



## THE LAKES OF THE JORDAN RIFT VALLEY

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### Abstract

This paper presents a summary of the proceedings of a workshop on the Lakes of the Jordan Rift Valley that was held in conjunction with the CRP on The Use of Isotope Techniques in Lake Dynamics Investigations. The paper presents a review of the geological, hydrogeological and physical limnological setting of the lakes in the Jordan Rift Valley, Lake Hula, Lake Kinneret and the Dead Sea. This is complemented by a description of the isotope hydrology of the system that includes the use of a wide range of isotopes: oxygen-18, deuterium, tritium, carbon-14, carbon-13, chlorine isotopes, boron-11 and helium-3/4. Environmental isotope aspects of the salt balances of the lakes, their palaeolimnology and biogeochemical tracers are also presented. The scope of application of isotopic tracers is very broad and provides a clear insight into many aspects of the physical, chemical and biological limnology of the Rift Valley Lakes.

### 1. GEOLOGY AND HYDROLOGY OF THE VALLEY

The Jordan Rift Valley which hosts three lakes of very different character is situated in the northern part of the East African-Syrian rift system. It developed on an active transfer fault which opened up during the late Miocene and Pliocene and has continually widened since. It was evidently connected to the ocean system for a long period, during which massive sedimentary sequences were deposited. These sediments are composed mostly of evaporites which form large diapirs, one in the southern part of the Dead Sea basin, the other in the divide between the two parts of the basin and another just south of Lake Kinneret. The evaporites are mainly rock salt. Pleistocene sediments reflect the acceleration of basin subsidence; they comprise several kilometers of lacustrine sediments. The structure of the Dead Sea basin is that of a fault bounded depression, divided internally into a number of segments by transverse faults. In the southern basin accumulation of Neogene and Pleistocene sediments probably exceeds 10 km; in the northern basin a relatively thinner cover overlies the Cretaceous sequence. The depth to basement was estimated from magnetic and gravity calculations at 8-10 km in the north and at probably 14 km in the south.

Deformation takes place mainly along the transverse and longitudinal faults leaving the intervening sediments relatively undeformed. Significant changes occur with time in the nature of deformation along the main faults. The geometry of the Dead Sea basin is probably controlled by stretching of the entire crust along its long axis. The deformation occurred wholly within the crust without the participation of the upper mantle.

The present valley constitutes an internal drainage basin of about 40,000 km<sup>2</sup>; of which the Dead Sea is the ultimate terminus. The main water carrier is the Jordan River which runs from Mt. Hermon through Lake Hula and Lake Kinneret to the Dead Sea and drains an area of

about 18,000 km<sup>2</sup>. Elevation difference between the headwater and the drainage basis is about 2000 m, the distance is about 200 km, and the mean precipitation depth decreases from north to south, from 1300 mm/y at Mt. Hermon to 80 mm/y at the Dead Sea. Three lakes lie along the course of the Jordan River: the Hula at an elevation of +70 m, the Kinneret at a mean elevation of -210 m, and the Dead Sea surface is situated at about 400 m below msl.

Additional waters drain periodically directly into the Dead Sea from an additional southern drainage basin, albeit an arid one.

In addition to the large changes in water balance over geologic times, most probably primarily controlled by climate changes during the Pleistocene and early Holocene, there have been major anthropogenic influences during this century. First the drainage and channeling of the Hula region, followed by the diversion of water both from Lake Kinneret and the Yarmoukh River for consumption and irrigation both in Israel and Jordan. This resulted in a marked decrease of the volume of flow in the lower Jordan River, as well as an increase in its salinity. The latter effect is due, in no small measure, to the diversion of a number of near-shore saline springs from Lake Kinneret to the lower Jordan.

Owing to the consumptive use of water and to fluctuations in precipitation depth, the discharge of the Jordan River into Lake Kinneret declined from 560 MCM/y (10<sup>6</sup> m<sup>3</sup>/y) in the 1930s and 1940s to 460 MCM/y in the 1980s and early 1990s. The outflow from Lake Kinneret dropped during that time from 530 to 50 MCM/y, while the mean volume south of the confluence of the Yarmoukh and Jordan Rivers, dropped from 980 to 180 MCM/y. The latter is the amount of water delivered into the Dead Sea.

## 2. THE LAKES OF THE JORDAN RIVER VALLEY

### 2.1. Lake Hula

The most upstream lake of the system, Lake Hula, is a good example of a strongly manipulated system. Almost completely drained around the mid-century in order to reclaim agricultural lands, it is being reflooded in recent years to re-establish a natural wetland reserve and in order to mitigate the ill effects of the dried swamp lands on the downstream river system, namely mainly massive release of nitrates and other nutrients. Geochemical studies on the re-claimed Hula wetlands is illustrating the beneficial effects of the (controlled) wetlands on the nutrient and sedimentary balance in the downstream river.

### 2.2. Lake Kinneret

Lake Kinneret (also known as Lake Tiberias, Sea of Galilee or Lake Genezareth), the only sweet-water lake of the region is of major economic importance (fisheries, recreation and tourism) and a source of about 1/4 of the freshwater supply for agricultural and urban use in Israel, mainly by means of the NWC (National Water Carrier). It lies approximately 210 m below msl. It measures 22 kms from north to south and 14 kms from east to west, has a surface area of about 170 square kms, a mean depth of 24 meters and a maximum depth of 43 meters. When full, the lake has a total water volume of four billion cubic meters. The climate in this region is semi-tropical with long, hot summers and relatively cold, rainy winters.

From about mid-May to Late December or early January, the lake is strongly stratified into two distinct water masses, a warm (22-30°C), well-mixed upper layer (*epilimnion*), progressively deepening from about 16 to 26 meters, and a deeper, colder (13-16°C) stratum

(*hypolimnion*). During the winter, this two-layer structure breaks down and the water masses are completely mixed.

The NWC was inaugurated in 1964. The NWC links Lake Kinneret to Israel's other water sources and thus the lake became an integral and vital element in the national water economy. Presently 400-430 million cubic meters of water are pumped annually from Lake Kinneret and flow through the NWC. An additional 100 million cubic meters are supplied to local consumers round the lake, in the Jordan Valley and on the Golan Heights. Although a major portion of this water is still used for agriculture, increasing amounts are now supplied for drinking and domestic purposes, as well as for industrial and municipal requirements. Another extremely important function of the NWC is to supply good-quality water for recharging the major underground aquifer which runs along the coast of Israel. All this explains why maintaining and, if possible, improving water quality in the lake is a matter of prime national concern.

As water began to be pumped through the NWC, two major difficulties became apparent. First, it turned out that the salinity of the lake water was sufficiently high to damage sensitive crops such as citrus and avocado. Furthermore, using this relatively high-salinity water could drastically accelerate salinization of the irrigated soils and of the coastal aquifer lying beneath them. Secondly, there were incipient problems of taste and smell and general water quality which threatened to affect the utility of the NWC. The latter consideration was particularly serious because the NWC is a single-channel system and therefore all the supply must meet drinking water standards or, at most, require only slight treatment in order to do so.

The first of these problems, salinity, was minimized by diverting several major saline inputs at the northwest of the lake into a "salt water diversion canal" which discharges into the southern Jordan. The diversion removes about 60,000 tons of salt from the lake each year. An exceptionally rainy winter in 1968-1969 also served to lower salinity and thus the chloride concentrations in the lake have fallen to about one-half their level in the late 1950s. The salt-water canal is also used to remove secondary-treated sewage from Tiberias and other settlements along the western shoreline, and a pipe network has been built to collect and transport effluents from the villages on the eastern side so that none of this pollution enters the lake.

The overwhelming majority of the salinity in the lake is due to saline springs (both on the shore and underwater) and possibly also to seepage or diffusion of salt through the bottom sediments. A major geophysical and geochemical research effort was conducted in recent years to determine the source of the salinity as well as the driving mechanism of its introduction into the lake. As part of this effort a large array of isotopic parameters were engaged, including the  $^{18}\text{O}$ ,  $^3\text{H}$  and  $^2\text{H}$  content of the water,  $^{14}\text{C}$  and  $^{13}\text{C}$  in carbonates, S isotopes in sulfates and  $^{37}\text{Cl}/^{35}\text{Cl}$  as well as  $^{36}\text{C}/^{35}\text{Cl}$  ratios. Rare gases, especially the  $^3\text{He}/^4\text{He}$  ratio,  $^{87}\text{Sr}/^{86}\text{Sr}$  as well as the  $^{11}\text{B}/^{10}\text{B}$  ratio were also measured. These and the general chemical composition of brines and brackish waters were discussed in a report by Bergelson, Nativ and Bein. Their conclusion, still somewhat debatable, is that the saline groundwater appears to be a mixture between a very saline end-member and meteoric fresh groundwater. The saline end member is an intensively evaporated marine brine which evolved in an inland basin within the Rift Valley. The intensive evaporation of this brine, beyond the onset of halite precipitation, is indicated by low values of the Na:Cl and Cl:Br ratios (0.5 and 150, respectively) and the high  $\delta^{11}\text{B}$  (+44‰) documented in the most saline groundwater. Gypsum precipitation decreased the sulfate concentrations in the residual

solution. The dense evaporated brine intruded the Rift Valley formations where it further evolved into Ca-chlorine brine. Its high Mg concentrations enhanced dolomitization, resulting in high Ca:Cl and low Mg:Cl ion ratios (90.33 and 0.09, respectively). Sulfate concentrations were further decreased as a result of both additional gypsum precipitation following the increased Ca concentrations and by sulfate reduction.

The original brine was later diluted by fresher water to form the Tiberias Brine. Considering the relatively low (~seawater) salinity of the Tiberias Brine with respect to that of the original brine, the latter accounts for most of salts in the Tiberias Brine and controls its ion ratios and chloride isotopes, whereas the diluting freshwater component contributed most of the water. Because of its large water contribution and relatively large bicarbonate concentrations (with respect to the original brine), the diluting freshwater component controlled the oxygen, hydrogen and carbon isotopic compositions of the Tiberias Brine. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  compositions is relatively light (-2.45 to -1.5‰ and -18.51 to -4.2‰) with respect to seawater, respectively, and the amount of radiocarbon (5.8 to 0.4 PMC) is also low.

A second dilution stage is believed to take place during the upwelling of the "Tiberias Brine" into shallow, freshwater aquifers to form the saline springs. Fresh groundwater, circulating in these aquifers mix with the Tiberias Brine, as evidenced by the measurable tritium (0-5.3 TU) and variable radiocarbon data of the saline springs. Although most of the upward migration must be rapid, as indicated by the high temperatures (up to 60°C) and radon fluxes, much slower transport, partly by diffusion, is proposed on the basis of the depleted  $^{37}\text{Cl}$  values (-0.7 to -0.4‰) and the presence of radiogenic helium ( $^4\text{He} = 3.97 \times 10^{-5} \text{ cm}^3/\text{liter}$ ,  $^3\text{He}/^4\text{He} = 2.053 \times 10^{-6}$ ) and of radium.

The spatially variable chemical and isotopic features of the saline water found in the various spring clusters around Lake Kinneret suggest not only differential dilution by fresh meteoric water, but also different evaporation levels and dolomitization intensities in the original brine end-member. The preservation of these distinct features suggest that percolation of the ancient brine at different times along the evaporation event occurred into tectonically isolated blocks.

### 2.3. The Dead Sea

The Dead Sea represents the ultimate, highly mineralized, terminal lake whose water balance is under extreme anthropogenic stress. The resultant drop in water level, increase in salinity and exposure of new coastal land areas, have provided the major motivation for research.

The negative water balance of the Dead Sea since the beginning of the century has resulted in a decrease in its water level by about 20 meters. This has been accompanied by various changes in the chemical and physical characteristics of the lake and its brine.

In the beginning of the century the Dead Sea was a meromictic (stratified) lake with a relatively diluted epilimnion, down to a depth of 40 meters, and an anoxic, halite-saturated hypolimnion which formed the main water body of the lake. However, the negative water balance of the lake resulted in a continuous increase in the salinity of the epilimnion, and to the deepening of the transition layer between the two water bodies. Eventually, in 1979 the Dead Sea overturned and the water column homogenized. The present hydrographic behavior of the Dead Sea is that of a quasi-holomictic lake - annual stratification develops in spring,

and is maintained throughout the summer by a stabilizing thermocline which overcomes the destabilizing halocline. Overturn takes place in autumn due to the cooling of the surface waters. This annual holomictic cycle was interrupted twice since 1979, when a diluted surface layer developed following the massive freshwater inflow into the Dead Sea during the exceptionally rainy winters of 1979/80 and 1991/92. The stratifications that developed following these winters lasted three and four years, respectively, before overturn took place again.

In 1976, following the decline in the water level, the shallow southern basin was disconnected and dried out from the main water body. Massive halite precipitation began in 1983 which, apart from a short period, has continued to the present. The halite precipitation, and the industrial activities of the potash industries south of the Dead Sea which pump out Dead Sea brine and evaporate it in evaporation ponds, have resulted in a change in the composition of the brine. This is exhibited by decreasing Na/Cl and increasing Mg/K ratio over the last four decades. The annual weight of halite that precipitated in the lake since 1983 was estimated by various calculation methods to be  $>100 \times 10^6$  tons. This does not include the salts that precipitate in the industrial evaporation ponds, estimated at about  $35 \times 10^6$  tons/year.

A model based on results obtained from evaporation experiments indicates that under the present conditions the rate of evaporation will gradually decrease as the salinity of the brine increases. On the basis of a simplified relationship between salinity and evaporation, it is estimated by Gavrieli, Weinstein and Yechieli that a new equilibrium between evaporation and input will be reached within 400 years at a water level of about 500 meters below MSL. At the new equilibrium level, the Dead Sea volume would have decreased to 2/3 of its present volume while its salinity and density would be about 380 g/l and 1.27, respectively. This process will be accompanied by a more halite precipitation and a decrease in Na/Cl ratio from 0.25 to about 0.1. However, the lake will not attain saturation with respect to carnallite ( $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$ ) which is the mineral precipitating in the industrial evaporation ponds.

The inhibiting effect of the increasing salinity on the microbial population can be seen and the lake is approaching almost total sterility. However short-lived algal blooms follow the dilution of the surface brine by winter floods. Recently Luz and Barkan of the Hebrew University found evidence also of microbial oxidation in the abyssal waters, based on the isotopic composition of dissolved oxygen and carbon-dioxide as described below.

The dramatic lowering of the water level of the Dead Sea is exposing former saline lake floor on the coastline. Studies were concerned with the hydrological and ecological consequences of this process. Studies by Yehieli et al. on the restructuring of the saltwater/freshwater interface zone are worth mention. An interesting study on the renascent plants in the newly exposed coastal zone, by Yakir and Yehieli, utilize stable isotopes to indicate that growth occurred by virtue of the discriminatory utilization of freshwater lenses in the soil column. These resulted from either floods or in zones where upwelling of fresh groundwaters occur.

Some of the up-to-date research achievements were summarized in the book "The Dead Sea: - the Lake and its Setting" (T. Niemi, Z. Ben-Avraham and J.R. Gat, editors) recently published by Oxford Press.

### 3 THE SALT BALANCE OF THE LAKES OF THE JORDAN RIFT VALLEY

By virtue of its topographic situation at the deepest spot in the Jordan Rift Valley, the Dead Sea can be expected to conform to the model of a terminal lake. In such a lake, all of the water influx by means of precipitation and surface or groundwater runoff is lost by evaporation. The incoming salts, whether by aeolian input into the region or those originating from weathering of soils and rocks, then supposedly accumulate in the lake. Ideally the salt inventory of the lake ( $Q_s$ ) would then be expressed as  $Q_s = \sum F_s C_s dt$ , where  $F_s$  and  $C_s$  are the water influx and the salt concentration in this stream, respectively. Under the assumption of steady state fluxes, the age of a lake can then be determined by comparing the salt inventory to the influx rates. This idea was already proposed in the 18th century, and applied to the case of the Dead Sea by Bentor [1].

In practice one often finds less than the expected salt load in a terminal lake. This discrepancy results from the burial of evaporites in the sediments (primarily gypsum, carbonates and halite) and because of the leakage of brines into and through the banks of the lake. Another possible factor is the aeolian export of seaspray. On the other hand, an excess of salt in the system may point to unaccounted submarine springs or salt seepages as well as the dissolution of minerals from the bottom layers, such as from salt diapirs.

Evidently then, one should add two terms (each either positive or negative) to the balance equation: one which accounts for the interaction of the lake with the sediments or its banks and another relating to the aeolian transport of salt. As discussed by Imboden and Lerman [2] these terms can reverse their sign on a variety of time scales, as a lake's condition changes.

In the case of the Dead Sea, three salient features dominate and determine the unique characteristics of the system:

- i) its position at the absolutely lowest elevation of the entire region;
- ii) the steep flanks bordering the Rift Valley, which limits the chance of aeolian export of salt from the region;
- iii) the varying water supply, which results in wide fluctuation of the water level of the lake and concurrently in changes of salinity and in the degree of saturation of halite in the Dead Sea brine. These were extreme when going back in time; the extent of the Pleistocene precursor to the lake, namely Lake Lisan, reached as far north as present-day Lake Kinneret (and its elevation about 200 m above the present level of the Dead Sea) and in the geological past there is evidence for a connection to the ocean, the area functioning as a lagoony system.

The obvious conclusion to be drawn from the first of these features is that an irreversible escape of brine from the lake and its coastal environment is not possible. However, due to the large fluctuations in lake level, a reversible salt flux associated with the bank storage, acting on a wide range of time scales, complicates the simple book-keeping for the system. For example, most of the salt springs near the Dead Sea shore are the result of flushing of the brines from the coastal area and saltwater - freshwater interface zone. The salinization of waters of Lake Kinneret (which is a major concern in the freshwater supply of Israel), is apparently due to such a reverse salt flux, bringing back brines from a pre Dead-Sea lake systems in the Rift Valley. The to-and-fro salt movement, which of course also modifies

the chemical character of the brine through rock-water interaction, appears to be the most dominant term of the salt balance.

As shown in the work of Shatkay et al. [3] the salinity on the Dead Sea shores (which derives both from coastal sea spray and newly exposed saline sediments) is, by and large, washed back into the sea unlike the situation for more open lakes, (such as Mono Lake [4]).

The conclusion to be drawn is that, in a way, the Dead Sea and its sedimentary sequence indeed functions as the ultimate terminal lake; this property is however realized on a very long (geological) time scale, with shorter term fluctuations of its salt content due to their temporary storage in adjoining formations.

In the final analysis, the major long term and irreversible losses of salinity for the Dead Sea system is of anthropogenic nature, resulting from the mineral exploitation of the Dead Sea works (in the form of potash, magnesium and bromine compounds), and the salinity pumped with the freshwaters diverted from the Jordan River watershed by the National Water Carrier and other irrigation schemes.

#### 4 THE ISOTOPIC PALEOLIMNOLOGY OF THE THREE LAKES OF THE JORDAN RIFT VALLEY

The flow of the Jordan River connects three lakes: Lake Hula, Lake Kinneret and the terminal Dead Sea. These lakes differ in elevation, water residence time, salinity level and characteristic geochemical and biological features. The prevailing environmental climatic conditions are also different to some degree.

The stable carbon and oxygen isotopic compositions of the carbonate formed within the lake waters and stored in the sediments, bear the record of paleolimnological evolution and climatic variations, respectively. The isotopic variations of carbon-13 and oxygen-18 have been measured in the sediments of the three Jordan Rift lakes. The imprint of regional climatic variations has been found in coeval segments of the sedimentary column (dated by  $^{14}\text{C}$ ) of the three lakes. The  $^{14}\text{C}$  dating also revealed that the ratio of the  $^{14}\text{C}$  activities in coexisting carbonate and organic phases might be an indicator for the degree of aridity in the lake's environment. The ratio  $^{14}\text{C}$  carbonate/ $^{14}\text{C}$  organic is much larger in the more humid conditions of Lake Hula and Lake Kinneret than in the arid environment of the Dead Sea. [5]

The carbonate- $^{13}\text{C}$  data indicate that productivity has increased gradually in Lake Hula from about 17000 years BP to present and in Lake Kinneret from 5100 years BP (the deepest available sediment section) to present [6]. In the Dead Sea, the  $^{13}\text{C}$  data suggest a higher stand from about 6700 years BP to 4500 years BP; the highest lake level was about 5500 years BP.

There is a remarkable agreement between the evidence provided by the  $^{18}\text{O}$  data of lakes Hula and Kinneret: warmer conditions prevailed from 5100 years to 2700 years BP, warmer than during the period 1200 years BP to 150 years BP [7,8]. In Lake Hula the track of the warmer period could be followed until about 8000 years ago (peaking at about 5300 years BP). The coolest period revealed by the  $^{18}\text{O}$  data in Lake Hula was from 17000 to 11000 years BP.

Summarizing the isotopic evidence of the three lakes: warmer climatic conditions than nowadays prevailed from about 8000 years BP to about 3000 years BP. Between 6700 and 4500 years BP and peaking at about 5500 years BP, the climate was also more humid.

## 5 BIO-GEOCHEMICAL TRACING OF LIFE IN THE DEAD SEA

Bio-geochemical tracers suggest that bacterial life may exist in the deep water mass of the Dead Sea. These tracers are the concentration of total dissolved carbon dioxide ( $\text{TCO}_2$ ), carbon isotopic composition of  $\text{TCO}_2$  ( $\delta^{13}\text{C}$ ), the ratio of dissolved oxygen to dissolved argon ( $\text{O}_2/\text{Ar}$ ) and the isotopic composition of the dissolved oxygen ( $\delta^{18}\text{O}$ ).

Unusual flooding during the winter of 1991/92 and freshening of the upper waters of the Dead Sea, resulted in a major algal bloom and in a very stable pycnocline that prevented ventilation of the hypolimnion. Following this flooding we have monitored  $\text{TCO}_2$ ,  $\delta^{13}\text{C}$ ,  $\text{O}_2/\text{Ar}$  and  $\delta^{18}\text{O}$  in a station located at the center of the lake. For several months after the formation of the stable pycnocline these parameters recorded changes in the deep water. In March 1992,  $\text{TCO}_2$  was 852  $\mu\text{mol/kg}$ , and in December 1992 it rose to 867  $\mu\text{mol/kg}$ . During the same period  $\delta^{13}\text{C}$  decreased from 1.6‰ to 1.2‰, and measurements of  $\text{O}_2/\text{Ar}$  ratio indicate lowering of the dissolved oxygen concentration. Thus the addition of  $\text{TCO}_2$  seems to be due to oxidation of organic matter. From mass balance of carbon and its isotopes this change can be calculated to result from the addition of 15  $\mu\text{mol/kg}$  of  $\text{TCO}_2$  with  $\delta^{13}\text{C}$  of -21‰. Based on this isotopic composition the source of this added carbon is not likely to be oxidation of sinking plankton from the algal bloom, because the  $\delta^{13}\text{C}$  of the latter is -13‰. The source of carbon may be detrital organic matter derived from the flood water or dissolved organic matter. The amount of labile organic matter was limited because after December 1992 the deep water did not show any significant change. This suggests that a limited amount of labile organic matter with  $\delta^{13}\text{C}$  of -21‰ was introduced to the Dead Sea during the floods, and rapid oxidation consumed all the labile material over a period of several months.

The mechanism of this oxidation is uncertain, but our new measurements of  $\delta^{18}\text{O}$  in the deep water is about 7‰ higher than at the surface. This enrichment in the heavy isotope is due to isotopic fractionation that took place during oxidation. The magnitude of this fractionation is calculated from the shift in  $\delta^{18}\text{O}$  and from the change in the  $\text{O}_2/\text{Ar}$  ratio as -18‰. This isotopic discrimination is typical of bacterial oxygen consumption. Our preliminary results thus suggest that bacteria were present in the deep water of the Dead Sea following the floods of 1991/92. Whether such bacterial activity is more common in the Dead Sea and occurs in holomictic years after normal winter floods, is an open question. More research on oxygen concentration and its isotopic composition is necessary before we can solve this interesting problem.

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