

DEAD SEA LEVELS DURING THE BRONZE AND IRON AGES

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ABSTRACT. The history of lake-level changes at the Dead Sea during the Holocene was determined mainly by radiocarbon dating of terrestrial organic debris. This article reviews the various studies that have been devoted over the past 2 decades to defining the Dead Sea levels during the Bronze and Iron Ages (~5.5 to 2.5 ka cal BP) and adds new data and interpretation. In particular, we focus on research efforts devoted to refining the chronology of the sedimentary sequence in the Ze'elim Gully, a key site of paleoclimate investigation in the European Research Council project titled Reconstructing Ancient Israel. The Bronze and Iron Ages are characterized by significant changes in human culture, reflected in archaeological records in which sharp settlement oscillations over relatively short periods of time are evident. During the Early Bronze, Intermediate Bronze, Middle Bronze, and Late Bronze Ages, the Dead Sea saw significant level fluctuations, reaching in the Middle Bronze an elevation of ~370 m below mean sea level (bmsl), and declining in the Late Bronze to below 414 m bmsl. At the end of the Late Bronze Age and upon the transition to the Iron Age, the lake recovered slightly and rose to ~408 m bmsl. This recovery reflected the resumption of freshwater activity in the Judean Hills, which was likely accompanied by more favorable hydrological-environmental conditions that seem to have facilitated the wave of Iron Age settlement in the region.

INTRODUCTION

The Dead Sea, a hypersaline (currently 340 g TDS/L) terminal lake located at the lowest elevation on Earth [water level at 427 m below mean sea level (bmsl) in 2014], is the modern remnant of a series of lakes that filled the tectonic depressions situated along the Dead Sea transform during the late Quaternary (Neev and Emery 1995; Stein 2001, 2014a,b). The watershed of the lakes that filled the Dead Sea Basin (Figure 1) is located between the desert belt and the Mediterranean climate zone and receives water and sediments from both regions. Thus, the Dead Sea, which is considered a “terminal trap” of these waters and sediment fluxes, is regarded as a regional gauge that records in its sedimentary archives the late Quaternary climate-hydrological history of these regions [e.g. Stein 2001, 2014a,b; Bookman (Ken-Tor) et al. 2004; Migowski et al. 2006; Kushnir and Stein 2010; Haliva-Cohen et al. 2012; Langgut et al. 2014; Neugebauer et al. 2014].

In this review, we focus on the lake-level history of the Dead Sea during the Bronze and Iron Ages (~5.5 to 2.5 ka cal BP). This period saw dramatic changes in the regional climate and in the development of human cultures. During the Early Bronze Age, cities such as Jericho, Bab edh-Dhra', and Arad prospered and olive horticulture spread in the Samaria and Judean highlands (Neev and Emery 1995; Rosen 2007). Numerous settlements flourished in the Judean Hills and in the northern Negev Desert as well as in the entire circum-Mediterranean (Finkelstein and Gophna 1993; Finkelstein 1995; Offer and Goossens 2004; Issar and Zohar 2007). In general, the climate was significantly more humid than in modern times (Litt et al. 2012). The Intermediate Bronze Age is described as a nonurban interlude, with low settlement activity, between the urban civilizations of the Early Bronze and the Middle Bronze Ages (Dever 1980). At that time, moderate climate conditions prevailed (Langgut et al. 2015). This low settlement scenario continued into the beginning of the Middle Bronze Age I. Settlement activity increased in the Middle Bronze Age II–III, with re-expansion to more southern areas (Gophna and Portugali 1988; Finkelstein and Langgut 2014).

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The Iron Age in Israel: The Exact and Life Sciences Perspective

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Figure 1 The catchment area of the Dead Sea (~40,000 km²) (brown line), the maximum extent of the Pleistocene paleo-Dead Sea (blue shading), and main sites on the western shores of the Dead Sea mentioned in the paper. Note that the Sea of Galilee is also referred to as Lake Kinneret. The Hula Lake is depicted as it was before its desiccation in the 1950s (due to human interference).

The Late Bronze Age is characterized by low settlement activity with a collapse of the entire settlement system towards the end of the period, when many sites were abandoned altogether. This collapse is largely contemporaneous with a drop in Dead Sea level and increasing aridity (Litt et al. 2012; Langgut et al. 2014). This period features a decrease in olive cultivation in the Samaria and Judean highlands (Litt et al. 2012). Aridity also affected the northern regions of the Dead Sea watershed (Schwab et al. 2004; Langgut et al. 2013, 2014, 2015), as well as other large regions all over the eastern Mediterranean, where prominent civilizations had previously thrived, e.g. the Hittite Empire in Anatolia, Cyprus, the Syrian coast, and Egypt (Ward and Joukowsky 1992; Drews 1993; Kaniewski et al. 2010, 2013). Immigrants from the Aegean Basin—the Sea Peoples—settled along the coastal regions of the Levant at the time of transition to the Iron Age (Stager 1995). A contemporary wave of settlement, representing the (proto)-Israelites, characterizes the Samaria and Judean Hills (Finkelstein 1995). This time period saw an increase in humidity in the Dead Sea area (Neumann et al. 2007; Litt et al. 2012; Langgut et al. 2014) as well as in northern Israel (Schwab et al. 2004; Langgut et al. 2013).

The focus of this review is the reconstruction of the Dead Sea level during the Middle Bronze to Iron Ages. In particular, we focus on research efforts devoted to refining the chronology of the sedimentary sequence in the Ze'elim Gully, a key site of paleoclimate investigation in the ERC Reconstructing Ancient Israel project. We compile the chronological data, mainly radiocarbon ages along with

the information on shoreline elevations, and link it with the cultural history in the southern Levant. The sedimentological and chronological data were derived from wadi (ephemeral stream) exposures and boreholes at several sites along the retreating western shores of the modern Dead Sea: mainly at the Ze'elim, Ein Gedi, and Ein Feshkha shores (Figure 1).

LIMNOLOGICAL SETTING OF THE HOLOCENE DEAD SEA

The Holocene Dead Sea evolved from Lake Lisan, its Pleistocene precursor, which filled the tectonic depressions along the central Dead Sea transform during the last glacial period ~70–14 ka cal BP (Haase-Schramm et al. 2004; Torfstein et al. 2013a,b). At its maximum elevation of ~160 m bmsl, Lake Lisan extended over the entire Dead Sea–Jordan–Kinnerot Basins from Hazeva in the south to the Bethsaida (Beteicha) Valley in the north, converging with the Sea of Galilee (Lake Kinneret; freshwater) (Bartov et al. 2003; Hazan et al. 2005; Stein 2014b). At ~14–13 ka cal BP, Lake Lisan declined from its high stand to below 450 m bmsl, rose back during the Younger Dryas, then declined again at ~11–10 ka cal BP (depositing a thick sequence of salts), and recovered in the Neolithic period (Stein et al. 2010). During the Holocene, the lake evolved through a complex limnological history with surface levels fluctuating between ~430 and 370 m bmsl [Bookman (Ken-Tor) et al. 2004; Migowski et al. 2006; Kushnir and Stein 2010]. The surface levels reflect the net freshwater influx (precipitation minus evaporation) into the lake that in turn mainly reflects the precipitation over the larger watershed regions. At the beginning of the 20th century, the lake stood at ~390 m bmsl and covered the southern shallow basin of the Dead Sea. Yet, during significant parts of the Holocene the southern Dead Sea was dry or precipitated salts (Neev and Emery 1995). A topographic sill at ~402–403 m bmsl separates the relatively deep northern basin and the shallow southern basin of the Dead Sea. When the lake level is high enough for the water to cross the sill, additional water is subjected to evaporation (similar to the current situation at the evaporation ponds of the Dead Sea Works potash plant). Thus, a significant increase in the water supply to the lake is required for the lake to rise above the sill and additional evaporation at the southern basin buffers lake-level rise (Bookman [Ken-Tor] et al. 2004).

It is noteworthy that during the past few hundred years the Dead Sea was characterized by salinity-driven stratification and only in 1977 did the lake overturn and attain its current configuration. The layered configuration reflects enhanced freshwater input to the lake. This is accompanied by supply of bicarbonate and sulfate ions that result in the precipitation of primary carbonate and gypsum in the lake (Stein et al. 1997; Barkan et al. 2001). When the supply of freshwater loaded with carbonate is limited, almost no aragonite precipitates into the lake (e.g. Waldmann et al. 2007; Stein 2014a).

RECONSTRUCTION OF DEAD SEA WATER LEVELS – BACKGROUND

General

The reconstruction of water-level curves of the ancient lakes that occupied the Dead Sea Basin in the past hundreds of thousands of years has been a major objective of Dead Sea researchers over the past decades, reflecting the potential of this curve to serve as a regional hydrological gauge [e.g. Bowman 1971; Neev and Emery 1995; Machlus et al. 2000; Frumkin et al. 2001; Bartov et al. 2002; Bookman (Ken-Tor) et al. 2004; Torfstein et al. 2009, 2013a; Waldmann et al. 2009]. The changes in the supply of water and sediments to the lake reflect the hydroclimate history of the watershed during Quaternary times and in turn are reflected in the lakes' limnology (composition and water levels) and sedimentology (sedimentary facies, Figures 2a,b) (Stein et al. 2001; Stein 2014a,b and references therein). A positive correlation exists between precipitation from 1870 until 1964—just before human intervention in the flow of the Jordan River—and recorded Dead Sea levels (Klein and Flohn 1987; Enzel et al. 2003). This is so despite all potential complexities that are involved in

the “transfer” of the hydroclimate configuration of the watershed into the lakes’ limnological and sedimentological properties. The lake rose when annual precipitation in Jerusalem exceeded $\sim 650 \pm 100$ mm and receded when the annual precipitation dropped to $\sim 450 \pm 100$ mm (Enzel et al. 2003). The most significant lake rise of the past decades (since the beginning of human intervention in the regional water balance) occurred in the winter of 1991/2, when anomalous amounts of rain fell in the watershed (e.g. ~ 1500 mm in Jerusalem compared to the annual mean of 550 mm). That winter the Degania Dam, which prevents the flow of the Jordan River out of the Sea of Galilee, was opened and the Dead Sea level rose by more than 1.5 m.

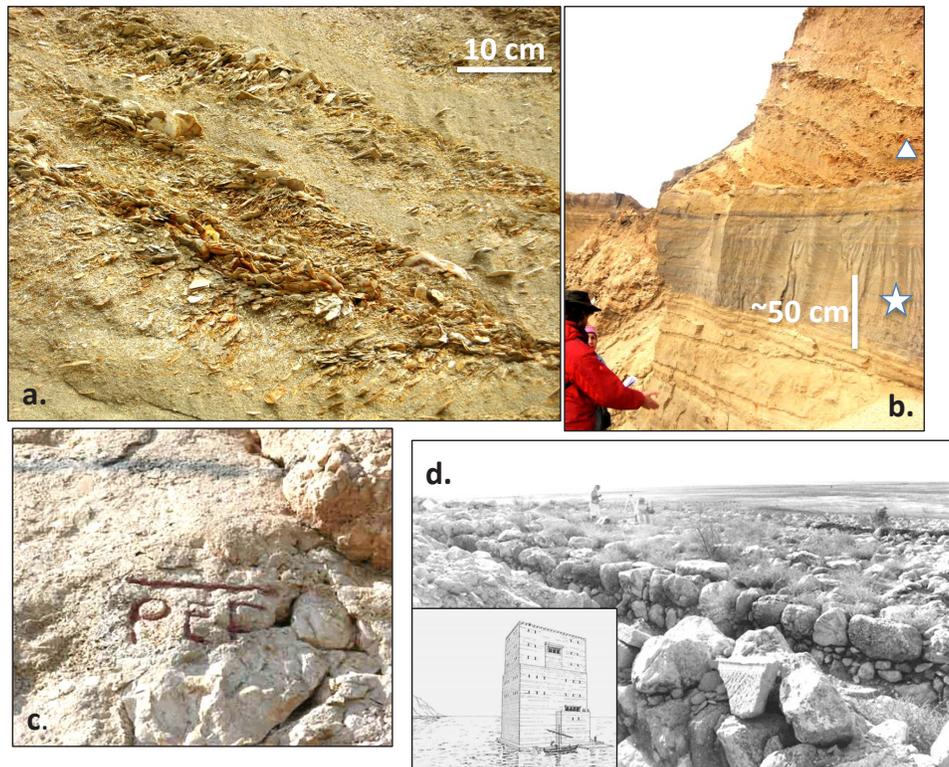


Figure 2 (a) Fragments of aragonite crusts in the Late Bronze Age beach ridge at the Ze’elim Gully outcrop; (b) transition from lacustrine fine clastics and aragonite laminae (star marking the Middle Bronze Age) to beach deposition (triangle marks the Late Bronze Age); (c) the PEF (British Palestine Exploration Fund) rock that marked the levels of the Dead Sea at the turn of the 20th century (~ 390 m bmsl); (d) Rujm el-Bahr Late Hellenistic–Early Roman anchorage site on the northern Dead Sea shore (in the inset: reconstruction of the anchorage and tower by Hirschfeld 2006).

At the turn of the 20th century, the British Palestine Exploration Fund (PEF) expedition began a 14-yr program to measure the level of the Dead Sea. A baseline level was established on a rock located above the modern road (No. 90) on the western coast near the Ein Feshkha Nature Reserve (Figure 2c). The marker is ~ 31 m above the current (2014) level—a difference that reflects the human intervention in the watershed. Yet, the high stand at the end of the 19th century was at a uniquely high level, since the lake stood at lower levels during most of the previous 400 yr.

The reconstruction of earlier lake levels requires identification and dating of ancient shorelines. Historical features such as piers or harbors can also be used for this purpose. At the Dead Sea, classic

examples are the Late Hellenistic–Early Roman anchorage piers at Rujm el-Bahr (Figure 2d) (at 393.1 m bmsl, placing the lake level of that time at ~394 m bm) and at Khirbet Mazin (390–394 m bmsl) (Hirschfeld 2006). A pioneering investigation into Dead Sea levels was attempted by measuring and dating wide versus narrow cave passages in the Mt. Sedom salt diapir (Frumkin et al. 1991, 2001; Frumkin 1997). Precise lake-level elevation reconstruction using salt cave data was hampered by uncertain rates of diapir rise (Frumkin et al. 2001). Beyond the historical data and cave evidence, the lake-level reconstruction is based on sedimentological features such as shoreline markers or near-shore sediments (Figures 2a,b). Comprehensive descriptions and reviews of methods of identification of the shoreline deposits characteristic of the Dead Sea Basin are given by Machlus et al. (2000), Bookman (Ken-Tor) et al. (2004), and Bookman et al. (2006). For the purpose of this review, we use the following criteria: (1) laminated detritus, laminated primary aragonite and detritus, indicating a few meters or more water depth; (2) silty-sandy detritus, indicating very shallow near-shore depths; and (3) sand, small pebbles, aragonite crusts, and wave-related structures (e.g. beach ridges, ripple marks), indicating former shorelines. Note that primary aragonite laminae precipitation, whether as lacustrine aragonite laminae or encrusted aragonite at the shore, require continuous supply of freshwater loaded with bicarbonate to the lake (Stein et al. 1997; Barkan et al. 2001; Torfstein et al. 2013a).

The dating of the shoreline markers is accomplished by several methods such as ^{14}C (discussed in the following sections) or the U-Th dating method, which is applicable for the primary aragonites deposited from the lake waters or encrusting pebbles and organic debris (Figure 2a). Based on these principles, level curves were reconstructed for the lakes that occupied the Dead Sea and Kinnarot basins during the past ~140 ka. These reconstructions included works by Neev and Emery (1995), Machlus et al. (2000), Frumkin et al. (1991, 2001), Bartov et al. (2002, 2003), Bookman (Ken-Tor) et al. (2004), Hazan et al. (2005), Waldmann et al. (2007, 2009), Stern (2010), and Torfstein et al. (2013a). Over this time interval, which encompasses the last interglacial period (Lake Amora–Samra), the last glacial (Lake Lisan), the post-glacial, and the Holocene (the Dead Sea), lake level fluctuated between 160 m bmsl and lower than 450 m bmsl. Recent studies of a core drilled in the deep basin of the Dead Sea suggest a possible extreme low stand of the last interglacial Lake Samra (the ICDP drilling project, Stein et al. 2011; Torfstein et al. 2015). Here, we focus on the chronology of the mid- to late-Holocene Dead Sea levels, when the Bronze and Iron Age cultures, which feature processes of settlement expansion and collapse, developed in the region.

RADIOCARBON DATING OF THE HOLOCENE DEAD SEA

The sediments comprising the Holocene sections deposited from the Dead Sea are termed the Ze'elim Formation [Yechieli et al. 1993; Bookman (Ken-Tor) et al. 2004]. The formation comprises sequences of laminated detritus (transported to the lake by seasonal floods) and primary aragonite, gypsum, and salt (details in Migowski et al. 2004, 2006; Haliva-Cohen et al. 2012; Neugebauer et al. 2014).

The chronology of the Ze'elim Formation is essential for the reconstruction of the Dead Sea level curve. Paleoclimate, paleoseismology, and palynology studies have been carried out using these indispensable outcrops (e.g. Enzel et al. 2000; Ken-Tor et al. 2001a,b; Neumann et al. 2007; Kagan et al. 2011; Langgut et al. 2014). The sediment exposures are rich in organic debris of seeds and wood that were transported from the surrounding mountains or the close marginal terraces by runoff and winter floods [Ken-Tor et al. 2001a,b; Bookman (Ken-Tor) et al. 2004; Migowski et al. 2006]. Early ^{14}C dating of Holocene sediments from cores drilled at the southern (shallow) basin of the Dead Sea was undertaken by D Neev and W C Broecker (published in Neev and Emery 1995). Yechieli et al. (1993) dated organic debris from a core (DSIF) drilled at the western side of the Ze'elim Plain (Figure 1), and reported several ^{14}C ages of post-glacial to early Holocene times. These researchers

also dated driftwood from the Ze'elim Gully floor near the Dead Sea shores in order to examine the residence time of wood at the shore environment and to estimate any delay between time of organic matter demise and incorporation into the sediment. All five driftwood samples yielded percent modern carbon (pMC) between 102 and 155, signifying that modern shore driftwood is post-bomb (younger than 40 yr old at time of sampling) and that transport time is insignificant for dating of geological and paleolimnological events (Yecheieli et al. 1993). Ken-Tor et al. (2001b) also demonstrated a short lag period between the beginning of ^{14}C decay and the deposition of the organic debris (usually less than a few decades, and no more than 2 centuries). In most of the chronological studies, researchers aimed to date "short-lived" organic debris (seeds, twigs) where equilibrium with the atmosphere and short transport time to the shoreline sediments can be assumed. We suggest that lacustrine sediments incorporate organic fragments recently washed off-shore, while near-shore lithologies, such as beach ridges, tend to also accumulate recycled organic remains.

The Ze'elim Gully has been a major site of study of the limnological and sedimentological history of the mid- to late-Holocene Dead Sea. This stems from its location at the Ze'elim Plain on the fringe of the fan delta of Nahal Ze'elim, a major wadi (ephemeral stream) that drains the southwest regions of the Dead Sea watershed, and from its rapid incision into the Ze'elim Plain (the previously submerged part of the fan delta), which comprises lacustrine and fluvial sedimentary facies. In the 1990s, the exposed gully walls were only 4 m deep beneath the plain surface. Ken-Tor et al. (2001a,b) and Bookman (Ken-Tor) et al. (2004) provided a detailed chronology of the sedimentary sections in two of the southern gullies that dissect the Ze'elim Plain. In their reconstruction of the paleoseismic history from these sections, through identifying and ^{14}C dating of the seismites, Ken-Tor et al. (2001a) produced an age-depth model based on 24 ^{14}C ages of short-lived plant remains. Remarkable correlation of all historically documented earthquakes to either sediment deformations or to depositional hiatuses supports Ken-Tor et al.'s (2001b) argument for a short (<50 yr) interval between plant death and burial in the sediment. Bookman (Ken-Tor) et al. (2004) used the chronological information from the Ze'elim Gully and from Nahal David outcrop (near Kibbutz Ein Gedi) (Figure 1), as well as identification and measuring of elevation of shoreline indicators, to produce a lake-level curve for the late Holocene (past 3000 yr) Dead Sea.

In December 1997, a joint team from the GFZ-Institute in Potsdam, Germany, and the Hebrew University, Israel, carried out a drilling campaign along the Dead Sea shores, with the aim of recovering the entire Holocene sedimentary record. Migowski (2001) and Migowski et al. (2004) presented a detailed sedimentary description and ^{14}C chronology of the 20-m-long core recovered at the Ein Gedi spa shore, covering the past 10,000 yr. Migowski et al. (2006) combined the lithological and ^{14}C -chronological information from three cores—Ein Gedi (DSEn), Ein Feshkha (DSF), and Ze'elim (DSZ)—to produce a lake-level curve for the entire Holocene Dead Sea. The DSEn core was dated by 20 ^{14}C ages and by laminae counting of ~1500 yr, from 200 to 1300 CE. Migowski et al. (2004) reported the appearance of various types of seismites along this core and a laminae-counted floating chronology of the seismites was matched with the historic earthquake catalog. The best-fit gave model ages younger than their calibrated ^{14}C ages, and thus in the time interval of ~3.0 to 0.2 ka BP the authors shifted the age-depth curve by 50–200 yr. At the interval discussed herein, there is only a small 50-yr shift. Other studies found no significant reworking time of the organic debris in the Ze'elim Formation (Ken-Tor et al. 2001a,b; Kagan et al. 2011; Langgut et al. 2014; Neugebauer et al., in press).

Ongoing gully incision at Ze'elim and Ein Feshkha alluvial fan plains, responding to the continuous anthropogenic drop of the Dead Sea, exposed new outcrops (Figure 3) previously only observed in cores. Neumann et al. (2007) and Kagan et al. (2011) took advantage of these new outcrops and

provided additional insight into the chronology, palynology, paleoclimate, and paleoseismology of the Late Holocene.

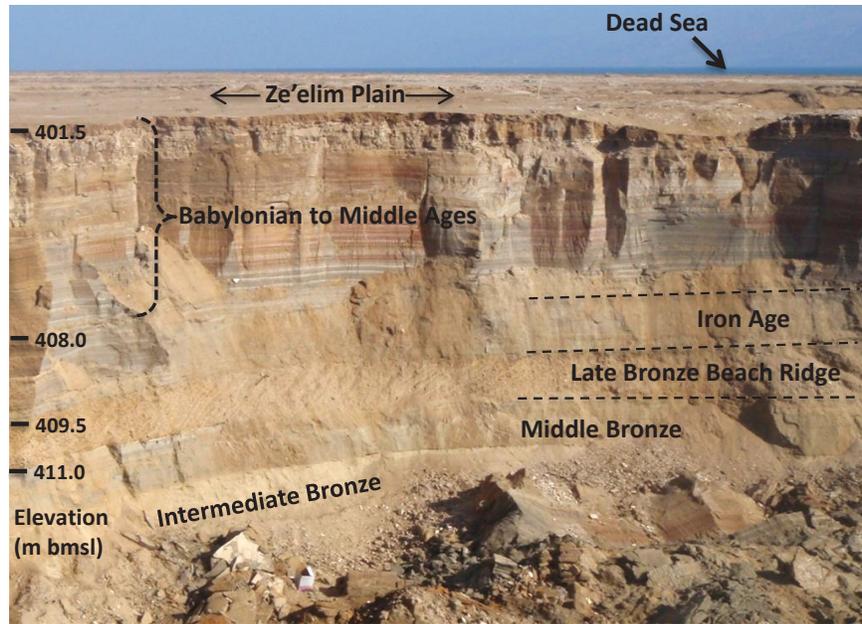


Figure 3 ZA3 outcrop section, with main archaeological periods and elevations

^{14}C dating of the more lake-ward Ze'elim Gully outcrop (ZA2) was established down to 10.5 m below the plain surface (12 ages) in the palynological study of Neumann et al. (2007) and the paleoseismic study of Kagan et al. (2011). The ZA2 section is a few hundred meters east of the Ze'elim A section (ZA1) [Bookman (Ken-Tor) et al. 2004], making it more lacustrine, but interfingering with shore facies. The section showed mostly continuous deposition, with perhaps minor hiatuses not identified by dating and one long hiatus ($\sim 7\text{--}4$ ka BP). This hiatus is, at least in part, only local since at the nearby ZA3 section part of this time interval is represented. At the Ein Feshkha Gully, Neumann et al. (2007) and Kagan et al. (2011) dated nine horizons along an almost 6-m section (from about 3300 to 550 yr cal BP), showing essentially continuous lacustrine deposition. In an effort to improve the chronology of the Ze'elim and Ein Feshkha sections, Kagan et al. (2010, 2011) produced Bayesian age-depth deposition models using the OxCal P_{sequence} model (see Bronk Ramsey 2008). In this manner, the Bayesian package provides a model age for every depth in the section, such as the earthquake marker depths, with a narrow uncertainty envelope. The application of this model allowed correlation of seismites to tens of historic earthquakes and an intrabasin correlation and comparison of seismite occurrence and characteristics at three sites. In a palynological-sedimentological study carried out as part of the Reconstructing Ancient Israel project, more than 10 ages were reported covering the Bronze and Iron Ages time interval in the Ze'elim Gully (ZA3 section) (Langgut et al. 2014).

LAKE LEVELS DURING THE BRONZE AND IRON AGE INTERVAL

General

This section summarizes the chronological and shoreline information established for the Bronze to Iron Age time interval in the Ze'elim Gully. The sedimentary sections were also studied for palynological investigation as reported by Langgut et al. (2014), and reviewed in this issue by Langgut et

al. (2015). A stratigraphic, mineralogical, and isotopic study of this interval is given by Kagan and colleagues in a forthcoming publication.

For the purpose of establishing a lake-level curve, the shoreline elevations and their ages obtained from the Ze'elim gullies were integrated with ^{14}C ages from other lacustrine and off-shore exposures from various sites: the Ein Gedi core (Migowski et al. 2006), the Ein Qedem outcrop (Stern 2010), the Ein Feshkha core (Migowski et al. 2006), the Ein Feshkha outcrop (Neumann et al. 2007; Kagan et al. 2011), the Arugot outcrop (Bartov et al. 2007), and the Darga outcrop (Kadan 1997; Enzel et al. 2000; Bartov et al. 2007). ^{14}C ages relevant to this discussion are listed in Table 1.

Late Chalcolithic Period and Early Bronze Age (~6000–2500 BCE; ~8 to 4.45 ka cal BP)

The time interval of the Chalcolithic period through the Early Bronze Age (Table 2) is not exposed in the Ze'elim Gully, where deposition was discontinuous at that time. Lake level was therefore estimated from drilled cores in the Ze'elim Plain, Ein Gedi spa shore, and Ein Feshkha (Migowski et al. 2004, 2006; Litt et al. 2012). Migowski et al. (2006) reconstructed an “approximate” level curve for the time intervals that lack direct shoreline evidence (Figure 4). Integrated with the evidence from the Nahal Darga exposure (Bartov et al. 2007) it appears that the Dead Sea rose from its early Holocene low stand (~8–6.5 ka cal BP) to its mid-Holocene high stand at ~6.3 ka cal BP. The low-stand period is characterized by gypsum and sand layers in the cores and supported by evidence from a salt tongue revealed in a core from the southern Dead Sea Basin (Neev and Emery 1995). At ~6.3 ka cal BP, laminated lake sediments exposed at the Darga and Arugot terraces mark a significant lake transgression to ~370 m bmsl (Bartov et al. 2007). Neev and Emery (1995) report on a lacustrine transgression at ~6.3 to 6.0 ka BP that interrupted the salty south basin of the Dead Sea. The transition to the Early Bronze Age is marked in the Ein Gedi core by deposition of laminated aragonite, indicating the onset of a significant lake rise at ~5.2 ka cal BP (Migowski et al. 2006). This rise was sufficient to cause the lake to cross the sill at ~4.9 ka cal BP (Neev and Emery 1995). This rise is corroborated by data of wide and high cave passages at Mt. Sedom, dated by wood fragments embedded in flood deposits from the caves (Frumkin et al. 1991; Frumkin 1997) and by pollen archives indicating especially high arboreal pollen percentages (Litt et al. 2012; Langgut et al. 2014). The humid period was characterized by the rise of large urban centers in the southern Levant (de Miroshchedji 1999; Greenberg et al. 2011).

Intermediate Bronze Age (~2500–1950 BCE; ~4.45 to 3.9 ka cal BP)

At ~4.4 ka cal BP, the lake dropped sharply based on gypsum deposition in the Ein Gedi core (Migowski et al. 2006) and microconglomerate, pebbles, and abundant gypsum precipitation at ~415–416 m bmsl at the Ein Qedem spring system outcrop (Stern 2010). This low stand is also indicated by narrower cave passage morphology at Mt. Sedom (Frumkin et al. 1991).

At the Ze'elim Gully (ZA3 section), in the middle of this time period, there is a 40-cm sequence of lacustrine detrital sediment representing a short lake rise. This event is also reflected in the Ein Gedi core lithology (at 5.8 m depth; Migowski et al. 2006), but was not noted in previous lake-level curves. A significant increase in olive pollen in the Ein Gedi core (Litt et al. 2012) and the Ze'elim Gully (Langgut et al. 2014) corroborates this event. Then, at ~4.1 ka cal BP, the lake level dropped, depositing gypsum and pebbles at the Ein Qedem site (415.5 m bmsl; Stern 2010) and shore sediments at the Ze'elim Gully section. A drought of more than 100 yr at the end of the Intermediate Bronze Age is also recorded in the isotopic composition of tamarisk wood from the Mt. Sedom Cave (southern Dead Sea) (Frumkin 2009). Carbon isotopes measured in speleothems from the Soreq Cave (Judean Hills) indicate a sharp rise in desert vegetation at this time (Bar-Matthews and Ayalon 2004).

Table 1 ¹⁴C age data for eight outcrop and core sites reviewed in this paper. Organic debris, e.g. leaves, twigs, and thin branches, were used for ¹⁴C dating. ¹⁴C ages are reported in conventional ¹⁴C yr (before present = 1950), in accordance with international convention (Stuiver and Polach 1977).

Lab #	Sample name	Location	Elevation [‡]	¹⁴ C age yr BP ± 1σ	Calibrated 2σ age range	Reference	Sampling location
RTT 5188	ZA-20	ZA2	409	2345 ± 40	2503–2289 BP*	K11	lacustrine, above BR
RTT 5189	ZA-18	ZA2	410	2820 ± 40	2935–2775 BP*	K11	lacustrine, above BR
RTT 5688	ZA-1071	ZA2	411	3320 ± 55	3690–3415 BP	this study	within BR
ZA871	ZA-871	ZA2	411	3175 ± 30	3453–3352 BP	N07,K11	within BR
RT 5191	ZA-51	ZA2	411	3500 ± 75	3974–3584 BP	N07,K11	silt & ac, within BR
RTT 5192	ZA-5	ZA2	412	3540 ± 45	3965–3695 BP	N07,K11	lacustrine, below BR
RTT 5193	ZA-10	ZA2	413	3475 ± 45	3863–3636 BP	N07,K11	sandy, ac, beach sediments, below BR
RTK 6325-1	FDd I(230)	ZA3	411	2895 ± 50	3210–2881 BP	LG14	lacustrine, above BR
RTK 6325-2	FDd II(230)	ZA3	411	2935 ± 50	3320–2963 BP	LG14	lacustrine, above BR
RTK 6324	FDd (164)	ZA3	411	3070 ± 50	3394–3084 BP	LG14	lacustrine, above BR
RTK 6323	FDa I (-5)	ZA3	413	3780 ± 50	4383–3985 BP	LG14	lacustrine, below BR
RTK 6323-2	FDa II (-5)	ZA3	413	3800 ± 50	4410–4000 BP	LG14	lacustrine, below BR
RTK 6459-2	FDa (-22)	ZA3	413	3790 ± 50	4410–3990 BP	LG14	silty lacustrine, below BR
AA42807	Ze'elim 27	ZA1	408.5	2775 ± 37	2960–2790 BP	BM04	above BR
AA42809	Ze'elim 28	ZA1	410	3130 ± 44	3470–3240 BP	BM04	youngest within BR
AA42806	Ze'elim 29	ZA1	410	3220 ± 36	3550–3360 BP	BM04	lacustrine, directly below BR
AA42810	Ze'elim 30	ZA1	410	3703 ± 37	4150–3920 BP	BM04	lacustrine, below BR
AA43160	Ze'elim B 8	ZB	408	2977 ± 48	3330–2990 BP	BM04	youngest within BR
RT5183	EFW-530	EFE	418	2850 ± 65	3065–2789 BP*	K11	lacustrine, 40 cm above gypsum domes
R.I.C.H.B.	Eh2	AR	374	5630 ± 40	6310–6450 BP	BT04	shore marker
R.I.C.H.B.	Eh3	AR	372	3330 ± 50	3630–3480 BP	BT04	shore marker
KIA32726	DS-F-B6o-73	EFC	418	2873 ± 88	3211–2862 BP*	K11	above sand and aragonite crusts
KIA11629	DS-En A5o-7	EGC	419	3065 ± 40	3377–3084 BP	M06	lacustrine, above sand
KIA9123	DS-En B4-78	EGC	419	3545 ± 35	3956–3701 BP	M06	sand in core
982G	Mi-15	MSd		3100 ± 55	3446–3172 BP	F91	wide cave passages
AA75250	N-2-240	EQ	415	3188 ± 35	3562–3435 BP	OS10	conglomerate
Mi12	982E	MSd		3030 ± 50	3442–3077 BP	F91	wide cave passages
810D	SN5	MSd		3580 ± 80	4141–3646 BP	F91	narrow cave passages
886C	MM2	MSd		4250 ± 95	5214–4451 BP	F91	wide cave passages
886F	Me3	MSd		4350 ± 75	5286–4745 BP	F91	wide cave passages
810E	Qo1	MSd		4360 ± 140	5440–4570 BP	F91	wide cave passages
848D	MS1	MSd		4440 ± 120	5465–4823 BP	F91	wide cave passages

Notes: All dates from wood pieces and plant fragments. BP = before present, calculated as AD 1950, as customary. BR = Late Bronze Beach Ridge at Ze'elim Gully. ZA2 = Ze'elim Gully A, south side, lakeward; ZA3 = Ze'elim Gully A, north side, lakeward; ZA1 = Ze'elim Gully A, south side, landward; ZB = Ze'elim Gully B, south side; EFE = Ein Feshkha Nature Reserve Gully; AR = Arugot River; EFC = Ein Feshkha core; EGC = Ein Gedi core; EQ = Ein Qedem; MSd = Mount Sedom salt caves. References: LG14 = Langgut et al. 2014; BT04 = Bartov 2004; BM = Bookman (Ken-Tor) et al. 2004; M06 = Migowski et al. 2006; N07 = Neumann et al. 2007; K11 = Kagan et al. 2011; F91 = Frumkin et al. 1991; OS = Stern 2010. Calibration of ZA2 previously published ages, as in K11. Ages marked with * are model ages (Bayesian age-depth modeling, see Kagan et al. 2011). ‡ Absolute elevation m below main sea level, rounded to 1 m. The elevations of the MDd (Mt Sedom salt caves) samples are not given since they were measured upstream from the relict cave outlets and due to uncertainties in diaper uplift corrections (Frumkin et al. 1991; Frumkin 1997).

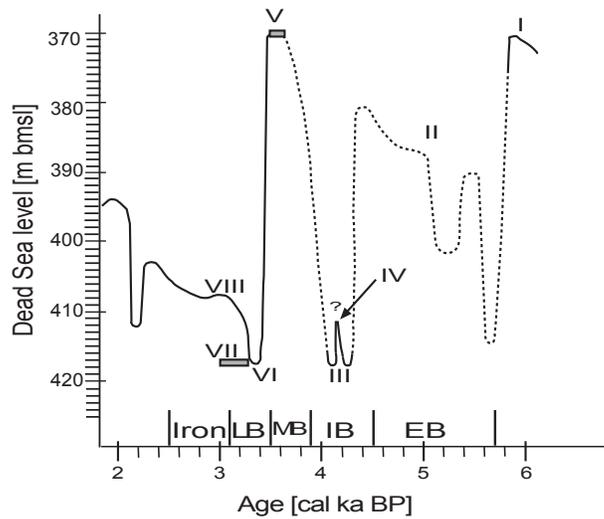


Figure 4 Dead Sea levels during the Bronze and Iron Ages. Lake levels are based on previous works by Bookman (Ken-Tor) et al. (2004) [Ze'elim and Nahal David (Ein Gedi) outcrops], Bartov (2004) [Arugot and Darga outcrops], Migowski et al. (2006) [DS cores], Stern (2010) [Ein Qedem outcrop], Kushnir and Stein (2010)'s interpretation, and on new data (Ze'elim outcrops) and interpretations from this study. References for some specific parts of the curve: I - Bartov et al. 2007; II - Frumkin et al. 1991; Migowski et al. 2006; III - Stern 2010; IV- this study; V - Bartov 2004; VI - Stern 2010; VII - beach ridge, this study and Bookman (Ken-Tor) et al. 2004; VIII - Bookman (Ken-Tor) et al. 2004. For ages, see Table 1. Dashed part of the curve is based on relative lake-level fluctuations.

During the Intermediate Bronze Age, large settlements were abandoned and the population moved towards a more rural way of life (Dever 1980). Increased settlement in the Negev Desert with possible transhumance links with the highlands in the Dead Sea catchment area is discussed by Langgut et al. (2014).

Middle Bronze Age (~1950–1550 BCE; ~3.9 to 3.5 ka cal BP)

Establishing the history of the Dead Sea watershed hydrology during the Middle to Late Bronze time interval is crucial for understanding the environmental background of the Late Bronze archaeologically attested settlement fluctuations. Thus, we devoted efforts to establishing in great detail the lake-level structure during this period. Data, however, as the discussion below shows, are limited.

The low lake levels of the Intermediate Bronze Age continued for a short time into the Middle Bronze Age, but then the Dead Sea rose, reaching the high stand of ~370 m bmsl (Figure 4). The shoreline that marks this elevation was documented in both the Arugot and Darga valleys; however, it was dated only at the former, to 3630–3480 yr cal BP (Table 1; Bartov et al. 2007). This high stand is consistent with evidence for a relatively high lake stand from subaqueous deposition at the Ze'elim Plain (Neumann et al. 2007; Kagan et al. 2011), Ein Qedem (Stern 2010), Ein Gedi and Ze'elim cores (Migowski et al. 2006), deep Dead Sea cores (Neugebauer et al., in press), and the southern subbasin cores (Neev and Emery 1995). Mt. Sedom Cave data indicate a high lake level at 3446–3172 cal BP (Frumkin et al. 2001). Since the age and identification of the high shoreline is essential for reconstructing the level fluctuations at this time, in this study we revisited the Arugot and Darga exposures, documented them in detail, and verified the existence of the pebbly shore marker at ~370 m bmsl, dated by Bartov et al. (2007).

According to pollen archives, these wetter conditions are indicated by a significant increase in Mediterranean trees; they have been attributed to the expansion of Mediterranean forest into the Judean Highlands (Litt et al. 2012; Langgut et al. 2014, 2015). Archaeology presents a picture of low settlement activity in the Intermediate Bronze Age, continuing into the Middle Bronze Age I, and then increased settlement activity in the Middle Bronze Age II–III, with re-expansion to more southern areas (Gophna and Portugali 1988; Finkelstein and Langgut 2014).

Table 2 Summary of archaeological periods, Ze'elim Gully sedimentary environment, and lake-level conditions.

Period	Date	Environment at Ze'elim Gully site	Comments regarding lake level
Iron Age	1150–586 BC (~3100–2536 BP)	<i>lacustrine</i>	Rise in LL to moderate/low level
Late Bronze Age	1550–1150 BC (~3500–3100 BP)	<i>lacustrine</i>	Slight LL recovery
		<i>shore</i> (beach ridge)	Drastic drop in lake level
Middle Bronze Age	MB II–III, 1750–1550 BC (~3700–3500 BP)	<i>lacustrine</i>	Very high lake level
		MB I, 1950–1750 BC (~3900–3700 BP)	<i>shore</i>
Intermediate Bronze Age	2500–1950 BC (~4450–3900 BP)	<i>shore, lacustrine, shore</i>	Low lake level, with short lake rise in the middle of the period
Early Bronze Age	3500–2500 BC (~5450–4450 BP)	<i>hiatus/truncated</i>	High lake level

Notes: Lake-level interpretation from this study and from Frumkin et al. (1991), Bartov (2004), Bookman (Ken-Tor) et al. (2004), and Migowski et al. (2006). The dating of the archaeological periods follows, as far as possible, ¹⁴C results of Levantine archaeological sites from the last decade [Regev et al. (2012) for Early Bronze and Intermediate Bronze Ages; Bietak (2002) for beginning of Middle Bronze Age; the transition from the Middle to the Late Bronze Age, now broadly fixed in the mid-16th century BCE, is yet to be verified; Finkelstein and Piasezky (2010) and Toffolo et al. (2014) for the Iron Age].

Late Bronze Age (~1550–1150 BCE; ~3.5 to 3.1 ka cal BP)

The Late Bronze Age begins with a severe lake drop, well documented in many geological archives: the Ze'elim Plain, Ein Qedem, Ein Feshka Gully, and Ein Gedi cores. The lowest stand was identified at the Ein Qedem shore (415 m bmsl) and was ¹⁴C dated to 3562–3435 yr cal BP by Stern (2010). The uncharacteristic lithology of this period in the Ein Gedi core (Migowski et al. 2006; Neugebauer et al., in press), displaying sand and gypsum, also indicates a very low stand (at ~3.5–3.3 ka cal BP). Within the uncertainties in the ¹⁴C calibration (Reimer et al. 2009), the ages of the Nahal Arugot high stand (3630–3480 yr cal BP) and the Ein Qedem low stand (3562–3435 yr cal BP) seem very close. We suggest that the high stand occurred towards the beginning of that range (late Middle Bronze Age) and the low stand towards the end of it (Late Bronze Age). The Ze'elim Gully displays a thick (>1 m) beach ridge during the Late Bronze Age. The lower constraint for this low stand is given by an age of 3550–3360 cal BP (Bookman [Ken-Tor] et al. 2004) taken from lacustrine sediment directly below the beach ridge. Organic matter from lacustrine sediment ~80 cm below the beach ridge in the ZA-2 section yields an age of 3965–3695 cal BP, which, based on approximate sedimentation rate, would give an age of ~3.7–3.4 ka cal BP directly below the beach ridge (Kagan et al. 2011). There is possibly a short sedimentary hiatus between this lacustrine sediment and the beach ridge.

The pollen data from the Late Bronze Age interval recovered from the Sea of Galilee and Ein Feshka sedimentary sections is characterized by extremely low arboreal vegetation percentages (Langgut et al. 2014, 2015), in agreement with the arid conditions inferred from the Ze'elim Gully sediments.

The recovery of the Dead Sea began towards the end of the Late Bronze Age, with evidence seen

in the existence of aragonite crusts in the beach ridge. The beach ridge is a prominent sedimentary feature of a sequence of recycled aragonite crusts comprising a foresets-backsets structure (Figures 2a,b). The aragonite crusts, at various stratigraphic levels in the Ze'elim Formation, were formed along the shoreline marking enhanced supply of freshwater rich with bicarbonate (e.g. Bookman [Ken-Tor] et al. 2004); on the shoreline they were subjected to wave action, which constructed the foresets and backsets. Thus, the beach ridge structure marks the time of resumption of freshwater activity in the Judean Hills (after the extreme dry event of the Late Bronze Age) and the elevation of the shoreline where the structure was formed. Along with the aragonite crusts, the waves collected and amalgamated wood fragments that were incorporated within the aragonite crust layers of the beach ridge. ¹⁴C dating of the youngest group of wood remains in the beach ridge yielded ages that lie in the interval of ~3.4 to 3.2 ka cal BP (Table 1). The youngest of these dates (3470–3240 cal BP; Bookman [Ken-Tor] et al. 2004) marks the approximate time of formation of the beach ridge structure, slightly preceding the end of the Late Bronze Age. Lacustrine subaqueous sediments indicating further lake rise were deposited above the beach ridge. They include organic matter dated to 3394–3084 yr cal (Table 1; chronology from Langgut et al. 2014). The younger part of this calibration range is at the transition to the Iron Age.

At the Ein Feshkha site, the Ze'elim beach ridge structure is correlated with a layer containing gypsum domes that were probably deposited in shallow waters (Neumann et al. 2007). ¹⁴C ages of organic debris recovered from a laminated section ~40 cm above the gypsum dome horizon yielded an age of 3258–2788 BP (Neumann et al. 2007; Kagan et al. 2011), indicating lake-level recovery earlier than that. The Ein Feshkha sediments support the scenario described above, with the lowest stand being represented by the gypsum domes and resumption of lacustrine deposition above that, but still within the Late Bronze Age.

Continuous speleothem growth at the Soreq Cave in the Judean Hills throughout the Holocene (Bar-Matthews and Ayalon 2004) indicates that rainfall there was always >300–350 mm/yr (Vaks et al. 2010); nonetheless, slower speleothem growth during the Late Bronze Age (Bar-Matthews and Ayalon 2004; Vaks et al. 2010) may signify drier conditions. Sampling resolution is uncharacteristically low in this interval of the Soreq Cave stable isotope record, where each data point represents ~102 yr, meaning that rapid events may not be apparent (Bar-Matthews and Ayalon 2004).

Severe, long-term droughts may be the main reason for the sociopolitical collapse in the eastern Mediterranean area during the “Crisis Years” (Carpenter 1966; Weiss 1982; Neumann and Parpola 1987; Alpert and Neumann 1989; Ward and Joukowsky 1992; Issar 1998). In the Levant, the Crisis Years are represented by destruction of urban centers, decline of village life, and changes in settlement patterns. Textual evidence from several places in the Ancient Near East attest to drought and famine starting in the mid-13th century BCE and continuing until the second half of the 12th century BCE (see in this issue, Langgut et al. 2015 and references therein).

Our reconstruction of the Dead Sea levels indicate that the recovery of the hydrological system occurred at ~3.2 ka cal BP, slightly before the time indicated by the palynological, archaeological, and historical findings. Possibly the conditions leading to the recovery of the hydrological system of the Dead Sea watershed heralded the recovery of the regional settlement system.

The global climatic reasons for this catastrophic drop of the Late Bronze Dead Sea and its recovery during the end of the Late Bronze Age and Early Iron Age are complex and beyond the scope of this paper. Other similar abrupt lake drops occurred throughout the Holocene and were correlated by Kushnir and Stein (2010) with times of global abrupt climate events referred to as the Holocene

Rapid Climate Change (RCC, Mayewski et al. 2004). Kushnir and Stein (2010) argued that these abrupt events were the result of extreme cold temperatures in the North Atlantic and extreme cold air outbreaks over the Mediterranean that caused cooling of the deep seawater layers, resulting in cold summer sea temperatures and weakening of the winter Mediterranean cyclones.

Iron Age (1150–586 BCE; ~3.1–2.5 ka cal BP)

By ~3.1 ka cal BP, the Dead Sea had somewhat recovered, rising from its low stand of below 414 to ~408 m bmsl. Although the lake recovered from its extreme minima, low lake-level deposition continued at the Ze'elim site, with silty detritus and some aragonite laminae. The Ein Gedi core shows enhanced primary aragonite precipitation, indicating more stable lake conditions (Migowski et al. 2004; Waldmann et al. 2007). Deeper lacustrine conditions returned to the Ze'elim site only about a millennium later, at the end of the Hellenistic period to beginning of the Roman period, when lake levels rose significantly [Bookman (Ken-Tor) et al. 2004; Migowski et al. 2006].

The resumption of hydrological activity in the Dead Sea watershed that led to the recovery of lake level is expressed in the development of Iron Age settlements in the Judean Hills. This required not only freshwater supply but also soil development, which was perhaps made possible by the transport of desert dust from the Sahara Desert and leaching of the carbonates to the Dead Sea when more precipitation and vegetation were available (Haliva-Cohen et al. 2012; Belmaker et al. 2014; Stein 2014a). While the movement of the Sea Peoples over the Mediterranean possibly reflects environmental stress such as severe droughts in their source regions during the Late Bronze circum-Mediterranean crisis, the Iron Age settlement recovery was most likely supported by the resumption of freshwater activity, recovery of the vegetation, and formation of mountain soils.

SUMMARY

The terminal and hypersaline Dead Sea stores in its sedimentary archives the climate-hydrological history of its large watershed. The reconstruction of level curves for the lakes that occupied the Dead Sea Basin during the late Quaternary requires information on the shoreline elevations and their ages. This information is obtained by sedimentological and geological means and by radiometric dating methods. Here, we reviewed the studies that established the lake-level curve of the late Holocene Dead Sea, including new data. In particular, we focused on the time interval of the Early Bronze to the beginning of the Iron Age that is characterized by dramatic changes in the regional climate and human culture history. In the mid-Holocene, the lake rose several times to its highest Holocene stand of ~370 m bmsl, but also displayed abrupt declines. The most dramatic decline occurred in the Late Bronze Age when the lake level dropped by more ~50 m to below 414 m bmsl. This was shortly followed by a rapid but limited rise to ~408 m bmsl, close to the transition to the Iron Age. The resumption of freshwater activity was likely accompanied by vegetation recovery and soil production in the Judean Hills terrain. These hydrological-environmental developments made the Iron Age settlement and demographic growth in the region possible.

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