Environ Earth Sci (2010) 59:1417–1430
DOI 10.1007/s12665-009-0128-z

ORIGINAL ARTICLE

Landslides along the Jordanian Dead Sea coast triggered by the lake level lowering

D. Closson · N. Abou Karaki · F. Hallot

Received: 30 September 2008 / Accepted: 21 February 2009 / Published online: 14 March 2009

Abstract The level of the Dead Sea lowers 1 m/year and this rate is in acceleration. The decline is causing one of the major environmental disasters of the twenty-first century. The freshwater resources management policy of Israel, Jordan, and Palestine controls the phenomenon. Since the 1960s, the level of this terminal lake dropped by 28 m and its surface shrunk by one-third. In the 1990s, international builders created major tourist resorts and industrial plants along the Jordanian shore while, during the same period, geological hazards triggered by the level lowering spread out. From the very beginning of the year 2000, sinkholes, subsidence, landslides, and river erosion damaged infrastructures more and more frequently: dikes, bridges, roads, houses, factories, pipes, crops, etc. Until present, scientific articles about this ongoing disaster concerned only sinkholes and subsidence phenomena. This paper focuses on the landslides issue along the Jordanian coast. Based on a set of ground observations collected since 1999, the dynamics of the triggering factors in relation to the evolution of the hydro-geological setting is discussed. It is inferred that the recent industrial and tourist infrastructures never took into consideration the very important geotechnical constraints resulting from the Dead Sea lowering.

Keywords Landslides · Coastal hazards · Dam geology

Introduction

Since the mid-1960s, the Dead Sea (DS) shoreline is continuously shrinking back, causing the emergence of muddy-gravelly new lands, very fragile in regards to erosion. As the salinity of this terminal lake is ten times greater than the ocean one, the new emerged lands have been described as a salt-karst system (Closson et al. 2007).

The receding of the shoreline reflects the negative water balance caused by the overexploitation of water resources in the catchment area and the pumping of the DS brine by the Arab Potash Company (Jordan) and the Dead Sea Work (Israel) to make fertilizers. Since the mid-1960s, the decline is accelerating. Over the past 10 years, the level drops by 1 m/year on average (Abelson et al. 2006). In 2008, the elevation is about 421 m below the mean sea level (bMSL) while it was 395 m bMSL in 1960.

From the 1980s, numerous sinkholes and subsidence zones appeared all along the shore. An increasing number of new areas are being threatened or destroyed. Some affected places can be found as far as five kilometers further inland. The scientific literature attest the importance of this issue (e.g., Salameh and El-Naser 2000; Taqieddin et al. 2000; Arkin and Gilat 2000; etc.). During the last 10 years, hectometric landslides destroyed four Jordanian coastal segments. No paper was published yet on this specific issue. This work contributes to shed a light on the ongoing situation, and to clarify the origin of these landslides based on geomorphologic observations.

D. Closson (✉) · F. Hallot
Signal and Image Centre, Royal Military Academy,
Brussels, Belgium
e-mail: damien.closson@yahoo.fr; dclosson@mail.com

F. Hallot
e-mail: frederic.hallot@rma.ac.be

N. Abou Karaki
Environmental and Applied Geology Department,
University of Jordan, Amman, Jordan
e-mail: naja@ju.edu.jo

Study area and method

Area of interest

The Jordanian coast of the DS constitutes the 70-km-long area of interest (Fig. 1, nos. 1–17). The shore is characterized by three kinds of environment: wide muddy-gravelly deltas (Fig. 1, nos. 1–3, 8–12, 17); rocky cliffs and steep slopes combined with minor gravelly deltas (Fig. 1, nos. 4–7); a wide wave-cut platform (Fig. 1, nos. 14–16) around the former Lisan peninsula (Fig. 1, no. 13).

The deltaic zone of the Jordan River and Wadi Udheimi (Fig. 1, nos. 1–3), northern DS, is dedicated to intense tourism developments around Suweimeh (Fig. 1, no. 3). In the south, a wide mudflat slowly developed in the extension of three coalescing alluvial fans: Wadi Mutayl, Wadi Ibn Hammad, and Wadi Kerak, accompanying the retreating DS shoreline (Fig. 1, nos. 8–12). The new exposed lands are uncultivated because of their salt content, sinkholes and "quick sand". Irrigated agriculture spread between the hamlet of Ghor al-Haditha and the circular depression of Birkat el Haj (Fig. 1, nos. 11, 12). A third major deltaic zone (Fig. 1, no. 17) extends in the northern part of the dried-up Lynch Strait (Fig. 1, no. 16).

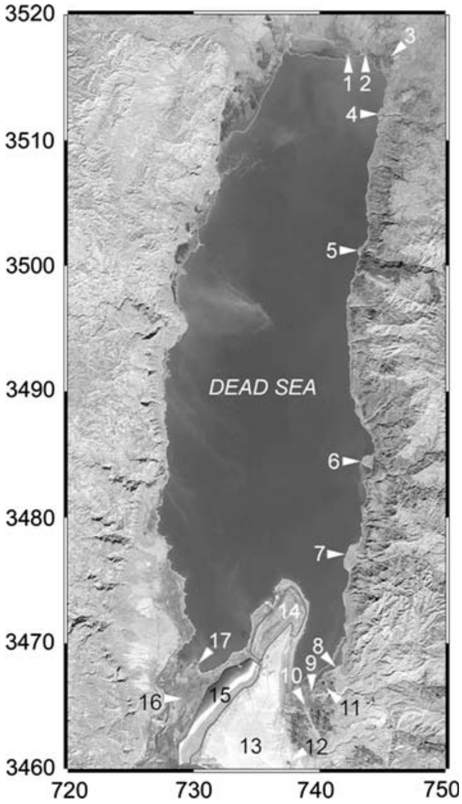


Fig. 1 Location map: no. *1* and *17* are the limits of the study area. *1* delta of the Jordan River; *2* delta of Wadi Udheimi; *3* the hamlet of Suweimeh; *4* delta of Wadi Mukheiras; *5* delta of Wadi Zerqa Mai'n; *6* delta of Wadi Mujib; *7* delta of Wadi Shuqeiq; *8* delta of Wadi Mutayl; *9* delta of Wadi Ibn Hammad; *10* delta of Wadi Kerak; *11* Ghor al Haditha; *12* Birkat el Haj; *13* the Lisan Peninsula; *14* Saltpan 19 of the Arab Potash Company (*outlined*); *15* Saltpan 18 of the Arab Potash Company; *16* dried-up Lynch Strait, a land bridge between the eastern and the western DS coast; *17* delta of Wadi Araba

A wide mountainous segment punctuated by minor deltas extends from Wadi Mukheiras to Wadi Mutayl (Fig. 1, nos. 4–8). Gravelly beaches are generally absent. The few ones have a steep slope. Micro cliffs are very apparent in the sediments and attest the presence of past shorelines. Numerous springs can be found all along this 40-km segment. Flat surfaces are found over the recently emerged deltas. They attracted the attention of the land planners for the development of tourist resorts, e.g., the delta of Wadi Mukheiras (Fig. 1, no. 4) had been entirely built.

The Lisan area (Fig. 1, no. 13) is made of sub-horizontal layers of salty marls uplifted by the rising of a major salt diapir. Four decades ago, the Lisan was a peninsula. Nowadays, it is surrounded by a kilometric wave-cut platform (Fig. 1, nos. 14–16) made of marls and gypsum. During the 1990s, the Arab Potash Company built over two huge salt evaporation ponds at a cost of 38 and 32 millions U.S. Dollars (Fig. 1, nos. 14, 15). Further west, since the end of the 1970s, the eastern and western shores of the DS are connected by a land bridge (Fig. 1, no. 16) that is the bottom of the dried-up Lynch Strait.

Method

Since the appearance of a wide landslide in September 1999, regular field surveys, once or twice a year, have been done to observe, locate and map traces of landslides. At present, four active places have been recognized along the Jordanian coast. Three of them are expanding year after year. Causal dynamics have been deduced from diachronic analysis of ground observations and measurements. The procedure to get knowledge of this issue was the following:

- to collect, scan, geocode, and digitize available topographic and geological maps (Jordan 1:50,000 series, in Arabic. The Jordan maps were scanned, cropped and georeferenced at the Natural Resources Authority of Jordan as part of a project sponsored by the National Endowment for the Humanities, the American Center for Oriental Research, and the Department of Antiquities of Jordan. There are 171, 15-minute sheets available. http://gaialab.asu.edu/Jordan/SLevant50k.php);
- acquire satellite images and aerial photographs (assessment of stereo pairs) with large temporal (1953–2008), spectral (visible-microwave) and spatial (1 m at best) resolution;

- integrate these elements in a single database;
- understand and clarify the various hydrogeological settings, interrelations, connections of the aquifers, and also to monitor the springs in the areas of interest;
- perform image and diachronic analysis in order to get knowledge and map the position of the past shorelines, the gradual appearance of new springs along the shore, the development of vegetation, the setting up of the chronological appearance of sinkholes, and the development of major infrastructures such as roads, dams, etc.;
- record all observations with a Global Positioning System (GPS) during surveys;
- monitor the evolution of the phenomena and update the database;
- collect and synthesize all available data and observations in the Earth Science literature, with a special interest in hydrology (e.g., Glaser 2002), climatology and seismicity (Abou Karaki 1987). The subject of landslides lies at the heart of a tectonically active area.

Background

Environmental conditions along the Dead Sea coast

The DS is a hypersaline terminal lake located in a pull-apart basin, which is one of the major components of the Jordan–Dead Sea Transform fault system. It is the lowest place on Earth with an elevation of 421 m bMSL in 2008. Most of the DS coastal areas are over complex faulted zones related to the DS pull-apart basin. The area of interest is prone to earthquakes and soil liquefaction. Most of the area is characterized by highly karstic and fractured rock formations that are genetically connected with faults. Karstic conduits extend from the land into the sea, and the prevailing seaward-sloping rock strata. A steep escarpment characterizes the morphology. The difference in the elevation between the lake and the highlands to the east is more than 1,210 m over a horizontal distance of 15 km. Hot and sulfur springs are found in many places. Due to the maximum level of the lake at about 180 m bMSL in the Pleistocene, marine/saline sediment deposits are the direct causes of the observed high salinity of some springs adjacent to the shore.

The groundwater discharging along the DS escarpment shows a variety of chemical compositions and electrical conductivity (EC) values (Salameh and Hammouri 2008). The water discharges from different aquifers such as, Upper Cretaceous limestones, Lower Cretaceous sandstones, Permo-Triassic limestones, sandstones and siltstones, and Cambrian Ordovician limestone and sandstones. From Wadi Ibn Hammad (Fig. 1, no. 9) northwards the groundwater chemistry gradually begins to change: the EC values increase to 1,500–2,000 μS/cm in Zara area (Fig. 1, between nos. 5 and 6), 2,000–3,000 μS/cm in Zerka Ma'in area (Fig. 1, no. 5), and 5,000–8,000 μS/cm further north in Suweimeh area (Fig. 1, no. 3).

Climate conditions range from semi-arid to arid. The average annual temperature is 24°C. Precipitation varies from 100 mm/year in the north to 70 mm/year in the south. The potential evaporation rate is about 2,500 mm/year. The vegetation is very sparse. Only briars and some brackish water tolerant plants grow. The agriculture is limited on small fields of fruit-tree plantations and tomato fields.

The beginning of landslide hazards along the Jordanian Dead Sea coast

The starting event dates back to September 6th, 1999. It destroyed more than 100 m of a resthouse beach. Probably dreading the negative impact over the development of touristic resorts along the coast, Jordanian Authorities minimized the significance of this incident and its causal factors by suggesting that a sanitation problem was the triggering element: "Biltaji (*Jordanian tourism minister at that period*) said the concerned authorities will deal with the landslide in cooperation with the Ministry of Tourism. He said no one was at the resthouse when the landslide occurred on Monday (6th September 1999) and no material damage was caused. He said the resthouse was ordered closed due to its violation of public health safety rules. He gave no further details. (…)" (Jordan Times 1999). Since then, three other similar events occurred. One affected the northern DS, about 1 km northwards from the first. The two others hit the southern part of the lake, in Ghor Al Haditha and the Lisan peninsula (Fig. 1, nos. 11–13). In the 1980s, these latest places were already affected by sinkholes and subsidence (Taqieddin et al. 2000). For obvious reasons, the few scientists monitoring the environmental deterioration suspected that the first event was rather a consequence of the DS lowering than a broken sewage (Salameh and El-Naser 2000). However, at that time, the place was far from the well-known southern hazardous zones. Moreover, all along the western DS coast, no landslide related to the lake level decline was mentioned in the scientific literature. Questions arose about if it was the beginning of a proliferation process (like sinkholes and subsidence) or just an isolated case. Other interrogations concerned the nature of the changes in the hydrological setting, and the time needed before a new event occur. The experience gained through the knowledge of subsidence and sinkholes issues showed that geological hazards at the DS need a certain delay to appear after the triggering event. For example, the DS level declined in the mid-1960s but sinkholes became a more and more important issue only 20 years after (Shalev et al. 2006). In some places, rates of subsidence were constant and then accelerated suddenly (Closson, 2005), suggesting that some "thresholds" had been passed over. While several places were destroyed, others were considered as "safe" for years. Then, suddenly, they were affected by ground collapses, leading to abandon the idea to draw a "fixed" risk map in such a dynamic environment because the hydrogeological setting is continuously changing in a way that is difficult to predict.

Results

This section presents the observations recorded since 1999 along the DS shore. Four landslides are described. The causal factors will be discussed in the next point. At the exception of the event dating back to September 1999, the accurate timing of the three other landslides is unknown due to the absence of continuous monitoring. All features have in common the fact that they initiated out of sediments that emerged during the last 40 years.

Two landslides affecting the northern Dead Sea coast

Figure 2 locates two hectometric landslides affecting the northern DS area (white arrowheads). The ribbon of light gray color corresponds to the lands that emerged between 1973 and 2000. Practically, Fig. 2 illustrates the seaward displacement of the shoreline three decades before the first landslide hit the coast. The upper and lower limits of this ribbon are the contour lines of ~397 and ~416 m bMSL. Nowadays, the elevation of the DS level is 421 m bMSL.

Landslide no. 1

Figure 2 locates landslide no. 1; it affects an area between elevations 400 m bMSL (top) and 421 m bMSL (toe). It is an active, retrogressive and enlarging landslide. Year after year, the surface of rupture is extending in the direction opposite to the movement of the displaced material. Its velocity is slow (1.6 m/year to 156 m/year) (Turner and Schuster 1996). While the upper part clearly shows slumps landforms, the lower part is mostly characterized by earthflow deformations (Figs. 3, 4). The higher springs-level was located at 406 m bMSL in May 2008.

In the upper part, slump is large and complex. Material moved as a unit with displacements along curved slip planes. Tilted masses moved backward into the slope. Material of the toe presents pancake-shaped zone of liquefied material. Slumps could occur over a saturated zone ~10–15 m below. Investigations indicated a significant amount of water coming down with the slide (Fig. 4). The lower part is an earthflow. It is a thick, sticky fluid, probably flowing over a specific layer of clay. Landforms are characterized by a mass of broken and disrupted soil, and raised, lumpy terrain.

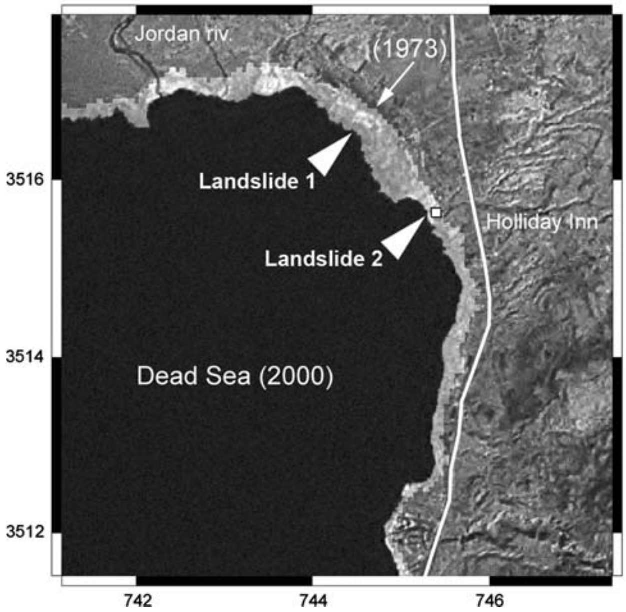


Fig. 2 Location map of two hectometric landslides affecting the northern DS coast (Suweimeh area). The ribbon of *light gray color* corresponds to the lands that emerged from 1973 (~397 m bMSL) to 2000 (~416 m bMSL). In 2008 the level is ~421 m bMSL. The "Holiday Inn" is a hotel built from 2006 to 2008 at the same place of the destroyed "Social Security" beach area. The delta of the Jordan River constitutes the borderline with the West Bank. The white line corresponds to the DS main road. Background: Landsat image (2000). UTM, WGS84, coordinates in kilometers

Landslide no. 1 developed in material consisting of thin-bedded, silty-clayed layers of a dark-brown to ocher color at the surface and a bright gray to black color within the sequences. Single persistent limy or evaporitic white layers which occasionally show an orange-red to russet color are intercalated. The whole formation is rich in organic material indicated by the black color of the clay and the organic smell. Very significant is the appearance of autochthonous grown halite-crystals. The salt-crystals appear as single crystals or are to be found as accumulated crystals within a nest. This formation has a thickness of more than 20 m and is terraced by the retreat of the DS. These successive beach erosion scarps represent progressive levels of the DS drawdown. They are visible from the former 1960' shoreline to the present coast. The single terrace steps have thickness of less than 1 m and further away from the present-day shoreline the thickness grows up to 2 m. The different height of the steps inform on the speed of retreat of the DS to the recent water level.

Fig. 3 Point of view toward the north. In the foreground, sapping and slipping landforms characterize headward gully erosion; the background presents a complex landslide combining slump and earthflow features (see Fig. 4). The affected area shows several amphitheaters, each one originated on a set of springs or in a place that concentrate (s/d) groundwater. Amphitheaters developed through backward erosion piping phenomenon. Water flows through the pores of the soil. Erosion is caused only by intergranular flow causing excessive seepage forces at an exit face. These seepage forces cause a boil condition or particle detachment

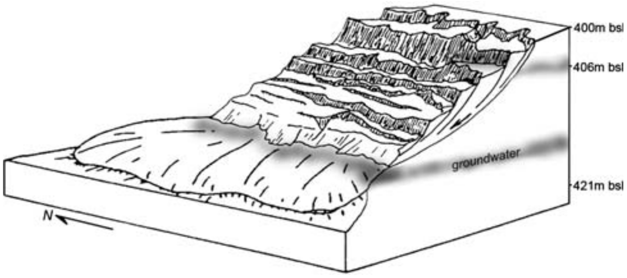


Fig. 4 The upper part of the landslide presents slump characteristics, i.e., rotational earthslides moving downhill with minimal deformation along a concave failure plane. In the lower part, *pancake-shaped* zone of liquefied material attest that earthflows move at varying rates depending on factors such as slope angle and flow composition. The landslide contains numerous springs where well-developed vegetation exists. The area of the earthflows is completely devegetated

Landslide no. 2

Landslide no. 2 is probably the first event of this kind along the DS coast, dating back to September 6th, 1999 (Fig. 5). It was a very rapid landslide (3 m/min to 5 m/s) (Turner and Schuster 1996). Since then, it is inactive (Fig. 6a). However, one has to mention that a decametric sinkhole appeared in 2004 over the main scarp. In May 2007, a wall built to hide this scarp partly collapsed, letting visible seepage of brine (Fig. 6b). In May 2008, three salty springs were observed in the zone of accumulation.

Landslide no. 2 affected an area characterized by a fuzzy contact between two formations: the same one than for landslide no. 1, about 1 km northwestwards (dark-brown thin-bedded silty-clayed layers with evaporitic white layers intercalated), and a formation made of fluviatile and lacustrine gravels. Gravels are subangular to subrounded. The thickness reaches several decameters. The gravels are poorly sorted and loose to weakly cemented. The single clasts reach sizes up to 30 cm in diameter. The gravels consist of limestone, dolomite, dolomitic limestone, sandstone, and even basalt clasts. In a wadi located 100 m south of the landslide area, the gravels are visible in cross bearing graded bedding. Wave-cut banks do not develop in such materials because they do not possess sufficient strength to support vertical banks. Wide, gently sloping beaches form along the bank. Such soils are particularly susceptible to internal erosion processes, such as piping, that are especially aggravated by rapid DS lowering. Irregular ground, potholes, linear ridges, and depressions along the shorelines are characteristic of such soils. Fluctuations and rapid

Fig. 5 September 6th, 1999, part of a touristic beach at the northern DS was destroyed by a sudden ground collapse. In 2004, a decametric sinkhole occurred close to the wall where people were looking at the scarp (*upper middle*). From 2006, the whole area was included into the perimeter of the private beach of a new five-star resort (Holiday Inn). The scarp was covered by a stone wall. In May 2007, the wall collapsed partially. In May 2008, three salty springs were found along the seepage surface (the beach). They attest that water is flowing below the hotel and its surroundings, continuing to dissolve salt remains

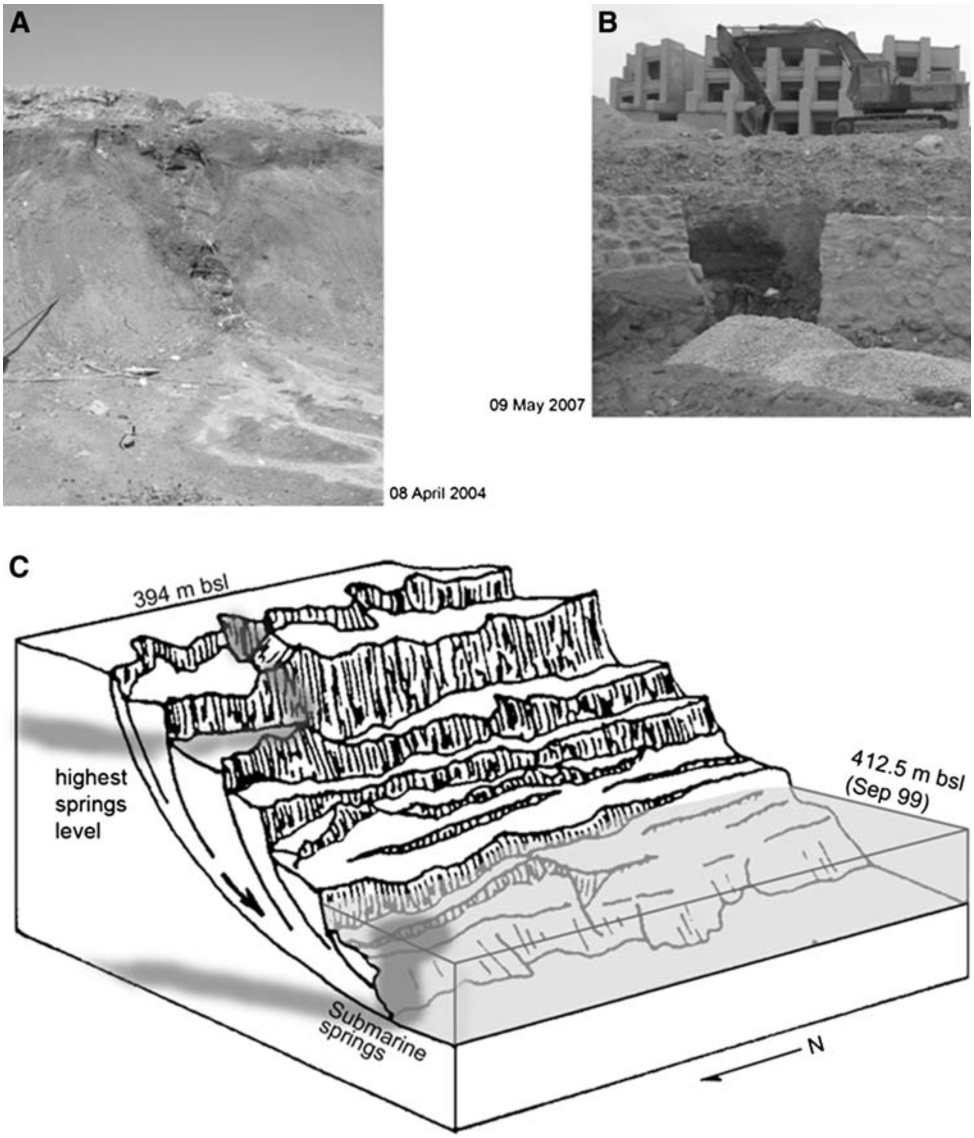


Fig. 6 **a**, **b** A seepage zone along the main scarp observed 3 years apart. **b** In 2006, architects created garden-terraces in front of a new five-star hotel. They used the main scarp as a limit of two terrace levels. In 2007, part of the wall collapsed. **c** Scheme of the southern part of landslide no. 2 based on Fig. 5

DS drawdowns can cause the buildup of high fluid pressures within the soil pores. When the level drops, the soil releases this water rapidly, resulting in small-scale slumping, piping, and wasting.

Seepage and springs can be found in many places along this coastal segment. Swimmers indicated the presence of submarine springs close to the shoreline. Three of them, close to the Holiday Inn were analyzed. Table 1 gives the details.

Table 1 compares salty springs with fresh water (irrigation water). S1 is by far the most salty spring. It attests that dissolution phenomenon is very high. The sinkhole that appeared in 2004 in the immediate vicinity of S1 could result from such dissolution. S2 and S3 also attest that salt dissolution is very present in the basement of the Holiday Inn.

Two landslides affecting the southern Dead Sea coast

While the northern landslides occurred along the DS shore, those in the southern part appeared several hundred meters inland (Fig. 7) but always in areas that were covered by the DS four decades ago.

Landslide no. 3

Landslide no. 3 is located in the region of Ghor Al-Haditha (Fig. 7), a place affected by sinkholes and strong subsidence since the end of the 1980s. It appeared slowly at the toe of Wadi Mutayl alluvial fan at the end of the 1990s. It is always active but slow (1.6 m/year to 156 m/year) (Turner and Schuster 1996), and its dynamic nature is attested by multiple geomorphic features.

Table 1 analysis of four water samples

Sample	EC(µs/cm)	pH	HCO$_3$ (meq/l)	CI (meq/l)	T.H (meq/l)	Ca (meq/l)	Mg (meq/l)	Na (meq/l)	K (meq/l)	NO$_3$ (meq/l)	SO$_4$ (meq/l)	Cation	Anion	Ratio
GAH: irrigation water	1,068	7.45	3.3	3	5	2.3	2.7	3.3	0.6	0.12	2.2	8.9	8.62	0.015
Suweimeh: springs 1	192,100	5.2	68.1	108.8	98	51	47	115	7.06	0	20	220.06	202.9	0.04
Suweimeh: springs 2	51,400	7.25	46	48	62	40	22	50	3.6	0.2	12.3	115.6	106.5	0.04
Suweimeh: springs 3	34,700	7.16	32	29.2	45	27	18	35	1.3	0.3	11.8	81.3	74.02	0.047

Three of them correspond to springs along the shore in the lower part of the landslide area

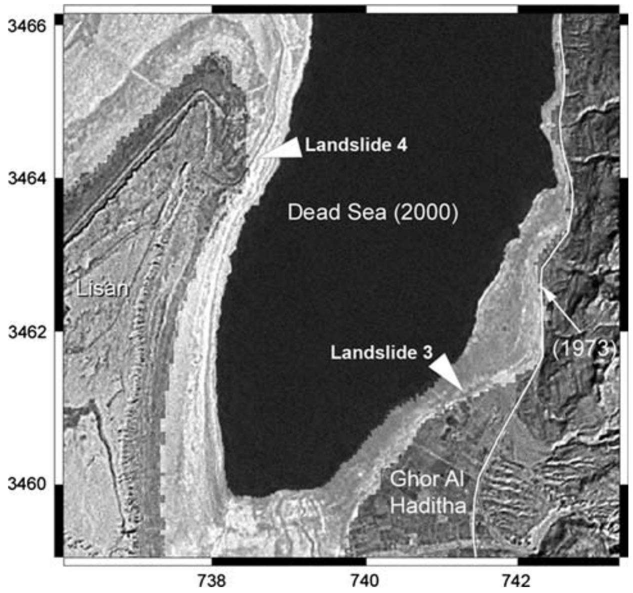


Fig. 7 Location map of two hectometric landslides affecting the southern DS coast. The ribbon of *light gray color* corresponds to the lands that emerged from 1973 (~397 m bMSL) to 2000 (~416 m bMSL). In 2008 the level is ~421 m bMSL. Background: Landsat image (2000). UTM, WGS84, coordinates in kilometers. The *white line* corresponds to the DS main road

The ground is made of fine/coarse-grained silica, sand and pebble size gravel with thin intercalations of laminated marl. In the sinkholes affecting the area, the gravels are visible in cross bearing graded bedding. These deposits are characterized by a shallow aquifer which is one of the primary sources to supply domestic, agriculture, and industrial water. The water in the alluvial aquifer has historically been fresh and suitable for most potable uses. Table 2 compares samples of water taken in Ghor Al Haditha. The reference is the water used by farmers to irrigate their crops. The sample water taken in the depression clearly shows that dissolution of salt is very high.

The first report about landslide no. 3 dates back to the end of 2003. Repeated ground failures had cut an access road between the production site of the "Numeira Mixed Salts & Mud Company" and the DS main road. These cracks grew bigger year after year and are well apparent over the Ikonos satellite images in Fig. 8, on the east side. The company found another road to export its goods but it was again threatened by geological hazards. In 2008, the road was totally cut by a decametric sinkhole and strong subsidence producing metric cracks. Furthermore, the factory itself was badly affected. A small sinkhole (metric) appeared near the northwestern corner inside the factory the 19th May 2008. A much bigger (decametric) one appeared the 26th July, about 20 m from the first. A month later, they were followed by two similar sinkholes very close to the factory fences. Finally, a decision was taken to move the company to Ghor Safi, some 30 km southward.

The first survey was undertaken in April 2004. Since then, repeated observations have been done leading to the creation of a dedicated database gathering high-resolution satellite images, pictures of relevant information, GPS tracks and waypoints, water samples, characterization of fractures, and faults, etc. Based on this dataset, a hypothesized model is presented on Figs. 9 and 10.

Figure 8 presents the landscape of the affected area. Vegetation grew up because of rich freshwater supply at the toe of Wadi Muthayl alluvial fan. Slump failure brought about by seepage. The subsequent backward erosion results in a vertical face prone to slump. Eventually it will trigger a complete failure of the alluviums. Black arrows delineate wide shallow subsidence area caused by the dissolution of an important salt layer some 20–30 m below the ground level. The heart of the depression is indicated by sub-circular ponds that are sinkholes. The dark area in the north is the mudflat that appeared after the retreat of the DS shoreline.

Table 2 comparison of water samples highlighting the phenomena of salt dissolution in the landslide area

Sample	EC(μs/cm)	pH	HCO_3 (meq/l)	CI (meq/l)	T.H (meq/l)	Ca (meq/l)	Mg (meq/l)	Na (meq/l)	K (meq/l)	NO_3 (meq/l)	SO_4 (meq/l)	Cation	Anion	Ratio
Irrigation water	1,068	7.45	3.3	3	5	2.3	2.7	3.3	0.6	0.12	2.2	8.9	8.62	0.015
Landslide no. 3	21,600	7.1	19	33	20	11.7	8.3	39	2	0.12	6.6	61	58.72	0.02

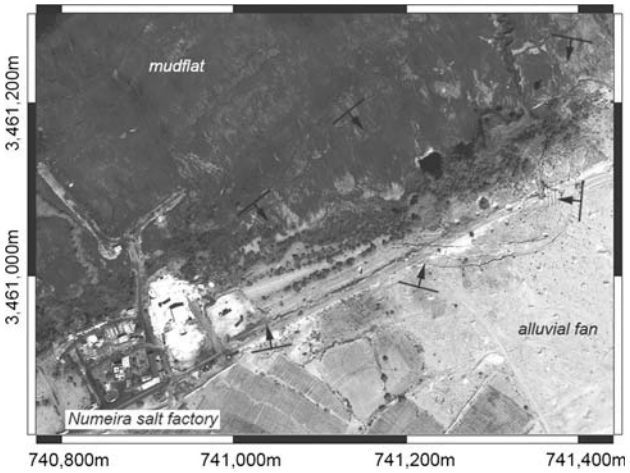


Fig. 8 Ikonos image acquired in 2006 showing the landslide area. Scarps are well visible on the *right side*. *Craters* that punctuate this zone are indeed sinkholes. In May 2008, multiple ground failures and collapses led to abandon the "Numeira mixed Salts & Mud Company" (around 30 employees) to avoid incidents

Landslide no. 4

Landslide no. 4 is active but very slow (16 mm/year to 1.6 m/year) (Turner and Schuster 1996). It developed inside the former salt evaporation pond no. 19 of the Arab Potash Company built at the end of the 1990. The dike of this huge production unit (6.35 km × 2.7 km) was set up over a wide wave-cut platform that slowly emerged from the 1960s (Fig. 16, foreground). The soft foundation is made of sub-horizontal layers of laminated evaporites (gypsum, aragonite, calcite, and anhydrite) and mudstone. This saltpan was destroyed during filling operation in March 2000. Radar interferometry techniques applied to ERS satellite images have shown that the collapsed dike segment (more than 1.6 km) was over a place suffering the strongest rate of subsidence for the whole DS area (Baer et al. 2002; Closson et al. 2003a). In 2005, sinkholes and springs of brackish water were found in the extension of the remaining dike.

After the major incident of 2000, the whole remaining part of the dike recorded tens of decimetric fractures and sinkholes of small extension (Closson 2005; Closson and Abou Karaki 2007, Closson et al. 2007). Decametric landslides affected the slope of a specific dike segment, 2 km east of the destroyed part, in a place where strong subsidence had also been recorded. These facts attested that the geological causal factors at the origin of the dike collapse were always active. In 2007, from interferograms created with ENVISAT images (scenes older than 2003), Baer et al. (2007) have shown that subsidence was stronger than before in the northern part of the Lisan. By comparison with inteferograms generated from ERS images (Closson et al. 2003b), the area affected by subsidence was also wider than before and encompassed the place occupied by landslide no. 4.

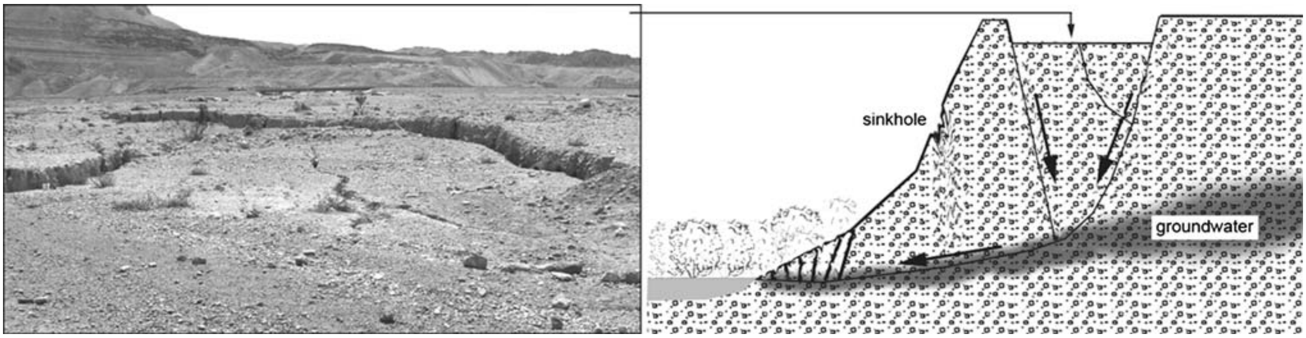
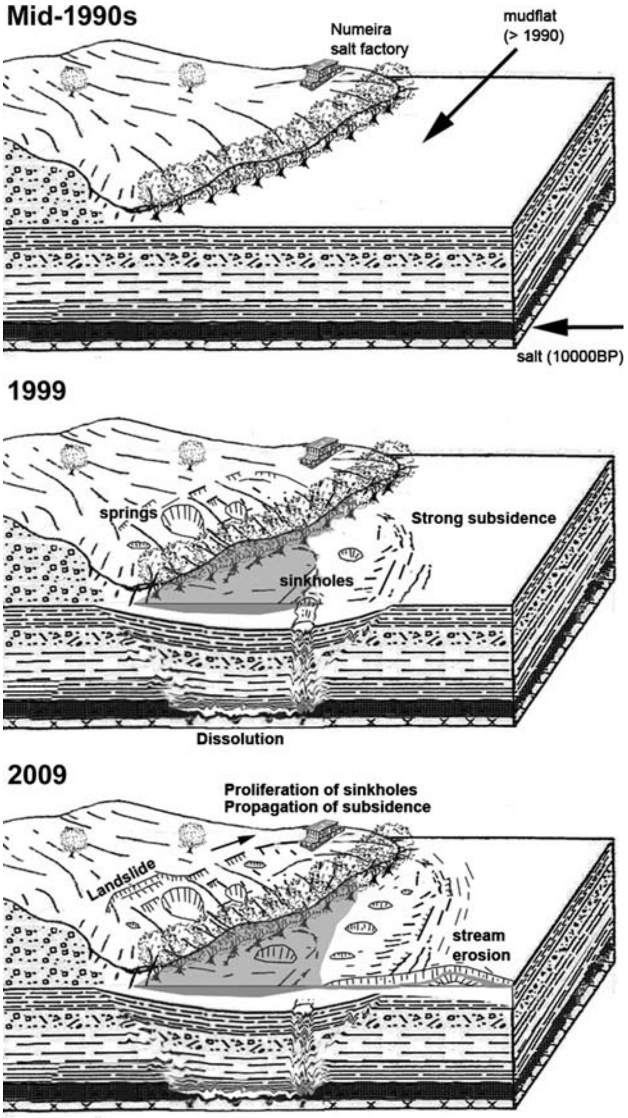


Fig. 9 The picture on the *left* shows a graben developed along the main scarp (coord. UTM 741360; 3461250—see Fig. 8) and cutting the road between the salt factory and the DS main road. On the *right*, the scheme shows a hypothetic cross-section with some elements of explanation for the development of the landslide



◀ **Fig. 10** Scheme (mid-1990s) presents the *panoramic view* of the area until the end of the 1990s. Elevation ranges from 395 m bMSL at the Numeira salt factory to 410 m bMSL over the mudflat. The landscape is the one of the contact between the alluvial fan of Wadi Mutayl and the mudflat resulting of the DS level lowering. As mentioned earlier, freshwater is present in the area and allows the development of natural vegetation along the margin of the alluvial fan. The subsurface is essentially made of alluviums, clay, and marl. During a survey in the mid-1990s, in Ghor Al Haditha, a particularly thick layer of salt was found some 25–30 m in the underground (Taqieddin et al. 2000). This layer is probably the same found in several places along the western coast too and dated by Yechieli et al. (1993) between 11,315 ± 80 and 8,440 ± 95 years BP (around 10,000 BP). This particular salt deposit could result from a sudden reduction of the DS watershed due to a volcanic eruption (Salameh and Al-Farajat 2007). Scheme (1999) illustrates the situation at the end of 1990s. By comparison with two other major hazardous places in Ghor Al Haditha, subsidence and sinkholes can be explained by the dissolution of the 10,000-year-old salt layer by unsaturated water with respect to salt. Drastic changes in the hydrogeological setting are a consequence of the rapid DS level (base level) lowering. As a result, new springs appear in unexpected places. They created well apparent decametric amphitheaters few years apart. The Numeira salt factory was safe at that moment but the road connecting the production site to the DS main road was cut off by major cracks. Scheme (2009) shows that the affected area grew bigger in the direction of the salt factory while the very first failures enlarge drastically. The strong subsidence created a closed depression that is partly filled with water coming from the two springs. The lake grew up until an outlet has naturally been created (at 410 m bMSL), probably after a phase of overflow during winter 2004–2005. Lateral erosion took place rapidly in this fragile environment

In 2005, two dike failures 500 m apart belonging to landslide no. 4 were already apparent (Closson 2005). The shape of the main scarp became clearly visible only from 2007 (Fig. 11). In its present configuration, landslide no. 4 is of the confined type, i.e., the upper part undergoes relevant deformation whereas the toe is more or less stable.

Figure 12 is an Ikonos image showing the position of the scarp in the environment of saltpan 19. Two topographic cross sections (Figs. 13, 14) realized with a handle GPS device are located. They underline the importance of the reinforced embankment. Indeed, subsidence dates back to the 1990s and engineers that built saltpan 19 encountered many problems of stability. The changes in the hydrogeological settings created geological hazards mostly in the northern and eastern parts of the Lisan. Since their first occurrence in 1992, their intensity increased drastically and forced engineers to strengthen the initial dike with huge terraces to increase the safety factor. The collapse proved they failed in their approach to evaluate accurately the danger and to find adequate measures.

Evidence of water circulation in the foundation is attested by numerous pop-up structures at the toe of landslide no. 4 (Fig. 15). Outcrops suggested that such landforms could result from the hydration of anhydrite (Closson et al. 2007). The resulting gypsum occupying more space than anhydrite, creates pressure leading to pop-up structures when the ground is covered by salt deposits.

Discussion: mechanism at the origin of the landslides

Geological hazards related to the fluctuations of the lake level were anecdotic before the 1980s. Then, year after year, they became a major issue. Studies undertaken in the 1990s on both sides of the DS have shown that causal factors of sinkholes and subsidence derive from modifications of the hydrogeological setting in combination with specific local conditions. The main conclusions of these studies can be summarized as follows:

1. the 1 m/year level lowering creates a head difference between the DS and the groundwater levels. To rebalance the system, groundwater has to move

Fig. 11 Picture of the main scarp acquired in 2007. The crack was some 513 m long in May 2008. Underground water seeping into the sub-horizontal layers is responsible of this failure

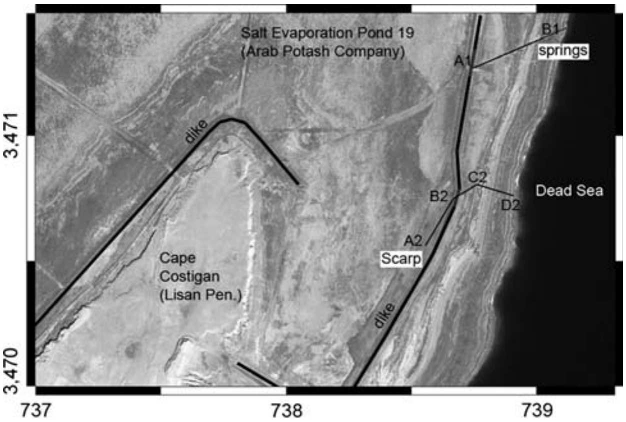


Fig. 12 Ikonos image acquired in 2006 showing the position of the main scarp of landslide no. 4, two topographical cross-cuts (A1–B1) (A2–B2–C2–D2), and the position of major springs. The fault zone east of the Lisan (Fig. 16) appears to control the underlying geologic structure of this zone and sets the stage for near-continuous land slippage

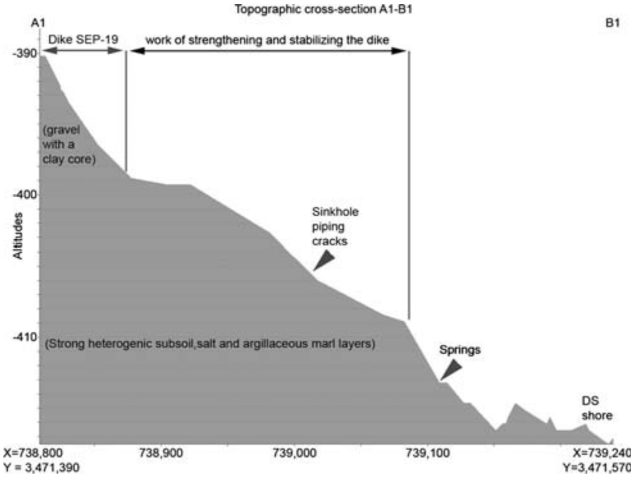


Fig. 13 Elevation along the profile A1–B1 (Fig. 12)

downwards and seawards. But, year after year, the level continues to lower at an accelerating rate. Consequently, the system is dynamic. The disequilibrium acts as a pump for the whole groundwater in the vicinity of the shore. As a consequence, freshwater is injected laterally and new springs/seepages appear in the recently emerged areas making these zones unstable;

2. in the new emerged lands, groundwater has to move downwards and seawards. Indeed, faults and fractures concentrate the flows and play the role of conduits. Sinkholes appear generally in lineaments;
3. intersections of conduits are the most hazardous places;
4. the presence/absence of a 10,000-year-old salt layer is one of the prime factors for dissolution phenomena leading to subsidence and wider sinkholes.

Based on this knowledge, one can look again at the four landslides from this point of view. Table 3 summarizes the main observations. The (+) gives a qualitative assessment of the intensity.

The present status of each landslide is given in Table 4.

Comparison between Tables 3 and 4 emphasizes the key role played by underground water in the activity of the landslides. Landslide nos. 1 and 3 are the more active ones, while landslide nos. 2 and 4 are very slow. It is noticed that landslides nos. 1 and 3 differ completely in terms of presence of sinkholes, subsidence, and faults or fractures. Here, the sediments are probably at the origin of this difference: clay in the first case, gravels in the second. Both have a slow development. Their style differs too: complex and multiple.

Few springs have been noticed in landslides nos. 2 and 4. In consequence, their activity is very slow. On the one hand, strong subsidence was detected in the northern part of the Lisan, including the zone of landslide no. 4. No evidence of subsidence exists for landslide no. 2. On the other hand, one sinkhole occurred in landslide no. 2 and no one for landslide no. 4. The overall activity is diminishing for landslide no. 2 but increases slowly for landslide no. 4. One has to note that the size of landslide no. 4 is at least five times greater than that of landslide no. 2.

When analyzing the overall data of landslide no. 4, the global impression is that it is a consequence of the

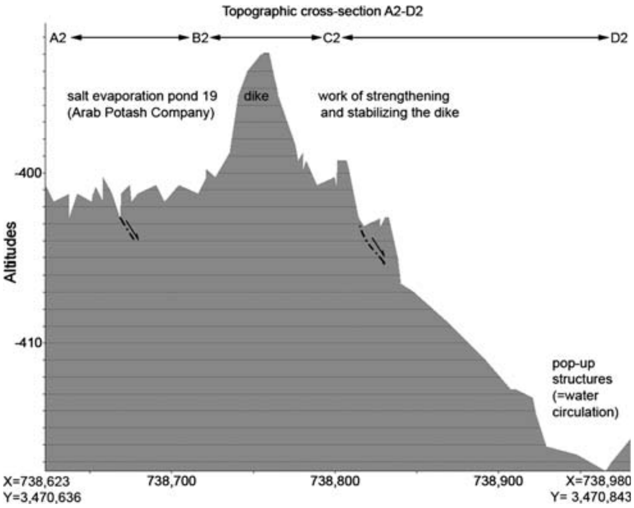


Fig. 14 Elevation along the profile A2–D2 (Fig. 12). Location of scarps and geomorphic features testifying the circulation of unsaturated water with respect to salt in the basement of saltpan 19

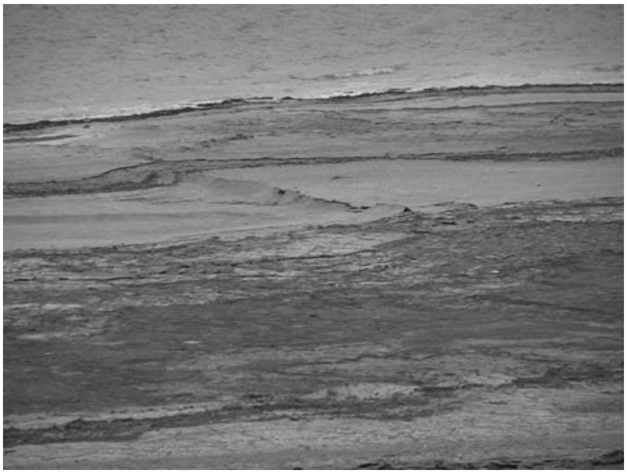


Fig. 15 Looking toward the toe of the landslide from the dike. Water circulation is apparent through numerous pop-up structures linked to the circulation of unsaturated water in the underground

widespread subsidence of the northern Lisan. The moving mass is considerable. The fault scarp is more or less 500 m long, the fissure width ranges from 1 to 10 cm, the height of the landslide is about 12 m, and its length is evaluated at 150 m. The density of the Lisan marls is 1.3 g/cm^3. The movement is very slow because the energy needed to move such a mass is important and derive only from the hydrogeological imbalance caused by the abrupt lowering of the DS.

In all, these factors suggest that once the mass rendered very unstable, slippage could occur suddenly with a threat of provoking a mini tsunami in the Bay of Ghor Al Haditha.

The former Lisan peninsula is a fault-bounded, uplifted geological unit. Observations of its eastern margin (Fig. 16) suggest that landslide no. 4 could be structurally controlled. The fault running along the eastern side extends under saltpan 19, passing by the area of the landslide.

Several studies around the DS have shown that structural elements play an important role of conduit for the underground water finding new paths to reach quickly the lowering base level. This role of conduit is evidenced by the fact the most sinkholes appear in lineaments having orientations in agreement with the observed directions of the major structural features.

Faults playing the role of conduits are discontinuities able to cause failures of a dike. “Internal erosion” is suitable to describe the failure mechanism associated with the uncontrolled flow of water. Water can damage a dike as it flows through cracks, discontinuities at the interfaces between the “conduit” and the dike or its foundations. Seepage flow for internal erosion is typically concentrated. A failure due to internal erosion often leaves a tunnel-shaped void along the conduit. Several examples of such tunnels have been found in the Lisan area (Closson et al. 2007).

It is worth commenting on the origin of groundwater displacements in the recently emerged areas. The hydraulic equilibrium which exists between two fluids of different densities in a homogeneous, unconfined coastal aquifer is described by the Ghyben-Herzberg equation. Under hydrostatic conditions, there is a balance between the weight of the freshwater and the weight of the saline water at their interface (Fig. 17a).

From studies and experiment undertaken in the second half of the 1990s, Salameh and El-Naser (2000) have shown that the theoretical interface configuration calculated according to the Ghyben-Herzberg and Glover equations were confirmed by measurements carried out along the eastern shores of the DS, to the northeast of the Lisan Peninsula. They found that the interface according to Ghyben-Herzberg led little further seaward than the interface obtained from geoelectric soundings and slightly further than the Glover one, which is to be explained by the dynamic approach of Glover, where the freshwater pressure is not only required to compensate the density difference, but also to keep the groundwater flowing.

More recent studies suggested that the post-2000 situation is changing. Akawwi (2006) showed that the submarine groundwater discharged into the Dead Sea in the upper 16 m in Suweimeh area (Fig. 1, no. 3), in the upper 25 m in Zarka Ma’in area (Fig. 1, no. 5), in the upper 15 m in Zara (Fig. 1, between nos. 5 and 6), and it is discharged in the upper 18 m in Wadi Mujib (Fig. 1, no. 6). Kiro et al. (2006) monitored the fresh-saline interface and groundwater level over the past 3 years in the alluvial fan of Wadi Arugot (western side of the DS) up to 2 km from the coast. The groundwater level has decreased at almost the same

Table 3 Description of the landslide areas in regard to causal factors deduced from previous studies concerning sinkholes and subsidence

Landslides	Springs	Subsidence	Sinkholes	Fault/fracture	Salt layer
No. 1	Yes (+++)	Not detected	No	Not sure	Residue
No. 2	Yes (+)	Not detected	Yes (one)	Not detected	Residue
No. 3	Yes (++)	Yes (+++)	Yes (+++)	Inferred	Yes
No. 4	Yes (+)	Yes (+++)	No	Inferred (Fig. 16)	Salty marls (Lisan form)

All landslides have in common the presence of water and salt. Their morphological expression in combination with typical karstic features (sinkholes and subsidence) varies greatly

Table 4 Summary of the status of the four landslides in 2008

Landslides	State	Velocity	Style	Distribution of activity
No. 1	Active (+)	Slow (1.6 m/year to 156 m/year)	Complex (slump, earthflow)	Retrogressive enlarging
No. 2	Active (−)	Very rapid in Sep 1999 (3 m/min to 5 m/s) then very slow to inactive	Single	Diminishing
No. 3	Active (++)	Slow (1.6 m/year to 156 m/year)	Multiple (repeated slump)	Enlarging
No. 4	Active (+)	Very slow (16 mm/year to 1.6 m/year)	Single	Confined

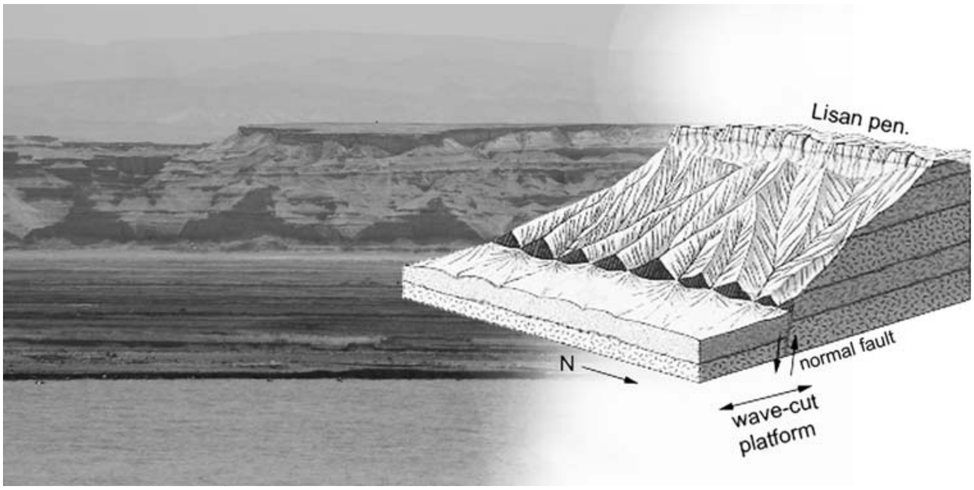
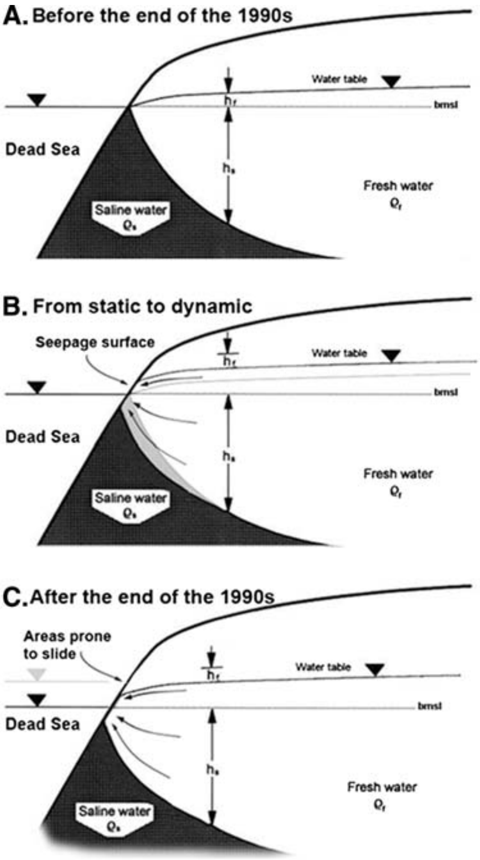


Fig. 16 Vestiges of a fault plane preserved in an alignment of triangular facets. The fault scarp had been produced by active normal faulting along the eastern margin of the former Lisan peninsula. Repeated faulting has produced a rock cliff tens of meters high. Erosion modified the fault scarp but, because the fault plane extends hundreds of meters down into the bedrock, its effects on erosional landforms persisted for several thousand years. Landslide no. 4 is in the extension of this major fault. Playing the role of conduit, this fault is suspected of bringing fresh/brackish water in the northern Lisan thus provoking strong subsidence and other hazards

rate as the Dead Sea in recent years. The fresh-saline interface has also decreased, reaching a 2-m drop near the coast in the last 2 years. Furthermore, a rapid decrease in water salinity above the fresh-saline interface indicated a fast flushing rate of the Dead Sea water in the aquifer. An interesting observation at boreholes farther from the coast is an upward movement of the fresh-saline interface. This upward movement is not affected by the Dead Sea level drop, and could be the response of the interface to the groundwater level drop.

Conclusion

This paper contributed to replace four landslides encountered along the Jordanian DS shore in their setting. It is the



ρs *g *hs = ρf *g *(hs + hf) ⇨

ρf = ρs/(1+hf/hs) ⇨

hs = hf * ρf / (ρs-1) ⇨

hs = 4 * hf

hs = depth to freshwater/seawater interface below sea level

hf = height of water table above sea level

ρf = density of freshwater (=1)

ρs = density of DS water (= 1.225)

g = gravitational acceleration

Fig. 17 **a**, **b** Salameh and El-Naser (2000) have shown that the drop of the DS level has an effect on groundwater by increasing the head differences between the Dead Sea and the groundwater levels in the surrounding areas; **c** then the groundwater drainage is increasing toward the DS. The area previously occupied by the DS water become gradually flushed and occupied by freshwater. This in turn becomes saline due to the residuals of the Dead Sea water in the aquifer matrix

first attempt to bring an overview of the landslide hazards issue along the eastern side of the DS. One has to note that no similar features have been described for the western shore. Many differences exist between the eastern and western shore in the topic of sinkholes, subsidence, and the hydrogeological setting. The problem of landslides further increases the geological contrast between the two shores of the DS.

The approach consists of regularly collecting and comparing data to help resolve some problems generated by the landslide within the framework of land planning and development of infrastructure along the DS coast. Four parameters have been studied: state, velocity, style, and distribution of activity (Table 4).

In conclusion, this article has shown, first, that the Monday 6th September 1999 event was indeed the first of a series of new threats: landslides, at least for the eastern coast of the DS. It suggests that the whole geosystem is changing in a cascading way. The parameters controlling the stability of the ground move toward new values with the modification of the hydrological system in equilibrium with the level of the DS, which lowers at an accelerating rate. Second, the 22nd March 2000, sinkholes and subsidence destroyed 1,650 m of dike of one major saltpan belonging to the Arab potash Company (Fig. 1, see no. 14). Since then, year after year, the remaining parts of this rigid structure continue to record new damages such as one hectometric landslide. This fact consolidates the general opinion that the new emerged lands are unsuitable for any kind of construction, even in places carefully studied with powerful means by civil engineers and declared "safe". It also supports the idea that the mapping of risks is an extremely difficult task in this very dynamic environment.

Acknowledgments We dedicate this work to PE Lamoreaux who died in June 2008. PE Lamoreaux participated with our team on a previous paper published in Environmental geology entitled "Karst system developed in salt layers of the Lisan Peninsula, Dead Sea, Jordan". May he rest in peace; we will keep his memory forever. We thank Professor Elias Salameh for sharing his long experience of the Dead Sea hydrogeological setting, and his advices, as well as the students of the Environmental & Applied Geology Department of the University of Jordan. The research of Damien Closson is supported by the Royal Military Academy of Belgium and the NATO Science Programme/Cooperative Science and Technology Sub-Programme/ Collaborative Linkage Grant no. 982884. The work of Najib Abou Karaki was partly supported by the European Community through the project APAME ''Archaeoseismology and Paleoseismology for the protection of Cultural Heritage and Archaeological sites in the Middle East, The Impact of Large Earthquakes on Archaeological Sites and Cultural Heritage in the Middle East (Jordan, Lebanon, Syria, and Turkey)'' ICA3-CT 2002-10024. The support of these parties is highly appreciated.

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