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ORIGINAL ARTICLE

The role of volcanic eruptions in blocking the drainage leading to the Dead Sea formation

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Abstract The shrinkage of the Lisan Lake (LL) to form the recent Dead Sea (DS) was mainly a result of the reduction of the catchment area from around 157,000 km^2 during Late Pleistocene to 43,000 km^2 presently. The reduction in the catchment area resulted from the eruption and spread of the basalt flows of Jabal Arab-Druz (JAD), which together with the resulting deposition of thick rock debris and gravels occupied the drainage system. The filling of the pre-basalt drainage system, which used to feed the Dead Sea, with basalts and alluvial sediments blocked the inflows from reaching the Dead Sea. Local base levels along the basalt flow boarders such as Azraq Oasis, Sirhan Basin and Damascus Oasis, and numerous pools and mud flats were created.

Keywords Lisan Lake · Dead Sea · Jabal Arab-Druz · Volcanic eruptions · Blocking of drainage

Introduction

The present Dead Sea (henceforth DS) is an exitless lake with a surface area of around 660 km^2 and a water level of 418 bsl (2005). The DS forms the base level for a catchment area of about 43,000 km^2, which extends into Jordan, Syria, Lebanon, Palestine and Israel (USGS 1998; Arkin 1982).

The shrinkage of the DS area from 950 km^2 during the 60s of the last century to around 660 km^2 presently has been caused by anthropogenic activities (Salameh and Naser 1999).

The DS precursors occupied different extensions along the Jordan Rift system, extending further north and south of the present DS (Quennel 1959; Bender 1968; Neev and Emery 1967).

The last precursor of the DS, the Lisan Lake (henceforth LL), existed 50,000–12,000 years ago (Kaufman 1971) and extended to approximately 40 km south of the present DS and 110 km to its north, with a water level of about 180 m bsl (Neev and Emery 1967; Begin et al. 1974).

Numerous workers attributed the shrinkage of LL to climatic changes, dry periods and tectonic activities (Neev and Emery 1967; Horowitz 1979; Goldberg 1994; Niemi and Ben-Avraham 1997; Niemi et al. 1997; Bar Yousef 1987; Druckman et al. 1987 among others).

The dry event that lead to the shrinkage of LL must have started approximately 11,000–10,000 years ago (Frumkin 1997; Horowitz 1979; Begin et al. 1974).

In this paper, the main reason behind the shrinkage of LL to form the present DS is attributed to a reduction in the catchment area as a result of the eruption of Jabal Arab-Druz (henceforth JAD) volcanism, and the blocking of the drainage system, of the catchment areas lying north, east and south of JAD from flowing into the LL drainage system. Basalt flows and rapidly eroded and deposited sediments consisting of gravels and sands and rock debris filled the pre-basalt drainage system and hindered the surface water from reaching the DS.

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Methodology

In this article, the present catchment area of the Dead Sea is extended to include all the drainage areas, which were blocked by the basalt eruptions and by the alluvial and colluvial sediments by using topographic maps, elevation models and land sat images. The calculation of pre-eruption discharges is accomplished using actual climatic and water discharge information. In areas where runoff and recharge/rainfall ratios are not found, data from similar surrounding areas are used.

The blocked-off drainage area is subdivided into the following five catchments areas (Fig. 1):

1. the Damascus Basin,
2. the Hammad Basin in Syria,
3. the Hammad Basin in Jordan,
4. the Azraq Basin,
5. the Sirhan Basin.

After carrying out the discharge calculations, an initial water balance for LL is calculated.

Catchment areas

The catchment area of the present DS

The present catchment area of the DS extends into Jordan, Syria, Lebanon, Palestine and Israel. It measures about 43,000 km^2 (USGS 1998; Arkin 1982) and drains areas receiving as much as 1,200 mm/year of precipitation in the north, decreasing to 60 mm/year in the southeast and to 30 mm/year in Wadi Araba and the southeastern catchment of Sinai Peninsula (Fig. 2).

The catchment areas to the north east, east and south east of JAD volcanic rocks (presently not draining into the DS system)

These catchment areas consist of Damascus Basin in the north, Hammad Basin in Jordan and Syria in the northeast and Azraq and Sirhan Basins in the southeast of JAD.

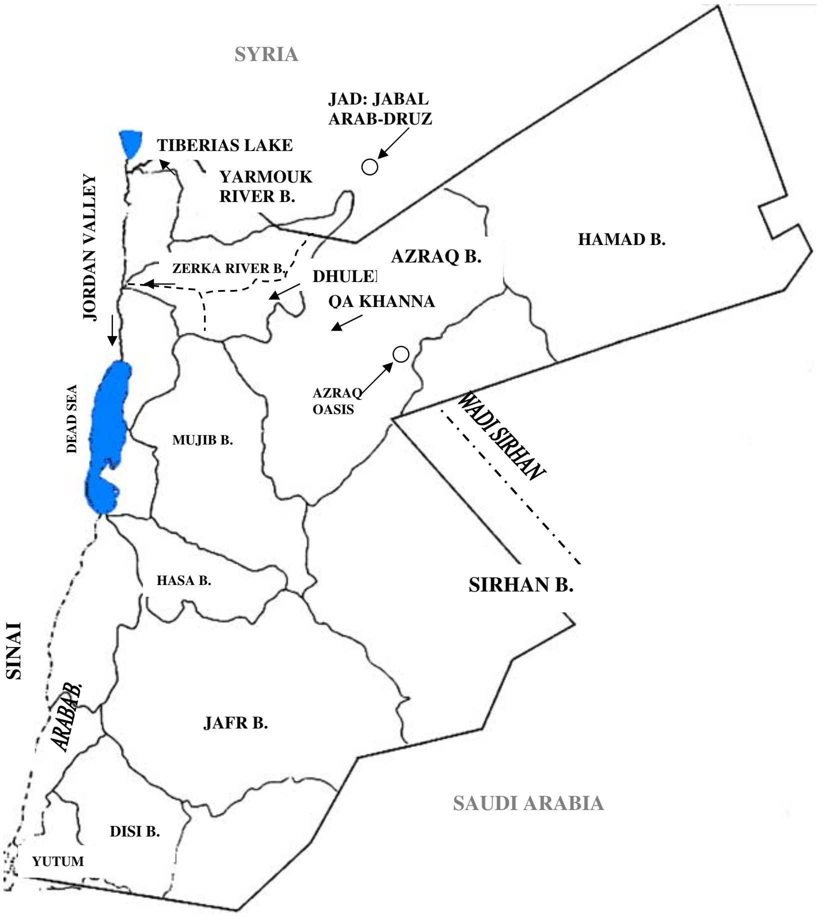

Fig. 1 Location map of the study area and the sites mentioned in the article

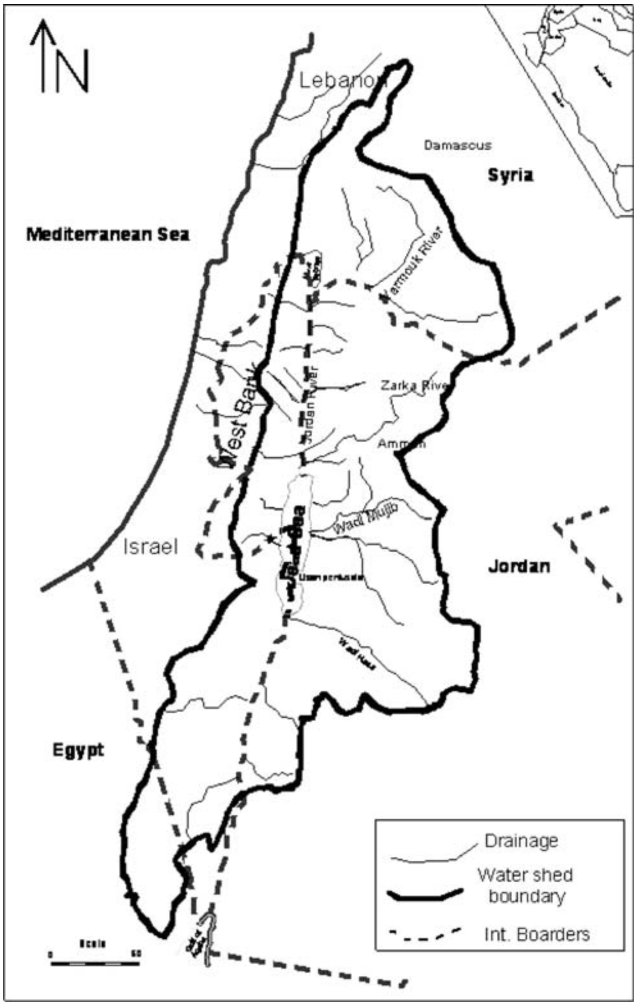

Fig. 2 Catchment area of the Dead Sea

Nowadays, all these areas drain their water toward the borders of the basalt flows of JAD to form oasis and mudflats (Fig. 3).

Arguments supporting pre-basalt drainage toward the DS

The following lines of evidence are supposed to support the thesis that the drainage basins of Damascus, Hammad in Jordan and in Syria, Azraq and Sirhan had drained into the DS in the pre-basalt eruption.

The present drainage pattern of Damascus, Hammad in Jordan and in Syria, Azraq and Sirhan Basins flows toward the borders of JAD basaltic flows (Fig. 3). The figure shows that during the pre-basalt eruption era (by eliminating the basalts), the drainage was directed toward the west.

The topographic elevation model (Fig. 4) shows that the basaltic heights of JAD form a barrier, which blocks the water flows of the surrounding catchments lying further N, NE, E and SE of JAD. By eliminating JAD basalts (topographic heights), the topography would slope again toward the Jordan Rift Valley area via the Yarmouk and the Zerka River gorges (Fig. 1).

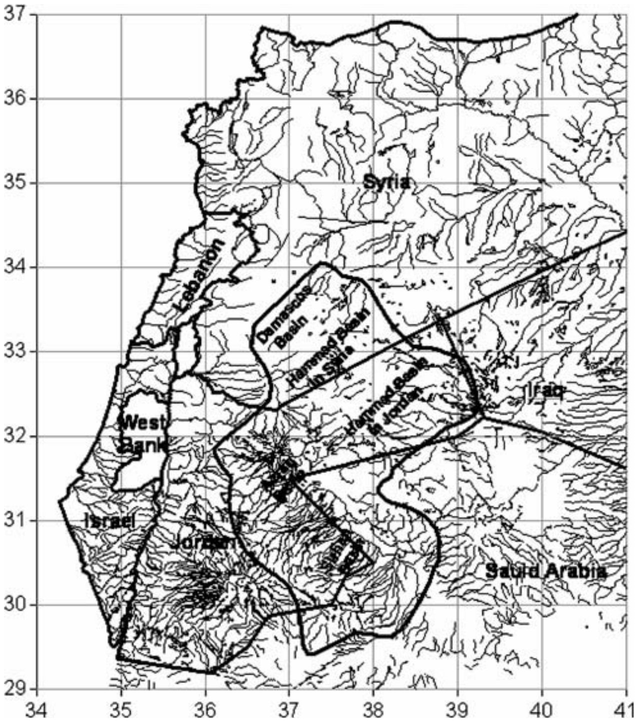

Fig. 3 The drainage pattern of Damascus, Hammad, Azraq and Sirhan Basins, which is directed toward the borders of the basalts of JAD

The topography of the base of the basalt flows in the JAD area and its surroundings (BGR 1997) slopes toward the center of the eruptions underneath the JAD (Fig. 5). The area underlying JAD shows collapses, which form a topographic depression. This depression had not existed during the pre-eruption era, because it otherwise would have been filled with sediments received from the huge surrounding catchment (tens of thousands of square kilometers).

If the pre-basalts terrains were restored, then the water flows of the larger catchments mentioned above would drain again into the Yarmouk and Zerka Rivers, tributaries of the Jordan River, and hence into the DS (Fig. 6).

"The watershed between the Jordan Rift Valley and the inland drainage has been influenced and moved westward as a result of the eruption of the basaltic mountains of Jabal Druz" (Quennel 1959).

The land relief (base of the basalt flows) along Wadi Dhuleil and its surroundings slopes westward to the Zerka River (Mac Donald 1965). The base of the basalt flows in the area extending as far as Qa Khanna (Fig. 1) slopes west (Al-Bis 2000).

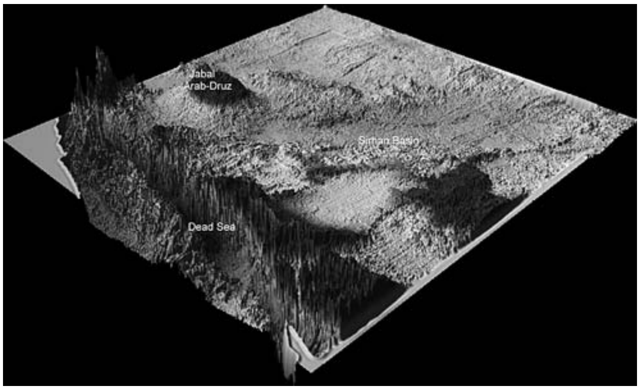

Fig. 4 Digital topographic elevation model of the study area showing that JAD basaltic heights form a barrier to the surface water of the surrounding catchments, which lie to the N, NE, E and SE of JAD. By eliminating the basalts of JAD, the topography and hence the surface drainage would slope toward the Jordan Rift Valley through the gorges of the Zerqa and Yarmouk Rivers

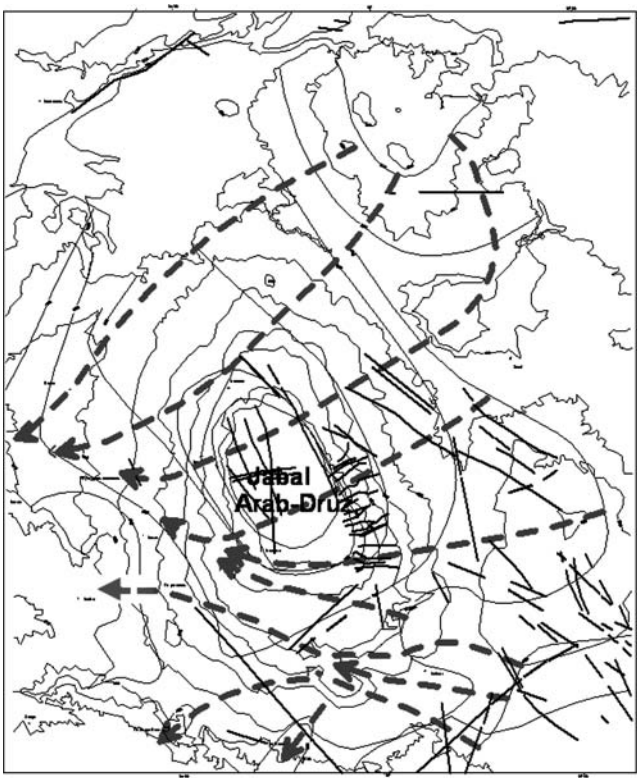

Fig. 5 Topography of the base of JAD (BGR 1997). Surface water would accordingly flow toward west (collapses beneath JAD caused by the mass eruptions are neglected and thought of as restored)

The base of Qa Khanna, now filled with post-eruption sediments, lies 40–50 m below that of Azraq. This means that the Azraq area had drained west during the pre-basalt-eruption era (Mudallal 1968).

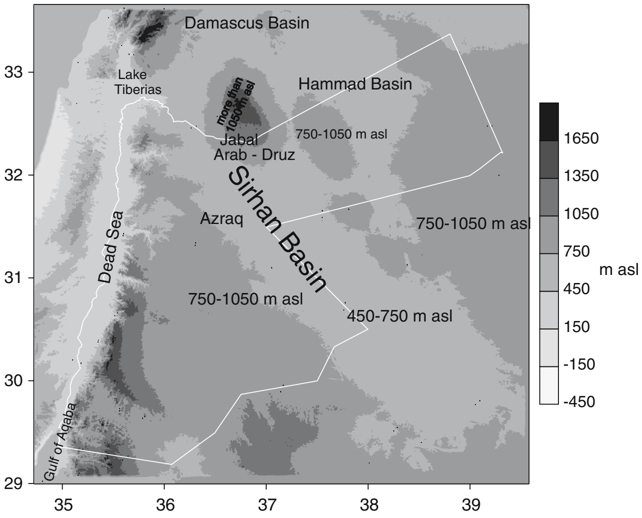

Fig. 6 The areas lying to the N, NE, E and SE of JAD have the lowest topographic levels relative to the further surroundings, indicating the drainage toward the low-lying areas of the Jordan Rift Valley

The above information allows us to conclude that the pre-basalt drainage of Sirhan and Azraq Basins was oriented westward toward Dhuleil, and from there toward the Zerka River and partly toward the Yarmouk River.

Age relationships

The volcanic activity of the JAD area took place in six phases. The first of them started in the Miocene and the fifth continued into the Pleistocene (Bender 1968). The sixth phase covered the areas occupied by the first five phases and extended far beyond them. The six phases continued most probably into the Holocene and can therefore be correlated with the sub-recent gravels of JAD and its surroundings, which were first described by Dubertret (1929).

According to Bender (1968), the last lava flow of JAD may have taken place in prehistoric time, as shown by the C14 age determination of the organic matter contained in the lava. This organic matter had an age of around 4,000 years (de Vries and Barendsen 1954).

The major phase of blocking the drainage to LL by the basalts and lava flows must have taken place when the sixth basalt flow spread and covered all the five older flows in addition to the areas beyond that. Fast accumulation of gravels and rock debris also filled the former drainage system during Late Pleistocene, when strong taphrogenic and strike slip movements along the Jordan Rift Valley took place (Quennel 1959).

As an evidence for this, it was found that alluvial gravels in the Wadi Dhuleil area cover the most recent basalts with a total thickness of 60–80 m (Al-Bis 2000). The high relief produced by the volcanic eruptions, with necks reaching up to 1,300 m above the surroundings, accompanied by taphrogenic activities resulted in strong deposition of the Pleistocene–Holocene rock debris, which consequently blocked the former drainage and created local base levels for surface water at the borders of the lava and basalt flows in the form of playas, mudflats and pools, where the water accumulated, evaporated and was hindered from reaching the Lisan Lake and was lost by evaporation.

Estimation of water discharge before blocking

Assuming that the present climatic conditions were the same during the pre-basalt era, the following drainage systems were contributing water to the LL, in addition to what the DS used to receive four decades ago, during the pre-developmental era of its feeding waters.

The Damascus Basin

This basin consists of two main drainage subbasins, the northwestern which drains toward the center of the basin and the southern, which drains parts of JAD basalt area and flows northward toward the center of the basin, and has a total catchment area of 10,700 km^2 (Fig. 3).

The total surface and groundwater throughput is calculated to be 790 MCM/year, of which 200 MCM/year flow as flood and 590 MCM/year as base flow. The water originates mainly in the northwestern part of the basin: Anti-Lebanon mountains (Koudmani and Hadid 1987). During the pre-eruption era of the basalts, the land surface (base of the basalt flows) showed drainage toward the Yarmouk River (BGR 1997).

Hammad Basin in Syria

This basin consists of the catchment areas, which drain southwest toward the northeastern borders of the basalt flows, and mudflats or temporary water pools formed at these borders. This extensive drainage area measures 29,300 km^2.

It is worth mentioning here that the catchment and drainage systems in the eastern parts of this basin are not well defined because of the very flat morphology.

The average precipitation over the basin (neglecting the effects of the highlands of the basalt mountain of JAD) is calculated to be 110 mm/year (DoM).

The flood flow/rainfall ratio was measured to equal 3.5% (Hammad Basin 1980). Accordingly, the direct flood flow would amount to 112.8 MCM/year. Base flow is not found in the area; but as indicated by the groundwater potential lines (BGR 1997), infiltration water flows toward the west. The average groundwater replenishment in the Hammad has not been calculated in any of the studies. But, considering the catchment area of the DS as a whole with a flood flow of 3.6% and a base flow of 10% of the precipitation amounts over its drainage basin (Table 1) may give an indication of the groundwater replenishment in the Hammad Basin, which then discharges as base flow.

Table 1 gives the runoff/precipitation ratios for the different basins within the present DS drainage area and its surroundings. It shows that base flow to precipitation ratios range from 5% in the Mujib Basin to 29.7% in the Hasa Basin. Such base flows are the results of infiltration to the groundwater bodies and their later discharge through springs and seepages. In the Hammad and Sirhan Basins, the groundwater does not surface within the area, but continues its flow westward toward the DS. The base flow of the whole DS catchment of 10% of precipitation amounts was calculated in the course of study of the NWMP (1977), whereas catchments with sub-catchments similar to those of Hammad and Sirhan, such as Mujib and Hasa, have ratios of 5–7%.

For comparison purposes, the Zerka River has a base flow/precipitation ratio of 12.3%, but it drains the eastern and western parts, where the western parts have a higher base flow/precipitation ratio and the eastern a lower one. Therefore, using a base flow ratio or a recharge/precipitation ratio of about 6% would be a very appropriate approximation. In this case, the throughput of groundwater originating from the Syrian Hammad to the LL system would have, during the pre-basalt eruption phases, amounted to $29{,}300 \times 10^6\ km^2 \times 6 \times 10^{-2} \times 110 \times 10^{-3}\ m^3/year = 193$ MCM/year.

Table 1 Flood and base flow/rainfall ratios for different catchments of the Dead Sea and Lisan Lake

Basin	Total (%)	Flood (%)	Base flow (%)
Dead Sea Basin	13.6	3.6	10
Mujib Basin	10	5	5
Yarmouk Basin	14	6.4	7.6
Hasa Basin	33	3.3	29.7
Zerka Basin	19.6	7.2	12.3
Hammad Basin		3.5	
Dhuleil Basin		3.4	
Azraq Basin		4.2	
Damscus Basin	24.65	6.25	18.4
Sirhan Basin		2.4	4.5

Hammad Basin in Jordan

This basin together with the Hammad Basin in Syria forms one drainage basin. They are dealt with separately because the available information separates them into two different study units. The Hammad Basin in Jordan measures 18,480 km^2 and drains from east westward toward the eastern borders of the JAD basalt cover, where the surface runoffs collect in playas and pools.

The average precipitation over the area is 78 mm/year, with flood flow/precipitation ratio of 3–5% (Hammad Basin 1980), and a recharge/precipitation ratio of 6% resembling that of the Hammad Basin in Syria.

The surface discharge then amounts to 50.5 MCM/year, and the groundwater throughput, prior to the basalt eruption, amounts to 86.5 MCM/year.

Recharge in areas like Hammad and Sirhan is very limited. But barren, jointed and fractured rocks must allow for the infiltration and recharge of aquifers.

Azraq Basin

The basin consists of a catchment extending from JAD to Azraq Oasis, with an area of 11,588 km^2 (NWMP 1977). The average precipitation rates (after discounting the present higher precipitation rates due to the high highlands created by the basalt flows of JAD) would be around 180 mm/year.

The flood flow/precipitation ratio of 4.2% (NWMP) allows to calculate the flood discharge to equal 87.6 MCM/year.

The groundwater throughput lies in between that of the Hammad and Zerka Basins of 6 and 12.3%, respectively, and is assumed to be around 8.1%. The calculated groundwater throughput then equals 168.9 MCM/year.

Sirhan Basin

Although this basin drains into Saudi Arabia to the Sirhan depression, which slopes toward Azraq, there are indications that it used to drain its water during the pre-basalt-eruption era toward Azraq in the northwest and from there toward Dhuleil, Zerka and eventually Yarmouk Rivers on its course to LL.

The evidence for that flow pattern is the flatness of the Wadi Sirhan bottom and its slope toward Azraq Oasis (Fig. 4), of which the base of the basalts slopes toward the Dhuleil, Yarmouk and Zerka Rivers.

The catchment area of Sirhan measures 87,000 km^2 and receives an average rain of 47 mm/year, with a flood flow/precipitation ratio of 2.4% and a groundwater recharge ratio of 4.5% of precipitation. The surface flood flow would accordingly amount to 98 MCM/year and the groundwater throughput to 184 MCM/year.

Summary of flow amounts that were blocked by the basalt flows from reaching the LL/DS system

The surface and groundwater amounts, which were blocked by the basalt eruptions, basalt flows and sediments from reaching the DS system and which had arrived at LL during the pre-basalt-eruption era, are summarized in Table 2.

Lisan Lake

The area occupied by LL at its highest level of –180 m bsl (Fig. 7) during the Upper Pleistocene, 70,000 years ago (Bender 1968; Horowitz 1979), measured around 2,920 km^2 (topographic maps of the RJGC 1986, Jordan).

Precipitation over the Lisan Lake area

If the present climatic conditions were also prevailing during the pre-basalt-eruption era, then the average amount of precipitation at an elevation of –180 m bsl would be

1. 430 mm/year over the northern 1/3 of the LL area,
2. 280 mm/year over the middle 1/3 of the LL area,
3. 220 m over the southern 1/3 of the LL area (RJGC atlas 1986).

The total amount of precipitation over the LL area is then calculated to be around 880 MCM/year (the difference in LL width along its length is neglected). This was calculated by taking the average present annual rainfall gradient between the highlands and the Jordan Valley of 30 mm/100 m difference in topographic elevation by using information from the Department of Meteorology/Jordan (DoM) and the National Atlas of Jordan (RJGC 1986).

Table 2 Flood and groundwater flows blocked by the basalt eruptions from reaching the Dead Sea system (MCM/year)

Basin	Flood flows	Groundwater flows	Total
Damascuas	200	590	790
Hammad/Syria	112.8	193	305.8
Hammad/Jordan	50.5	86.5	137
Azraq	87.6	168.9	256.5
Sirhan	98	184	282
Total	548.9	1222.4	1771.3

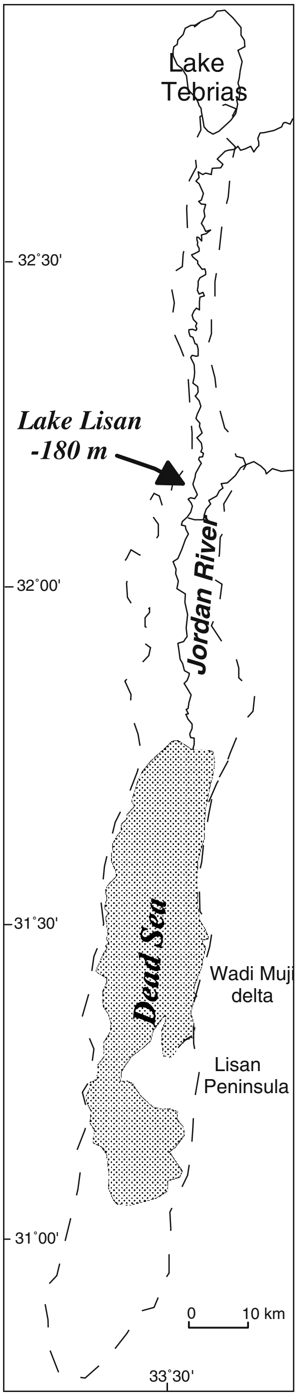

Fig. 7 Area occupied by the Lisan Lake at its level of 180 m bsl

Evaporation from Lake Lisan

The present potential evaporation in the southern DS area is given in the National Atlas of Jordan (RJGC 1986) as 2,050 mm/year for fresh water, decreasing to 1,900 mm/year in the northern Jordan Valley area.

The gradient of the annual evaporation between the highlands at around 800 m a.s.l. and the Jordan Valley is calculated to equal an increase of 38 mm/100 m of drop in elevation.

This means that for a fresh water lake at –180 m a.s.l., the evaporation rate at its southern end would be around 80 mm/year less than the present potential evaporation of 1970 mm/year. In the northern Jordan Valley it would be around 40 mm/year less than the evaporation rate at present or 1860 mm/year (the difference in evaporation between the southern parts of LL and its northern parts is calculated to be 1970 – 1860 = 110 mm/year).

Other conditions must have also played their part, but minor roles in the evaporation process, especially the salinity of LL water, which reduces evaporation the higher it is, and the extension of the LL relative to that of the DS, which means reduced evaporation rates the larger the lake surface area.

For the water balance of LL, fresh water conditions are considered and the present climatic conditions are assumed to have prevailed at the time when the LL existed.

Actual evaporation from Lake Tiberias is calculated to equal 1620 mm/year (using figures of the Unified Development Plan 1953). Therefore, LL lying 30 m above the present level of Lake Tiberias would have an evaporation rate of around 1,600 mm/year.

The difference in the actual evaporation between the northern and the southern parts of LL, as calculated above, would be 110 mm/year.

If the present rate of actual evaporation of Lake Tiberias is applied for the southern part of LL, then the actual evaporation there would be 1,600 + 110 = 1,710 mm/year. Over LL, the average evaporation will then be (1,710 + 1,600)/2 = 1655 mm/year.

Simplified water balance of LL

The incoming water to LL would amount to

1. precipitation over the LL area 880 MCM/year;
2. surface and groundwater from the blocked areas due to basalt eruptions 1777 MCM/year;
3. inflows into DS during the pre-development era; five decades ago (Salameh and Naser 1999) equal 1,890 MCM/year.

The total of incoming water amounts then to 4,547 MCM/year.

The only losses from the exitless lake are caused by evaporation from the lake surface, which as mentioned above are calculated from the actual evaporation from LL to equal 1,655 mm/year. With an area of LL of 2,920 km^2 the evaporation amount would be 4,832 MCM/year.

The difference between the calculated higher evaporation amounts and the lower incoming water amounts of less than 300 MCM/year (around 6.5% of the total incoming water) can either be attributed to different climatic conditions, with a reasonably wetter climate with around 10% more precipitation, or slightly lower temperatures of about 2 °C or both.

The difference can also be attributed to the eventual higher salinity of LL water, because the used figures for evaporation in this article are valid for fresh water and not for brackish or salty water.

Environmental impacts of blocking the drainage system

The blocking of the drainage, whether partial or as a whole, must have its environmental impacts in both the LL and its immediate surroundings and on the blocked catchments themselves.

Implications for the blocked catchments

The blocking by the basalts and clastic sediments created new base levels for both surface and groundwater in the form of oases, pools and mudflats at the borders of the basalt flows. Such base levels are the Azraq, Damascus and Wadi Sirhan oases series among others. These new local base levels served as sedimentation basins for their respective catchments, where a variety of sediment sequences composed of clastics and evaporites have accumulated (Khoury 2003; Salameh 1975).

The water accumulated in the new base levels brought about changes in the local climate and hence in wild animal and plant species. This also helped to establish human settlements as witnessed by the artifacts found in areas surrounding the local base levels (Bender 1968).

Implications for the Jordan Rift Valley

The shrinkage of LL from around 3,000 km^2 to around 1,000 km^2 must have resulted in lower humidity in the Jordan Valley area and its surroundings due to the decreasing evaporation amounts from the shrinking LL lake. This must have caused changes in the types of vegetation, animal life and climatic conditions.

The drop in the water level of LL from 180 to 490 m bsl must have caused a lowering in the groundwater levels in the LL surrounding areas in order to adjust to the new base levels ending in the level of the DS. The drop in the groundwater level to reach at a new equilibrium of the salt LL and DS waters and the fresh groundwater must be around 210 m in height [180 (LL level) – 390 (DS level) = 210 m]. Accordingly, fresh groundwater must have gradually occupied aquifer parts, which before the drop in LL level had been occupied by salty LL water beneath the salt/fresh water interface of that period.

The dropping groundwater level must have also caused springs along the upper reaches of valleys pouring into the Jordan Valley area to cease. This in turn must have deprived humans and animals of their water and resulted in their migration to the downstream area. Generally, that must have caused changes in the habitat.

In the Jordan Rift Valley itself the amount of water reaching LL decreased and hence the sediment loads. And because a good portion of the catchment area became covered by volcanic rocks, the composition of the incoming water and sediments into the Valley must have changed, especially during the volcanic-eruption phases. This may now explain some aspects of the composition of LL sediments and the present composition of the DS water, such as the high bromide concentration (Bender 1968; Bentor 1961).

Summary and conclusions

The present day catchment area of the DS can in no way account for the existence of a larger lake, even if climatic conditions were wetter. A lake such as the Lisan Lake with around 2,920 km^2 in area must get additional inflows in order to exist and continue for tens of thousands of years. Even doubling the amounts of precipitation along the present DS catchment would not have helped sustaining the LL. This indicates that climatic changes during the last 10,000 years alone could not have produced the shrinkage of the LL to form the DS.

The morphology of the surrounding areas of the DS catchment, especially in the northeast and east, which are occupied by the JAD basaltic eruption is unique. Then, from all the surrounding areas of the basalts, Damascus Basin in the north, the Hammad Basin in Syria and Jordan in the east and northeast, Azraq in the south and Sirhan in the southeast, the present drainage pattern is directed toward a center, which is the basalt-covered area. At the borders of the basalt flows with the older rocks and morphology, the floodwaters from all the above-mentioned basins nowadays form pools, oasis and mudflats. This indicates that the surface water drainage prior to the basaltic eruptions was directed toward the basalt area center.

The structure contours of the base of the basalts show topographic slopes toward the center of the basalt eruptions of Jabal Arab Druz.

The collapses, which formed the topographic depression in the original topography underlying the JAD area, are certainly the results of the eruptions and were created during the eruptions of the basalts and not before that. They cannot be older than the eruptions; otherwise sediments of the surroundings would have filled them.

In the area to the south of the basalt flows, the pre-eruption topography shows drainage toward west and northwest, toward the Dhuleil area and the Zerka and Yarmouk Rivers.

Accordingly, the pre-eruption drainage of Damascus, Hammad, Azraq and Sirhan Basins was directed toward the tributaries of the Jordan River and from there to the DS system.

Considering the prevailing climatic conditions and ignoring the effects of the raised Jabal Arab-Druz area, the above-mentioned additional catchments would have contributed a total of 1,771 MCM/year of water to LL. In addition, the area of LL of 2,920 km^2 would have received 880 MCM/year of direct precipitation. To that the inflows to the DS of 1,890 MCM/year in the pre-development era of the water resources (during the last five decades) would make the total inflows to LL equal 4,547 MCM/year. Evaporation from LL, the only losses from the lake's water, would have amounted to 4,832 MCM/year.

The in-balance of incoming versus outgoing water amounts of around 10% may be the result of a wetter or a colder climate. They can also be attributed to the higher salinity of LL water than that of fresh water conditions assumed in the calculations in this article.

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