km^3 $year^{-1}$, the Aral Sea could be refilled in about 10 years. To keep the salinity of the Aral Sea at a low level, a large additional input of fresh water would be necessary, however, in addition to diluting the saltwater transported via the pipeline to the Aral Sea (Cathcart 2008).

These and similar projects that focus on restoring the water volume of the Aral Sea to its initial state cannot be considered realistic. This conclusion is drawn not only based on the enormous material and financial expenses involved in such an effort, but also because the technical possibilities of implementing such schemes in the foreseeable future are extremely doubtful. Furthermore, the introduction of water from the Black Sea to the Caspian Sea will inevitably increase the latter's salinity and change its ionic composition, thereby affecting the biota of this unique continental water body. Moreover, after refilling the Aral Sea with water up to the initial, or some smaller volume, it will be necessary to pump several tens of km^3 of saline Caspian Sea water, or a mixture of Caspian Sea and Black Sea water, into the Aral Sea every year thereafter to compensate for evaporation, because freshwater run-off from the Amu Darya and the Syr Darya will be insufficient for this purpose. The result will be a rapid increase in Aral Sea salinity. Instead of providing a solution, therefore, this approach actually would make the situation worse than the present one (Badescu & Schuiling 2009).

Plans to divert water to the Dead Sea from the Mediterranean Sea, or from the Red Sea, or even both, have a long, interesting history. Captain Allen (1855) of the British Royal Navy published a 384-page book in 1855, titled 'The Dead Sea, A New Route to India.' This book was published at the time the French were planning to construct the Suez Canal. Captain Allen thought he could offer a better, cheaper alternative with his proposal. The Dead Sea and much of its surrounding areas, including most of the Jordan Valley, are located below the sea level. Digging a canal from the Mediterranean Sea (Haifa bay) eastwards, therefore, and a canal from Aqaba at the Red Sea coast northwards (about 60 and 70 km in length, respectively, according to Allen's map; about 40 and 110 km, respectively, based on the area's true topography) would suffice to open a passage to India. The entire area in between these water bodies (i.e. Dead Sea; Jordan River; Sea of Galilee; etc.) would become one large lake navigable by ships. According to Allen's calculations, the cost would be relatively low, with the advantages far outweighing the obvious disadvantages, such as flooding, loss of agricultural areas, and even the loss of places sacred to Christianity and other religions. Some years later, it appears that a company was formed to assess the possibilities for implementing this plan. Captain Allen, however, had made a major error in his calculations. While stating that such a plan was 'destined to be revived every 10 years by persons who are ill-acquainted with practical engineering,' Conder (1883) reported that the involved costs would be many times that quoted by Allen, the latter apparently not too familiar with local geology or the price of available manpower. More important, however, was the observation that the area to be filled with seawater, with a depth of nearly 400 m at the deepest point, was so large, and local evaporation so rapid, that even with canals wide enough for the largest ships existing at that time, it would take at least a hundred years for the whole area to fill up and make the new proposed passage to India become operative.

A more interesting scheme to connect the Dead Sea with the Mediterranean Sea by means of a canal that exploited the difference in elevation (at that time) of nearly 400 m to generate hydroelectric energy, was first proposed by a Swiss engineer, Max Bourcart, in 1899. Bourcart's ideas were gratefully adopted by Theodor Herzl (1860–1904), the father of the Zionist idea to establish a Jewish state. In his 1902 novel, 'Altneuland' (Old New Land), the idea is explained as follows (Herz 1902):

> '… The Dead Sea, as everyone knew, was the lowest point on the earth's surface, lying three hundred and ninety-four meters below the level of the Mediterranean. To convert this tremendous difference in levels into a source of power was the simplest idea in the world. There was a loss of only eighty-odd meters in the course of the Canal from the coast to the Dead Sea. There still remained, therefore a net difference of over three hundred feet. The Canal, which was ten meters wide and three deep, provided about 50 000 horse-power. … While driving down from Jericho, they had not been able to get a full view of the Dead Sea. Now they saw it lying broad and blue in the sun, no smaller than the Lake of Geneva. On the northern shore, near where they stood, was a narrow, pointed strip of land, extending behind the rocks over which the waters of the Canal came thundering down. Below were the turbine sheds; above, extensive factory buildings. There were, in fact, as far as the eye could reach around the shore, numerous manufacturing plants. The water power at source had attracted many industries; the Canal had stirred the Dead Sea to life'. (translation: L. Levensohn 1987).

Following the 1973 energy crisis, Herzl's vision was revived and large-scale feasibility studies were conducted to evaluate the economic, environmental and engineering aspects of such a canal and/or tunnel from the Mediterranean Sea to the Dead Sea, with hydroelectric power plants exploiting the difference in elevation (Ne'eman & Schul 1983; Weiner 1985). The Israeli government founded the 'Mediterranean Sea-Dead Sea Company' in 1984 for this purpose, although it was subsequently abandoned both because of economic reasons and international objections to the project.

The idea of a water 'carrier' to the Dead Sea, this time via a canal or pipeline from the Red Sea – Gulf of Aqaba, was considered again after the 1994 peace treaty between Israel and the Hashemite Kingdom of Jordan. The principal objective of this project, sometimes termed the 'Peace Conduit', was to exploit the elevation difference between these seas to desalinize seawater on the shores of the Dead Sea by reverse osmosis. The added water also should raise the Dead Sea water level and, after an initial filling stage, stabilize it, preventing a further water level decrease, and further deterioration of the local infrastructure. During the World Summit on Sustainable Development held in Johannesburg in 2002, the two countries jointly announced their commitment to the project. A feasibility study of the Red Sea – Dead Sea Water Conveyance Study Program is currently being conducted, financed by the World Bank. This project has the potential to halt, and even reverse, the undesirable environmental processes currently occurring in the Dead Sea basin. There is a possibility, however, that mixing of seawater and sea brine might also lead to undesirable changes in the lake. Before a decision is made on the construction of the water carrier, therefore, it is essential that the long-term evolution and future characteristics of the Dead Sea be known, and anticipated changes examined, in order to minimize possible negative impacts of seawater introduction into the Dead Sea (Gavrieli & Oren 2004; Gavrieli *et al.* 2005).

FISHERIES IN THE ARAL SEA AND DEAD SEA – NOW AND IN THE FUTURE

Recent measures taken to restore at least some part of the former Aral Sea have already resulted in the return of a healthy population of different kinds of fish, and even a partial restoration of the commercial fishery in the lake.

Fishery activities on the Aral Sea only began in the second half of the 19th century, after the region joined the Russian Empire. The fishery became an important branch of the local economy in the 20th century. The fish fauna of the Aral Sea initially included 20 species (Nikolsky 1940), most of them being commercially important. The main fish were bream, carp, roach and pike-perch. More fish species were introduced during the years 1927–1963, with the number of species reaching 34. The aboriginal fish fauna of the Aral consisted of many freshwater species that spawn in fresh water, and which also can spawn in the brackish Aral Sea water, as well as two anadromous species (salmon trout; ship sturgeon). The best places for fish spawning in the lake were freshwater bays near the deltas, and the lakes near the lower reaches of the influent rivers. There were also spawning areas in the Aral Sea itself (Nikolsky 1940; Bervald 1964).

Regulation of the water flows through the Syr Darya and Amu Darya, and the increased water withdrawals, resulted in a decreased water level in the Aral Sea, drying of the deltas and increased water salinization. These factors had a strong impact on the Aral Sea fish populations and especially on the conditions necessary for their reproduction. The spawning areas had shrunk almost fivefold by the mid-1960s, with reproduction of the main commercial fish species decreasing accordingly. The spawning areas within the lake had disappeared altogether by 1975. The catastrophic deterioration of conditions for natural fish reproduction had a profound effect on the state of the commercial fish populations. The first indications of negative impacts of the increased salinity on adult fishes were obtained in 1971, with natural reproduction of commercial fish in the Aral Sea ceasing completely by the mid-1970s. Fish catches decreased from 34 160 tonnes in 1961 to 14 960 in 1976, and to 2935 tonnes in 1980 (Z. Ermakhanov, pers. comm.).

Flounder from the Sea of Azov was introduced into the Aral Sea during the years 1979–1987 in an attempt to continue fishery activities under the conditions of progressing salinization (Lim 1986). This species can spawn at salinities between 17 and 60 g L^{-1}. The flounder had settled throughout the lake in the early 1990s where the salinity ranged between 15 and 50 g L^{-1}. Flounder were the only fish caught in the Aral Sea between 1991 and 2000, with catches exceeding 1000 tonnes in some years (Z. Ermakhanov, pers. comm.). When the salinity of the Large Aral Sea reached 60–70 g L^{-1} at the end of the 1990s, however, the flounder population died, with no more fish being detected in the lake.

Run-off from the Syr Darya again began to enter the Small Aral Sea in 1988. A freshened water zone was again formed, becoming populated by aboriginal food fishes migrating from nearby lacustrine systems through the Syr Darya. The area of low-salinity waters (1–10 g L^{-1}) has since increased to 600 km^2. Fish other than flounder can now spawn and pasture over almost the entire Small Aral Sea. Stabilization of the hydrological regime and freshening of the water volume now enable development of an abundance of such fish as carp, bream, pike-perch, zherekh (asp; *Aspius aspius*), etc., to fish densities needed for a commercial fishery. The fish catch in 2008 was 1490 tonnes, including 410 tonnes of flounder (Z. Ermakhanov, pers. comm.).

In contrast to the Aral Sea, the waters of the Dead Sea and its precursors have been much too salty, even for the most salt-tolerant fish, for at least thousands of years. As illustrated above, continuing drying out of the lake causes a further increase in its overall salt concentration and a relative increase in the divalent cations, magnesium and calcium, making conditions in the lake ever more extreme for even microbial forms of life. If the above-discussed plans for a canal or a pipeline between the Red Sea or the Mediterranean Sea and the Dead Sea are ever implemented, this possibility will undoubtedly result in the dilution of the upper water layers in the lake and their reduced salinity. Based on current models that consider the physical properties of the lake, the expected quantities of seawater to be brought to the Dead Sea and local evaporation, this proposed plan will not result in a sufficiently diluted upper water layer to support higher forms of life, including fish. This means that the project would probably not result in the fulfilment of the prophesy of Ezekiel (47: 8–10); namely, that fish will eventually return to the Dead Sea in large numbers.

CONCLUSIONS

Terminal hypersaline desert lakes are found on different continents, and vary greatly in size, depth, salinity, and limnological and biological properties. Their properties also change with time, often causing significant environmental and economical problems. In spite of the different conditions prevailing in the Aral Sea and the Dead Sea, much can nevertheless be learned from comparative studies, not only of their present properties but also of their evolution.

In spite of the very differing nature of the Aral Sea and the Dead Sea with respect to surface area, depth, salt concentration and ionic composition, biological properties, and human exploitation, the above historical survey highlights a striking number of similarities. It is the conviction of these authors that many lessons can be learned by comparing the fate of terminal desert lakes, both at the present time as well as in the past. Such understanding can contribute much towards development of the proper management of such lakes.

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